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South African artist
Marcus Neustetter
uses the term *the
vertical gaze* to
describe the act of
looking, whether
into the night sky

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Conference 9819: Infrared Technology and Applications XLII

Monday - Thursday 18-21 April 2016

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9819-1, Session 1

Small SWaP TEC-less SWIR Camera with Current Mirror Pixel and Temperature Dependent Non-Uniformity Corrections

Jonathan Nazemi, Robert M. Brubaker, UTC Aerospace Systems (United States)

Next generation SWIR imaging systems will require significantly lower power consumption than those currently fielded. A major source of power consumption is the thermoelectric cooling (TEC) device, which provides a stable operating temperature for the focal plane array and allows for the use of simple non-uniformity corrections. Significant power savings can be achieved by eliminating the thermoelectric cooling (TEC) device, however, removing the TEC allows for the operating characteristics of the imager to vary greatly over wide temperature ranges. This challenge was successfully addressed in our previous work with a device that incorporated a CTIA pixel architecture. We now turn our focus to a buffered current mirror pixel architecture, which provides superior day-night imaging performance compared to a CTIA architecture, but exhibits a significantly greater temperature dependence and pixel to pixel variability. We developed a TEC-less camera platform, and then fully explored its electro-optical characteristics from -40 °C to 60 °C. From this data, we developed algorithms that provide temperature based non uniformity corrections of -0.5 % over the entire operating temperature. The observed non uniformity was found to be equivalent to, and in some cases better than the standard TEC camera. Additionally, over the same temperature range, the 640 x 512 resolution camera system exhibited power consumption in the range from 1.2-1.3 W, including all on-board processing.

9819-2, Session 1

High Definition 10µm pitch InGaAs detector with Asynchronous Laser Pulse Detection mode

Avraham R. Fraenkel, SCD Semiconductor Devices (Israel); E. Berkowicz, L. Bykov, R. Dobromislin, R. Elishkov, A. Giladi, Semiconductor Devices (Israel); I. Grimberg, SCD Semiconductor Devices (Israel); I. Hirsh, E. Ilan, C. Jacobson, I. Kogan, P. Kondrashov, I. Nevo, I. Pivnik, S. Vasserman, Semiconductor Devices (Israel)

In recent years SCD has developed InGaAs/InP technology for Short-Wave Infrared (SWIR) imaging. The first product, Cardinal-640, has a 640x512 (VGA) format at 15µm pitch, and more than a thousand units have already been delivered.

We now present Cardinal-1280, having the smallest pitch available today (10µm), with a 1280x1024 (SXGA) format. Cardinal-1280 supports both long-range daylight imaging, and passive or active imaging in Low Light Level (LLL) conditions.

The Readout Integrated Circuit supports snapshot imaging at 13 bit resolution with a frame rate of 160Hz at full format or 640Hz with 2x2 binning, a Low Noise Imaging (LNIM) mode with 35e- readout noise, and has internal Correlated Double Sampling (CDS). An asynchronous Laser Pulse Detection (ALPD) mode is implemented with 2x2 binning in parallel to SWIR imaging (with 10 µm resolution). The new 10 µm pixel is sensitive down to the visible (VIS) spectrum, with a typical dark current of ~ 0.5fA at 280K, and a quantum efficiency >80% at 1550nm.

The Focal Plane Array is integrated into a ruggedized, high vacuum integrity,

metallic package, with a Thermo-Electric Cooler (TEC) for optimized performance, and a high grade Sapphire window. We will present the architecture and preliminary measurement results.

9819-3, Session 1

IR CMOS: a silicon sensor for Nightglow imaging

Martin U. Pralle, James E. Carey, Christopher J. Vineis, SiOnyx Inc. (United States)

SiOnyx has extended the spectral sensitivity of a high performance low cost CMOS image sensor to cover the spectral band from 400nm to 1200nm. The enhanced quantum efficiency is combined with a CMOS sensor design that demonstrates state of the art read noise characteristics and low fixed pattern noise. The resultant sensor exhibits high signal to noise ratio throughout all lighting conditions from noon day sun to moonless clear starlight. In outdoor nighttime conditions, the extended quantum efficiency at wavelengths beyond 1000nm enables the silicon sensor to image "nightglow" illumination. This spectral range has historically only been accessible using non-silicon based SWIR sensors. This enables a true digital nightvision sensor with demonstrated imaging performance at 60 FPS at light levels below 1 mLux. The quantum efficiency enhancement is achieved by utilizing SiOnyx's proprietary ultrafast laser semiconductor processing technology that enhances the absorption of light within a thin pixel layer. Recent progress in device architecture has enabled a further step change in near infrared quantum efficiency performance leading to improved nightglow imaging. SiOnyx has integrated this sensor into various camera systems for surveillance, nightvision and 1064nm laser see-spot.

Demonstrated performance characteristics:

Pixel size : 5.6 & 10 µm

Array size: 720P/1.3Mpix

Frame rate: 60 Hz

Read noise: 2 ele/pixel

Spectral sensitivity: 400 to 1200 nm (with 10x QE at 1064nm)

Daytime imaging: color (Bayer pattern)

Nighttime imaging: moonless starlight conditions

1064nm laser imaging: daytime imaging out to 2Km

9819-4, Session 1

Verification of sensitivity enhancement of SWIR imager technology in advanced multispectral SWIR/VIS zoom cameras with constant and variable F-number

Martin Huebner, Bertram Aichtner, Michael Kraus, Mario O. Münzberg, Airbus DS Optronics GmbH (Germany)

Current designs of combined VIS-color/SWIR camera optics use constant F-number over the full field of view (FOV) range. Especially in the SWIR, limited space for the camera integration in existing system volumes and relatively high pitch dimensions of 15µm or even 20µm force the use of relatively high F- numbers to accomplish narrow fields of view < 2.0° with reasonable resolution for long range observation and targeting applications. Constant F-number designs are already reported and considered [1] for submarine applications. The comparison of electro-optical performance was

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based on the given detector noise performance and sensitivity data by the detector manufacturer [1] and further modelling of the imaging chain within linear MTF system theory.

The visible channel provides limited twilight capability at F/2.6 but in the SWIR the twilight capability is degraded due to the relatively high F-number of F/7 or F/5.25 for 20 μm and 15 μm pitch, respectively. Differences between prediction and experimental verification of sensitivity in terms of noise equivalent irradiance (NEI), scenery based limiting illumination levels and imager MTF resolution are shown for the visible and the SWIR spectral range. Within this context, currently developed improvements using optical zoom designs for the multispectral SWIR/VIS camera optics with continuously variable F-number are discussed, offering increased low light level capabilities at wide and medium fields of view while still enabling a NFOV $< 2^\circ$ with superior long range targeting capabilities under limited atmospheric sight conditions at daytime.

[1] M. Hübner et al., 'Improved sensitivity performance of SWIR imager in a multispectral VIS/SWIR zoom camera for long-range surveillance tasks' [9451-1], SPIE DSS 2015, Vol. 9451

9819-5, Session 1

Numerical modeling of extended short-wave infrared InGaAs focal plane arrays

Andreu Glasmann, Hanqing Wen, Enrico Bellotti, Boston Univ. (United States)

Indium gallium arsenide (InGa_{1-x}As) has been an ideal material choice for short wave infrared (SWIR) imaging due to its low dark current and superb quantum efficiency between 0.9 and 1.5 μm . By increasing the indium composition of the alloy, it is possible to decrease the energy gap from 0.74 eV to 0.47 eV and consequently increase the cutoff wavelength from 1.7 μm to 2.63 μm . As a result, the InGaAs absorber is no longer lattice matched to the InP substrate introducing lattice strain and electrically degrading misfit dislocations through the material. Growing layers of a compositionally graded material, such as InAsP or InAlAs, can increase device performance by eliminating lattice mismatch at the absorbing layer. In comparison to the high-performance 1.7 μm InGaAs focal plane arrays, there has been little effort in optimizing material parameters for extended wavelength device simulation. The purpose of this work is to demonstrate a robust 3D numerical model of extended wavelength In_{0.83}Ga_{0.17}As focal plane arrays by using a similar approach as outlined in earlier work (DeWames, 2015; Wichman, 2015). Using comparable device architecture as recently published work (Haimei Gong, et. al, 2014; Xue Li, et. al 2014; Arslan, Y., et. al 2014), we simulate typical device characteristics such as dark current, quantum efficiency, and performance over temperature. Auger and radiative recombination parameters for In_{0.83}Ga_{0.17}As are calculated using the Green's function formalism previously applied to HgCdTe, InAsSb, and In_{0.53}Ga_{0.17}As (Hanqing Wen, et. al, 2014-15).

9819-6, Session 1

A 400 KHz line rate 2048-pixel stitched SWIR linear array

Ankur Anchlia, Rosa M. Vinella, Daphne Gielen, Kristof Wouters, Vincent Vervenne, Peter Hooylaerts, Pieter D. Deroo, Wouter Ruythooren, Danny De Gaspari, Johan Das, Xenics NV (Belgium); Patrick J. Merken, Xenics NV (Belgium) and Royal Military Academy (Belgium)

Xenics has developed a family of stitched SWIR long linear arrays that work up to 400 KHz of line rate. These arrays serve medical (3D SD-OCT) and industrial applications that require high line rates as well as Space applications that require long linear arrays.

The arrays are based on a modular ROIC design concept: modules of 512 pixels are stitched during fabrication to achieve 512, 1024 and 2048 pixel

arrays. Each 512-pixel module has its own on-chip digital sequencer, analog readout chain and 4 output buffers. This modular concept enables a long array to run at a high line rates irrespective of the array length, which limits the line rate in a traditional linear array. The ROIC is flip-chipped with InGaAs detector arrays.

The FPA has a pixel pitch of 12.5 μm and has two flavors: Square (12.5 μm) and rectangular (250 μm). The front-end circuit is based on Capacitive Trans-impedance Amplifier (CTIA) to attain stable detector bias, and good linearity and signal integrity, especially at high speeds. The CTIA has an input auto-zero mechanism that allows to have low detector bias (<20mV). An on-chip CDS facilitates removal of CTIA KTC and 1/f noise, and other offsets, achieving low noise performance. There are five gain modes in the FPA giving the full well range from 85Ke- to 40Me-. The FPA operates in Integrate While Read mode and, at a master clock rate of 60MHz and a minimum integration time of 1.4 μs , achieves the highest line rate of 400 KHz.

In this paper, measurements results will be presented in order to demonstrate the detector performance.

9819-7, Session 1

MCT SWIR modules for passive and active imaging applications

Rainer Breiter, Matthias Benecke, Detlef Eich, Heinrich Figgemeier, Andreas Weber, Joachim C. Wendler, Alexander Sieck, AIM INFRAROT-MODULE GmbH (Germany)

Based on AIM's state-of-the-art MCT IR technology, detector modules for the SWIR spectral range have been developed, fabricated and characterized. While LPE grown MCT FPAs with extended 2.5 μm cut-off have been fabricated and integrated also MBE grown MCT on GaAs is considered for future production.

Two imaging applications have been in focus operating either in passive mode by making use of e.g. the night glow, or in active mode by laser illumination for gated viewing. Dedicated readout integrated circuits (ROIC), realized in 0.18 μm Si-CMOS technology providing the required functionality for passive imaging and gated imaging, have been designed and implemented. For both designs a 640x512 15 μm pitch format was chosen. The FPAs are integrated in compact dewar cooler configurations using AIM's split linear coolers. A command and control electronics (CCE) provides supply voltages, biasing, clocks, control and video digitization for easy system interfacing.

For imaging under low-light conditions a low-noise 640x512 15 μm pitch ROIC with CTIA input stages and correlated double sampling was designed. The ROIC provides rolling shutter and snapshot integration. A larger format 1024x768 in a 10 μm pitch is under development. The module makes use of the extended SWIR spectral cut-off up to 2.5 μm .

To be used for active gated-viewing operation SWIR MCT avalanche photodiodes have been implemented and characterized on FPA level in a 640x512 15 μm pitch format. The specific ROIC provides also the necessary functions for range gate control and triggering by the laser illumination.

The paper will present the development status and performance results of AIM's MCT based SWIR Modules for imaging applications.

9819-8, Session 1

Short-wavelength infrared photodetector with InGaAs/GaAsSb superlattice

Chuan Jin, Shanghai Institute of Technical Physics (China) and Univ. of Chinese Academy of Sciences (China); Jianxin Chen, Qingqing Xu, ChengZhang Yu, Shanghai Institute of Technical Physics (China)

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In this paper, our recent study on InGaAs/GaAsSb photodetector for extended short wavelength infrared detection is reported. First of all, the InGaAs/GaAsSb SL structure were grown and characterized. XRD and AFM results show that the lattice mismatch and the root-mean-square roughness of the sample are as small as and 0.1Å, respectively. The variable-temperature PL spectra were measured from 78K to 308K, results show that the temperature dependence of transition energy fits well with the Varshni's equation. Then, different diameter devices with top-illuminated mesas were fabricated by using conventional photolithography and liftoff techniques. The devices are fabricated without passivation layer and Ti(20nm)-Pt(30nm)-Au(300nm) layers were deposited by e-beam evaporator to form the contact. The electrical and optical properties of the devices were measured as well.

Experimental results showed the devices has a QE product of 10.42% in 2.1um at 300K, and the 100% cutoff wavelength is at 2.5um as expected. The Johnson-noise limited D^* can reach 1.0×10^{10} Jones at 2.1um and 300K, which is better than previous reports. Dark current measurement illustrates the activation energy is 0.39eV. And the rapidly dark current drop with temperature suggests the dominant mechanism for the dark current in the regime is the thermal generation of carriers.

9819-9, Session 1

Recent development of SWIR focal plane array with InGaAs/GaAsSb type-II quantum wells *(Invited Paper)*

Hiroshi Inada, Kenichi Machinaga, Sundararajan Balasekaran, Kouhei Miura, Takahiko Kawahara, Masaki Migita, Katsushi Akita, Yasuhiro Iguchi, Sumitomo Electric Industries, Ltd. (Japan)

In the short wavelength infrared (SWIR) region up to 2.5µm, low cost, high responsivity focal plane array (FPA) are expected for many industrial applications such as mining, recycling plastic and remote monitoring of infrastructure. HgCdTe (MCT) is predominantly used for infrared imaging applications even in SWIR region. However, MCT is expensive and contains environmentally hazardous substances. Therefore, its application has been restricted mainly military and scientific use and was not spread to commercial use. Recently, InGaAs/GaAsSb type II quantum well structures are considered as an attractive material for realizing low dark current PDs owing to lattice-matching to InP substrate. Moreover, III-V compound material systems are suitable for commercial use. In this report, we describe successful operation of FPA with InGaAs/GaAsSb quantum wells and mention improvement of optical characteristics.

Planar type pin-PDs with 250-pairs-InGaAs(5nm)/GaAsSb(5nm) quantum well absorption layer were successfully fabricated. The p-n junction was formed in the absorption layer by the selective diffusion of zinc. InGaAs layer which was adopted as a layer for adjusting concentration distribution of zinc, were grown on quantum wells. Electrical and optical characteristics of FPA or pin-PDs were investigated. Dark current of $1 \mu\text{A}/\text{cm}^2$ at 213K, which showed good uniformity and lead to good S/N ratio in SWIR region, were obtained. Moreover, we could successfully reduce of stray light in the cavity of FPA. As a result, the clear image was taken with 320x256 format. This result means FPA using InGaAs/GaAsSb type-II quantum wells is a promising candidate for commercial applications.

9819-10, Session 1

2D SWIR image sensor with extended wavelength cutoff of 2.5 µm on InP/InGaAs epitaxial wafers with graded buffer layers

Prabhu Mushini, Wei Huang, Robert M. Brubaker, Manuel Morales, Matthew Dobies, Scott P. Endicter, Wei Zhang, William J. Gustus, Gary Mathews, Namwoong Paik, Sensors

Unlimited, a United Technologies Co. (United States); THuc-Uyen Nguyen, Sensors Unlimited, A UTC Aerospace Systems Company (United States)

Two-dimensional photo detector arrays with cutoff wavelength up to 2.5 µm were fabricated on InP/InGaAs epitaxial wafers with graded buffer layers in 320x256 geometry on a 12.5µm pitch. Novel growth and fabrication techniques were employed to fabricate these arrays and optimize the performance. The dark current performance of the detector was investigated for a wide range of temperatures. The fabricated detector array was mated with a ROIC and packaged with a multi stage TEC and investigated further at the FPA level. The effect of the graded buffer layers on the sensor performance was investigated and the results were compared to other methods used to develop and fabricate 2D image sensors on extended wavelength materials.

9819-25, Session 1

High-performance mid- and long-wavelength infrared photodetectors based on InAs/InAs_{1-x}Sb_x type-II superlattices *(Invited Paper)*

Manijeh Razeghi, Northwestern Univ. (United States)

High performance mid- and long-wavelength infrared (MWIR & LWIR) detection is a very powerful tool for different military applications, such as tracking and reconnaissance missions, and civilian safety. InAs/InAs_{1-x}Sb_x type-II superlattices (T2SLs) material system is a desirable candidate for realization of high-performance single- and dual-band imaging systems in different infrared regimes.

We have demonstrated high-performance LWIR nBn photodetectors based on InAs/InAs_{1-x}Sb_x type-II superlattices. The photodetector's 50% cut-off wave-length was 10µm at 77 K. The photodetector with a 6µm-thick absorption region exhibited a peak responsivity of 4.47 A/W at 7.9µm, corresponding to a quantum efficiency of 54% at 90 mV bias voltage under front-side illumination and without any anti-reflection coating. With an R_xA of 119Ω·cm² and a dark current density of 4.4x10⁻⁴ A/cm² under 90 mV applied bias at 77 K, the photodetector exhibited a specific detectivity of 2.8x10¹¹ Jones.

Additionally, we have demonstrated bias-selectable dual-band MWIR/LWIR photodetector with 50% cut-off wavelengths of 5.1 and 9.5µm, respectively. The mid-wavelength channel exhibited a quantum efficiency of 45% at 100 mV bias voltage under front-side illumination and without any anti-reflection coating. With a dark current density of 1x10⁻⁷A/cm² under 100 mV applied bias, the mid-wavelength channel exhibited a specific detectivity of 8.2x10¹² Jones at 77 K. The long-wavelength channel exhibited a quantum efficiency of 40%, a dark current density of 5.7x10⁻⁴A/cm² under -150 mV applied bias at 77 K, providing a specific detectivity value of 1.64x10¹¹ Jones.

9819-39, Session 1

High-performance short-wavelength infrared photodetectors based on InAs/InAs_{1-x}Sb_x/AlAs_{1-x}Sb_x type-II superlattices for high operating temperature applications *(Invited Paper)*

Manijeh Razeghi, Northwestern Univ. (United States)

High performance short-wavelength infrared (SWIR) active detection and imaging at high operating temperatures is a very powerful tool for different military applications, such as tracking and reconnaissance missions, and civilian safety. InAs/InAs_{1-x}Sb_x type-II superlattices (T2SLs) material system is a desirable candidate for realization of high-performance single- and dual-band imaging systems in different infrared regimes.

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We report the demonstration of high-performance short-wavelength infrared n-i-p photodiode based on InAs/InAs_{1-x}Sb_x/AlAs_{1-x}Sb_x type-II superlattices on GaSb substrate. The device is designed to have a 50% cut-off wavelength of 1.8μm at 300 K. The photodetector exhibited a room-temperature (300 K) peak responsivity of 0.47 A/W at 1.6μm, corresponding to a quantum efficiency of 37% at zero bias under front-side illumination, without any anti-reflection coating. With an R0xA of 285Ω·cm² and a dark current density of 9.6x10⁻⁵A/cm² under -50 mV applied bias at 300 K, the photodiode exhibited a specific detectivity of 6.45x10¹⁰cm·Hz^{1/2}/W. At 200 K, the photodiode exhibited a dark current density of 1.3x10⁻⁸A/cm² and a quantum efficiency of 36%, resulting in a detectivity of 5.66x10¹² cm·Hz^{1/2}/W.

9819-11, Session 2

Mid- and thermal-infrared remote sensing at the Jet Propulsion Laboratory *(Invited Paper)*

William R. Johnson, Jet Propulsion Lab. (United States)

The mid and thermal infrared for the Earth surface is defined between 3 and 14μm. In the outer solar system, objects are colder and their Planck response shifts towards longer wavelengths. Hence for these objects (e.g. icy moons, polar caps, comets, Europa), the thermal IR definition usually stretches out to 50μm and beyond. Spectroscopy has been a key part of this scientific exploration because of its ability to remotely determine elemental and mineralogical composition. Many key gas species such as methane, ammonia, sulfur, etc. also have vibrational bands which show up in the thermal infrared spectrum above the background response.

Over the past few decades, the Jet Propulsion Laboratory has been building up a portfolio of technology to capture the MTIR for various scientific applications. Three recent sensors are reviewed: The airborne Hyperspectral thermal emission spectrometer (HyTES), the ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Mars Climate Sounder (MCS)/DIVINER. Each of these sensors utilize a different technology to provide a remote sensing product based on MTIR science. For example, HyTES is a push-brooming hyperspectral imager which utilizes a large format quantum well infrared photodetector (QWIP). The goal is to transition this to a new complementary barrier infrared photodetector (CBIRD) with a similar long wave cut-off and increased sensitivity. ECOSTRESS is a push-whisk Mercury Cadmium Telluride (MCT) based high speed, multi-band, imager which will eventually observe and characterize plant/vegetation functionality and stress index from the International Space Station (ISS) across the contiguous United States (CONUS). MCS/DIVINER utilizes thermopile technology to capture the thermal emission from the polar caps and shadow regions of the moon. Each sensor utilizes specific JPL technology to capture unique science.

9819-12, Session 2

High-performance infrared fast cooled detectors for missile applications *(Invited Paper)*

Yann Reibel, Laurent Espuno, Ahmad F. Sultan, Thibault Augey, Pierre Cassaigne, Rachid Taalat, Hubert Huet, Laurent Rubaldo, Noura Matallah, SOFRADIR (France)

SOFRADIR was selected in the late 90's for the production of the 320?256 MW detector for major European missile programs. This experience has established SOFRADIR as a key player in the field of missile programs.

SOFRADIR has developed a vast portfolio of lightweight, compact and high performance JT-based solutions for missiles. ALTAN is a 384x288 Mid Wave infrared detector with 15μm pixel pitch, and is offered in a miniature ultra-fast Joule-Thomson cooled Dewar.

Since Sofradir offers both Indium Antimonide (InSb) and Mercury Cadmium

Telluride technologies (MCT), we are able to deliver the detectors best suited to customers' needs.

In this paper we are discussing different figures of merit for very compact and innovative JT-cooled detectors and are highlighting the challenges for infrared detection technologies.

9819-13, Session 2

The Miniaturized Infrared Detector of Atmospheric Species (MIDAS) a low-mass, MWIR low-power hyperspectral imager *(Invited Paper)*

Casey I. Honniball, Robert Wright, Paul G. Lucey, Sarah T. Crites, Hawaii Institute for Geophysics and Planetology (United States)

Emerging interferometric techniques have improved the use of microbolometer sensitivity for hyperspectral imaging. With little power consumption compared to photon-detecting arrays that require cryogenic cooling, microbolometer arrays are attractive candidates for imaging instruments on small satellites. In this presentation we describe a prototype instrument under development at the University of Hawai'i. The Miniaturized Infrared Detector of Atmospheric Species (MIDAS) is a Mid Wave Infrared (MWIR; 2.4-4 microns) hyperspectral imager for Earth science applications. MIDAS uses a Sagnac interferometer to decompose the light into its component frequencies using a beamsplitter and two mirrors to generate an interference pattern which, when sampled and processed using standard Fourier transform techniques, allows a calibrated spectral radiance spectrum to be derived for each scene element. In previous work we demonstrated the ability to collect high quality hyperspectral data for terrestrial surfaces in the Long Wave Infrared using microbolometer arrays with interferometric spectrometers. In the MWIR, however, this is more challenging due to lower signal availability, and is further complicated for daytime observations with the mixing of reflected and emitted signals. The primary aim of MIDAS is detection of methane using the 3.4 micron absorption feature for applications like fire characterization, volcano monitoring, and industrial site studies where there is an abundance of signal from localized high temperature sources. A cooled photon-detector version of MIDAS will be used to quantify the sensitivity of the uncooled microbolometer version. Both prototypes have been assembled for benchtop characterization, and preliminary science data collection is underway using calibrated gas cells.

9819-14, Session 2

SKYWARD: the next-generation airborne infrared search and track *(Invited Paper)*

Luca Fortunato, Giangiuseppe Colombi, Aurora Ondini, Carlo Quaranta, Claudio Giunti, Barbara Sozzi, Giorgio Balzarotti, SELEX ES S.p.A. (Italy)

Infrared Search & Track systems are an essential element of the modern and future combat aircrafts. Passive automatic search, detection and tracking functions, are key points for silent operations or jammed tactical scenarios.

SKYWARD represents the latest evolution ofIRST technology in which high quality electro-optical components, advanced algorithms, efficient hardware and software solutions are harmonically integrated to provide high-end affordable performances. Additionally, the reduction of critical opto-mechanical elements optimises weight and volume and increases the overall reliability.

Multiple operative modes dedicated to different situations are available; many options can be selected among multiple or single target tracking, for surveillance and engagement, and imaging, for landing or navigation aid, assuring the maximum system flexibility.

The high quality 2D-IR sensor is exploited by multiple parallel processing

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chains, based on linear and non-linear techniques, to extract the possible targets from background, in different conditions, with false alarm rate control.

A widely tested track processor manages a large amount of candidate targets simultaneously and allows discriminating real targets from noise whilst operating with low target to background contrasts.

The capability of providing reliable passive range estimation is an additional qualifying element of the system.

Particular care has been dedicated to the detector non-uniformities, a possible limiting factor for distant targets detection, as well as to the design of the electro-optics for a harsh airborne environment.

The system can be configured for LWIR or MWIR waveband according to the customer operational requirements. An embedded data recorder saves all the necessary images and data for mission debriefing, particularly useful during in-flight system integration and tuning.

9819-15, Session 3

Pyxis handheld polarimetric imager

David B. Chenault, Joseph L. Pezzaniti, Justin P. Vaden,
Polaris Sensor Technologies, Inc. (United States)

The instrumentation for measuring infrared polarization signatures has seen significant advancement over the last decade. Previous work has shown the value of polarimetric imagery for a variety of target detection scenarios including detection of manmade targets in clutter and detection of ground and maritime targets while recent work has shown improvements in contrast for aircraft detection and biometric markers. These data collection activities have generally used laboratory or prototype systems with limitations on the allowable amount of target motion or the sensor platform and usually require an attached computer for data acquisition and processing. Still, performance and sensitivity have been steadily getting better while size, weight, and power requirements have been getting smaller enabling polarimetric imaging for a greater or real world applications.

In this paper, we describe Pyxis, a microbolometer based imaging polarimeter that produces live polarimetric video of conventional, polarimetric, and fused image products. A polarization microgrid array integrated in the optical system captures all polarization states simultaneously and makes the system immune to motion artifacts of either the sensor or the scene. The system is battery operated, rugged, and weighs about a quarter pound, and can be helmet mounted or handheld. On board processing of polarization and fused image products enable the operator to see polarimetric signatures in real time. Both analog and digital outputs are possible with sensor control available through a tablet interface. A top level description of Pyxis is given followed by performance characteristics and representative data.

9819-16, Session 3

Geolocating thermal binoculars based on a software defined camera core incorporating HOT MCT grown by MOVPE

Luke Pillans, SELEX ES Ltd. (United Kingdom)

Geo-location is the process of calculating a target position based on bearing and range relative to the known location of the observer. As the usable range of a handheld thermal imager increases geo-location becomes more important because user estimates of target location tend to be less accurate at longer ranges. Firefly is a software defined camera core incorporating a system-on-a-chip processor running the Android operating system. The processor has a range of industry standard serial interfaces which were used to interface to peripheral devices including a laser rangefinder and a digital magnetic compass. The core has built in GPS which provides the third variable required for geo-location. The graphical capability of Firefly allowed flexibility in the design of the man-machine interface (MMI), the finished system gives access to extensive functionality without appearing

cumbersome or over-complicated to the user. This paper covers both the hardware and software design of the system, including how the camera core influenced the selection of peripheral hardware, and the MMI design process which incorporated user feedback at various stages.

9819-17, Session 3

WFOV imaging sensor performance considering FPA sensitivity and resolution (Invited Paper)

Sung-Shik Yoo, Kenton A. Green, Northrop Grumman Electronic Systems (United States); Ronald G. Driggers, Justin Sigley, Orges Furxhi, St. Johns Optical Systems (United States)

In the past several decades, a number of technologies in infrared (IR) detector material have sufficiently advanced in maturity to demonstrate theoretically-predicted sensitivity. In parallel to infrared detector material technology advances, tremendous development has been made to realize state-of-art readout chips (ROIC) with significantly reduced noise, long integration capability, and reduced pitch size such that resolution is optically limited. The outcome of both of these technological advances is the practical realization of high resolution and high sensitivity focal plan array (FPA) imaging sensors, allowing IR system engineers to design innovative imaging systems that had never before been imagined.

The use of such state-of-art high performance IR FPAs, however, is still limited to high value systems and platforms mainly in military and space applications, and so the two inter-related constraints of low demand and highly customized production still inhibits efforts to further reduce both FPA and systems cost. To complement the above trends, low-end performance monolithic IR sensors have recently become commercially available for applications such as cell phones at greatly reduced cost, but with reduced resolution and sensitivity. If a detector technology could leverage both the advanced high resolution photo-detector ROICs and the low-cost monolithic FPA fabrication techniques, a path forward for commercialization of high-performance infrared FPAs is clear, depending on the application's system performance needs. Recently a thermo-electrically cooled (TEC) FPA was demonstrated using polycrystalline PbSe directly deposited on ROIC wafers and excellent performance was confirmed with measured NEDT of 26 mK and pixel operability of 99.8% at an operating temperature of 230K (f/1, 3-5 ?m). Since the structure is a monolithic FPA, the detector fabrication process lends itself to wafer-scale packaging, testing and evaluation, and will reduce the production cost tremendously in the near future.

Also due to the simple pixel structure, the opportunity has presented itself for scalability to increased resolution with reduced pitch. With optimizations to deposition and material processing, analysis suggests high-SNR photo-carrier-generated detection will increase the operating temperature to room temperature, removing the cryo-cooling constraints on FPA and optics and enabling new opportunities for greatly-reduced camera cores.

The typical long-range performance analysis of imaging sensor system performance is predicted based on both resolution and sensitivity of a cryo-cooled sensor with large optics, therefore driving inherently high system cost. In this study, considering the opportunities described above for high-resolution, small SWaP low-cost imagers, our analysis is concentrated on wide field-of-view (FOV) sensors of typically 90 degree coverage or more per sensor. This includes applications such as target detection (and identification although not usually performed in WFOV), driving performance, and threat warning. Our analysis quantifies the system parameters for aperture (SWaP)-constrained applications where performance is resolution-limited and not sensitivity-limited, providing further evidence that emerging monolithic imagers will provide an outstanding sensor for wide field military applications.

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9819-18, Session 4

Gibbs free energy assisted passivation layers

Ömer Salihoglu, Bilkent Univ. (Turkey); Tunay Tansel, Hacettepe Univ. (Turkey); Mustafa Hostut, Akdeniz Üniv. (Turkey); Yuksel Ergun, Anadolu Univ. (Turkey); Atilla Aydinli, Bilkent Univ. (Turkey)

Surface passivation is extremely critical in Type-II superlattice (T2SL) InAs/GaSb photodetectors, due to large number of very thin alternating layers. Different etch rates of InAs and GaSb during mesa definition lead to roughness on the mesa side walls. A conformal coating can be critical to cover all the tiny undulations on mesa side walls. Components of InAs/GaSb SL are chemically very reactive. Their surfaces are easily oxidized and a native oxide layer of several nanometers thick is quickly formed upon exposure to air. Adsorbed oxygen diffuses through the surface, reacts with Ga, Sb, In and As atoms then forms native oxides such as Ga₂O₃, Sb₂O₃, In₂O₃, As₂O₃ and InAsO₃ some of which is conductive. This mechanism is responsible for the formation of additional conductive channels and consequently, leads to a large surface component of dark current.

We have compared electrical performance of type-II superlattice photodetectors, designed for MWIR operation, passivated by different passivation techniques. We have used ALD deposited Al₂O₃, HfO₂, TiO₂, ZnO, PECVD deposited SiO₂, Si₃N₄ and sulphur containing ODT SAM passivation layers on InAs/GaSb p-i-n superlattice photodetectors with cutoff wavelength at 5.1 µm. In this work, we have compared the result of different passivation techniques which are done under same conditions, same epitaxial structure and same fabrication processes. We have found that ALD deposited passivation is directly related to the Gibbs free energy of the passivation material. Gibbs free energies of the passivation layer can directly be compared with native surface oxides to check the effectiveness of the passivation layer before the experimental study.

9819-19, Session 4

Thermal instability of GaSb surface oxide

Koji Tsunoda, Yusuke Matsukura, Ryo Suzuki, Masaki Aoki, Fujitsu Labs., Ltd. (Japan)

Type-II super-lattice (T2SL) infrared photodetectors have been attracting the interest of the IR detector community due to their expected high performance comparable, or even better than, II-VI MCT detectors, which maintains the material advantage of mechanically robust and chemically stable III-V materials the same as quantum well or dot detectors.

One disadvantage of T2SL detectors, however, is their high side wall leakage current, believed to be caused by the side wall oxide formed during the fabrication process. To suppress this leakage current, a variety of treatment techniques, such as sulfur termination or dry plasma treatment, or specific device structures, such as shallow etched mesa isolation (SEMI) structure, have been proposed.

In this presentation, we investigated the GaSb oxide characteristics both in a comparison with III-V GaAs oxide to stress the specificity of the GaSb oxide even among the III-V compound semiconductor family and in terms of the thermal (in)stability, having the device fabrication process in mind, to clarify the origin of the side wall leakage current.

We found that, first, GaSb oxide formation is very different from those of GaAs, even though both GaSb and GaAs are among the same Ga-V compound semiconductor family. One amazing finding is that GaSb oxide can be formed even during DI water immersion. Second, thermally treated GaSb oxide forms elemental Sb, and we speculate that this Sb would be the cause of the leakage current.

9819-20, Session 4

**T2SL technology for LWIR detectors
(Invited Paper)**

Philip C. Klipstein, Eran Avnon, Daniel Azulai, Yael Benny, Avraham R. Fraenkel, Alex Glozman, Elad Hojman, Olga Klin, Leonid Krasovitsky, Lidia Langof, Inna Lukomsky, Michal Nitzani, Itay Shtrichman, Noam Rappaport, Noam Snapi, Eliezer Weiss, SCD Semiconductor Devices (Israel); Avi Tuito, Israel Ministry of Defense (Israel)

SCD has developed a range of advanced infrared detectors based on III-V semiconductor heterostructures grown on GaSb. The XBn/XBp family of barrier detectors enables diffusion limited dark currents comparable with MCT Rule-07 and high quantum efficiencies. SCD's 15 micron pitch "Pelican-D LW" XBp type II superlattice (T2SL) detector was designed with a -9.5 micron cut-off wavelength and a format of 640x512 pixels. The detector contains InAs/GaSb and InAs/AlSb T2SLs, engineered using k.p modeling of the energy bands and photo-response. The wafers are grown by molecular beam epitaxy and are fabricated into Focal Plane Array (FPA) detectors using standard FPA processes, including wet and dry etching, indium bump hybridization, under-fill, and back-side polishing. The FPA has a quantum efficiency above 50%, and operates at 77K with background limited performance. The pixel operability of the FPA is above 99% and it exhibits a stable residual non uniformity (RNU) of better than 0.04% of the dynamic range. The FPA uses a new digital read-out integrated circuit (ROIC), and the complete detector closely follows the interfaces of SCD's MWIR Pelican-D detector. The T2SL technology is now in the process of qualification and transfer to production at SCD, and first Pelican-D LW prototypes are being integrated into new electro-optical systems. A comparison with other T2SL technologies such as InAs/InAsSb will be made, and the potential of our design for a monolithic MW/LW dual band pixel will be highlighted.

9819-21, Session 4

Optimization of the electro-optical performances of MWIR InAs/GaSb superlattice pin photodiodes with asymmetrical designs

Isabelle Ribet-Mohamed, Edouard Giard, ONERA (France); Marie Delmas, Jean-Baptiste Rodriguez, Philippe Christol, Institut d'Electronique et des Systèmes (France)

Asymmetrical InAs/GaSb superlattice (SL) pin photodiodes were recently proposed to both decrease the dark current (since it should decrease the intrinsic carrier concentration) and increase the quantum efficiency (since it should increase the wavefunctions overlap) of MWIR SL photodetectors. An improvement of more than one decade on the dark current has been demonstrated with an InAs-rich design, but the quantum efficiency (QE) of the first pin photodiodes didn't reach the expected values.

In this paper, we show that the low QE was due to a non-optimal collection of the carriers, penalized by a very short holes diffusion length L_h. Fitting our experimental data with a fully analytical model, we estimated that L_h was lower than 100nm @77K. This value is coherent with the 30-35ns minority lifetimes we have measured on InAs-rich samples. To overcome this difficulty, two solutions were proposed and tested : the first one is to change the side of the illumination, and the second one is to switch minority carriers type by doping the structure. The former concept was validated with the realization of a 320x256 focal plane array, for which a QE of 42% was measured at 77K (mean value in the range [3-4.7µm]). The latter concept led to the realization of single elements with a slightly p-doped active zone. Quantum efficiencies as high as 60% were measured at operating temperatures varying from 77K to 130K and at zero bias voltage. A BLIP temperature of 110K was also determined.

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9819-22, Session 4

High performance type-II superlattice focal plane array with 6 μ m cutoff wavelength

Kouhei Miura, Kenichi Machinaga, Sundararajan Balasekaran, Takahiko Kawahara, Masaki Migita, Hiroshi Inada, Yasuhiro Iguchi, Sumitomo Electric Industries, Ltd. (Japan); Michito Sakai, Junpei Murooka, Haruyoshi Katayama, Japan Aerospace Exploration Agency (Japan); Masafumi Kimata, Ritsumeikan Univ. (Japan)

The cutoff wavelength of 6 μ m is preferable for the full usage of the atmospheric window in the mid-wavelength region. An InAs/GaSb Typell superlattice (T2SL) is the only known infrared material that has a theoretically predicted higher performance than HgCdTe and also the cutoff wavelength can be easily controlled by changing the thickness of InAs and GaSb. In this study, we used a p-i-n structure with a 300 period superlattice consisting of InAs/InSb/GaSb (9MLs/0.8MLs/7MLs) which was grown on a Te-doped GaSb substrate by molecular beam epitaxy. A mesa-type photodiode array with 320x256 pixels and 30 μ m pixel pitch was fabricated. Mesa structures were formed by inductively coupled plasma reactive ion etching with halogen gas mixture. Prior to the deposition of the SiO₂ passivation film, dry cleaning was applied for reducing the dark currents. The photodiode array has an n-on-p structure and n-electrodes and p-electrodes were formed on the n-type InAs cap layer of each pixel and p-type GaSb buffer layer, respectively. The photodiode array was hybridized with the commercially available ROIC using indium bumps. The NETDs measured with F/2.3 optics were 32mK and 45mK at 77K and 100K, respectively. The operability was over 99%. This FPA is suitable for full usage of the atmospheric window in the mid-wavelength region.

9819-23, Session 4

Indium-bump-free antimonide superlattice membrane detectors on a silicon substrate

Seyedeh Marziyeh Zamiri, Brianna Klein, Theodore Schuler-Sandy, The Univ. of New Mexico (United States); Stephen A. Myers, SKINfrared LLC (United States); Francesca Cavallo, Sanjay Krishna, The Univ. of New Mexico (United States)

Wafer level integration of photonic detectors on silicon substrate is expected to dramatically bring down the cost of detectors. State-of-the-art fabrication of focal plane arrays (FPA) is based on wafer level processing including mesa delineation, surface passivation, metal evaporation and indium deposition. Following these steps is a die-level fabrication with dicing, flip-chip bonding to a silicon read-out integrated circuit, substrate thinning/removal and packaging. The latter steps are low-yield processes that dramatically increase the cost and fabrication time. In the recent past, significant advancements have been made in the field of III-V materials integration onto alternate substrates, which are cheaper and easy to manufacture. In this work we have developed an epitaxial lift-off approach to transfer InAs/InAsSb type II superlattice membranes (T2SL-M) from the GaSb native substrate on a Silicon substrate and process Indium bump free detector on the new substrate. The T2SL detector was a PIN homojunction with 14ML InAs - 12ML InAs_{0.81}Sb_{0.19} that was grown on a 70 nm Al_{0.4}Ga_{0.6}Sb sacrificial layer. T2SL-M were partially released from the original GaSb substrate by selective lateral removal of the sacrificial layer in a diluted HF solution. Pixels were then removed from GaSb substrate with polydimethylsiloxane PDMS and transferred to a Si substrate deposited with a thin layer of Ti/Au/Ti which serves as the bottom metal contact of the detector. The pixels were then covered with SiNx to passivate them as well as increase the adhesion of the detector pixels to the new substrate. Top contact with an aperture was defined for front side illumination of the substrate. The integrity of the T2SL-M upon transfer to the new host was

confirmed by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The optical quality of the released and transferred T2SL-M is evaluated by photoluminescence (PL) at room temperature. Moreover, STEM represents the quality of the interface between transferred pixels and new substrate as well as I-V measurement and spectral response of indium bump free mid infrared photodetector on Si which show performance of the operating device.

This work was supported by AFRL FA9453-14-1-0248

9819-24, Session 4

Type-II superlattice infrared detector technology at Fraunhofer IAF

Robert Rehm, Volker Daumer, Tsvetelina Hugger, Norbert Kohn, Wolfgang Luppold, Raphael Müller, Jasmin Niemasz, Johannes Schmidt, Johannes Schmitz, Frank Rutz, Tim O. Stadelmann, Matthias Wauro, Andreas Wörl, Martin Walther, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

Fraunhofer IAF develops type-II superlattice (T2SL) infrared (IR) detectors for the mid- (3-5 μ m, MWIR), long-wavelength (8-12 μ m, LWIR) and very long-wavelength (>12 μ m, VLWIR) regimes. The highly flexible T2SL detector technology allows covering of a wide range of applications from high-operating temperature (HOT) single element IR detectors, e.g., for laser-based sensing systems, to cooled focal plane array (FPA) detectors for high-performance imaging cameras. The freedom of design inherent to InAs/GaSb T2SLs is nowadays used to realize novel device types based on heterojunction concepts to suppress several dark current components. In the LWIR, our first heterojunction-based FPAs with a spatial resolution of 640x512 pixels on a 15 μ m pixel pitch already reach a noise equivalent temperature difference (NETD) below 30 mK with F/2-optics against a 300 K background. The present talk will summarize the results achieved so far and give an overview of the ongoing development T2SL detector technology work at Fraunhofer IAF.

9819-26, Session 4

Advantages of T2SL: Results from production and new development at IRnova

Linda Höglund, Carl Asplund, Rickard Marcks von Württemberg, Himanshu Kataria, Dan Lantz, Sergiy Smuk, Eric Costard, Henk Martijn, IRnova AB (Sweden)

In recent years Type-II superlattices have proven to be an excellent candidate for high end Infrared Detectors and are now competing with the traditional state-of-the-art technologies. IRnova has been manufacturing type-II MWIR detectors based on InAs/GaSb superlattices since 2014. Results from the first years of production of an MWIR detector with 320x256 pixels on 30 μ m pitch using the ISC9705 readout circuit will be presented in terms of operability and other key production parameters. The main performance parameters will be compared with other IR technologies. Results on image stability and correctness of T2SL detectors will be presented (both from 320 x 256 detectors with 30 μ m pitch and 640 x 512 detectors with 15 μ m pitch using the ISC0403 readout circuit). The spatial noise is less than 60 % of the temporal noise over a large scene temperature span and stays below the temporal noise even after repeated detector temperature cycles. No deterioration of image quality over time can be observed. IRnova will also give a status update on the development of T2SL detectors for the SWIR, MWIR and LWIR region for existing and new applications. Recent work on development towards higher operating temperature, smaller pitch and larger format arrays will also be presented.

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9819-91, Session 4

High-temperature turn-on behavior of an nBn infrared detector

David Ting, Alexander Soibel, Linda Höglund, Cory J. Hill, Sam Keo, Anita M. Fisher, Arezou Khoshakhlagh, Sarath Gunapala, Jet Propulsion Lab. (United States)

The nBn photodetector architecture proposed and demonstrated by Maimon and Wicks provides an effective means for lowering generation-recombination dark current by suppressing Shockley-Read-Hall processes, and for reducing surface leakage dark current. This has been especially beneficial for III-V semiconductor based infrared photodiodes, which traditionally tend to suffer from excess depletion dark current and lack of good surface passivation. Recently Soibel et al. [Appl. Phys. Lett. 105, 023512 (2014)] analyzed the high-temperature characteristics of a mid-wavelength infrared detector based on the Maimon-Wicks InAsSb/AlAsSb nBn design, and found that the quantum efficiency does not degrade when the operating temperature increases to above room temperature. However, it was also found that the turn-on bias becomes larger at higher temperatures. This counter-intuitive behavior was originally attributed to the change in the band alignment between the absorber and top contact layers caused by the shift of the absorber and the heavily-doped contact layer band edges relative to the Fermi energy, and thereby forming a larger hole blocking barrier at higher temperature. We provide additional analysis that demonstrates the inadequacy of the original argument, and show that at higher temperature more applied bias is required to overcome the hole-blocking barrier as it is more difficult to deplete the regions in the vicinity of the AlAsSb barrier due to high intrinsic carrier density levels. We also provide clarification on basic device dark current and quantum efficiency characteristics.

9819-27, Session 5

1/f noise origin update (Invited Paper)

Paul R. Norton, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

No Abstract Available

9819-28, Session 5

Development of dual-band barrier detectors (Invited Paper)

Elena Plis, Stephen A. Myers, David A. Ramirez, Sanjay Krishna, SKINfrared LLC (United States); Edward P. Smith, Scott M. Johnson, Raytheon Co. (United States); Borys P. Kolasa, SKINfrared LLC (United States) and Raytheon Co. (United States); Craig A. Keasler, Raytheon Co. (United States)

Multiband detector capability is desirable in a variety of infrared (IR) applications related to remote sensing and object identification. Mercury cadmium telluride (MCT) photodiodes and quantum well infrared photodetectors (QWIPs) have been the dominant technologies for such applications. In the recent past newer material system, the InAs/GaSb type-II strained layer superlattices (T2SLs), has been a subject of active research to meet next-generation sensor requirements. With excellent control over individual layer thicknesses provided by the molecular beam epitaxy (MBE) technique, T2SL multiband focal plane arrays (FPAs) are expected to demonstrate better spatial uniformity compared to MCT. Additionally, T2SLs have intrinsically higher quantum efficiency than QWIPs, in which the absorption of normally incident light is forbidden by optical selection rules.

Here we report on development of dual-band T2SL detectors with barrier designs at Skinfrared. Over the past five years, we demonstrated mid-wave/

long-wave (MW/LWIR, cut-off wavelengths are 5 μm and 10.0 μm), and LW/LWIR (cut-off wavelengths are 9 μm and 11.0 μm) detectors with the nBn and pBp designs. Dark current of last generation bulk-limited pBp detectors is competitive with recent Raytheon Vision systems (RVS) example nBn performance. Details of single-element dual-band detector performance as well as FPAs will be discussed during the presentation.

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9819-29, Session 6

The role of infrared technologies and systems in the German Federal Defense Forces (Keynote Presentation)

K. H. Rippert, Bundesamt für Ausrüstung, Informationstechnik und Nutzung der Bundeswehr (Germany)

No Abstract Available

9819-30, Session 7

Bulk growth and surface characterization of epitaxy ready cadmium zinc telluride substrates for use in IR imaging applications

James P. Flint, Rebecca J. Martinez, Thomas E. M. Betz, Galaxy Compound Semiconductors, Inc. (United States); Jason M. MacKenzie, Francis J. Kumar, Glenn Bindley, Redlen Technologies (Canada)

Cadmium Zinc Telluride (CZT) is an important compound semiconductor material upon which Mercury Cadmium Telluride (MCT) layers are deposited epitaxially to form structures that are used in high performance detectors covering a wide IR spectral band. The epitaxial growth of high quality MCT layers presents many technical challenges and a critical determinant of material performance is the quality of the underlying bulk CZT substrate. CZT itself is a difficult material to manufacture where traditional methods of bulk growth are complex and low yielding, which constrains the supply of commercially available substrates. In this work we report on the epitaxy-ready finishing of Travelling Heather Method (THM) grown Cd_{0.96}Zn_{0.04}Te grown substrates. The THM method is well established for the growth of high quality CZT crystals used in nuclear, X-ray and spectroscopic imaging applications and in this work we demonstrate the application of this technique to the growth of IR specification CZT substrates in areas of up to 5 cm x 5 cm square. We will discuss the advantages of the THM method over alternative methods of bulk CZT growth where the high yield and material uniformity advantages of this technique will be demonstrated. Chemomechanical polishing (CMP) of 4 cm x 4 cm CZT substrates reveals that III-V (InSb/GaSb) like levels of epitaxy-ready of surface finishing may be obtained with modified process chemistries. Surface quality assessments will be made by various surface analytical and microscopy techniques from which the suitability of the material for subsequent assessment of quality by epitaxial growth will be ascertained.

9819-31, Session 7

Rapid development of high-volume manufacturing methods for epi-ready GaSb wafers up to 6" diameter for IR imaging applications

Nathan W. Gray, Andrew G. Prax, Jonathan M. Demke,

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Daniel R. Johnson, Joseph G. Bolke, W. B. Alexander, 5N Plus Inc. (United States)

We present a new method to produce low-cost, high quality gallium antimonide (GaSb) substrates for type-II superlattice structures for large MWIR-VLWIR imaging detectors. This method applies high-volume wafer manufacturing standards learned from the silicon industry to increase performance and value of our wafers.

The rapid development cycle of only six months from project start to epi-ready 6" GaSb wafers was the culmination of our optimized process for developing a crystal growth process. We outline this general process using GaSb as a case-study, acknowledging significant learning taken from the development of InSb and previously Ge crystal growth in-house. All of these crystal growth technologies achieved new levels of manufacturing success by challenging traditional practices and incorporating significant lessons and know-how from the more mature silicon industry.

The development effort resulted in a new encapsulant-free GaSb single crystal growth method using a modified Czochralski puller, routinely yielding more than seventy 6" wafers per crystal or several hundred 3" or 4" wafers per crystal. This timely development meets the needs of the type-II superlattice market and promises to deliver quality substrates at an improved cost structure that will foster growth and development in this market.

GaSb wafers grown using this method were processed into epi-ready substrates and characterized extensively for bulk crystal quality (x-ray rocking curve and x-ray topography), electrical properties and uniformity, surface condition, and wafer flatness. Furthermore, superlattice structures were grown on these substrates and characterized to demonstrate the substrate quality and maturity of the process.

9819-32, Session 7

Enabling on-axis InSb crystal growth for high-volume wafer production: characterizing and eliminating variation in electrical performance for IR focal plane array applications

Jason L. Merrell, Nathan W. Gray, Joseph G. Bolke, 5N Plus Inc. (United States); Andrew N. Merrell, The Univ. of Utah (United States); Andrew G. Prax, Jonathan M. Demke, Nikolas W. Gossett, 5N Plus Inc. (United States)

InSb focal plane array (FPA) detectors are key components in IR imaging systems which significantly impact both cost and performance. Detector performance is affected by the electronic and crystallographic quality and uniformity of the semiconductor substrate. Formerly an off-axis growth technique met the needs of the market for the low volume, small diameter {111} InSb wafers, however with the growing demand for larger focal plane arrays and improved economies of scale, larger wafer diameters challenged the limits of the growth techniques.

High-volume, high-yield production of {111} plane InSb wafers to the standards required for FPA device manufacture requires growth of on-axis <111> crystals. This improves the structural survivability of larger diameter long crystals but can be hampered by severe non-uniform dopant incorporation on {111} crystallographic planes exposed to the growth interface, a phenomenon known as the "facet effect." We report on newly developed growth methods that eliminates the negative effects of anisotropic dopant incorporation enabling high volume manufacturing of {111}-oriented substrates. This growth process scales easily with the dimensional needs of wafer industry as well as offers greatly enhanced wafer yield per crystal. We discuss in detail the thermodynamic mechanism for the facet effect, and it's subsequent control or elimination to achieve viable on-axis growth. We also report extensive characterization of wafers from crystals grown using these methods, including crystal quality, electronic properties and uniformity on macroscale, and we also report on a characterization technique to measure microscale dopant variation across the wafer.

9819-33, Session 8

Long wavelength resonator-QWIPs

Kwong-Kit Choi, U.S. Army Research Lab. (United States); Steve C Allen, Yajun Wei, L-3 Communications - Cincinnati Electronics (United States); Jason N. Sun, Kimberley A. Olver, Richard X. Fu, U.S. Army Research Lab. (United States)

We are developing resonator-QWIPs for long wavelength detection. The cutoff wavelength is about 10.5 microns. R-QWIP pixels with 25 micron pitch were hybridized to fanout circuits for radiometric measurements. In one of the material designs, we adopted a coupled double-well design in each quantum well period to broaden the material absorption bandwidth. Detector structure that contains 19 QW periods is labeled as DW1, and that contains 8 QWs are labeled as DW2. Both materials are moderately doped to 0.5E18/cm³ to obtain a proper balance between quantum efficiency and dark current. For the DW1 R-QWIPs, we observed a peak QE of 37% under positive substrate bias and 20% under negative bias, showing a large polarity asymmetry. On the other hand, for the DW2 R-QWIPs, we observed similar QE of 35% and 34% under the respective polarities. The detection bandwidths in all cases are approximately 2 microns. We attribute the QE asymmetry in DW1 to the highly localized resonant optical intensity distribution in the resonator volume and the nonlinear potential profile of the QW layers. Under positive bias, the high field domain in the QWIP layer coincides spatially with the high intensity region and thus it yields a higher QE. And this observed QE matches the amount of optical absorption predicted by EM modeling. For DW2, since its layer thickness is thinner, all the QWs are within the high intensity region irrespective to bias polarity. The location of the high field domain thus becomes less relevant. Because of their moderate doping density, the dark current is observed to be the same as the background photocurrent under F/2 optics and 300 K background at the operating temperature of 65 K. In addition to the fanout study, we have also fabricated focal plane arrays for imaging demonstration. The preliminary FPA result is consistent with that of the test structures.

9819-34, Session 8

QWIPs at IRnova: a status update

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IRnova has a long history of producing QWIP detectors for LWIR band. In this paper an overview will be given of the current products (detectors with 640x480 and 384x288 pixels respectively, on 25µm pitch) and their performance. Their superior stability and uniformity inherent to detectors based on the III/V material system will be demonstrated. Furthermore, a detector specifically designed for a hand held system used for the detection of SF6 gas will be presented. The detector format is 320x256 pixels with 30µm pitch using the ISC9705 read out circuit. The peak wavelength is at 10.55 µm and NETD 22mK.

9819-72, Session 8

Study on reflow process of SWIR FPA during flip-chip bonding technology

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Flip-chip bonding is a familiar hybridization technology used for the fabrication of infrared Focal Plane arrays (FPA). Reflow soldering and thermo-compression are two main types of flip-chip technology used for infrared FPA hybridizing. In comparison to reflow soldering, thermo-compression require higher pressure to weld solder bumps. Reflow soldering is the primary method for Flip-chip bonding to avoid overpressure defects,

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but it's often operated at the higher temperature. Reflow process is also used to reform the solder bumps especially for high density package. Reflow process during flip-chip bonding technology in short wavelength infrared (SWIR) InGaAs/InP FPA due to its high temperature stability was studied in this paper. Indium material is the ideal solder for infrared FPA due to its plasticity in wide temperature range. The amorphous indium bump was converted into spherical bump restricted on UBM (under bump metallization) by surface tension forces during reflow. But many factors have effects on Indium bump reflow process, for example, the thickness of oxide layer, the impurity in Indium bump etc. In order to analyze the transformation of Indium oxide and effects on Indium bump reflow process, the InGaAs/InP FPAs plated Indium bumps were stored in different environment. Before reflow process, the Indium bumps were investigated by XPS (X-ray Photoelectron Spectroscopy) in detail. The profiles of Indium bumps after reflow process were observed by SEM (scanning electron microscopy). The effects of impurity in Indium bumps and the interaction between Indium and the metal in UBM during reflow were discussed. The characteristics of InGaAs photodetectors haven't deteriorated after reflow was confirmed in this paper.

9819-92, Session 8
Colloidal quantum dots for low-cost MWIR imaging

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Monodisperse suspensions of HgTe colloidal quantum dots (CQD) are readily synthesized with infrared energy gaps between 3 and 12 microns. Infrared photodetection using dried films of these CQDs has been demonstrated up to a wavelength of 12 microns, and HgTe CQD devices with 3.6 micron cutoff have been reported and show good absorption ($>10^4 \text{ cm}^{-1}$), response time and detectivity ($2 \cdot 10^{10}$ Jones) at a temperature of 175 K; with the potential of uncooled imaging. The synthesis of CQDs and fabrication of detector devices employ bench-top chemistry techniques, leading to the potential for rapid, wafer-scale manufacture of MWIR imaging devices with low production costs and overhead. The photoconductive, photovoltaic and optical properties of HgTe CQD films will be discussed relative to infrared imaging, along with recent achievements in integrating CQD films with readout integrated circuits to produce CQD-based focal plane arrays.

9819-64, Session PSTue
Extraction of static parameters to extend the EKV model to cryogenic temperatures

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The electric simulation models, necessary in the CMOS circuits design, provided by the foundries are valid in general at the standard temperature range of -40 to 65 °C. These models are not suitable to the design of circuits intended to operate at cryogenic temperatures as is the case of cooled infrared readout circuits.

In order to generate a library of CMOS electric simulation models valid at cryogenic temperatures the characterization of wide and long CMOS transistors are investigated.

The EKV2.6 model, which is an industry-standard compact simulation model for CMOS transistors, is used in this characterization. Due to its relatively small number of parameters this model is well suited to the parameter extraction procedures when not disposing of an expensive automated parameter extraction system.

It is shown that to provide an appropriate cryogenic IV-characteristic it is

sufficient to extract only five parameters - threshold voltage V_{T0} , body effect GAMMA, Fermi potential PHI, transconductance factor KP, and the vertical characteristic field for mobility reduction E_0 . The proposed approach is tested above strong freeze-out temperature in a standard 0.35um and 3.3V CMOS technology, employing extraction procedures recommended in the literature.

9819-65, Session PSTue
Bandwidth control of wavelength-selective uncooled infrared sensors using two-dimensional plasmonic absorbers

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Although typical uncooled infrared sensors (IR) can be used to record information such as the shape, position and average radiant intensity of objects, these devices cannot record color (wavelength) information. The inclusion of wavelength selectivity would pave the way for the development of advanced uncooled IR sensors that can provide color information and also multi-color image sensors, which would have significant advantages for applications such as fire detection, gas analysis, hazardous material recognition, and biological analysis. We have previously demonstrated an uncooled IR sensor using a two-dimensional plasmonic absorber (2D PLA) with wavelength selectability over a wide range in the mid- and long-IR regions. The PLA has a 2D Au-based periodic array of dimples, in which surface plasmon modes are induced and wavelength-selective absorption occurs. However, the dependence of the absorption bandwidth on certain structural parameters has yet to be clarified. For practical application of such sensors to tasks such as gas detection, the bandwidth is an extremely important factor. In the present study, control of the bandwidth is theoretically investigated using a rigorous coupled wave analysis approach. It is demonstrated that the dimple sidewall structure has a large impact on the bandwidth and can be used to control both narrow- and broad-band absorption. Increasing the slope of the sidewalls is found to decrease the bandwidth due to suppression of cavity-mode resonance in the depth direction of the dimples. These results will contribute to the development of high-resolution wavelength-selective uncooled IR sensors.

9819-66, Session PSTue
Graphene on plasmonic metamaterials for infrared detection

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Graphene consists of a single layer of carbon atoms with a two-dimensional hexagonal lattice structure. Recently, it has been the subject of increasing interest due to its excellent optoelectronic properties and interesting physics. Graphene is considered to be a promising material for optoelectronic devices due to its fast response and broadband capabilities. However, graphene absorbs only 2.3% to all wavelengths which limits the performance of photodetectors that are based on it. One promising approach to enhancing the optical absorption of graphene is the use of plasmonic resonance. Plasmonics is a field that has been receiving considerable attention from the viewpoint of both fundamental physics and practical applications, and graphene plasmonics has become one of the most interesting topics in optoelectronics. The ability to control plasmons in graphene is expected to enhance the performance of both graphene and plasmonic devices.

In the present study, we investigated the optical properties of graphene on a plasmonic metamaterial absorber (PMA). The PMA was based on a metal-insulator-metal structure, in which surface plasmon resonance was induced. The graphene was synthesized by chemical vapor deposition and was transferred onto the PMA, and the reflectance of the PMA in the infrared

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(IR) region, with and without graphene, was compared. The presence of the graphene layer was found to lead to significantly enhanced absorption only at the main plasmon resonance wavelength. The results obtained in the present study are expected to lead to improvements in the performance of IR detectors.

9819-68, Session PSTue

Inductively coupled plasma etching of HgCdTe IRFPAs detectors at cryogenic temperature

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To fabricate various advanced structures in HgCdTe, the Inductively Coupled Plasma enhanced Reactive Ion Etching system is indispensable. However, due to low damage threshold and complicated behaviors of mercury in HgCdTe. The lattice damage and induced electrical conversion is very common. According to the ultrafast diffusion model during etching period. Mercury interstitials may not diffuse deep into the material at cryogenic temperature. In this report, ICP etching of HgCdTe at cryogenic temperature was implemented. The etching system with cryogenic assembly is provided by Oxford Instrument. The sample table was cooled down to 120K with liquid nitrogen. The mask of SiO₂ with a contact layer of ZnS functioned well at this temperature, where no shrinkage or shedding occurred as happened with traditional PR mask. The selectivity and etching velocity maintained the same as reported in the etching of room temperature. Most important of all, the etching induced electrical conversion was reduced at cryogenic temperature. Under low temperature baking procedure, the vacancy doped p-type sample was healed, reaching a hall concentration of positive 7.8E15/cm³ and mobility of 684.6[cm²/(V*s)], which is impossible for HgCdTe etched under room temperature. Meanwhile, comprehensive mechanism involving more than mercury interstitial is needed, as the mercury interstitials may not be removed under low temperature.

9819-69, Session PSTue

Effect of stress on dark current of HgCdTe IRFPAs detectors on Si substrates

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Si substrates has been widely used in fabrication of HgCdTe infrared focal plane arrays (IRFPAs) detectors which usually operate at low temperature. In spite of perfect thermal match of Si substrates with Si ROICs, performance of HgCdTe IRFPAs detectors on Si substrates might be seriously impaired by stress resulting from large lattice mismatch between HgCdTe epitaxial films and Si substrates as well as thermal mismatch at low temperature between different layers of IRFPAs detectors, which have been observed in many situations and could not yet been explained clearly. In order to evaluate how stress affects HgCdTe IRFPAs detectors at low temperature, specially designed equipment has been adopted, allowing to adjust stress state of samples conveniently at low temperature through intentionally exerting deformation on them. Current voltage (I-V) property of HgCdTe IRFPAs detectors has been investigated at different stress states, which could be simulated and computed by means of finite elements analysis. Also spectral response has been measured at low temperature and shows little change under different stress states. It is shown that relation of dark current and stress state is complex and generally compressive stress could raise dark current more apparently than tensile stress, under which possible mechanism is presented.

9819-70, Session PSTue

Design and realization of 512x8 TDI over-sampling readout system in digital domain for infrared

Bing Han, Shanghai Institute of Technical Physics (China)

In order to make the infrared image sensors suitable for space high resolution imaging applications, a real time realizing TDI Over-sampling readout system in digital domain which is based on FPGA (Field Programmable Gate Array) is presented in this paper. A 512x8 silicon Over-sampling readout system based on FPGA is designed and realized for cooled MWIR scanning focal plane arrays (FPAs).The TDI algorithm accumulates the corresponding pixels of adjoining frames in digital domain, so the gray values increase by M times, where M is for the integration number and the maximum of M is eight. Thus, in signal-to-noise ratio the image's quality can be improved and specifically the SNR of the IRFPA can be improved by M. In addition, the over-sampling system has better performance at target energy gathering, clutter suppression and dim target detection, and improves the spatial resolution of linear detector in the scanning direction. Experiments show that the non-linearity in 8 times accumulated is less than 9%, the measured NETD is less than 22mK and the SNR is improved by 2.59. Every parameter is better than UN-TDI. Captured example images are showed in paper.

9819-71, Session PSTue

Tests at sea comparing different wavelengths

Leif Lagerkvist, Saab AB (Sweden)

This presentation shows the results from a test campaign in Sweden. The purpose of the evaluation was to compare different camera performances with respect to the camera wavelength band, not primarily cameras from different suppliers. Two of the cameras were equipped with detectors operating in the long wavelength band and three had detectors operating in the medium wavelength band.

Besides the above mentioned cameras the image from an existing 2nd generation LW camera on the tracking system on-board was recorded. This camera is equipped with a mechanically scanned 4x288 pixel array.

The tests were performed on-board a ship from the Swedish Navy in the archipelago south of Stockholm during winter time.

The IR-cameras were borrowed from different suppliers and they are all more or less commercially available as is. This means that there are differences e.g. regarding field-of-view, f#, number of pixels, NETD etc. but this was acceptable for the purpose of the tests.

The tests took place during two days with both gray skies and sunshine. There were two tasks that were of special interest; one was to observe how good image could be achieved for objects relatively near-by and with how much details and the other task was to measure the range performance against a target. The target was in this case an outgoing Cessna tracked by the on-board tracking system.

The image quality and visible details in the image were evaluated by looking towards targets of opportunity. There were also some observations on a target flying over water with solar glint present.

9819-73, Session PSTue

Long-wavelength infrared photodetector using submonolayer quantum dots

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Quantum dot (QD) infrared detectors can be used for a variety of applications in the military, medical, and industrial areas. Infrared photodetectors based on submonolayer (SML) QDs have been widely researched in recent years due to the higher QDs density, better uniformity, and no wetting layer as compared to the Stranski-Krastanov QD. In this study, we report on InAs SML QD infrared photodetector performance for long wavelength infrared detection. The SML QD infrared photodetector samples were grown by molecular beam epitaxy (MBE) system with As₂ cracker source on a semi-insulating GaAs substrate. The device structure consists of InAs SML QDs embedded in In_xGa_{1-x}As quantum well (QW) surrounded by GaAs and Al_xGa_{1-x}As barrier. In order to investigate the structural properties of SML QDs, we took cross-sectional STEM images. The SML QD devices were processed in 410?410 μm² mesas using inductively coupled plasma etching, followed by the contact metal deposition. The devices had a circular aperture of 300 ?m in diameter for IR detection. We have measured the polarization dependent spectral response of SML-QD based photodetector using various angular in-plane and out-plane polarizations. We also report a systematic approach for controlling the intersubband transition energy level in SML QD infrared photodetectors, in order to control the peak wavelength of the device. Detailed study of device design, fabrication and characterizations for these SML QD infrared detectors will be presented.

9819-74, Session PSTue

NIRCA ASIC for the readout of focal plane arrays

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This work is a continuation of our preliminary tests on NIRCA the Near Infrared Readout and Controller ASIC [1]. The primary application for NIRCA is future astronomical science and Earth observation missions where NIRCA will be used with mercury cadmium telluride image sensors (HgCdTe, or MCT) [2], [3], [4]. Recently we have completed the ASIC tests in the cryogenic environment down to 77 K. We have verified that NIRCA provides to the readout integrated circuit (ROIC) regulated power, bias voltages, and fully programmable digital sequences with sample control of the analogue to digital converters (ADC). Both analog and digital output from the ROIC can be acquired and image data is 8b/10b-encoded and delivered via serial interface. The NIRCA also provides temperature measurement, and monitors several analog and digital input channels. The preliminary work confirms that NIRCA is latch-up immune and able to operate down to 77 K. We have tested the performance of the 12-bit ADC with pre-amplifier to have 10.8 equivalent number of bits (ENOB) at 1.4 MSps and possibility to sample at 2 MSps. The 1.8-V and 3.3-V output regulators and the 10-bit DACs show good linearity and work as expected. The programmable sequencer is implemented as a micro-controller and we provide source code examples that illustrate how to operate the device in user applications. The test results of the working prototype ASIC show good functionality and performance from room temperature down to 77 K.

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9819-75, Session PSTue

High-spectral resolution airborne short-wave infrared hyperspectral imager

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Short Wave InfraRed(SWIR) spectral imager is good at detecting difference between materials and penetrating fog and mist. High spectral resolution SWIR hyperspectral imager plays a key role in developing earth observing technology. Hyperspectral data cube can help band selections that is very important for multispectral imager design. Up to now, the spectral resolution of many SWIR hyperspectral imager is about 10nm. A high sensitivity airborne SWIR hyperspectral imager with narrower spectral band will be presented. The system consists of TMA telescope, slit, spectrometer with planar blazed grating and high sensitivity MCT FPA. The spectral sampling interval is about 3nm. The IFOV is 0.5mrad. To eliminate the influence of the thermal background, a coldshield is designed in the dewar. The pixel number of spatial dimension is 640. Performance measurement in laboratory and image analysis for flight test will also be presented.

9819-76, Session PSTue

The investigation of dynamic time delay integration technique of infrared TDI-CMOS

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In the scanning imaging system, the time-delay integration (TDI) sensor is often used to extend the effective exposure time. For the traditional TDI-CCD sensor, the process of TDI is implemented by charge transfer among the adjacent pixels along the scanning direction and thus it requires velocity matching strictly between the scanning speed and the charge transfer speed. From the view point of imaging, velocity mismatch leads to image degradation as the system modulation transfer function (MTF) degrades. However, in recent years, research on TDI-CMOS is gradually increasing and indicates two kinds of methods to implement the process of TDI in voltage domain and digital domain. When in the digital domain, the output voltage of sensor is firstly converted to digital signal by analog to digital converter (ADC), and then does the process of TDI. That makes it possible to exploit the image information of the digital signal before TDI process to get the transition image of every integration stage of the sensor which avoids the charge transfer along with the scanning direction between adjacent pixels. Though a thorough analysis about the TDI process of the TDI-CMOS sensor, we propose a novel method to detect the velocity mismatch by means of transition image matching, and it helps to implement the dynamic TDI by select the optimal integration stages

9819-77, Session PSTue

Au/Cr-ZnO-Ni structured metal-insulator-metal diode fabrication using Langmuir-Blodgett technique for infrared sensing

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The thin nanolayer film of ZnO was synthesized through Langmuir-Blodgett (LB) organic precursor film. The zinc stearate monolayer was formed at air-water interface using zinc acetate as a subphase. The zinc stearate monolayers were deposited on silicon (Si), glass, and gold (Au)/chromium (Cr) plated Si substrates using LB technique. Later, the zinc stearate multilayers LB films on substrates were annealed at two different temperatures (300°C and 550°C) for the fabrication of zinc oxide (ZnO) nanolayer film. The zinc stearate monolayers as well zinc oxide (ZnO) nanolayer films were characterized using atomic force microscopy (AFM) and X-ray diffraction techniques. The X-ray diffraction measurement has shown the hexagonal wurtzite structure of the ZnO nanolayer on the substrate. The average surface roughness was estimated to be 1.076 nm using AFM technique. The metal-insulator-metal (MIM) diode structure was realized by sandwiching ZnO nanolayer film between thin layer of Au/Cr and Nickel (Ni) on silicon substrates. The electron tunneling conduction mechanism is understood through the current-voltage (I-V) characteristics of MIM diode. The highest measured sensitivity magnitude of 20 in inverse of voltage (V⁻¹) with rectification ratio of nearly 10 at ±400 mV in MIM diode is an indicative of its potential application in infrared sensing applications. However, the thin film of ZnO synthesized using LB film as an insulating layer in metal-insulator-metal diode structure was studied for the first time.

9819-78, Session PSTue

Modeling, design, and fabrication of rectenna arrays for infrared energy harvesting and detection applications

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Current energy harvesting and detection devices operating in THz frequency regime endure inadequate efficiency despite the fact considerably high fabrication cost. Antenna-coupled rectifiers (rectennas) are one of the most potential candidates for newer paradigms arising in THz energy harvesting and detection realm. Employing THz antennas coupled with Metal-Insulator-Metal (MIM) tunneling diodes termed as rectenna is viable solution for efficient THz energy harvester and detector rendering significantly low fabrication cost. In this paper, innovative and efficient antenna-coupled metal-insulator-metal diode for energy harvesting and detection applications at 60 THz is presented.

The MIM diode model is developed and optimized for THz energy harvesters. MIM diodes are modelled and simulated in MATLAB environment. Parametric analysis to extract the physical properties of MIM structure is performed and IC compatible material sets for MIM structure are selected for fabrication of diodes at desired frequency. Unlike the material choices already available in the literature comparatively hard to process and expensive like Ni and Nb₂O₅, Single layer insulator Metal-Insulator-Metal (MIM) and double layer insulator Metal-Insulator-Insulator-Metal (MIIM) diodes are fabricated with materials set Au, Al, Cr, Ti, Al₂O₃, Cr₂O₃ and TiO₂. Electrical DC measurements and characterization of fabricated MIM and MIIM diodes are conducted to evaluate device performance. At zero bias, resistance of approximately 2.3 kΩ and responsivity of about -6.02 A/W are obtained. The measured resistance and responsivity from these diodes leads to overall 12% efficiency enhancement in rectennas for THz energy harvesting.

9819-79, Session PSTue

Development of microcrystalline Si/SiGe multi-quantum well bolometer detector for infrared imaging systems

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This paper presents initial results of Multiple Quantum Well (MQW) type detector arrays in mono-crystal Silicon Germanium (SiGe) process with different pitch sizes such as 25μm, 17μm and 12μm which is first time in SiGe process. Ge concentration up to 50% is achieved with high TCR value and 1/f noise. Bolometer arrays are two dimensional arrays that respond to the electromagnetic radiation through change in electrical material properties by temperature increase. By being used in uncooled systems, bolometers hold more than 90% of share in the infrared imaging market. Today's uncooled IR imaging market is dominated by bolometers and bolometer market is shared between 70%VOx and 30% ?-Si detectors. VOx technology has %3/K compared to %3/K ?-Si detectors and hence is superior. However, it is very costly due it can not be processed in standard silicon foundries. Yet, both detectors are inferior in performance to those manufactured by mono-crystalline materials. Recently, mono-crystal SiGe MQW detectors have shown both high TCR and low 1/f noise. In order to increase the TCR, measure of sensitivity, Ge concentration is to be increased with two fundamental problems. Due to mismatches of lattice constants between Si and SiGe the interface creates stress and dislocations occur, causing dysfunctionality. In the literature %30 Ge concentration has been shown but not above. Theoretically, it is possible to achieve %4.5/K TCR value by increasing the Ge concentration up to 50%, however this creates the deformation of epitaxial layers due to strain relaxation.

9819-80, Session PSTue

Influences of thicknesses and structures of barrier cap layers on As ion profiles and implant damages in HgCdTe epilayers

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The different barrier layers (ZnS, CdTe and CdTe/ZnTe) were covered on the CdZnTe-base (LPE) and GaAs-base (MBE) HgCdTe epilayers, respectively, and the influences of the thicknesses and structures of these barrier layers on the dopant profiles and implant damages in As-implanted HgCdTe were investigated by SIMS and BFTEM.

For the ZnS-coated samples (the ZnS layer was deposited by thermal evaporation, thus it has polycrystalline structure), the depths of As profiles and the thickness ratio of the amorphous HgCdTe to the total damage layer in as-implanted samples have almost the same decreasing trend with increasing the thickness of barrier layer; and there is an optimized thickness of barrier layer to obtain the deepest As profile for the annealed samples, that is, the depths of the As profiles in the annealed samples have a maximum with increasing the ZnS thickness (too thick barrier layer can reduce the efficient dose and peak concentration).

For the CdTe-coated samples (the CdTe layer was also deposited by thermal evaporation, but it has column structure), the depths of As profiles in as-implanted samples have a more remarkable decrease with increasing the thickness of barrier layer; it is noteworthy that the column structure of the thermal-evaporated CdTe results in the barrier layer induced channeling effect (BLICE, i.e., an approximately linear distribution of As ions occurs in the deep HgCdTe) of As diffusion after Hg overpressure annealing and the increase in the thickness of CdTe layer could only suppress the BLICE effect somewhat. For the CdTe/ZnTe-coated sample (the CdTe/ZnTe layer was grown in-situ by MBE on HgCdTe, so it has single crystal like structure), a thin layer (-20nm) of short defects occurs at the interface between HgCdTe and CdTe after As ion implantation, which is quite different from the ZnS-coated and CdTe-coated samples. By BFTEM and DFTEM, it can be found that the amorphization of the CdTe/ZnTe layer also occurred during As ion implantation, and the generation of the thin defect layer at the interface may be related with this amorphization. The SIMS profile indicates that the BLICE effect did not occur to the in-situ CdTe/ZnTe coated sample after Hg overpressure annealing.

In this paper, it can be concluded that a) the barrier layer can absorb the damage of the implanted As ions to the HgCdTe lattice, but too thick barrier layer could decrease the efficient dose and peak concentration;

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b) compared with the CdTe layer with column structure, the CdTe/ZnTe composite layer with single crystal like structure can suppress effectively the BLICE effect, which is because the compact barrier layer, the thin extra defect layer and the amorphous HgCdTe layer hinder the formation of the deep channels into HgCdTe; c) additionally, the CdTe -base barrier layers can provide higher efficient doses and peak concentrations than the ZnS barrier layer under the same conditions of ion implantation.

9819-81, Session PSTue

A study of the preparation of epitaxy-ready polished surfaces of (100) Gallium antimonide substrates demonstrating ultra-low surface defects for MBE growth

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Gallium antimonide (GaSb) is an important Group III-V compound semiconductor which is suitable for use in the manufacture of a wide variety of optoelectronic devices such as infra-red (IR) focal plane detectors. A significant issue for the commercialisation of these products is the production of epitaxy ready GaSb, which remains a challenging substrate material to manufacture, as the stringent demands of the MBE process, requires a superior quality starting wafer. In this work large diameter GaSb crystals were grown by the Czochralski (Cz) method and wafers prepared for CMP (chemo-mechanical polishing). Innovative epi-ready treatments and novel post polish cleaning methodologies were applied. The effect of these modified finishing chemistries on substrate surface quality and the performance of epitaxially grown MBE GaSb IR detector structures were investigated. Improvements in the lowering of surface defectivity, maintaining of the surface roughness and optimisation of all flatness parameters is confirmed both pre- and post-MBE growth. In this paper, we also discuss the influence of bulk GaSb quality on substrate surface performance through the characterisation of epitaxial structures grown on near zero etch pit density (EPD) crystals. In summary, progression and development of current substrate polishing techniques has been demonstrated to deliver a consistent improved surface on GaSb wafers with a readily desorbed oxide for epitaxial growth.

9819-82, Session PSTue

Development of the InSb technology in Russia: 60 years

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Thanks to the pioneering works of N.A. Goryunova (USSR) and H.J. Welker (Germany), the development of physics, chemistry and technology of the AIIIBV binary compounds, which began in the late 1950s, had led to creation of one of the most popular photoelectronic semiconductor material - single crystals, and later epitaxial layers of indium antimonide (InSb). This material is associated with a real breakthrough in the field of photonics for the 3-5 μ m range.

The current development of photonics on the basis of the InSb is directed to creation of two-dimensional (matrix) photodetectors, both hybrid and monolithic.

Two types of the current-voltage characteristic instability for planar photodiodes, which appear as "explosive" noises, are detected and theoretically explained. The first type appears with a positive charge built in the passivating oxide (the InSb native anode oxide), if $Q_{ss} > 3 \cdot 10^{11} \text{ cm}^{-2}$. The second type of noise is observed with a negative charge by Q_{ss} fluctuations near a border with the p+ layer. The use of an additional short-circuited planar p-n junction around the basic photodiode provides the low dark currents which are not higher than $3 \cdot 10^{-7} \text{ A/cm}^2$ with up to 200 mV displacement.

For different applications, the 640x512 focal plane arrays (with the 15 μ m pitch) have been created by similar methods with integrated cooling systems.

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Leakage currents in InSb FPA's photodiodes

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The principal causes of FPA's pixel defects due to photodiodes leakage currents in InSb focal plane arrays have been investigated. Currently achieved number of InSb FPAs defects is about 0.1 %, mainly due to the semiconductor material and device technology.

The presentation contains a lot of statistical data concerning the defects of FPAs fabricated from different InSb ingots. Correlation was founded: the higher leakage currents at reverse diode voltage the more the number of defects. Minimum of defects one can obtain from the ingot with low concentration of $\sim 10^{14} \text{ cm}^{-3}$ and low dislocations density. Usually all FPAs from one wafer are of similar defect level. FPA produced from the different wafers of one ingot sometimes have a large difference in defect level that can be explained by influence of wafer different processing after ingot sawing.

The maps of sole defects before and after substrate thinning are similar, so process of substrate thinning does not add defects. The images obtained by summing defective clusters (that is all defects, except sole defects) have shown allocation of corners that is connected with edge effects in technological operation: unbonding and an overclamping indium bumps after bonding in corners, cracks along the edges after thinning, etc.

In this paper we have tried to find the principal causes of these defects to improve our technology:

- decrease of dislocation density in initial material;
- improvement of the wafers processing;
- optimization of technological operation to eliminate errors.

9819-84, Session PSTue

Optical and current characteristics of SWIR FPAs based on InGaAs-InGaAlAs-InAlAs double heterostructures

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The InGaAsP single layer material and InGaAs-InGaAlAs-InAlAs double heterostructures on the InP substrates are applicable for fabrication SWIR FPAs with low dark currents.

A method used for the calculation of the dielectric function in InGaAs, InGaAsP layers at energies above and below the fundamental absorption edge is based on the influence of transitions at Γ -, L-, X-points over an extended energy range. The theoretical models for refractive index and absorption coefficient are obtained using a quantum mechanical calculations of the dielectric constant in a compound semiconductors. Kramers-Kronig relations provide a useful tool to deal with the optical constants. Values of refractive index and absorption coefficient were estimated over the whole energy interval for direct and indirect transitions in Brillouin zone.

The InGaAs-InGaAlAs-InAlAs double heterostructure on the InP substrate included InGaAs narrow gap absorption layer, InGaAlAs graded band gap layer, and InAlAs large bandgap layer. The dark current voltage and temperature dependencies have been measured in single absorption layer InGaAs-InP structure and double InGaAs-InGaAlAs-InAlAs heterostructure photodiode. In double InGaAs-InGaAlAs-InAlAs heterostructure photodiodes the dark current is more than a factor of 100 smaller than in the single InGaAs-InP heterostructure photodiodes. On the base of current-voltage characteristics numerical simulation we determined the optimal operating temperature up to 280 K.

9819-85, Session PSTue

Investigation of 10x1024 MCT SWIR FPA with time delay integration

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This paper shows the results of 10x1024 MCT SWIR focal plane array investigations by using two different techniques. We used FPA in scanning mode with imitation of the point target in our first experiment. The noise equivalent photocurrent and modulation transfer function (MTF) were calculated. In second experiment the system was operating in low frequency modulation mode and the Lambert low radiation was used as the FPA input signal. The values of noise equivalent photocurrent were achieved $2.8 \cdot 10^{-14}$ W/pixel in both experiments because of using special recalculation methods which depend on FPA structure and parameters. The RMS value of internal FPAs' noise (0.75 mV) is explained mainly by the charge fluctuation of integration capacitance in multiplexor's cell (kTC - noise).

FPA is used at the signal registration mode in the first experiment, but it isn't mostly convenient because of some disadvantages: the experiment complexity and long measuring time.

The only factor, which increases the time of measurement in second experiment, is the noise frequency band of the device, so this time was for about one minute for all elements of the FPA. The equipment, which is used in this experiment, is quite cheap and easy configurable.

The mathematical model of TDI FPA is also demonstrated and the modeling results match the experimental data.

9819-86, Session PSTue

Calibration of spectral responsivity of IR detectors in the range from 0.6 μm to 24 μm

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We report the upgraded performance of the National Institute of Standards and Technology (NIST) facility for spectral responsivity calibrations of infrared (IR) detectors in both radiant power and irradiance measurement modes. The extension of the wavelength range of the previous scale, below 0.8 μm and above 19 μm in radiant power mode as well as above 5.3 μm in irradiance mode, became available as a result of multiple improvements. The calibration facility was optimized for low-level radiant flux. A significantly reduced noise-equivalent-power and a relatively constant spectral response were achieved recently on newly developed pyroelectric detectors. Also, an efficient optical geometry was developed for calibration of the spectral irradiance responsivity without using an integrating sphere. Simultaneously, the upgrade and the maintenance of the NIST transfer standards, with extended spectral range, was supported by spectral reflectance measurements of the transfer standard pyroelectric detector using a custom integrating sphere and Fourier transform spectrometer. The sphere reflectance measurements performed in a relative mode were compared to a bare gold-coated mirror reference, separately calibrated at the Fourier transform Infrared Spectrophotometry facility to 18 μm . As of now, the reflectance data for the pyroelectric standard, available in the range up to 30 μm , are supporting the absolute responsivity scale in the radiant power mode by the propagation of the reflectance shape to the tie-spectrum in the overlapping range. Typical examples of working standard pyroelectric-, Si-, MCT-, InSb- and InGaAs- detectors are presented and their optimal use for scale dissemination is analyzed.

9819-87, Session PSTue

A real-time adaptive blind pixel detection algorithm for DTDI IRFPA

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Digital Time Delay and Integration (DTD) based on Infrared Focal Plane Array (IRFPA) can improve the sensitivity of the infrared imaging system and the detectivity in small target detection. Caused by the defects of material and manufacture, IRFPA contains fixed and random blind pixels while the random ones change with the ambient temperature and the operating time, which will lead to a system performance degradation. To evaluate the blind pixel's influence upon the system and enhance the image quality, a real-time blind pixel detection algorithm is proposed. The algorithm utilizes the correlation of the same row pixels formed against the same object during the scanning process of TDI, the response curve generated by normal pixels should be similar in shape and length while the blind one has a unique distribution. Response curve of the same row pixels are computed and compared in shape and length periodically, then the potential blind pixels are extracted and probability table of the blind pixels is determined by its temporal accumulation. Finally accumulation weights of pixels are generated by the probability table, and the blind pixel compensation is performed during the TDI accumulation process. The algorithm was implemented on the 512*8 midwave IRFPA DTDI imaging system and the experiment results show that the algorithm accomplish the detection and compensation of the blind pixels in real-time without interrupting the working state of TDI imaging.

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9819-88, Session PSTue

On the figure of merit of uncooled bolometers fabricated at INO

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This paper reports the NETD values of various uncooled bolometers fabricated at INO. They are measured using an external readout circuit that emulates the readout scheme of a commercial ROIC. The measured NETD values range between 6 and 74 mK depending on the pixel pitch and response time. The pixel pitches considered are 12, 17 and 35 μm . The figure of merit of the detectors characterized is below 350 mK^2ms .

9819-89, Session PSTue

InGaAs/InP PIN photodetector arrays made by MOCVD-based zinc diffusion processes

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InGaAs-based long-wavelength near-infrared detector arrays are very important for high dynamic range imaging sensors operating seamlessly from daylight to dark environments. These detector devices are usually made using an open-hole diffusion technique which provides low leakage current and high reliability. The diffusion process is usually done in a sealed quartz ampoule with dopant compounds like ZnP_2 , ZnAs_2 , CdP_2 , etc., side by side with semiconductor samples. Even when the ampoule is prepared and the sealing process is performed in a very clean environment, the devices can have significant variations from run to run. In this work we demonstrated using MOCVD growth chamber to perform the diffusion process. The advantages of such a process are that the tool is constantly kept in an ultra clean environment and can reproducibly provide clean processes without introducing unexpected defects. We can independently control the temperature and flow rate of the dopant - they are not linked as in the ampoule diffusion case. The process can be done on full wafers with good uniformity through substrate rotation, which is good for fabricating large detector arrays. We have fabricated different types of InGaAs/InP detector arrays using dimethyl zinc as the dopant source and PH_3 or AsH_3 for surface protection. Pre-studies of Zn-diffusion profiles in InGaAs and InP at different temperatures, flow rates, diffusion times and followed annealing times were conducted to obtain good control of the process. Grown samples were measured by CV profilometer to evaluate the diffusion depth and doping concentration. The dependence of the diffusion profile with temperature, dopant partial pressures, and annealing temperature and time and some of the fabricated device characteristics will be reported.

9819-90, Session PSTue

Design and analysis of frequency selective surface coupled microbolometers

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Frequency Selective Surfaces (FSS) consist of periodic arrays of sub-wavelength antenna elements. They allow the absorbance and reflectance of a surface to be engineered with respect to wavelength, polarization and angle-of-incidence. This paper uses the FSS approach to control the absorbance of microbolometers for uncooled infrared sensing applications. Both narrowband and broadband near perfect absorbing surfaces are synthesized and applied engineer the thermal response of the microbolometers. The paper focuses on simple FSS geometries (hexagonal close packed disk arrays) that can be fabricated using conventional lithographic tools for use at thermal infrared wavelengths (feature sizes $> 1 \mu\text{m}$). The affects of geometry and material selection for these applications is described in detail. The use of the FSS removes the requirement for a conventional Fabry-Perot cavity and increases the degrees of freedom available for thermal design. A coupled full wave electromagnetic/transient thermal model of the entire microbolometer is developed and analyzed using the finite element method with commercial tools (HFSS and ANSYS). These simulations use measured ellipsometric and temperature coefficient of resistance data. The thermal performance of the microbolometer is used to guide the FSS selection and implementation, with the integration of the sensing layer into the FSS lowering the thermal mass of the device. This combined modeling permits prediction of the overall device sensitivity, time-constant and the specific detectivity. Finally, the theoretical results for the FSS microbolometer are compared to conventional cavity-based microbolometers.

9819-35, Session 9

State of the art of AIM LWIR and VLWIR MCT 2D focal plane detector arrays for higher operating temperatures

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Cryogenically cooled $\text{Hg}(1-x)\text{Cd}x\text{Te}$ (MCT) quantum detectors are unequalled for applications requiring high imaging as well as high radiometric performance in the infrared spectral range. Compared with other technologies they provide several advantages, such as the highest quantum efficiency, lower power dissipation compared to photoconductive devices and fast response times, hence outperforming micro-bolometer arrays. However, achieving an excellent MCT detector performance at long (LWIR) and very long (VLWIR) infrared wavelengths is challenging due to the exponential increase in the thermally generated photodiode dark current with increasing cut-off wavelength and operating temperature. Dark current is a critical design driver, especially for LWIR / VLWIR applications. Therefore, low dark current technologies are the prerequisite for serving higher operating temperature (HOT) applications. AIM will present its latest results on both n-on-p and p-on-n low dark current planar MCT photodiode technology LWIR and VLWIR two-dimensional focal plane detector arrays with a cut-off wavelength $>11\mu\text{m}$ at 80K and a 640x512 pixel format at a 20 μm pitch. Dark currents significantly reduced as compared to 'Tennant's Rule 07' at yet good detection efficiency $>60\%$ as well as results from electro-optical detector performance characterization will be presented, paving the way for a new generation of HOT LWIR FPA with excellent NETD performance.

9819-36, Session 9

Development of 10 μm pitch XBn detector for low SWaP MWIR applications

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Shrinking the pixel size in advanced infrared detectors allows either a reduction in the system size for the same detector format or an increase

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in the pixel count for the same Focal Plane Array (FPA) dimensions. Smaller pitch and larger format enables new applications such as long range surveillance, advanced search and track, missile warning, persistent surveillance, and infrared spectroscopy. In the last two decades SCD has followed this path of reducing the pixel size in InSb detectors for Mid-Wave Infrared (MWIR) applications, developing and manufacturing FPAs from 30 μ m down to 10 μ m pitch. The Blackbird InSb detector with 1920x1536/10 μ m format was introduced in 2013.

Modern electro-optical systems are also designed towards a more compact, low power, and lower cost solution in mind compared to traditional systems. In order to meet these requirements, detectors are being developed to work at Higher Operating Temperatures (HOT). In the last few years SCD has introduced 15 μ m pitch MWIR detectors based on the novel X_{Bn}-InAsSb technology, which enables outstanding electro-optical performance at temperatures as high as 150K.

Two X_{Bn} FPA formats were developed and are now in production: 640x512/15 μ m and 1280x1024/15 μ m. Following the above trends, SCD is currently developing a 10 μ m X_{Bn} pixel, designed to operate at 150K with performance similar to the mature 15 μ m pixel.

In this paper we present results from X_{Bn} FPA test devices, where the X_{Bn} array is Flip-chip bonded to a Readout Integrated Circuit (ROIC) with 10 μ m pitch. Test measurements in a laboratory Dewar at 150K demonstrate dark current of less than 200fA, quantum efficiency greater than 70%, operability higher than 99.5%, and excellent array uniformity.

9819-37, Session 9

Progress in MOCVD growth of HgCdTe epilayers for infrared detectors (*Invited Paper*)

Artur Kowowski, VIGO System S.A. (Poland); Waldemar Gawron, Piotr M. Martyniuk, D. Stępień, Military Univ. of Technology (Poland); Krystyna Kolwas, The Institute of Physics (Poland); Jozef F. Piotrowski, VIGO System S.A. (Poland); Pawel Madejczyk, Malgorzata Kopytko, Military Univ. of Technology (Poland); Adam Piotrowski, VIGO System S.A. (Poland); Antoni Rogalski, Military Univ. of Technology (Poland)

In this paper we present the status of HgCdTe MOCVD growth with emphasis on technological progress in fabrication of different types of HOT infrared photodetectors achieved recently at the Institute of Applied Physics, Military University of Technology and Vigo System S.A. It is shown that MOCVD technology is an excellent tool for HgCdTe barrier detector architecture growth with a wide range of composition, donor/acceptor doping and without post grown annealing. Particular progress has been achieved in the growth of (100) HgCdTe epilayers for long wavelength infrared photoresistors operated in HOT conditions.

The barrier device performance is comparable with state-of-the-art of HgCdTe photodiodes. The detectivity of HgCdTe detectors without optical immersion is close to the value marked HgCdTe photodiodes. Dark current densities are close to the values given by "Rule 07".

9819-38, Session 9

Analysis of Auger suppressed HgCdTe detectors for HOT applications

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The dark current in intrinsically limited LWIR HgCdTe detectors is dominated by Auger recombination. Within the last few years, several groups have

explored adopting heterojunction-based Auger suppressed type device architectures, whereby very low doping is employed to deplete the active layer and suppress the Auger recombination rate, potentially decreasing the dark current by several orders of magnitude. These device architectures can yield significantly higher operating temperatures than conventional detectors. Interesting trends have emerged from the experimental results produced by several groups, whereby the suppression of the Auger recombination rate depends heavily on device area, temperature, voltage etc. Due to the presence of the heterojunction and three-dimensional effects, numerical simulations are required to incorporate intelligent heterojunction device design which engineers' effective suppression of the Auger attributed dark current. ARL has been performing physics based numerical modeling to assess the performance of HgCdTe Auger suppressed architectures. The finite element method (FEM) was utilized to perform the drift-diffusion analysis by simultaneously solving the carrier continuity and Poisson equations on either two-dimensional (2D) or three-dimensional (3D) finite element grids. With this comprehensive numerical model the experimental results in the literature are interpreted and analyzed, explaining the various trends that have emerged thus far. Finally, based on the numerical results, optimal Auger suppressed designs are proposed to maximize the benefits of this approach.

9819-93, Session 9

High-operating temperature short-wavelength interband cascade infrared photodetectors

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While there has been significant progress in type-II superlattice (SL) detectors in recent decades, issues such as relatively short diffusion length, carrier lifetime, and small absorption coefficient are still open problems for this material system. These limitations can be mitigated in a multiple-stage discrete absorber architecture in which individual absorbers are separated by unipolar barriers and the thickness of every absorber is kept shorter than the diffusion length of minority carriers. Interband cascade infrared photodetectors (ICIPs) are constructed based on such a multiple-stage architecture by utilizing unique band alignments in the InAs/GaSb/AlSb material system, with each stage composed of two selective barriers (called electron and hole barriers) on the two sides of an absorber. ICIPs have advantages such as efficient minority carrier collection, high device resistance, reduced shot noise, feasibility to perform well at high temperatures, and high speed operation without compromising sensitivity. ICIPs for the MWIR to VLWIR ranges have been demonstrated, but there has been no work on SWIR ICIPs. In this work, we report on high temperature operation (250-340 K) of short-wavelength interband cascade infrared photodetectors (ICIPs) with InAs/GaSb/Al_{0.2}In_{0.8}Sb/GaSb superlattice absorbers. Two ICIP structures, one with two and the other with three stages, were designed and grown to explore this multiple-stage architecture. At $\lambda=2.1 \mu\text{m}$, the two- and three-stage ICIPs had Johnson-noise-limited detectivities of 5.1×10^9 and $5.8 \times 10^9 \text{ cm}^2\text{Hz}^{1/2}\text{W}^{-1}$, respectively at 300 K.

9819-40, Session 10

Understanding the image quality and range performance trades for high-operating temperature (HOT) MWIR detectors

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In recent years a number of manufacturers have introduced their version of HOT detectors into the market. New HOT detector configurations and capabilities are appearing and the integrator is faced with the daunting

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challenge of determining the appropriate detector manufacturer and configuration for the application. This paper provides an analysis of the different detector materials, formats and pitches as well as ROIC performance variants that determine image quality and/or range. This analysis is exclusive of variations in IR Camera performance as these variables can be independent of detector performance and more due to Video Electronics algorithms and software.

The paper treats each detector configuration as a system and tabulates the influence of each major design variable with respect to image quality (MTF) and range (Detect/Recognize/Identify) using the Night Vision Integrated Performance Model (NV-IPM). We compare detector materials which include MCT, XBN and nBN to detector pitches ranging from 10 μ m to 30 μ m, to formats ranging from 1/4 VGA (320X256) to HD (1920X1536) and to ROIC capabilities. ROIC integration capacitor and floor noise can also be significant range limiters. The paper identifies imaging scenarios where those differences are impacted due to detector configuration. These include Low Contrast targets and/or Low Background environments. We finally show how advances already in design phase at the major companies will impact MWIR sensing performance.

9819-41, Session 10

Suppression of dense array dark currents by diffusion control junctions

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The pixel pitches of current technological interest for cooled photovoltaic HgCdTe detector arrays range from the 3 to 6 micron range in SWIR to the low-to-mid-teens in LWIR. Depending on architecture and operating conditions, the diffusion lengths of minority carriers in narrow-gap absorbing layers can be considerably longer than these pitches. This is known as the dense array condition. Here, the macroscopically measurable qualities of detectors are determined not only by their operating conditions, but also by those of their neighbors (Grimbergen, 1976). In particular, the lateral diffusion currents in a dense array are controlled by the profile of the minority carriers between individual detectors which in turn are controlled by the boundary condition imposed by the applied bias (Wichman, 2014).

In this paper, a detector architecture is introduced which leverages the ability to suppress lateral diffusion currents in dense arrays by including "diffusion control junctions" in a standard double-layer planar heterostructure design. Operating principles and performance trends are discussed and some preliminary design optimization is performed using drift-diffusion based 3D finite-element method numerical simulations. Dark current suppression is investigated as a function of temperature and detector design. Impact on array quantum efficiency and modulation transfer function are considered.

9819-42, Session 10

State of the art HOT performances for Sofradir II-VI extrinsic technologies

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SOFRADIR is the worldwide leader on the cooled IR detector market for high-performance space, military and security applications thanks to a well mastered Mercury Cadmium Telluride (MCT) technology, and recently thanks to the acquisition of III-V technology: InSb, InGaAs, and QWIP quantum detectors. As a result, strong and continuous development efforts are deployed to deliver cutting edge products with improved performances in terms of spatial and thermal resolution, low excess noise and high operability. The actual trend in quantum IR detector development is the design of very small pixel, with high operating temperature.

To maintain the detector performances and operability at high temperature, the number of pixels exhibiting extra noise like 1/f and RTS noise must be limited. This paper presents the recent developments achieved in Sofradir in terms of HOT MCT extrinsic p on n technology, blue MW band (cut-off wavelength of 4.2 μ m at 150K) and extended MW band (cut-off wavelength of 5.3 μ m at 130K). Comparison between optimized and non-optimized technology will be presented in terms of NETD temperature dependency, MTF, 1/f noise and the corresponding impact on RFPN (Residual Fixed Pattern Noise) and its stability up to 170K will be shown. Correlation with RTS and DLTS studies will be discussed.

9819-43, Session 10

High-operation temperature mid-wavelength interband cascade infrared photodetectors grown on InAs substrate

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Cryogenic cooling has always been the burden of infrared systems. The new trade of IR system for next generation is "SWaP3", which stands for small size, low weight, low power, low price and high performance. In this case, infrared system work at high temperature is one of the most important missions in this new trade. In recent years, interband cascade detectors (ICIP) based on type-II superlattice have shown great performance potential at high operation temperature.

In this work, we will report our recent study of ICIP structure for high operation temperature mid-wavelength infrared photodetectors. We examined the photo generation carriers' transport of ICIP by comparing three detectors grown on InAs substrate. All these detectors have the same mid wavelength superlattice absorption region consisting 8 ML InAs and 7 ML GaAsSb in one period. The absorption region thickness of the PIN structure and two barriers structure are both 1 μ m. The absorption region thickness for the first stage of the ICIP is 1 μ m and for the second stage is 1.25 μ m to absorb more photos to match the first stage. The electron relaxation region is composed of InAs/AlSb coupled multiple quantum wells to form an energy ladder in the conduction band, and the separation between adjacent energy levels are designed close to longitudinal optic (LO)-phonon energy. The interband tunneling region was designed as a 10 periods GaAsSb/AlSb superlattice, also acted as an electron barrier. The valence band of the GaAsSb/AlSb superlattice is positioned above the conduction band of the bottom energy level in the final InAs quantum well to allow the interband tunneling of photo-generated carriers into the second stages.

Optical and electrical performance of three detectors over a wide range of temperatures are given in this work. Our result showed two stages ICIP has a QE product of 27% at 80K, and increased to 45% at the temperature of 160K. At room temperature of 300 K, the detector had a QE product of 20%, which is the highest QE at room temperature for mid wavelength superlattice detectors reported.

The Johnson-noise limited D* reaches 1.64 \times 10¹⁴ Jones at 3.65 μ m and 80K, and 4.1 \times 10¹⁰ Jones at 3.8 μ m and 200K. The 300 K background limited infrared performance (BLIP) operation temperature is estimated to be over 140 K. We will also design and compare more stages ICIPs as well.

9819-44, Session 10

High-temperature operation In_{1-x}Al_xSb infrared focal plane

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A high temperature operation mid-wavelength 128 \times 128 infrared focal plane arrays (FPA) based on low Al component In_{1-x}Al_xSb was presented in this work. InAlSb materials were grown on InSb (100) substrates using MBE technology which was confirmed by XRD and AFM analyses. We have designed and grown two structures with and without barrier. The pixel of

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the detector had a conventional PIN structure with a size of 50 μ m \times 50 μ m. The device fabrication process consisted of mesa etching, passivation, metallization and flip-chip hybridization with readout integrated circuit (ROIC), epoxy backfill, lap and polish. Diode resistance, imaging, NETD and operability results are presented for a progression of structures that reduce the diode leakage current as the temperature is raised above 80K. These include addition of a thin region of InAlSb to reduce p-contact leakage current, and construction of the whole device from InAlSb to reduce thermal generation in the active region of the detector. An increase in temperature to 110K, whilst maintaining full 80K performance, is achieved. The I-V curves were measured at different temperature. Quantum efficiency, pixel operability, non-uniformity, and the mean NETD values of the FPAs were measured at 110K. This gives the prospect of significant benefits for the cooling systems, including, for example, use of argon in Joule-Thomson coolers or an increase in the life and/or decrease in the cost, power consumption and cool-down time of Stirling engines by several tens of percent.

9819-45, Session 11

Dual-band uncooled infrared sensors employing Fano resonance in plasmonic absorbers

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Wavelength-selective uncooled infrared (IR) sensors have significant advantages for applications such as fire detection, gas analysis, hazardous material recognition, and biological analysis. We have previously demonstrated an uncooled IR sensor based on a two-dimensional plasmonic absorber (2D PLA) that exhibited wavelength-selective absorption over a wide range spanning the mid- and far-IR regions. The 2D PLA had a Au-based 2D periodic dimple-array structure, in which surface plasmon modes were induced, leading to wavelength-selective absorption. The absorption wavelength was determined by the period of the surface dimples. However, dual-band operation has not yet been investigated. The ability to absorb in two different wavelength bands is extremely important for application of such IR sensors to object recognition.

In the present study, a dual-band uncooled IR sensor was developed based on a 2D PLA with asymmetric dimple periods (2-D PLA-AP). To achieve multiband absorption, the Au-based dimples were given a different period in the orthogonal X and Y directions. The sensor was fabricated using complementary metal oxide semiconductor and micromachining techniques. Measurement of the spectral responsivity demonstrated that selective absorption occurred in two different wavelength bands, which were determined by the dimple periods in the X and Y directions. The results obtained in this study can be applied to the development of advanced sensors that are capable of multiband detection in the IR region.

9819-46, Session 11

A miniature QVGA microbolometer camera core using a wafer-level-vacuum-packaged sensor and an ASIC

Selim Eminoglu, Mikro-Tasarim San. ve Tic. Ltd. Sti. (Turkey)

This paper reports the development of a new miniature QVGA microbolometer camera cored called MicroCore-3825, which is developed to demonstrate the key features of the MT3825BA microbolometer ROIC such as high integration level, low noise, and low-power in a small volume. The MicroCore-3825 uses a wafer-level-vacuum-packaged (WLVP) microbolometer FPA built using MT3825BA ROIC and used together with the MTAS1410X4 ASIC. The FPA has a format of 384 \times 285 and pixel pitch of 25 μ m. MT3825BA has a system-on-chip architecture, allows generation of all the required timing, biasing, and performing Non-Uniformity-Correction (NUC) on-chip in the ROIC without requiring any external components

or inputs, thus enabling the development of compact and low-noise microbolometer cameras, with reduced size, weight, and power (SWaP). The MTAS1410X4 ASIC has 4 parallel ADC channels with 14-bit resolution, input range up to 4V, and conversion speed up to 10 MHz. This ASIC is used to digitize the analog video outputs of the MT3825BA ROIC, and to control an external flash memory holding various NUC data of the microbolometer FPA. The camera core is composed of 3 miniature circuit boards each measuring less than 20 mm \times 20 mm \times 20 mm, where the first board holds the WLVP microbolometer sensor, the second board holds the ASIC, and the third board holds the miniature connector, which provides power and digital I/O signal signals for the camera core. There is a temperature sensor in the camera core, which is integrated on the ROIC and can be readout as part of the regular video stream by the ASIC, simplifying to implement temperature based NUC functions in the camera body. The use of the ASIC also reduces the overall power dissipation of the sensor core compared to solutions that use commercially available ADCs and related support circuitries. The camera core using the MT3825BA ROIC and MTAS1410X4 ASIC can be powered up from a single 3.6 V supply and dissipates less than 300 mW at 30 fps, simplifying the TEC-less operation. This new camera core is provided to our customers together with an imaging software capable of measuring basic sensor parameters such as resistance, noise, and NETD distributions of the manufactured FPAs.

9819-47, Session 11

Measurement results of a 12 μ m pixel size microbolometer array based on a novel thermally isolating structure integrated on a 17 μ m ROIC (*Invited Paper*)

Dirk Weiler, Kai-Marcel Muckensturm, Frank Hochschulz, Claudia Busch, Thomas Gerschke, Simone Wall, Jennifer Heß, Daniel Würfel, Renee Lerch, Holger Vogt, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany)

In this paper electro-optical results of an uncooled 12 μ m pixel size microbolometer array placed on top of a 17 μ m QVGA-ROIC are presented. The pixel design is based on a novel approach to realize the thermal isolation of the microbolometers. The thermally isolating structure is placed in the cavity between the suspended membrane and substrate. This maximizes the absorption area of the membrane by the omission of conventional microbolometer legs resulting in a high pixel fill factor. The resistive sensing layer of the microbolometer pixel consists of a nanocrystalline silicon germanium material. The inclusion of nanocrystallites enhances the stability and electrical properties of the sensing layer resulting in low 1/f noise compared to amorphous silicon while maintaining a high TCR. The uncooled IRFPAs are designed for thermal imaging applications in the LWIR (8 .. 14 μ m) range with a full-frame frequency of 30 Hz. The readout architecture is based on massively parallel on-chip Sigma-Delta-ADCs for direct digital conversion of the sensing layer resistance. A low-cost chip-scale-package is used as the vacuum package. Both readout architecture and chip-scale-package are described detailed in previous publications [1-2]. The IRFPAs are completely fabricated at Fraunhofer IMS on 200 mm wafers by using post-processing steps for monolithic integration of the microbolometer and the chip-scale-package. Electro-optical measurements are carried out to characterize the performance of the 12 μ m pixel size microbolometer arrays. The results indicate that our novel thermally isolating structure is very beneficial for design of highly sensitive microbolometers, even for pixel pitches below 12 μ m.

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9819-48, Session 11

**Uncooled 10um FPA development at DRS
(Invited Paper)**

George D. Skidmore, DRS Technologies, Inc. (United States)

No Abstract Available

9819-49, Session 11

**Design and simulation of multi-color
infrared CMOS metamaterial absorbers**

Zhengxi Cheng, Bin Ma, YongPing Chen, Shanghai Institute of Technical Physics (China)

Metamaterial electromagnetic wave absorbers, which usually can be fabricated in a low weight thin film structure, have a near unity absorptivity, and therefore have been widely applied from microwave to optical waveband. Multi-color infrared metamaterial absorbers are designed with standard commercial 0.5 μm 2P3M and 0.35 μm 2P3M CMOS technology. Metal-insulator-metal (MIM) three-layer sandwich metamaterial structure are formed by CMOS metal interconnect layers and inter metal dielectrics layer. The top metal layer is a periodic aluminum square array with width ranging from submicron to several microns, and the bottom metal layer is a continuous aluminum layer. Post-CMOS process is adopted to etch dielectrics layers on the surface of the top metal layer to exposure the top metal surface. According to the thickness of the left dielectrics, the top metal square can be covered by the dielectrics layer, or surrounded by the dielectrics layer to form damascene structure, or elevated from the dielectrics layers between the top metal layer and the bottom metal layer. In this design, the absorption peak position and intensity of MIM metamaterial absorbers both can be theoretically tuned in 5-20 μm waveband by adjusting the top aluminum square width and period. The infrared absorption spectra of the absorbers with different top square sizes and periods are verified with finite element method simulation, and the effects of the left dielectrics layer thickness after etching are also simulated and intensively discussed. The CMOS metamaterial absorbers can be inherently integrated in many kinds of MEMS devices fabricated with CMOS technology, such as uncooled bolometers, infrared thermal emitters.

9819-50, Session 11

**Responsivity improvements for a
vanadium oxide microbolometer using
sub-wavelength resonant absorbers**

Evan M. Smith, Univ. of Central Florida (United States) and Plasmonics, Inc. (United States); Janardan Nath, Robert E. Peale, Univ. of Central Florida (United States); James C. Ginn III, David J. Shelton, Plasmonics, Inc. (United States)

Subwavelength metal/oxide structures that feature long-wave infrared (LWIR) plasmonic absorption resonances have been deposited on uncooled vanadium-oxide microbolometer pixels. Dispersion of the dielectric refractive index provides for multiple overlapping resonances that span the 8-12 μm LWIR wavelength band, a broader range than can be achieved using the usual quarter-wave cavity engineered into the air-bridge structures. Experiments demonstrate responsivity improvements exceeding 70%. Detector noise is unaffected. The thermal response time increases 16% due to the added heat-capacity, but the detectors remain sufficiently fast for usual IR imaging frame rates.

9819-52, Session 12

**Latest achievements on MCT IR detectors
for science imaging**

Pierre Castelein, Olivier Gravrand, CEA-LETI (France); Johan Rothman, MINATEC (France); Clement Lobre, Nicolas Baier, CEA-LETI (France); Olivier Boulade, Commissariat à l'Énergie Atomique (France); Bruno Fièque, SOFRADIR (France); Cyril Cervera, Eric D. de Borniol, CEA-LETI (France); Philippe Chorier, SOFRADIR (France)

HgCdTe (MCT) is a very versatile material for IR detection. Indeed, the ability to tailor the cutoff frequency as close as possible to the detection needs makes it a perfect candidate for high performance detection in a wide range of applications and spectral ranges. Moreover, the high quality material available today, either by liquid phase epitaxy (LPE) or molecular beam epitaxy (MBE) allows for very low dark currents at low temperatures and make it suitable for very low flux detection application such as science imaging. MCT has also demonstrated its robustness to aggressive space environment and faces therefore a large demand for space application such as staring at the outer space for science purposes in which case, the detected photon number is very low. This induces very strong constraints onto the detector: low dark current, low noise, low persistence, (very) large focal plane arrays. The MCT diode structure adapted to fulfill those requirements is naturally the p/n photodiode. Following the developments of this technology made at DEFIR and transferred to Sofradir in MWIR and LWIR ranges for tactical applications, our laboratory has consequently investigated its adaptation for ultra-low flux in different spectral bands, in collaboration with the CEA Astrophysics lab. Another alternative for ultra low flux applications in SWIR range, has also been investigated with low excess noise MCT n/p avalanche photodiodes (APD). Those APDs may in some cases open the gate to sub electron noise IR detection.

This paper will review the latest achievements obtained on this matter at DEFIR (LETI and Sofradir common laboratory) from the short wave (SWIR) band detection for classical astronomical needs, to the long wave (LWIR) band for exoplanet transit spectroscopy, up to the very long waves (VLWIR) band.

9819-53, Session 12

**Further developments of 8 μm pitch MCT
pixels at Selex ES**

David Jeckells, R. Kennedy McEwen, Sudesh K. Bains, Martin Herbert, SELEX ES Infrared Ltd. (United Kingdom)

Selex ES introduced high performance mercury cadmium telluride (MCT) infrared detectors on an 8 μm pitch in 2015 with their SuperHawk™ device which builds on standard production processes already used for the manufacture of 24 μm , 20 μm , 16 μm and 12 μm pitch devices. The flexibility of the proprietary Selex ES designed diode structure, used in conjunction with the mature production Metal Organic Vapour Phase Epitaxy (MOVPE) MCT growth process at Selex ES, enables fine control of diode electrical and optical structure including free choice of cut-off wavelength. The mesa pixel design inherently provides major system performance benefits by reducing blurring mechanisms, including optical scattering, inter-pixel cross-talk and carrier diffusion, to negligible levels. The SuperHawk detector has been demonstrated unrivalled MTF & NETD performance, even when operating at temperatures in excess of 120K.

The SuperHawk Integrated Detector Cooler Assembly (IDCA) benefits from recent dewar developments at Selex ES, which have improved thermal efficiencies while maintaining mechanical integrity over a wide range of applications, enabling use of smaller cryo-coolers to reduce system SWAP-C. Performance and qualification results are presented together with example imagery.

From its initial conception, SuperHawk was designed to provide an easy

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high resolution upgrade for systems currently based on standard definition 16 μ m and 15 μ m infrared detector formats. Such a camera upgrade, based on the successful SLX-Hawk product, will be described.

The paper also addresses further work to increase the operating temperature of the established 8 μ m process, exploiting High Operating Temperature (HOT) MCT at Selex ES, as well as options for LWIR variants of the SuperHawk device.

9819-54, Session 12

Small pixel pitch MCT IR-modules

Holger Lutz, Rainer Breiter, Detlef Eich, Heinrich Figgemeier, Petra Fries, Stefan Rutzinger, Joachim C. Wendler, AIM INFRAROT-MODULE GmbH (Germany)

It is only some years ago, since VGA format detectors in 15 μ m pitch, manufactured with AIM's MCT n-on-p LPE standard technology, have been introduced to replace TV/4 format detector arrays as a system upgrade.

In recent years a rapid increase in the demand for higher resolution, while preserving high thermal resolution, compactness and low power budget is observed. To satisfy these needs AIM has realized first prototypes of MWIR XGA format (1024x768) detector arrays in 10 μ m pitch. They fit in the same compact dewar as 640x512, 15 μ m pitch detector arrays. Therefore, they are best suited for system upgrade purposes to benefit from higher spatial resolution and keep cost on system level low.

By combining pitch size reduction with recent development progress in the fields of miniature cryocoolers, short dewars and high operating temperatures the way ahead to ultra-compact high performance MWIR-modules is prepared.

For cost reduction MBE grown MCT on commercially available GaAs substrates is introduced at AIM. Recently, 640x512, 15 μ m pitch FPAs, grown with MBE have successfully passed long-term high temperature storage tests as a crucial step towards serial production readiness level for use in future products.

Pitch size reduction is not limited to arrays sensitive in the MWIR, but is of great interest for high performance LWIR or 3rd Gen solutions. Some applications such as rotorcraft pilotage require superior spatial resolution in a compact design to master severe weather conditions or degraded visual environment such as brown-out. For these applications AIM is developing both LWIR as well as dual band detector arrays in HD-format (1280x720) with 12 μ m pitch.

This paper will present latest results in the development of detector arrays with small pitch sizes of 10 μ m and 12 μ m at AIM, together with their usage to realize compact cooled IR-modules.

9819-55, Session 12

Recent progress in MBE grown HgCdTe materials and devices at UWA

Renjie Gu, Wen Lei, Jarek Antoszewski, Imtiaz Madni, The Univ. of Western Australia (Australia); Gilberto Umana-Menbreno, University of Western Australia (Australia); Lorenzo Faraone, The Univ. of Western Australia (Australia)

In the frontier area of infrared detectors, HgCdTe has dominated the high performance end of the market for decades. At present, the research in this field is directed towards high pixel density, high yield, reduced cooling and hyperspectral operation, as well as towards the choice for the substrate for HgCdTe epitaxy: the high cost and high performance lattice-matched CdZnTe versus limited performance of lower cost lattice-mismatched alternatives (eg. Si, GaAs, etc.). Although large size CdZnTe ingot technology has been developed recently, it is still associated with an extremely high cost. Meanwhile, the performance of HgCdTe detectors on alternative substrates is still significantly below that achievable on CdZnTe

due to large lattice mismatch leading to high defect density. Therefore, new alternative substrate technologies are needed that are better matched to the lattice constant and/or CTE of HgCdTe. In this work, we proposed GaSb as a new alternative substrate for growing HgCdTe, and demonstrated its feasibility. The material quality of MBE grown HgCdTe on GaSb substrates demonstrates the great potential of GaSb as the next generation alternative substrate for MBE growth of high quality HgCdTe infrared materials.

9819-56, Session 12

Latest developments of 10 μ m pitch HgCdTe diode array from the legacy to the extrinsic technology

Nicolas Péré-Laperne, Jocelyn Berthoz, Rachid Taalat, Laurent Rubaldo, Alexandre Kerlain, Emmanuel Carrère, Loïc Dargent, SOFRADIR (France)

Sofradir recently presented Daphnis, its latest 10 μ m pitch product family. Both Daphnis XGA and HD720 are 10 μ m pitch mid-wave infrared focal plane array. Development of small pixel pitch is opening the way to very compact products with a high spatial resolution. This new product is taking part in the HOT technology competition allowing reductions in size, weight and power of the overall package.

This paper presents the recent developments achieved at Sofradir to make the 10 μ m pitch HgCdTe focal plane array based on the legacy technology. Electrical and electro-optical characterizations are presented to define the appropriate design of 10 μ m pitch diode array. The technological tradeoffs are explained to lower the dark current, to keep high quantum efficiency with a high operability above 110K, F/4. Also, Sofradir recently achieved outstanding MTF demonstration at this pixel pitch, which clearly demonstrates the benefit to users of adopting 10 μ m pixel pitch focal plane array based detectors.

Furthermore, the HgCdTe technology has demonstrated an increase of the operating temperature, plus 40K, moving from the legacy to the p on n one at a 15 μ m pitch in mid-wave band. The first realizations using the extrinsic p on n technology and the characterizations of diodes with a 10 μ m pitch neighborhood will be presented in both mid-wave and long-wave bands.

9819-57, Session 12

Recent progress on dark current characterization of very long-wavelength HgCdTe infrared photodetectors and HgCdTe APDs in SITP

Weida Hu, Jiale He, Weicheng Qiu, Zhenhua Ye, Lu Chen, Chun Lin, Li He, Xiaoshuang Chen, Wei Lu, Shanghai Institute of Technical Physics (China)

Detection in the very long wave infrared range (LWIR, 12-15 μ m) using third-generation infrared focal plane array (FPAs) is essential for remote atmosphere sounding. Indeed, these wavelengths are particularly rich in information about humidity and CO2 levels and provide additional information about cloud structure and temperature profile across the atmosphere. However, the dark current characteristic and associated noise behavior of the HgCdTe photodiode in the wavelength range of 12-15 μ m, operating at -77K, are very sensitive to surface passivation techniques as well as to surface material treatments. For current HgCdTe material and device technology, detection of LWIR and VLWIR energy is the subject of current research. Within this range of shrinking band-gaps in detector material, precise control of the quality of the surface passivation and treatment is of great importance. The underlying physics of dark current mechanism is theoretically investigated by using a previously developed simultaneous current extraction approach and numerical simulations.

In addition, HgCdTe electron avalanche photodiodes (e-APD) have been

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widely used for low-flux and high-speed application. To better understand the dark current transport and electron-avalanche mechanism of the devices and optimize the structures, we perform accurate numerical simulations of the current-voltage characteristics and multiplication factor in planar and mesa homojunction (p-i-n) HgCdTe electron-avalanche photodiodes.

9819-58, Session 13

Review of an assortment of IR materials-device technologies for imaging in spectral bands from the visible to very long wavelengths (Invited Paper)

Roger E. DeWames, Fulcrum Co. (United States) and U.S. Army RDECOM NVESD (United States) and U.S. Army Research Lab. (United States)

An important question in the selection of an IR technology for a variety of mission requirements is what IR technology is optimum for the fabrication of IR Focal Plane Arrays, FPAs? In this study the question is addressed starting from the optical and transport properties and features of the IR material systems, the identification of the dominant carrier recombination mechanisms for a wide range of voltage and temperature and illumination conditions and the resulting influences on the performance of the FPA detector array. The IR technologies included are: Uncooled monolithic non-crystalline VOx and α -Si: H microbolometer arrays, lattice matched P+n InP/In_{0.53}Ga_{0.47}As/InP heterojunction photodiodes, p+n homojunction bulk InSb, P+n Hg_{1-x}Cd_xTe, x=0.6-0.2, heterojunction photodiodes, III-V p- type II binary InAs/GaSb and n type II InAs/ InAs_{1-x}Sb_x for imaging in the MWIR-VLWIR spectral bands. Figures of merit include dark currents (V, T), spectral quantum efficiency (V, T) for individual diodes and focal plane arrays

9819-59, Session 14

RF switching network: a novel technique for IR sensing (Invited Paper)

Deborah Mechtel, R. Brian Jenkins, Peter Joyce, Charles Nelson, U.S. Naval Academy (United States)

Rapid sensing of near infrared energy on a composite structure would provide information that could mitigate damage to composite based structures. This paper describes a novel technique that implements photoconductive sensors in a radio frequency (RF) switching network designed to locate in real time the position and intensity of incident radiation on a composite structure.

In the implementation described here, photoconductive sensors act as rapid response switches in a two layer RF network embedded in FR-4 laminate. To detect radiation, phosphorous doped silicon photoconductive sensors are inserted in GHz range RF transmission lines. Photoconductive sensors use semiconductor materials that are optically sensitive at material dependent wavelengths. Incident radiation at the appropriate wavelength produces hole-electron pairs, so that the semiconductor becomes a conductor. By permitting signal propagation only when a sensor is illuminated, the RF signals are selectively routed from the lower layer transmission lines to the upper layer lines, thereby pinpointing the location and strength of incident radiation on a structure.

Simulations based on a high frequency 3D planar electromagnetics model are presented and compared to experimental results. Experimental results are described for GHz range RF signal control for 300mW incident energy from 975nm and 1060nm wavelength lasers where, upon illumination, RF transmission line signal output power doubled when compared to non-illuminated results. Experimental results are reported for 100W incident energy from a 1060nm laser. Test results illustrate that real-time signal processing would permit a structure or vehicle to be controlled in response to incident radiation

9819-60, Session 14

A 1024x768-17 μ m ROIC for uncooled microbolometer FPAs

Selim Eminoglu, Mikro-Tasarim San. ve Tic. Ltd. Sti. (Turkey)

This paper reports the development of a new microbolometer Readout Integrated Circuit (ROIC), called MT10217BA. It has a format of 1024 x 768 (XGA) and a pixel pitch of 17 μ m. MT10217BA is Mikro-Tasarim's fourth microbolometer ROIC, which is developed specifically for surface micro machined microbolometer detector arrays using high-TCR pixel materials, such as VOx and a Si. MT10217BA has a system-on-chip architecture, where all the timing, biasing, and pixel non uniformity-correction (NUC) operations in the ROIC are applied using on-chip circuitry simplifying the use and system integration of this ROIC. MT10217BA has a serial programming interface that can be used to configure the programmable ROIC features and to load the NUC data to the ROIC. MT10217BA has a total of 4 analog video outputs and 2 analog reference outputs, placed at the top and bottom of the ROIC, which can be programmed to operate in the 1, 2, and 4-output modes at pixel output rates up to 12 MHz. The ROIC is designed to support pixel resistance values ranging up to 100k Ω . MT10217BA is operated using conventional row based readout method, where pixels in the array are readout in a row-by-row basis, where they are biased and integrated using synchronously applied NUC data. The NUC data is applied continuously in a row-by-row basis using the serial programming interface operated at 20 MHz supporting frame rates as high as 30 fps. The bias voltage of the pixels can be programmed over a 1.0 V range to compensate for the changes in the detector resistance values due to the variations coming from the manufacturing process. The ROIC has an on-chip integrated temperature sensor with a sensitivity of better than 5 mV / K, and the output of the temperature sensor is embedded in the analog video stream. MT10217BA can be used to build a microbolometer FPAs with an NETD value below 60 mK using a microbolometer detector array fabrication technology with a nominal detector resistance of 60 K Ω , a high TCR value (> 3 % / K), and a sufficiently low pixel thermal conductance (Gth \leq 10 nW / K). MT10217BA ROIC die measures 20.7 mm x 20.3 mm in a 180 nm CMOS. MT10217BA is fabricated on 200 mm diameter CMOS wafers with 48 parts per wafer. The microbolometer ROIC wafers are engineered to have flat surface finish to simplify the wafer level detector fabrication and wafer-level vacuum packaging (WLVP). The ROIC runs on 3.3 V analog and 1.8 V digital supplies, and dissipates less than 230 mW in the 4 output mode at 30 fps. Mikro-Tasarim provides tested ROIC wafers and offers compact test electronics and software for its ROIC customers to shorten their uncooled FPA and camera development cycles. MT10217BA can also be used together with MTAS1410X4, a 4-channel microbolometer ASIC from Mikro-Tasarim, to develop compact, low-noise, and low power uncooled microbolometer sensors cores and cameras.

9819-61, Session 15

Implementation of TDI based digital pixel ROIC with 15 μ m pixel pitch

Omer Ceylan, Melik Yazici, Atia Shafique, Yasar Gurbuz, Sabanci Univ. (Turkey)

A 15 μ m pixel pitch digital pixel for LWIR time delay integration(TDI) applications is implemented which occupies one fourth of pixel area compared to previous digital TDI implementation. TDI is implemented on 8 pixels with oversampling rate of 2. ROIC provides 16 bits output with 8 bits of MSB and 8 bits of LSB. Pixel can store 75 M electrons with a quantization noise of 500 electrons. Digital pixel TDI implementation is advantageous over analog counterparts considering power consumption, chip area and signal-to-noise ratio. Digital pixel TDI ROIC is fabricated with 0.18 μ m CMOS process. In digital pixel TDI implementation photocurrent is integrated on a capacitor in pixel and converted to digital data in pixel. This digital data triggers the summation counters which implements TDI addition. After all pixels in a row contribute their information, the summed data is divided to

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the number of TDI pixels(N) to have the actual output which is square root of N improved version of a single pixel output.

voltage treated as fixed pattern noise is measured in the beginning of each frame and subtracted from the digital count to have the final digital output.

9819-62, Session 15

A 640x512-20 μ m dual-polarity ROIC for MWIR and LWIR hybrid FPAs

Selim Eminoglu, Mikro-Tasarim San. ve Tic. Ltd. Sti. (Turkey)

This paper reports the development of a new Dual-Polarity Direct-Injection (DI) Readout Integrated Circuit (ROIC), called MT6420DDA, designed to support back-to-back connected photodiodes with a single contact per pixel using dedicated p-on-n and n-on-p type pixel input circuitries. The ROIC has a format of 640 x 512 (VGA) and a pixel pitch of 20 μ m, and can be used to build dual-color or dual-band FPAs working in the MWIR and/or LWIR bands. The ROIC supports snapshot operation with Integrate then Read (ITR) and Integrate-while-Read modes (IWR). MT6420DDA has a system on-chip architecture, with programmable biasing, timing, and configuration. The ROIC supports 1, 2, 4, and 8-output modes at pixel output rates up to 12 MHz per output. It runs on 3.3 V analog and 1.8 V digital supplies, and dissipates less than 135 mW in the 4 output mode at 120 fps. The ROIC has separate programmable full well capacitance values of 1.5Me⁻, 3Me⁻, and 6Me⁻ for MWIR and LWIR spectral bands in the very-high-gain (VHG), mid gain (MG), and low-gain (LG) modes. The ROIC is designed to perform both regular frame based and interleaved exposure modes. In the frame based exposure mode, an alternating input polarity is used for each detector type for each frame during each integration, possibly with different full-well and integration time settings. In the interleaved integration mode, both type of pixels are exposed simultaneously, in an interleaved manner using multiples of short integration periods. The frame based exposure mode is simple, but the time stamp for each image frame is different. In the interleaved exposure mode is complex but results in a pseudo simultaneous registration of image frames for each color or spectral bands. The ROIC has been developed for cryogenic operation down to 77K with an input referred noise level of less than 510e⁻ rms in the low gain (LG) mode. The MT6420DDA ROIC has been fabricated on 200mm wafers containing 89 parts. Mikro-Tasarim provides tested ROIC wafers and offers compact test electronics and software for its ROIC customers to shorten their uncooled FPA and camera development cycles. MT6420DDA can also be used together with MTAS1410X8, an 8-channel ASIC from Mikro-Tasarim, that can be used to drive and digitize FPA outputs in the integrated-detector-cooler-assemblies (IDCAs) to build compact and low-noise cooled infrared camera cores.

9819-67, Session 15

Crosstalk study of near-infrared InGaAs detectors

Xue Li, Hengjing Tang, Tao Li, Cui Fan, Haimei Gong, Shanghai Institute of Technical Physics (China)

Crosstalk characteristics of high density FPA detectors attract widespread attention in the application of electro-optical systems. Crosstalk characteristics of near infrared InGaAs FPA detectors were studied in this paper. The mesa type detector was investigated by using laser beam induced current technique (LBIC) to measure the absorption outside the designed photosensitive area, and the results show that the excess absorption enlarge the crosstalk of the adjacent pixels. The structure optimization using the effective absorption layer between the pixels can effectively reduce the crosstalk to 2.5%. The major crosstalk components of the optimization photodetectors come from the electronic signal caused by carrier lateral diffusion. For the planar type detectors, test structures were used to compare the crosstalk of different structures, and the guard ring structure shows good suppression of the crosstalk. Then the back-illuminated 32x32 InGaAs photodiodes with 30 μ m pitch were designed, and LBIC was used to measure its lateral diffusion of the effective carriers and fill factor of photosensitive area. The results indicate that the fill factor of detectors is close to 98% when the diffusion region is optimized, and the minimum response exists between two neighborhood pixels. Based on these crosstalk measurement results and optimized structure designs, the linear type InGaAs photodiodes were designed and thus the InGaAs FPA assembly was fabricated. The assembly shows higher electro-optical performance and good improvement on crosstalk. The assembly was applied in infrared imaging system and modulation transfer function of FPA assembly was calculated to be 0.50 including the optical lens. The sharp image based on FPA assembly was obtained.

9819-63, Session 15

Power and area efficient digital pixel read out circuit design for mid-wave infrared application

Atia Shafique, Omer Ceylan, Melik Yazici, Yasar Gurbuz, Sabanci Univ. (Turkey)

This paper presents power and area efficient design methodology adopted for digital pixel readout integrated circuit (DROIC) for mid-wavelength infrared (MWIR) imaging applications. The pixel is designed for staring focal plane array (FPA) detectors with smaller pixel pitch of 15 μ m in 90nm CMOS technology. The front-end pixel design relies on coarse quantization with pulse frequency modulation (PFM) in-pixel and residue measurement being performed by the column level Analog-to-digital converter. The 25fFmosfet based integration capacitor is used for pixel design in order to reduce the dynamic power consumption to large extent. The charge handling capacity of 8Me⁻ can be achieved with 6-bits in-pixel memory along with 10-bits of residue measurement leading to overall 16-bit output resolution, which endures to achieve quantization noise as low as 22.5 ϵ and power dissipation well below 200nW per pixel with the frame rate of 400Hz. The offset voltage in the PFM loop intricate due to pixel-to-pixel process variations since residue charge is measured by the column ADC. Hence the offset

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9820-1, Session 1

Investigating binocular and temporal summation in human vision using complementary fused external noise

Christopher L. Howell, Jeffrey T. Olson, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

The impact noise has on the processing of visual information at various stages within the human visual system (HVS) is still an open research area. To gain additional insight, four experiments were administered to human observers using targets containing complementary information degraded with varying levels of noise. By ensuring complementary information exists within the targets to be summed, the effect of noise on the summation of visual information within the HVS can be better isolated. In experiment one the targets are fused into a single target before being displayed to the observer. In experiment two, each target is shown simultaneously on the display without fusing so that the observer is presented all the information unaltered. In experiment three, a two-field movie was created using each target and then temporally displayed to the observer. Lastly, in experiment four, a ninety degree mirror was used to direct each complementary target to both eyes independently allowing the information to be fused binocularly. These four experiments present diverse approaches for delivering external noise to the HVS and allows for a better understanding to how noise enters the HVS and what impact the noise has on the processing of visual information.

9820-2, Session 1

Method and tool for generating and managing image quality allocations through the design and development process

Andrew W. Sparks, Craig Olson, Michael J. Theisen, Chris J. Addiego, Tiffany G. Hutchins, Timothy D. Goodman, L-3 Sonoma EO (United States)

Performance models for infrared imaging systems require image quality parameters; optical design engineers need image quality design goals; systems engineers develop image quality allocations to test imaging systems against. It is a challenge to maintain consistency and traceability amongst the various expressions of image quality. We present a method and parametric tool for generating and managing expressions of image quality during the system modeling, requirements specification, design, and testing phases of an imaging system design and development project.

The parametric image quality tool uses published equations and methods to generate MTF curves in a three-step process. First, the conditions for each MTF expression are identified and added to the underlying allocation, including diffraction limit, obscuration, field-dependent design residual and fabrication errors, thermal and vibrational environment, image processing, and the presence or absence of various optical surfaces. Second, image quality degradations best modeled as RMS wavefront error are added together in RSS fashion and a lens MTF is generated. Third, the lens MTF is multiplied by any image quality degradations best modeled as MTF, such as jitter, linear smear, sampling, or footprint MTF to produce a system MTF.

The method begins with preliminary parametric estimates used to model expected system performance. Preliminary estimates are replaced by more detailed analyses as the design progresses. Measured data is fit to

the modeling parameters and included in the allocation. Every allocation and model input has traceability back to the same set of parameterized inputs. As changes occur within the allocation, all related outputs may be simultaneously and consistently updated.

9820-3, Session 1

Modeling detection and search for point and extended sources as a function of clutter

Melvin H. Friedman, Joseph P. Reynolds, U.S. Army RDECOM CERDEC NVESD (United States)

Travnikova has shown experimentally that search for a point source in a background without clutter is described by the Rayleigh distribution. Krendel et. al. have shown that search for an extended circular target in an uncluttered background is described by the exponential distribution. This paper describes a search model where, in the absence of clutter, the exponential distribution for a circular extended source transitions to a Rayleigh distribution for a point source. By data mining existing literature or by doing in-house experiments we investigate how detection thresholds and search models transition with clutter. It is anticipated that Travnikova's and Krendel's results will be confirmed by experiments performed at NVESD.

9820-4, Session 1

Comparative low-light level (LLL) imaging capabilities of SWIR detectors

Niels F. Jacksen, SCD.USA, LLC (United States); Gerald C. Holst, JCD Publishing (United States)

This paper describes the challenges applying high performance, InGaAs detectors for light weight handheld tactical applications, emphasizing LLL performance and high temperature ambient environments. Although InGaAs detectors are manufactured by a number of companies, the SCD InGaAs detector technology offers new ROIC architectures that, combined with its High Sensitivity / Low Dark Current detector, enables the next GEN handheld Night Vision Imaging Module. We review night vision Key Performance Parameters and provide comparative performance of our new detector to mainstream LLL electron bombarded technologies. This includes analysis of device physics limitations of those technologies compared to InGaAs Focal Planes. The Low Noise Imaging Mode, developed by Semiconductor Devices to support its multifunction InGaAs detectors, is analyzed by modeling and verified by radiometric testing under laboratory and field environments. We use the capabilities of the Night Vision Integrated Performance Model (NV-IPM) as well as analytical capabilities developed by one of the authors to quantitatively assess performance. The paper provides a technology roadmap forecasting continued improvements in Night Vision imaging using TEC-LESS InGaAs focal planes down to 5um pitch with spectral sensitivity extended out to 2.5 μ m. Finally we provide a performance / reliability preliminary specification demonstrating that InGaAs focal planes are the technology of choice for High Performance, Low SWaP Hand Held applications.

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9820-5, Session 1

Visible band image generation in the night vision integrated performance model

Brian P. Teaney, Joseph P. Reynolds, U.S. Army RDECOM CERDEC NVESD (United States)

The generation of accurate reflective band imagery is complicated by the intrinsic properties of the scene, target, and camera system. Unlike emissive scenes, which can be represented in equivalent temperature given some basic assumptions about target characteristics, visible scenes depend highly on the illumination, reflectivity, and orientation of objects in the scene as well as the spectral characteristics of the imaging system. Once an image has been sampled spectrally, much of the information regarding these characteristics is lost. In order to provide reference scene characteristics to the image processing component, the visible image processor in the Night Vision Integrated Performance Model (NV-IPM) utilizes pristine hyper-spectral data cubes. Using these pristine, spectral scenes the model is able to generate accurate representations of a scene for a given camera system. In this paper we discuss the development of the reflective band image simulation component and various methodologies for collecting or simulating the hyperspectral reference images.

9820-6, Session 2

Measured system component development for the night vision integrated performance model

Brian P. Teaney, David P. Haefner, U.S. Army RDECOM CERDEC NVESD (United States)

The Night Vision Integrated Performance Model (NV-IPM) introduced a variety of measured system components in version 1.6 of the model. These measured system components enable the characterization of systems based on lab measurements which treat the system as a 'black-box.' This encapsulation of individual component terms into higher level measurables circumvents the need to development costly, time-consuming measurement techniques for each individual input. Each of the 'black-box' system components were developed based upon the minimum required system level measurements for a particular type of imaging system. The measured system hierarchy also includes components for cases where a very limited number of measurements are possible. We discuss the development of the measured system components, the transition of lab measurements into model inputs, and any assumptions and limitations inherent to this process.

9820-7, Session 2

Relative effectiveness of video with serial visual presentation for target reconnaissance from UAVs

Frank E. Skirlo, CACI International Inc. (United States); Melvin H. Friedman, U.S. Army RDECOM CERDEC NVESD (United States)

Reconnaissance from an unmanned aerial vehicle (UAV) is often done using video presentation. An alternate method is Serial Visual Presentation (SVP). In SVP a static image remains in view until replaced by a new image at a rate equivalent to the live video. Mardell et al. have shown, in a forest environment, that a higher fraction of targets (people lost in the forest), are found with a SVP than with a video presentation. Here Mardell's experiment is repeated for military targets in desert, urban, and forest terrains at three different altitudes. It is anticipated that we too will find a higher fraction of targets using a SVP rather than a video presentation. Typically it takes 5 seconds to cover a video field of view and at 30 frames per second this implies that, for scenes where the target is not moving, 150 video images

have nearly identical information (from a reconnaissance point of view) as a single SVP image. This is highly significant since transmission bandwidth is a limiting factor for most UAVs. Finding targets in video or in SVP is an arduous task. For that reason we also compare aided target detection performance and unaided target detection performance on SVP images.

9820-9, Session 2

Comparing and contrasting 2D versus 1D performance modeling in NV-IPM v1.6

Jonathan G. Hixson, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Brian P. Teaney, U.S. Army RDECOM CERDEC NVESD (United States)

Version 1.6 of the Night Vision Integrated Performance Model (NV-IPM) introduced two-dimensional Modulation Transfer Function (MTF) and noise signals within the model architecture. These two-dimensional signals enable the model to more accurately treat systems with non-separable MTF components. These non-separable MTF components may be introduced by optical elements, electronic post-processing, or atmospheric effects. In this paper we discuss the differences between the new two-dimensional signal architecture and the one-dimensional separable representation used in earlier versions of the model and highlight some cases which demonstrate the utility of the two-dimensional signals.

9820-51, Session 2

Modeling demosaicing of color corrected cameras in the NVIPM

David P. Haefner, Brian P. Teaney, Bradley L. Preece, U.S. Army RDECOM CERDEC NVESD (United States)

A critical step in creating an image using a Bayer pattern sampled color camera is demosaicing, the process of combining the individual color channels using a post-processing algorithm to produce the final displayed image. The demosaicing process can introduce degradations which reduce the quality of the final image. These degradations must be accounted for in order to accurately predict the performance of color imaging systems. In this paper, we present analytical derivations of transfer functions to allow description of the effects of demosaicing on the overall system blur and noise. The effects of color balancing and the creation of the luminance channel image are also explored. The methods presented are validated through Monte Carlo simulations, which can also be utilized to determine the transfer functions of non-linear demosaicing methods. Together with this new treatment of demosaicing, the framework behind the color detector component in NV-IPM is discussed.

9820-10, Session 3

Performance of infrared search and track systems (IRST) using superresolution

Ronald G. Driggers, St. Johns Optical Systems (United States); Teresa L. Pace, L-3 Communications (United States); Carl Halford, St. Johns Optical Systems (United States)

Super-resolution has been shown to improve the system performance of target acquisition imagers in cases where the optical blur is small compared to detector sample spacing. The performance improvement has been shown to be significant for resolved targets in tasks of target identification. Researchers have been successful in quantifying the performance benefits of super-resolution in these target acquisition imaging systems and these improvements can be easily translated into intelligence, surveillance, and reconnaissance (ISR) system performance.

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What has not been quantified is the performance benefit of super-resolution in systems with unresolved targets. In this paper, we provide an initial analysis of super-resolution performance enhancement to systems involving unresolved targets. In particular, we are interested in the super-resolution benefits associated with infrared search and track (IRST) systems. We provide an analysis and some initial trade studies associated with staring infrared IRST systems.

9820-11, Session 3

Is there an optimum detector size for digital night vision goggles (DNVG)?

Gerald C. Holst, JCD Publishing (United States)

In previous studies maximum DRI range was achieved when $F\lambda/d$ approached 2. There was no constraint on magnification or field-of-view. This suggested that detector size approach $\lambda/2$ when $F = 1$. Night vision goggles typically have a fixed FOV of 40 deg with unity magnification. DNVG DRI range is limited by the human visual system resolution of 0.291 mrad (20/20 vision). This suggests the maximum number of horizontal detectors should be about 2000 with a minimum pixel size of about 8 μm when $F = 1$ and aperture = 1 inch. Values change somewhat depending upon f-number and noise. Ranges are provided for GaAs and InGaAs detectors under starlight conditions. The different spectral responses create MRC test issues.

9820-13, Session 3

Wavelet contrast metric

Bradley L. Preece, U.S. Army RDECOM CERDEC NVESD (United States)

Target acquisition performance depends strongly on the contrast of the target. The Targeting Task Performance (TTP) metric, within the Night Vision Integrated Performance Model (NV-IPM), uses a combination of resolution, signal to noise ratio (SNR), and contrast to predict and model system performance. While the dependence on resolution and SNR are well defined and understood, defining a robust and versatile contrast metric for a wide variety of acquisition tasks is more difficult. In this correspondence, a wavelet contrast metric (WCM) is developed under the assumption that the human eye processes spatial differences in a manner similar to a wavelet transform. The amount of perceivable information, or useful wavelet coefficients, is used to predict the total viewable contrast to the human eye. The WCM is intended to better match the measured performance of the human vision system for high-contrast, low-contrast, and low-observable targets. The new contrast metric will be incorporated using a modified TTP metric in the latest Army target acquisition software suite, the NV-IPM.

9820-52, Session 3

Efficient polarimetric BRDF transformations

Stefan Björkert, FOI-Swedish Defence Research Agency (Sweden); Ingmar G. Renhorn, Renhorn IR Consultant AB (Sweden)

In order to characterize a target, the basic information that is of interest is spectral, polarization and distance. Imaging spectropolarimetry is a powerful tool for obtaining the polarization state of a scene and to discriminate manmade objects in a cluttered background. With respect to polarization, often the measurements are limited to the first three vectors of the Stokes vector, excluding circular polarization. The scene is therefore characterized in four directions of linear polarization, I0, I90, I45 and I135. An efficient polarimetric BRDF model defined in a local coordinate system has recently been published. The model will now be extended to a global coordinate

system for linear polarized radiation. This includes the first three elements of the Stokes vector. We will provide examples for surface of intrinsically different scattering materials, bulk scattering materials and clear coated surfaces.

9820-14, Session 4

Performance assessment of a single-pixel compressive sensing imaging system

Todd W. Du Bosq, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Bradley L. Preece, U.S. Army RDECOM CERDEC NVESD (United States)

Conventional electro-optical and infrared (EO/IR) systems capture an image by measuring the light incident at each of the millions of pixels in a focal plane array. Compressive sensing (CS) involves capturing a smaller number of unconventional measurements from the scene and then using a companion process known as sparse reconstruction to recover the image as if a fully populated array that satisfies Nyquist criteria were used. Therefore, CS operates under the assumption that signal acquisition and data compression can be accomplished simultaneously. CS has the potential to acquire an image with equivalent information content to a large format array while using smaller, cheaper, and lower bandwidth components. However, the benefits of CS do not come without compromise. The CS architecture chosen must effectively balance between physical considerations (SWaP-C), reconstruction accuracy, and reconstruction speed to meet operational requirements. To properly assess the value of such systems, it is necessary to fully characterize the image quality, including artifacts and sensitivity to noise. Imagery of the two-handheld object target set at range was collected using a passive SWIR single-pixel CS camera for various ranges, mirror resolution, and number of processed measurements. For comparison, imagery from a traditional SWIR camera was also collected. Human perception experiments were performed to determine the identification performance within the trade space. The performance of the nonlinear CS camera was modeled with the Night Vision Integrated Performance Model (NV-IPM) by mapping the nonlinear degradations to an equivalent linear shift invariant model. Finally, the limitations of CS modeling techniques will be discussed.

9820-15, Session 4

Unified characterization of imaging sensors from VIS through LWIR

Martin Gerken, Harry H. Schlemmer, Mario O. Münzberg, Airbus Defence and Space (Germany)

Modern reconnaissance strategies are based on gathering information using as many spectral bands as possible. Besides the well known atmospheric windows at VIS, MWIR and LWIR wavelengths suitable for long range observation progress in detector technology has provided excess also to the SWIR atmospheric window from 1.0 to 1.7 μm . A concept for comparing the ranges achievable with sensors in different wavelength bands is presented.

In range simulation the contribution of the sensor can be fully characterized by using the Minimum Resolvable Contrast (MRC) and the Minimum Resolvable Temperature Difference (MRTD), both being a function of spatial frequency. Since the issues of MRC measurement in SWIR wavelength band have been solved [1] measured MRC and MRTD curves can now be obtained in all relevant spectral bands.

Based on measured MRC and MRTD data three imaging sensors in different wavelength bands (VIS, SWIR and MWIR/LWIR) which are in use on multispectral reconnaissance platforms are investigated. Range calculations done in parallel for the same type of atmosphere are used to analyse and compare the imaging performance. Examples of the results are illustrated by captured images.

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9820-16, Session 4

IR FPA performance modeling and testing

Alexander I. Patrashin, Igor D. Burlakov, Konstantin O. Boltar, Anatoly M. Filachev, Orion Research-and-Production Association (Russian Federation)

Model describing IR FPA operation and permitting possibility estimation of the particularly IR FPA fits the different applications requirements is developed. This model will be used for evaluation of IR FPA quality too. Usage of the cold shield transmission coefficient is the novel element of the developed model. This coefficient allows carrying out the correct calculation of the irradiance components, signals and noises of all array elements. Different spurious irradiance components are taking into account. Original analytical expressions describe FPA parameters and their dependencies on IR FPA design and operational conditions. The developed model permits to research dependences of the elements signals, noises and parameters for any structural or operational IR FPA characteristic too. The experimental verification of the model for SW, MW and LW IR FPA confirms the good repeatability of calculated and measured results. New method of IR FPA elements dark current and external quantum efficiency measurements is based on the above model. Presented analytical model will help to refine various design and structural IR FPA parameters at early development stage and can be used in different applications both for researchers and manufacturers.

9820-17, Session 5

NIR sensitivity analysis with the VANE

Justin Carrillo, Christopher T. Goodin, U.S. Army Engineer Research and Development Ctr. (United States); Alex E Baylot, US Army Engineer Research and Development Center (United States)

Near infrared (NIR) cameras, with peak sensitivity around 905 nm wavelengths, are increasingly found in object detection applications. These NIR cameras have been used in many applications for object detection such as pedestrian detection, occupant detection in vehicles, and vehicle detection. A simulated sensitivity analysis study was conducted using high performance computing (HPC) to determine the environmental effects on object detection in different terrains and environmental conditions. The Virtual Autonomous Navigation Environment (VANE) was used to simulate high-resolution models for environment, terrain, vehicles and sensors.

In the experiment, an active fiducial marker was attached to the rear bumper of a vehicle. The camera was mounted on a following vehicle, which trailed at varying standoff distances. Three different terrain conditions (rural, urban, forest), four environmental conditions (clear, hazy, dusty, rainy), three different times of day (morning, noon, evening), and six different standoff distances were used to perform the sensor sensitivity analysis. The NIR camera that was used for the simulations is the DMK firewire monochrome on a pan-tilt motor.

Standoff distance was varied along with environment and environmental conditions to determine the critical failure points for the sensor. Feature matching was used to detect the markers in each frame of the simulation, and the percentage of frames in which one of the markers was detected was recorded. The standoff distance produced the biggest impact on the performance of the camera system, while the camera system was not sensitive to environment conditions.

9820-18, Session 5

Foote's Law and its application to cameras

Charles Kim, Northrop Grumman Electronic Systems (United States)

In modeling and characterizing a focal plane array (FPA) with a uniform

source, estimating the irradiance on the FPA is mandatory. Many have developed needed formulas for such calculation. Those formulas often focus only on the center pixel of the FPA on the optical axis, ignoring all the other pixels. We use the Foote's law to derive the formulas for all the pixels in a simple configuration where the FPA is directly exposed to the uniform source. We extend the formulas for two more configurations: the FPA enclosed with a baffle and the FPA housed with a lens. Our results are compared with some existing formulas. They show differences, yet reach an agreement with some approximations. Our formulas are useful for modeling and trade study for the FPA, especially for cameras with wide field of view.

9820-19, Session 5

Applications of 3D noise measurements

David P. Haefner, Bradley L. Preece, Stephen D. Burks, U.S. Army RDECOM CERDEC NVESD (United States)

When evaluated with a spatially uniform irradiance, an imaging sensor exhibits both spatial and temporal variations, which can be described as a three-dimensional (3D) random process considered as noise. In the 1990s, NVESD engineers developed an approximation to the 3D power spectral density (PSD) for noise in imaging systems known as 3D noise. In this correspondence, we describe how a knowledge of the confidence intervals for the 3D noise measurement allows for determination of the sampling necessary to reach a desired precision. We also describe how the 3D noise measurement with the mixing matrix can be used as a predictive tool to assess statistical certainty of observed behavior, for example the contrast. Finally, we comment on the accuracy of the 3D noise model for real measured systems by calculating and comparing to the 3D power spectral density; we also include how the 3D PSD can be decomposed into the familiar 7 components.

9820-20, Session 5

Thermal imager static and dynamic sources of non-uniformities: from modeling to experimental data

Claudio Giunti, Barbara Sozzi, Monica Olivieri, Tiziano Marzoli, Stefano Zatti, Antonio Porta, SELEX ES S.p.A. (Italy); Fabrizio Faraci, Antonio Cassese, Altran Italia S.p.A. (Italy)

The spatial non-uniformity performance of a thermal imager is a major issue especially in automatic search and track of point targets applications. The high sensitivity achieved by infrared detectors requires taking into account all possible spatial noise sources.

In the past a model including opto-mechanics, dynamic and other environmental sources has been developed, normally this analysis is not addressed in current literature. The model was able to calculate the amount of photonic signal on every pixel coming from different sources and then estimated the residual spatial noise for a given NUC algorithm.

The previous two years of laboratory activity has been devoted to validating this model. In the paper we present the experimental results showing the agreement between measurements and model predictions. It is highlighted that contributions, often neglected, such as ghost effects due the optical system components and the lens emissivity, are important or sometime critical, in order to explain experimental data. Also the relative weight of each noise source is estimated.

Considering the ongoing growth of IR camera sensitivity, the system characterization is influenced by the set up profoundly. So the model has been used to estimate the spurious effect due to set up element (such as climatic chamber window), to evaluate how the set up can affect the measurements and consequently defining the best set up configuration.

Furthermore the agreement between the model results and the measurements confirms the basic hypothesis of the theoretical model.

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Besides, in the paper the measurements of key model parameters are shown and the decoupling of detector and opto-mechanical transfer function is assessed.

The results have been verified on a small series of IR system.

9820-21, Session 6

Multi-function infrared sensors for ground vehicles trade study (*Invited Paper*)

Keith A. Krapels, U.S. Army RDECOM CERDEC NVESD (United States); Ronald G. Driggers, Orges Fuxhi, St. Johns Optical Systems (United States)

A common approach to military sensor systems lately is to provide multifunction/multimission sensors in a single system. The approach makes sense when the sensor characteristics are similar enough to provide a low cost solution for various missions. It is not a good idea to develop a multifunction system where the overall system cost and complexity is much higher than a federated sensor system.

In this paper, we analyze a potential multifunction infrared sensor approach for ground combat vehicles, where the system is a hyperhemispheric sensor on the vehicle. The wide field of regard set of applications includes, hostile fire detection/location (direct fire guns), driving/mobility (degraded visual environments), threat warning (RPGs and ATGMs), situational awareness (people and vehicle threat detection/ID), and infrared search and track for counter unmanned aerial systems (C-UAS). We left out all narrow field functions such as target acquisition and we left out active infrared sensor systems such as optical augmentation. The authors believe that the passive, wide field applications are common enough to provide a lower cost multifunction system. However, each of these five applications have unique technical requirements which may drive sensor systems into impractical cost points for widespread Army use.

This paper is the beginning of a series of papers on ground combat vehicle sensors that highlight the new capabilities of the Night Vision Integrated Performance Model (NV-IPM) and includes trade studies, modeling, design analysis, system simulations, virtual prototyping, scenario analysis/constructive combat simulation, and laboratory/field measurements.

9820-23, Session 6

Range performance of notional hyperspectral imaging sensors

Van A. Hodgkin, Christopher L. Howell, U.S. Army RDECOM CERDEC NVESD (United States)

In the use of conventional broadband imaging systems, whether reflective (e.g., visible, near infrared, or shortwave infrared) or emissive (e.g., mid-wave infrared or long wave infrared), scene image contrasts are often so low that target discrimination is difficult or uncertain, and it is contrast that drives human-in-the-loop (HIL) sensor range performance. This situation can occur even when the spectral distribution of the target and background optical properties across the sensor waveband differ significantly from each other. The fundamental components of broadband image contrast are the spectral integrals of the target and background signatures, and this spectral integration can average out the spectral contrast differences between scene objects. In many low broadband image contrast situations hyperspectral imaging (HSI) can preserve a greater degree of the intrinsic scene spectral contrast for the display, and more display contrast means greater range performance by a trained observer. This paper documents a study using spectral radiometric signature modeling and the Night Vision Integrated Performance Model (NV-IPM) to show how waveband selection by a notional HSI sensor using spectral contrast optimization can significantly increase HIL sensor range performance over conventional broadband sensors.

9820-25, Session 6

Scenario-based analysis of binning in MWIR detectors for missile applications

Ulas Kürüm, Roketsan Roket Sanayii ve Ticaret A.S. (Turkey)

Binning is a relatively mature feature for silicon detectors used for obtaining better signal to noise ratio. In this study; a similar concept is proposed for MWIR detectors with emphasis on security related properties such as detection range and performance of an autonomous/semi-autonomous electro-optical system. The analysis and simulations has been performed for a fixed sample with predefined optical and electrical properties for noise and signal models for the clarity of the subject. The model includes aberrations and wave-like limits from optical effects on noise and signal. Also some behavioral effects such as searching and tracking and environmental effects such as vibration have been considered.

The simulations has been run for a basic missile like structure with an electro-optical payload.

The analysis consist of range performance for geometrical resolution (in other words how the image performs for "Johnson's Criteria") and sensitivity (SNR) aspects.

9820-26, Session 7

Long-exposure visible camera performance characterization

Cynthia D. Dawson, The Univ. of Alabama in Huntsville (United States)

The CMOS sensors used by modern digital SLR cameras provide high sensitivity, low noise, and low dark current. Under dark conditions, the level of dark current varies greatly across the array. The dark current values for individual pixels can be characterized under lens-cap conditions and used to remove the bias that is introduced when obtaining long-exposure images under dark conditions. The higher noise levels caused by the dark current and the residual of the bias removal provide limitations on the detection performance of visible cameras. In addition, the motion of the target must be considered due to the effective dilution of signal. Measurements of sensitivity, noise, and dark current for various models of CMOS sensors will be provided. These measurements will then be used to estimate the detection range for various classes of near-stationary targets under varying atmospheric and illumination conditions. The results are directly applicable to certain surveillance problems associated with low-light conditions where both the sensor and the target are nearly stationary. Several use cases will be considered include perimeter surveillance and satellite surveillance.

9820-27, Session 7

A point source detection model using energy and power spectral densities

Bradley L. Preece, U.S. Army RDECOM CERDEC NVESD (United States); George T. Nehmetallah, The Catholic Univ. of America (United States)

The purpose of this paper is to construct a robust modeling framework for imaging systems in order to predict the performance of detecting small unresolved targets such as Unmanned Aerial Vehicles (UAVs). The underlying principle is to track the flow of scene information and statistics, such as the energy spectra of the target and power spectra of the background, through any number of imaging components. This information is then used to calculate a detectivity metric. Each imaging component is treated as a single linear shift invariant (LSI) component with specified input and output parameters. A component based approach enables the inclusion of existing component-level models and makes it directly compatible

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with image modeling software such as the Night Vision Integrated Performance Model (NV-IPM). The modeling framework also includes a parallel implementation of Monte Carlo simulations designed to verify the analytic approach. However, the Monte Carlo simulations may also be used independently to accurately model non-linear processes where the analytic approach fails, allowing for even greater extensibility. A simple trade study is conducted comparing the modeling framework to the simulation.

9820-28, Session 7

The analysis and rationale behind the upgrading of existing standard definition thermal imagers to high definition

Tristan M. Goss, Paul W. Barnard, ASELNAN Inc. (South Africa)

With 640x512 pixel format IR detector arrays having been on the market for the past decade Standard Definition (SD) thermal imaging sensor have been developed and deployed across the world. Now with 1280x1024 pixel format pixels format IR detector arrays now becoming readily available designers of thermal imager systems face new challenges as pixel sizes reduce and the demand and applications for High Definition (HD) thermal imaging sensors increases. In many instances the upgrading of existing under-sampled SD thermal imaging sensors into more optimally sampled or oversampled HD thermal imaging sensors provides a more cost effective and reduced time to market option than to design and develop a completely new sensor.

This paper presents the analysis and rationale behind the selection of the best suited HD pixel format MWIR detector for the upgrade of an existing SD thermal imaging sensor to a higher performing HD thermal imaging sensor. Several commercially available and "soon to be" commercially available HD small pixel IR detector options are included as part of the analysis and are considered for this upgrade. The impacts of the proposed detectors has on the sensors overall sensitivity, noise and resolution is analyzed, and the improved range performance is predicted for several operational scenarios. Furthermore with reduced dark currents due to the smaller pixel sizes, most the candidate HD MWIR detectors are operated at higher temperatures when compared to their SD predecessors. Therefore, as an additional constraint and as a design goal, the feasibility of achieving upgraded performance without out any increase in the size, weight and power consumption of the thermal imager is discussed herein.

9820-29, Session 7

Characterization and recognition of mixed emotional expressions in thermal infrared face image

Priya Saha, Tripura Univ. (India); Debotosh Bhattacharjee, Jadavpur Univ. (India); Barin Kumar De, Tripura Univ. (India); Mita Nasipuri, Jadavpur Univ. (India)

Human facial expressions can be used as an informative and verifying medium in the field of security and surveillance. Very important application shall be detecting the motive and possible future action of a criminal mind, because various facial expressions are considered as a reliable tool to verify the concealed emotion of a person. Facial expressions in thermal infrared imaging have been introduced to solve the problem of illumination, which is an integral constituent of visual imagery. The paper investigates facial skin temperature distribution on total 18 thermal facial expressions of our created face database where six are basic expressions and rest 12 are a mixture of those basic expressions. Temperature analysis has been performed on three facial regions of interest (ROIs); periorbital, supraorbital and mouth. Temperature variability of the ROIs in different expressions has been measured using the interquartile range. The temperature variation measurement in ROIs of a particular expression corresponds to a vector, which is later used in recognition of mixed facial expressions using SVM classifier. This measurement is also used to identify distinctly specific facial

areas responsible for an expression in a thermal face image. Investigations show that facial features in mixed facial expressions can be characterized by positive emotion induced facial features and negative emotion induced facial features. In positive emotion induced facial features, changes in temperature distribution is more prominently detectable than negative emotion induced facial features.

9820-30, Session 8

Industry Presentation

Dario Cabib, CI Systems (Israel) Ltd. (Israel); Stephen D. Scopatz, Electro Optical Industries, Inc. (United States); Alan Irwin, Santa Barbara Infrared, Inc. (United States)

No Abstract Available

9820-31, Session 8

Thermal system field performance predictions from laboratory and field measurements (Invited Paper)

Stephen D. Burks, David P. Haefner, Joshua M. Doe, Brian P. Teaney, U.S. Army RDECOM CERDEC NVESD (United States)

Laboratory measurements on thermal imaging systems are critical to understanding their performance in a field environment. It is rarely a straightforward process to directly inject thermal measurements into thermal performance modeling software to acquire meaningful results, though. Some of the sources of discrepancy between laboratory and field are sensor gain and level, dynamic range, sensor display and display brightness, and the environment which the sensor is operating. If measurements for the aforementioned parameters could be performed, a more accurate description of sensor performance in a particular environment is possible. This research will also include the procedure for turning both laboratory and field measurements into system model.

9820-32, Session 8

MRC measurements of image intensifiers under realistic illumination conditions

Alexandre Vallières, NovaSyst (Canada); Nathalie Roy, Michel Dupuis, Daniel St-Germain, Jean-Claude Bouchard, Martin Bérubé, Defence Research and Development Canada, Valcartier (Canada); André Villemaire, NovaSyst (Canada); Mélanie Breton, Guillaume Gagné, AEREX avionique inc. (Canada)

A novel approach is used to characterize the performance of night vision goggles (NVG) in conditions more representative of night operation. The concept relies on a tumbling-E target and on a new LED-based illumination source that accurately emulates night sky spectral irradiances from starlight to quarter-moon conditions. The presented apparatus aims at reducing the error on the amount of photo-generated electrons compared to the STANAG 4351 procedure, while reducing the minimum resolvable contrast (MRC) testing time. We describe the set-up and we demonstrate that the novel approach can be a very efficient way to characterize NVG performance with a small error on the photo-electrons.

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9820-33, Session 8

Noise measurement on thermal systems with narrow band

Stephen D. Burks, David P. Haefner, U.S. Army RDECOM CERDEC NVESD (United States)

Thermal systems with a narrow spectral bandpass are useful for a variety of imaging applications. Additionally, the sensitivity for this class of systems is increasing as requirements for performance are increased. Unfortunately, the uncertainty in the blackbody temperature along with the temporal instability of the blackbody could lead to an increase in the measured noise. If the temporal uncertainty and accuracy of a particular blackbody is known, then confidence intervals could be adjusted for source accuracy and instability. Additionally, because thermal currents are a large source of temporal noise in narrow band systems, a means to mitigate them is presented and results are discussed.

9820-35, Session 9

Development of a high-definition IR LED scene projector

Steve W. McHugh, Dennis Norton Jr., Joseph D. Laveigne, Gregory Franks, Tony G. Vengel, Santa Barbara Infrared, Inc. (United States)

Next-generation Focal Plane Arrays (FPAs) are demonstrating ever increasing frame rates, dynamic range, and format size. These improvements in FPA performance and array format have challenged the test community to accurately and reliably test them in a Hardware-In-the-Loop (HIL) environment. To meet the demands of future FPA testing, Santa Barbara Infrared (SBIR) is developing a High Definition Infrared Light Emitting Diode (HDILED) IRSP system capable of maximum apparent temperatures of 1400K, maximum frame rates of 400Hz, and packaged in a 2048x2048 array format.

In this paper we will present our development work on infrared light emitting diodes (ILEDs) based on type-I multiple quantum wells and type-II interband cascaded active region designs. We give focus to the forward drive current versus radiative output response at both the low and high drive levels, as well as how to achieve the large dynamic range while maintaining adequate temperature resolution while projecting ambient scenes.

9820-36, Session 9

Display MTF measurements based on scanning and imaging technologies and its importance in the application space

Balvinder Kaur, Jeffrey T. Olson, Eric A. Flug, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Measuring the Modulation Transfer Function (MTF) of a display monitor is necessary for many applications such as: modeling end-to-end systems, conducting perception experiments, and performing targeting tasks in real-world scenarios. The MTF of a display defines the resolution properties and quantifies how well the spatial frequencies are displayed on a monitor. Many researchers have developed methods to measure display MTFs using either scanning or imaging devices. In this paper, we first present methods to measure display MTFs using two separate technologies and then discuss the impact of a display MTF on a system's performance. The two measurement technologies were scanning with a photometer and imaging with a CMOS based camera. To estimate a true display MTF, measurements made with the photometer were backed out for the scanning optics aperture. The developed methods were applied to measure MTFs of the two types of

monitors, Cathode Ray Tube (CRT) and Liquid Crystal Display (LCD). The accuracy of the measured MTFs was validated by comparing MTFs measured with the two systems. The methods presented here are simple and can be easily implemented employing either a Prichard photometer or an imaging device. In addition, the impact of a display MTF on the end-to-end performance of a system was studied using NV-IPM.

9820-37, Session 9

Achieving ultra-high temperatures with a resistive emitter array

Tom Danielson, Joseph D. Laveigne, Gregory Franks, Santa Barbara Infrared, Inc. (United States); Dennis Norton, Nicholas Holmes, Greg Matis, Steve McHugh, Santa Barbara Infrared Inc (United States); John Lannon, Scott Goodwin, RTI International (United States)

The rapid development of very-large format infrared detector arrays has challenged the IR scene projector community to also develop larger-format infrared emitter arrays to support the testing of systems incorporating these detectors. In addition to larger formats, many scene projector users require much higher simulated temperatures than can be generated with current technology in order to fully evaluate the performance of their systems and associated processing algorithms.

Under the Ultra High Temperature (UHT) development program, Santa Barbara Infrared Inc. (SBIR) is developing a new infrared scene projector architecture capable of producing both very large format (>1024x1024) resistive emitter arrays and improved emitter pixel technology capable of simulating very high apparent temperatures. During earlier phases of the program, SBIR demonstrated materials with MWIR apparent temperatures in excess of 1400K. New emitter materials have subsequently been selected to produce pixels that achieve even higher apparent temperatures. Test results from pixels fabricated using the new material set will be presented and discussed. A 'scalable' Read In Integrated Circuit (RIIC) is also being developed under the same UHT program to drive the high temperature pixels. This RIIC will utilize through-silicon vias and Quilt Packaging technologies to allow seamless tiling of multiple chips to fabricate very large arrays, and thus overcome the yield limitations inherent in large-scale integrated circuits. Results of design verification testing of the completed RIIC will be presented and discussed.

9820-38, Session 9

Automated and semi-automated field testing of night vision goggles

Stephen D. Scopatz, Dominic E. Paszkeicz, Electro Optical Industries, Inc. (United States); Brent Langsdorf, Nightline, Inc. (United States)

This paper will discuss the development and results of a new field portable test set for Gen 2 and Gen 3 intensifies tube based night vision goggles that automates many of the tests supported by currently available NVG test products. The major innovation is the use of MTF testing with a knife edge target that is well established in the laboratory environment to replace the operator's interpretation of the USAF 1951 resolution chart. Results will be presented to show the more consistent performance of the MTF approach compared to the known operator variations when humans determine resolution. Other standard tests are semi-automated and/or video assisted such as infinity focus, spot defects, and distortion. The presentation will show repeatability across test units and operators on the key tests. The presentation will include examples of the report files for each test run on each goggle that are automatically generated. All of this capability is provided in a package that matches the form factor of other products in use to test NVG's. A discussion of the user interface and the ease of use of the system will be included as well as the improvement is the test time for each goggle.

9820-39, Session 9

Design peculiarities of active vision systems based on powerful laser diode matrixes

Yahor V. Lebiadok, Dzmitri M. Kabanau, Vladimir V. Kabanov, Denis V. Shabrov, Alexandr P. Bunichev, B.I. Stepanov Institute of Physics (Belarus)

The powerful laser diode matrixes (LDM) based on the AlGaAs/GaAs heterostructures are used as illumination sources in the active vision systems (AVS) under consideration. The LDM lasing wavelength is in the range 790-880 nm (the atmosphere transparency spectral region), total optical output pulse power 4 kW, the LDM dimensions are 1.1 cm x 1.3 cm. The LDM was produced by JSC "Inject" (Russia).

Achievement of AVS's high efficiency is connected with a high average power of illumination, which along with peak optical power depends on the pulse duration and pulse repetition rate. In turn effective realization of the principle of range gated active vision supposes usage of short light pulses. The LDM radiation pulse duration must be about 10-300 ns for the application in the AVS which are used for the distances from 100 m up to 10 km. To achieve such pulse duration (about 30 ns) and high pulse repetition rate (up to 100 kHz) values as well as to satisfy requirements of AVS compactness special electric scheme and geometry of power supply is needed. Such schemes are discussed in the report.

Another problem related to using laser diode matrixes as illumination sources in AVS is LDM active layer heating as well as the LDM radiation divergence (and its concordance with objective field of view). The LDM passive cooling and method of radiation divergence control are also discussed.

9820-40, Session 10

Sensitivity and spectral response of commercially available microbolometer cameras

Sarah T. Crites, Paul G. Lucey, Univ. of Hawai'i (United States); Arleen Velasco, John L. Hinrichs, Spectrum Photonics, Inc. (United States); Mark Wood, Univ. of Hawai'i (United States) and Spectrum Photonics, Inc. (United States); Casey I. Honniball, Andrea Gabrieli, Univ. of Hawai'i (United States)

We have developed a procedure to characterize and directly compare the spectral response and sensitivity of infrared cameras in order to create measurement-based performance models for spectrometer systems employing commercial cameras. We use an Oriel 77250 monochromator with a 7 micron blaze grating backlit by a high-temperature blackbody to characterize each camera at 35 narrow wavelength bands between 7 and 14 microns. Sensitivity is characterized using a NIST-traceable large-area blackbody to measure broadband noise equivalent change in temperature (NEDT), and using the high-temperature blackbody and a narrow bandpass filter to obtain narrow band NEDT. The measurement of narrow band NEDT is critical to remove the effects of spectral response from the sensitivity characterization. We have thus far characterized six commercially available long wave infrared (LWIR, 7-14 microns) microbolometer cameras with a variety of frame rates and pixel sizes. We have focused on VOx detectors including a FLIR Photon 320, a FLIR Tau 640, a FLIR A35, and two LumaSense MC320 cameras, as well as one α -Si detector (a Sofradir PV640). We find that the Photon 320, operating at 30 Hz and with 38 micron pixels, outstrips the other cameras in terms of broadband sensitivity, with a broadband NEDT of 11-22 mK measured at 50 C. The relative spectral responses of the cameras provide a valuable tool for selecting a camera for incorporation into a spectrometer system, depending on the desired spectral signatures of interest.

9820-41, Session 10

Real-time simulation of thermal shadows with EMIT

Andreas Klein, MBDA Germany (Germany); Stefan Oberhofer, Munich University of Applied Sciences (Germany); Peter Schätz, MBDA Germany (Germany); Alfred Nischwitz, Munich University of Applied Sciences (Germany); Paul Obermeier, MBDA Germany (Germany)

No Abstract Available

9820-42, Session 11

Simulation of whitecaps and their radiometric properties in the SWIR

Frédéric Schwenger, Endre Repasi, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

A 3D simulation of the dynamic sea surface populated with whitecaps is presented. The simulation considers the dynamic evolution of whitecaps depending on wind speed and fetch. It is suitable for imaging simulation of maritime scenarios. The calculation of whitecap radiance is done in the SWIR spectral band by considering wave hiding and shadowing, especially occurring at low viewing angles.

Our computer simulation combines the 3D simulation of a maritime scene (open sea/clear sky) considering whitecaps and the simulation of light from a light source (e.g. laser light) reflected at the sea surface. The basic sea surface geometry is modeled by a composition of smooth wind driven gravity waves. The whitecap generation is deduced from the vertical acceleration of the sea surface, i.e. from the second moment of the wave power density spectrum. To predict the view of a camera, the sea surface radiance must be calculated for the specific waveband with the emitted sea surface radiance and the specularly reflected sky radiance as components. The radiances of light specularly reflected at the wind-roughened sea surface without whitecaps are modeled by considering an analytical statistical sea surface BRDF (bidirectional reflectance distribution function). A specific BRDF of whitecaps is used by taking into account their shadowing function. The simulation model is suitable for pre-calculation of reflected radiance of a light source for near horizontal incident angles where slope-shadowing of waves has to be considered.

The whitecap coverage is determined from the simulated image sequences for different wind speeds and is compared with whitecap coverage functions from literature. A SWIR-image of the water surface of a lake populated with whitecaps is compared with the corresponding simulated image. Additionally, the impact of whitecaps on the radiation balance for a bistatic configuration of light source and receiver is calculated for different wind speeds.

9820-43, Session 11

Investigation of the dynamic thermal infrared signatures of a calibration target instrumented with a network of 1-wire temperature sensors

Gareth D. Lewis, Patrick J. Merken, Royal Military Academy (Belgium)

The signatures from well-characterized geometric targets, such as the CUBI, are an essential component in the validation of infrared (IR) signature models and simulations. A simple target with known thermal and optical properties allows a detailed analysis of the influence from the environment on the radiance detected by an IR imaging device. In this paper, we describe

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a CUBI geometrical target recently fitted with 1-wire temperature sensors and present initial data from this system. The CUBI is 'L' shaped with a maximum dimension of 1 meter in height and minimum 0.5 meter in width. It is constructed of thin steel painted with Navy Grey, and the insulated by a layer of foam and ply-wood. There is no internal heat source. Digital 1-wire programmable temperature sensors (DS18B20) are mounted inside directly touching the steel at distributed positions over the upper surfaces. Temperature data is recorded every 20 seconds in orders to capture a range of dynamic thermal effects, and could be programmed to data rates as short as a few seconds. All the sensors were calibrated in a temperature controlled oven over the range from minus 20 to plus 50 degrees Celsius. A meteorological station is collocated with the CUBI and records relevant weather data every few minutes. Since May 2015, both CUBI temperature sensor data and weather data have been recorded almost uninterruptedly, and we plan to continue this experiment until January 2018. During periods foreseen to be of interest for dynamic changes in thermal radiance, a medium-wave band imager recorded images at a high frame-rate, which were later calibrated in terms of radiance. The imager was positioned close to the target at a fixed height. The sensors performed reliably and could be easily reprogrammed. The temperature data indicates a range of dynamic effects that require further study.

9820-44, Session 11

Image-based performance analysis of thermal imagers

Daniel Wegner, Endre Repasi, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

Due to advances in technology, modern thermal imagers resemble sophisticated image processing systems in functionality. Advanced signal and image processing tools – enclosed into the camera body – extend the basic image capturing capability of thermal cameras. This happens in order to enhance the display presentation of the captured scene or scene details. Usually, the implemented methods are proprietary company expertise, without extensive documentation. This makes the comparison of thermal imagers – especially from different companies – a difficult task (or at least very time consuming or expensive task, e.g. executing a field trial and/or an observer trial).

The Fraunhofer IOSB has started to build up a system for testing thermal imagers by image based methods in the lab environment. This will extend our capability of measuring the classical IR-system parameters (e.g. MTF, MTDP, etc.) in the lab. The system is set up around the IR-scene projector, which is necessary for the 'thermal display' of an image sequence for a unit under test.

An initial hardware configuration will be presented. Additionally, the preparation of an imaging suite (a set of image sequences) for the analysis of systems containing such 'black boxes' in the image forming path will be discussed. For example, a thermal camera equipped with turbulence mitigation capability represents such a 'closed' system.

The assessment of such cameras – including the measurement of their performance limits – is more feasible in the controlled environment in the lab than in the field. In the lab, the same set of thermal test sequences is presented (projected) to every unit under test repeatedly. For turbulence mitigation tests, this could be the same turbulence sequence. A gradual variation of input parameters (e.g. thermal contrast) can be applied during system tests.

Additionally, the pros and cons of automatic evaluation methods by means of a 'standard image suite' will be discussed.

9820-45, Session 12

Application of cooled IR focal plane arrays in thermographic cameras

Birgit Vollheim, Maria Gärtner, Gunnar Dammass, Matthias Krausz, InfraTec GmbH (Germany)

As most of the cooled IR focal plane arrays (FPAs) are dedicated to Defense and Security applications, the performance of these detectors is usually optimized for the requirements of this scope. The usage for civil applications especially in thermographic, i.e. radiometrically calibrated, IR cameras leads to special demands on these FPAs which are discussed in this paper.

Whereas Defense and Security applications usually provide a scene at the given ambient temperature with smaller hot spots, thermographic cameras are often directed towards extended objects with a high temperature contrast to the background. This could generate artefacts in the image, such as pixel patterns and vertical or horizontal stripes. Other less-critical artefacts caused by an overlap of integration and read-out time in the preferred Integrate-While-Read (IWR) mode can usually be eliminated by a Non-Uniformity Correction.

A special challenge for radiometrically calibrated cameras are the wide temperature measuring ranges, which reach from -40 °C up to 2000 °C or even 3000 °C, conveniently split into various sub-ranges. Therefore, a linear and time-stable response of the photodiode array has to be ensured for low as well as high radiation intensities. The maximum detectable photon flux is defined by the allowed shift of the photodiode's reverse bias, which shouldn't get into the nonlinear part of the photodiode's I(V) curve even for the highest photocurrent. This limits the measurable highest object temperature in practice earlier than the minimum possible integration time. Higher temperature ranges have to be implemented by means of neutral or spectral filters.

Other demands concern the clock regime of the Read-Out-Circuit (ROIC). In pure IR imaging systems the FrameSync pulse usually starts the read-out time to ensure a short delay to the previous integration time. For thermographic cameras it is however more important to trigger the integration time with a very short delay.

Further investigations regarding the Non-Uniformity Correction (NUC), the frame rate dependency of the signal and the subframe capabilities of the ROICs will be presented in detail. We will also discuss the demands on the lens design for thermographic cameras when using cooled IR FPA detectors with large apertures.

9820-46, Session 12

3D flare particle model for ShipIR/NTCS

David A. Vaitekunas, Srinivasan Ramaswamy, W. R. Davis Engineering, Ltd. (Canada)

A key component in any soft-kill response to an incoming guided missile is the flare /chaff decoy used to distract or seduce the seeker homing system away from the naval platform. This paper describes a new 3D flare particle model in the naval threat countermeasure simulator (NTCS) of the NATO-standard ship signature model (ShipIR), which provides independent control over the size and radial distribution of its signature. The 3D particles of each flare sub-munition are modelled stochastically and rendered using OpenGL z-buffering, 2D projection, and alpha-blending to produce a unique and time varying signature. A sensitivity analysis on each input parameter provides the data and methods needed to synthesize a model from an IR measurement of a decoy. The new model also eliminated artifacts and deficiencies in our previous model which prevented reliable tracks from the adaptive track gate algorithm already presented by Ramaswamy and Vaitekunas (2015). A sequence of scenarios are used to test and demonstrate the new flare model during a missile engagement.

9820-47, Session 12

Digital imaging and remote sensing image generator (DIRSIG) as applied to NVESD sensor performance modeling

Kimberly E. Kolb, U.S. Army RDECOM CERDEC NVESD (United States); J. Andrew Hutchinson, Hee-Sue Choi, Clayton F. Hill, Balvinder Kaur, U.S. Army Night Vision &

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Electronic Sensors Directorate (United States); Jackson McClellan, Univ. of Delaware (United States); Jeffrey T. Olson, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Distribution Statement A: Approved for public release -

The demonstrated ability of the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) to synthesize, modify and degrade images in a controlled fashion and quantify the effect of these modifications on the performance by human observers and algorithms of detection, tracking, or target identification is critical to modeling, designing, and assessing imaging systems across all wavebands. Sensor performance modeling is migrating away from Fourier transform-based assessments because non-linear algorithm processing inhibits performance prediction. Thus, many new techniques are imaged-based and simulation serves as a viable tool for researching sensor performance.

The Night Vision Integrated Performance Model (NV-IPM) simulated the degrading effects of system sensitivity and resolution. It applied these effects to images of interest, both those synthesized using DIRSIG, a scene simulator and an image generator with full spectral and thermal object signatures which can couple with MODTRAN, and those collected in the field. Vehicle discrimination algorithms were then tested using the degraded images generated by the NV-IPM to determine failure points in controlled scientific experiments. The degree to which the algorithm performance agrees with simulated versus field collected imagery is the first step in validating this procedure. This virtual prototyping approach to sensor system design could dramatically save time and money for system development.

of COTs graphics cards is limited of 2560x1580 pixels at 60Hz. Moreover, there are significant challenges in real-time, closed-loop, physics-based IR scene generation for large format FPAs, including the size and spatial detail required for very large area terrains, and multi-channel low-latency synchronization to achieve the required bandwidth. In this paper, the authors present some of their ongoing research and technical approaches toward HWIL testing of large-format FPAs with wide-FOV optics. One approach presented is a hybrid projection/injection design, where digital signal injection is used to augment the resolution of current-art IRSPs, utilizing a multi-channel, high-fidelity physics-based IR scene simulator in conjunction with a novel image composition hardware unit, to allow projection in the foveal region of the sensor, while non-foveal regions of the sensor array are simultaneously stimulated via direct injection into the post-detector electronics.

9820-48, Session 12

**Multispectral synthetic image generation
for ground vehicle identification training**

Christopher May, Neil Pinto, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Jeff Sanders, Trideum Corp. (United States)

There is a ubiquitous and never ending need in the US armed forces for training materials that provide the warfighter with the skills needed to differentiate between friendly and enemy forces on the battlefield. The current state of the art in battlefield identification training is the Recognition of Combat Vehicles (ROCV) tool created and maintained by the Communications - Electronics Research, Development and Engineering Center Night Vision & Electronic Sensors Directorate (CERDEC NVESD). The ROCV training package utilizes measured visual and thermal imagery to train soldiers about the critical visual and thermal cues needed to accurately identify modern military vehicles and combatants. This paper presents an approach to augment the existing ROCV imagery database with synthetically generated multi-spectral imagery that will allow NVESD to provide improved training imagery at significantly lower costs.

9820-50, Session 12

**New technologies for HWIL testing of
WFOV, large-format FPA sensor systems**

Christopher E Fink, JRM Technologies, Inc. (United States)

Advancements in FPA density and associated wide-field-of-view infrared sensors (>=4000x4000 detectors) have outpaced the current-art HWIL technology. Whether testing in optical projection or digital signal injection modes, current-art technologies for infrared scene projection, digital injection interfaces, and scene generation systems simply lack the required resolution and bandwidth. For example, the L3 Cincinnati Electronics ultra-high resolution MWIR Camera deployed in some UAV reconnaissance systems features 16MP resolution at 60Hz, while the current upper limit of IR emitter arrays is ~1MP, and single-channel dual-link DVI throughput

Conference 9821: Tri-Technology Device Refrigeration (TTDR)

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9821-1, Session 1

Optical refrigeration: the journey into the cryogenic regime (*Invited Paper*)

Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Optical refrigeration (also known as laser cooling of solids) has advanced tremendously since its first experimental observation in 1995. Most recently, crystals doped with Yb ions have cooled to an absolute temperature of about 90K starting from room temperature, with even lower temperatures possible. Optical refrigeration is currently the only available technique for realizing an all-solid-state cryocooler. In this talk, I will present an overview of the recent advances in cooling rare-earth doped crystals. I will also discuss the prospects of cooling bulk semiconductors such as GaAs.

9821-2, Session 1

Measuring the anti-Stokes luminescence of CdSe/ZnS quantum dots for laser cooling applications (*Invited Paper*)

Ross S. Fontenot, Veerendra K. Mathur, John H. Barkyoumb, Naval Surface Warfare Ctr. Carderock Div. (United States); Carl E. Mungan, U.S. Naval Academy (United States); Rhanh N. Tran, Naval Surface Warfare Ctr. Carderock Div. (United States)

The first demonstration of laser cooling of solids was of an ytterbium doped fluorozirconate glass. While this groundbreaking work successfully showed that it is possible to cool solids using laser cooling, rare-earth materials are governed by Boltzmann statistics, which limits their cooling ability to about 100 K. Direct-bandgap semiconductors, on the other hand, are governed by Fermi-Dirac statistics, which allows for a theoretical cooling limit of 10 K as well as higher cooling efficiencies. Recently, it was demonstrated that it is possible to cool CdS nanoribbons by 40 K. They attributed the success to CdS strong electron-phonon coupling, which makes it possible to resonantly annihilate more than one longitudinal phonon during each up conversion cycle. To further increase the cooling power, a large external quantum efficiency is required. The nano structure is preferred because it creates confined excitons of tunable wavelength and reduces the self-absorption of the anti-Stokes fluorescence owing to the shorter length required to leave the crystal. However, organically passivated quantum dots have a low quantum yield due to surface related trap states. The core-shell nanostructure alleviates this problem by passivating the surface trap states and protecting against environmental changes and photo-oxidative degradation. As such, we chose to investigate CdSe/ZnS core shell structure for laser cooling applications. This talk will highlight the measurement of the anti-Stokes fluorescence, effects of laser wavelength on the anti-Stokes emission, optical absorption as a function of wavelength and power, and successful incorporation of CdSe/ZnS into polymers.

9821-3, Session 1

Non-resonant optical cavity design for optical refrigeration (*Invited Paper*)

Bernardo G. Farfan, ThermoDynamic Films (United States) and The Univ. of New Mexico (United States); Mohammad R. Ghasemkhani, Alexander R. Albrecht, The Univ. of New

Mexico (United States); Guy Symonds, ThermoDynamic Films (United States) and The Univ. of New Mexico (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States); Richard I. Epstein, ThermoDynamic Films (United States) and The Univ. of New Mexico (United States)

We present a study of optical refrigerators with non-resonant optical cavities. Designs have been studied to maximize pump light trapping to increase cooling power in optical refrigeration. The approaches of non-resonant optical cavities through highly reflective mirrors arrangement and the monolithic optical maze were studied. Ray-tracing simulations were performed to characterize and analyze the different light trapping configurations. Light trapping was studied for laser sources with high quality beams and for beams with large divergences, roughly corresponding to the output from fiber lasers and from diode lasers, respectively. We present a trade-off analysis between performance, reliability and manufacturability.

9821-4, Session 1

Integration of laser fluorescence coolers with High Operating Temperature (HOT) detectors (*Invited Paper*)

Niels F. Jackson, SCD.USA, LLC (United States); Richard I. Epstein, ThermoDynamic Films (United States); Alexander Veprik, SCD Semiconductor Devices (Israel)

Solid state cryo-refrigerators which are compact, efficient, reliable and non-mechanical are ideal for many electronics and sensor applications. This paper describes how a Ytterbium-based Laser Cooling system using Anti-Stokes Fluorescence has been integrated with modern High Operating Temperature (HOT) detectors. Operating in the 150K region, HOT detector cameras, whether in the MWIR and LWIR spectral bands, still require expensive mechanical Stirling cycle coolers to sustain the heat load at operating temperature. These coolers have served industry well over the last 40 years but have disadvantages due to large size, high audible and EMI noise, low MTTF reliability, and relatively high cost. With Thermoelectric technology still unable to demonstrate cooling below 180K, Laser cooling technology offers a unmatched set of solutions for the infrared detector industry.

We describe the principle of Anti-stokes fluorescence, technology challenges and recent results integrating new designs in proof-of-concept devices. We review design and performance of proof-of-concept optical refrigerators that have been developed to date. The paper provides critical performance data at 1020nm laser wavelengths of a prototype cooler integrated with the SCD Kinglet VGA XBN detector. The paper describes thermal link design alternatives between the Laser cooling crystal and the detector Cold Plate. It projects performance improvements due to material, interconnect and electronics advancements leading to a fieldable device, competitive with Stirling Coolers in 3-5 years. A Trade table is provided showing cooler Key Performance Parameters relating to commercial, industrial, military tactical and strategic reconnaissance applications demonstrating where Solid State Cooling would provide unrivaled value.

9821-5, Session 2

Raytheon advanced pulse tube cryocoolers

Ted Conrad, Raytheon Space and Airborne Systems (United States)

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Since the 1970s, Raytheon has developed, built, tested and integrated high performance cryocoolers. Our versatile designs for single and multi-stage cryocoolers provide reliable operation for temperatures from 10 to 200 Kelvin with power levels ranging from 50 W to nearly 600 W. These cryocoolers incorporate clearance seals, flexure suspensions, hermetic housings and dynamic balancing to provide long service life and reliable operation in all relevant environments.

Recently, Raytheon has developed an advanced regenerator technology capable of operating efficiently at high frequencies and outperforming traditional screen regenerators. Two single stage pulse tube coolers have been designed for use with this regenerator. The first is the Raytheon Advanced Miniature (RAM-100) cryocooler, a flight packaged, high frequency pulse tube cooler with an integrated surge volume and inertance tube. A prototype RAM cryocooler has been built and tested and the results are presented in this paper. Additionally, a single stage pulse tube cryocooler using Raytheon's next-generation compact inline architecture is currently being developed. Design details and performance predictions for this compact inline pulse tube cryocooler are presented as well.

9821-6, Session 2

Advantages of high-frequency pulse-tube technology and its applications in infrared sensing

Roel Arts, Daniel Willems, Jeroen Mullié, Tonny Benschop, Thales Cryogenics B.V. (Netherlands)

No Abstract Available

9821-7, Session 3

RICOR development of the next-generation highly reliable rotary cryocooler

Sergey V. Riabzev, Itai Regev, Ilan Nachman, Dorit Livni, Avishai Filis, RICOR Cryogenic & Vacuum Systems (Israel)

Early rotary cryocoolers were designed for the lifetime of a few thousands operating hours. Ricor K506 model's life time was only 5,000 hours, then the next generation K508 model was designed to achieve 10,000 operating hours in basic conditions, while the modern K508N was designed for 20,000 operating hours.

Nowadays, the new challenges in the field of rotary cryocoolers require development of a new generation devices that could compete with the linear cryocooler reliability, achieving the lifetime goal of 30,000 operating hours, and even more.

Such new cryocooler advancement could serve the new generation of high-temperature detectors that are currently under development, enabling the cryocooler to work more efficiently in the field.

The improvement of the rotary cryocooler reliability is based on a deep analysis and understating of the root failure causes, finding solutions to reduce bearings wear, using modern materials and lubricants. All of those were taken into consideration during the development of the new generation rotary coolers.

As a part of reliability challenges, new digital controller is under development, which allows new options, such as discrete control of the operating frequency. In addition, the digital controller will be able to collect data during cryocooler operation, aiming End Of Life prediction.

9821-8, Session 3

Status of ultra-long life coolers at AIM

Ingo N. Rühlich, Sebastian Zehner, Markus Mai, Thomas Wiedmann, Carsten Rosenhagen, AIM INFRAROT-MODULE GmbH (Germany)

Since 2007, AIM has been developing technologies for a substantial extension of cryocooler life times and reliability. On the compressor side, AIM designed Flexure Bearing Moving Magnet compressors featuring a contactless movement of the pistons inside the sleeve and the elimination of internal contamination potential. In parallel, a compact co-axial Pulse Tube coldfinger has been developed fitting into a standard 2"-inner dewar. The standard Stirling-expander has been replaced by a new expander made of a high performance one-piece plastic with less wear and a new pneumatic drive mechanism.

Combining these technologies on the on hand, AIM designs and delivers ultra-long life Pulse Tube Coolers for IR-detectors for space applications providing highest reliability with life times in excess of 100,000 hours and full in-orbit capability. On the other hand, AIM provides compact long life Stirling-Coolers including digital controller with life times of up to 50,000 hours to achieve lowest total cost of ownership.

This presentation will review the status of AIM's long life cryocoolers and gives an overview of its applications, qualification, life time testing and availability.

9821-9, Session 3

Development of a cryogenic integrated system with working temperature of 100K

Enguang Liu, Yinong Wu, Yueming Wang, Jiajia Wen, Gang Lv, Chunlai Li, Jia Hou, Liyin Yuan, Shanghai Institute of Technical Physics (China)

In some infrared systems, cooling down the optic components' temperature is a better choice to decrease the background radiation and maximize the sensitivity. This paper presents a 100K cryogenic optical system, for which some flexible thermal links and a cryogenic optical bench were developed. The whole infrared optic components which were assembled in a vacuum box were cooled down to 100K by two mechanical coolers. Low thermal conductivity supports and low emissivity multi-layers were used to reduce the cryogenic optical system's heat loss. The experimental results showed that in about eight hours, the temperature of the optical components reached 100K from room temperature, and the vibration from the mechanical coolers have nearly no affection to the imaging process by using of soft thermal links. Some experimental results of this cryogenic system will be discussed in this paper.

9821-10, Session 3

Overview of Sumitomo coolers and Dewars for space use

Kenichi Kanao, Katsuhiko Narasaki, Shoji Tsunematsu, Kiyomi Otsuka, Akinobu Okabayashi, Sumitomo Heavy Industries, Ltd. (Japan); Kazuhisa Mitsuda, Hiroshi Murakami, Takao Nakagawa, Institute of Space and Astronautical Science (Japan); Toshiyuki Nishibori, Ryota Sato, Hiroyuki Sugita, Yoichi Sato, Japan Aerospace Exploration Agency (Japan); Masahide Murakami, Univ. of Tsukuba (Japan)

Since 1987, Sumitomo Heavy Industries, Ltd (SHI). has been developing cooler and Dewar technology for space application with Japan Aerospace Exploration Agency. SHI has four types of coolers to cover temperature

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range from 1.7K to 80K or more.

Single stage Stirling coolers for 80K cooling were launched on the X-ray astronomical satellite "SUZAKU" (2005), Japanese lunar orbiter "KAGUYA" (2007), and the Japanese Venus Climate Orbiter "AKATSUKI" (2010). Two-stage Stirling coolers for 20K cooling were launched on the infrared astronomical satellite "AKARI" (2006). A 4K-class cooler consists of a 4He Joule-Thomson cooler with a two-stage Stirling as a pre-cooler. It was launched on the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES, 2009) aboard the Japanese Experiment Module of the International Space Station. A 1K-class cooler consists of a 3He Joule-Thomson cooler with a two-stage Stirling as a pre-cooler. It is now in the test of the engineering model on the ground. 1K-class coolers will be launched on SPICA and ATHENA project in 2020's.

In projects mentioned above, SHI also provided Dewars to cool detectors, mirrors and optics. SXS Dewar is our latest product having a hybrid cooling chain combined coolers and liquid helium. It is now in the final test and will be launched on the X-ray astronomical satellite "ASTRO-H" in 2016.

In this paper, SHI's cooler and Dewar technology and the life time test status of coolers will be described.

9821-11, Session 5

The integrated cryogenic system for the atmospheric vertical interferometric detectors on FY-4 Satellite

Yinong Wu, EnGuang Liu, Zhenhua Jiang, Baoyu Yang, Yongbin Mu, Shanghai Institute of Technical Physics (China)

The cryogenic system for the atmospheric vertical interferometric detectors on FY-4 satellite to be launched in 2016 includes the Stirling cryocooler which cools the long wave length infrared detector to 65K and the middle wave length focal plane detector to 80K, the radiant cooler which cools the aft optics components and the shell of detectors dewar to 200±1K, and the cryogenic heat pipe as well as some flexible thermal links etc. These cryogenic elements were integrated together in order to decrease the background radiation and maximize the sensitivity with high efficiency and high reliability. This paper summarizes the cryogenic integration design, technical challenges, and the results of thermal and performance testing at real cryogenic temperatures.

9821-13, Session 5

Multimodal tuned dynamic absorber for split Stirling linear cryocooler

Alexander Veprik, SCD SemiConductor Devices (Israel); Avi Tuito, Israel Ministry of Defense (Israel)

Forthcoming low size, weight, power and price split Stirling linear cryocoolers may rely on single-piston, contact seals compressors. Because of the high driving frequency, the weight of moving assemblies and their strokes are small. This results in low cooler induced vibration.

In vibration sensitive applications, the inline mounting of compressor and expander units results in consolidation of vibration export along single axis, thus allowing for effective use of single inline mounted translational Tuned Dynamic Absorber (TDA). Unfortunately, this configuration is not always feasible due to the packaging constrains.

The authors are presenting novel type of patent pending tunable multimodal TDA, having one translational and two tilting modes tuned to the same frequency. In one of the possible embodiments, a round planar spring supports the proof mass comprising two coaxial rings. The primary ring is connected to the peripheral portion of the planar spring and the secondary (correction) ring is movable along the primary ring, thus allowing for the fine adjustment of the aggregate moment of inertia without changing aggregate mass. Because of the planar spring design and tuning

feature, frequencies of the tilting modes may be finely matched to the fixed frequency of translational mode. The dynamic reactions (force and moment) produced by such a TDA are simultaneously counterbalancing vibration export produced by compressor and expander units of the U-shaped cryocooler and, therefore, reducing both linear and angular dynamic responses of the payload.

9821-14, Session 5

Tuned dynamic absorber for split Stirling cryogenic cooler

Alexander Veprik, SCD SemiConductor Devices (Israel); Avi Tuito, Israel Ministry of Defense (Israel)

Undamped tuned dynamic absorbers (TDA) find use, in particular, for attenuating tonal vibration export produced by the moving components of cryogenic cooler. For the best performance, the resonant frequency of TDA needs to be equal the driving frequency; precise frequency match is favorably achieved by changing the driving frequency and monitoring the cooler induced vibration. Also the design of TDA needs to be such as to minimize damping; this is achievable by using planar springs having zero friction interface features.

Accurate evaluation of effective mass, damping ratio and frequency is needed for TDA characterization during development and manufacturing. This data may be also important for the modelling the system dynamics. Any contact method of monitoring the dynamic response of the proof mass involves adding mass of the sensor and damping resulting from the connecting cable. Non-contact methods are requiring special and very expensive equipment. Sometimes TDA is encapsulated for the operation safety reasons, in these cases there is no direct access at all to the proof mass.

The authors are exploring the express method requiring no physical access to the proof mass. In this approach, the TDA is mounted upon the low frequency vibration mounted frame mimicking the payload inertia. The dynamic properties of TDA are then evaluated using the frequency response function – local acceleration – captured on the above frame using accelerometer, instrumented modal hammer and dual-channel signal analyzer. The authors are suggesting simple analytical expression for such a frequency response function and explain appropriate curve-fitting procedure.

9821-29, Session PSWed

Thermal management and design for optical refrigeration

Guy Symonds, Bernardo G. Farfan, Thermodynamic Films (United States)

This presentation describes some of our recent work in developing a robust and versatile optical refrigerator. This work focuses on minimizing energy losses through efficient design and material optimization. The cooler's thermal linkage system and housing are studied using thermal analysis software to determine the most thermally efficient design, minimizing thermal gradients through the device. Due to the extreme temperature ranges experienced by the device, material selection and characterization is key to an efficient and robust device. We describe the design constraints and material selections that have to been considered for thermally efficient, durable, optical refrigeration.

9821-30, Session PSWed

Experimental investigations and applications of cryogenic heat pipes

EnGuang Liu, Yinong Wu, Fan Yang, Yongbin Mu, Shanghai

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Institute of Technical Physics (China)

In some infrared systems, in order to decrease the background radiation and maximize the sensitivity, cooling down the aft-optics components' temperature is a better choice. Some two-phase flow devices such as grooved heat pipe or loop heat pipe (LHP) were used to link the cold sink and IR aft-optic components. This paper presents the testing results of cryogenic grooved heat pipes which were used in an infrared test systems in the temperature range of 160-210K with different heat load conditions. Also, some experimental results of cryogenic loop heat pipe are introduced in this paper.

9821-31, Session PSWed

Development of the radiant cooler and cryogenic heat pipes for 200K cryogenic optical system cooling

EnGuang Liu, Yinong Wu, Xiaofeng Yang, Yongbin Mu, Shanghai Institute of Technical Physics (China)

In the infrared system, in order to decrease the background radiation and maximize the sensitivity, cooling down the aft-optics components' temperature is a better choice. This paper presents a heat transfer system, in which a radiant cooler, cryogenic heat pipes and flexible thermal link were developed for heat transfer, and by which a cryogenic system was cooled down to 200K from room temperature. A scrolling mechanism was designed for the radiant cooler to anti-pollution and block sunlight in the initial orbit phase. The cryogenic heat pipes is a type of grooved heat pipe with the working fluid of ethane and working temperature ranging from 160K to 210K. Some experimental and simulation results of the radiant cooler, cryogenic heat pipes will be discussed in this paper.

9821-32, Session PSWed

RICOR K527 cryocooler model overview and applications

Sergey V. Riabzev, Ilan Nachman, Eli Levin, Adam Perach, Dan Gover, RICOR Cryogenic & Vacuum Systems (Israel)

The K527 linear single-piston cryocooler was developed in order to meet the requirements of reliability, compactness, efficiency, and versatility for a wide range of applications such as hand held, 24/7 and MWS. The compressor was developed using optional Tuned Dynamic Absorber (TDA) to control induced vibration where necessary.

During the recent years the cryocooler was employed in variety of electro-optical systems. Some of these systems are sensitive to induced vibrations, so the TDA option is essentially useful there. Other systems, such as MWS, are not sensitive to cryocooler vibration, however required to withstand high level of environmental vibration and temperature. Hence, the K527 design can be easily adapted to any specific requirements. Also, the latest K527 version designed to be integrated into the RICOR standard K508 cold finger, in order to provide versatility to detectors that are already designed for the K508 cryocooler type.

The reliability of the K527 model is of a high priority. In order to meet the 30,000 working hours target, a special design features were implemented. Currently, ten K527 cryocooler samples are running under the life demo test, thus acquiring at the moment 10,000 working hours without degradation

9821-33, Session PSWed

Investigation of anti-Stokes Raman processes at phonon-polariton resonances for phonon removal and laser cooling

Yujie J. Ding, Lehigh Univ. (United States)

We review the progress made by us on Raman oscillation, frequency upconversion, and amplification in a second-order nonlinear medium at the phonon-polariton resonance. For the co-propagating configuration, the small-signal gain for Raman oscillation reaches 2.2 per cm and per W of the input power. For the counter-propagating optical fields, frequency upconversion is feasible without any input at the anti-Stokes frequency with its conversion efficiency approaching 10% without an input and significantly higher with an input. These Raman processes can be used to effectively remove transverse-optical phonons before decaying to lower-frequency phonons. The counter-propagating configuration offers advantages for amplifying extremely weak signals and efficient phonon removal.

9821-15, Session 6

Introduction to cryogenic solid state cooling (*Invited Paper*)

Joseph P. Heremans, The Ohio State Univ. (United States)

No Abstract Available

9821-16, Session 6

Tuning thermoelectric properties of rare earth alloys and compounds at low-temperature using chemical pressure (*Invited Paper*)

Donald T. Morelli, Michigan State Univ. (United States)

Intermediate valence compounds often display large magnitudes in the Seebeck coefficient at low temperatures. This intermediate valence effect is a result of a fluctuating number of electrons in the f-shell and generally appears in compounds containing rare-earth elements such as Yb. In a series of Yb-compounds and alloys, we show that Yb valence can be tuned by controlling the unit cell size through compositional variation. Both the temperature dependence and magnitude of the Seebeck coefficient can be varied in a systematic way, leading to gigantic thermoelectric power factor and enhanced thermoelectric figure of merit at cryogenic temperatures.

9821-17, Session 6

BiSb and spin-related thermoelectric phenomena (*Invited Paper*)

Joseph P. Heremans, The Ohio State Univ. (United States)

No Abstract Available

9821-18, Session 7

The thermoelectric Thomson cooler: how it can achieve cryogenic cooling and how one might make one (*Invited Paper*)

G. Jeffrey Snyder, Northwestern Univ. (United States)

No Abstract Available

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9821-19, Session 7

p x n transverse thermoelectrics: advantages of single-leg thermoelectric geometry for scalable integration and cryogenic cooling. (Invited Paper)

Matthew Grayson, Northwestern Univ. (United States)

Transverse thermoelectrics offer an alternate path for integrated solid-state cryogenic cooling, provided materials with sufficiently large transverse Seebeck coefficients can be identified. Under the p x n-type transverse thermoelectric paradigm [1] electrons dominate conduction in one direction and holes dominate perpendicularly, allowing electrical current to drive transverse heat flow. Whereas bulk anisotropic crystals, superlattices, and nanowire arrays have been previously considered as p x n materials, this work focuses on sequential ion implantation and regrowth as a strategy for engineering a large transverse Seebeck coefficient in a thin p x n film. Individual p- and n-type AlGaAs layers with thickness $d = 500$ nm are grown successively on GaAs substrate via molecular beam epitaxy. After each layer growth, proton ion-implantation isolation with energy $E = 50$ keV is used to induce conductivity anisotropy in the layer by ion-implanting non-conductive strips of width $W = 5\text{-}20$ μm to separate conductive strips of similar width. Such n-type strips are orthogonally aligned atop p-type strips. Secondary ion mass spectroscopy (SIMS) on single layers confirms H-implantation depth commensurate with layer thickness even after 430 degrees Celsius anneal. Electrical transport measurements show desired conductivity anisotropy within each layer, with the strip direction 10,000 times more conductive than transverse. The separate Seebeck coefficient for the implanted p- and n-type layers approaches $S = 400$ $\mu\text{V}/\text{K}$, and results of the transverse Seebeck measurement will be reported for the two-layer structure, demonstrating proof-of-principle for ion implantation as a means of fabricating artificial p x n transverse thermoelectrics.

[1] Chuanle Zhou, S. Birner, Yang Tang, K. Heinselman, and M. Grayson, Phys. Rev. Lett. 110, 227701 (2013).

9821-20, Session 7

Next-GEN MWIR detector technology roadmap: a synergistic approach (Invited Paper)

Niels F. Jacksen, SCD.USA, LLC (United States); Terry Golding, Amethyst Research Inc. (United States); Daryoosh Vashae, North Carolina State Univ. (United States)

This paper describes new MWIR imaging and cooling technologies being investigated by SCD.USA-Infrared with its partner, Amethyst Research. We show new device architectures that accomplish 1) High QE Photon detection using PN Junction and Barrier devices, 2) Monolithic architecture allowing for Wafer Level Processing of Photon Detection devices, 3) Integral high efficiency Thermoelectric Coolers using Mercury Cadmium Telluride (MCT) based thermopiles that sustains 150K detector temperature and 4) Use of 45nm Silicon-on-Sapphire (SOS) Readout VLSI Integrated Circuit to perform signal processing, ADC, Multiplexing and On-Chip Image Processing.

Adaption of SOS technology to the production of monolithic Photon detectors has intrinsic benefits such as ultra low dark current enabling higher detector operational temperatures and lower cross talk due to front side illumination and passivation. SOS circuits are also intrinsically radiation hardened. We describe the technical challenges for this next generation device as well as investigations underway to resolve these challenges. These include:

- Creation of barrier/interface layers allowing deposition / fabrication of defect free high QE Photon detection in the MWIR spectral band
- Creation of barrier layers allowing deposition / fabrication of low defect, high efficiency MCT Thermopiles on the backside of the sapphire wafer.
- Creation of high fill factor detector structures adapting matrix

architectures used in Thin Film Displays

- Development of high density multilevel metallization structures to access individual pixels.

Finally, we present a technology roadmap leading to introduction of TRL 5/6 detectors for military tactical and strategic applications

9821-21, Session 8

Modular cooler concepts for HOT and 3rd-gen applications

Ingo N. Rühlich, Carsten Rosenhagen, Markus Mai, Thomas Wiedmann, Sebastian Zehner, AIM INFRAROT-MODULE GmbH (Germany)

One of the most important objectives in the development of IR detectors is to achieve improved SWaP characteristics. The availability of advanced detector materials allowing the operation at significantly higher operating temperatures - HOT - is the key enabling technology for a new level of SWaP. Lower heat load at much higher operating temperature allowed designing of a more compact, high efficient cryocoolers. Besides HOT detectors there another trend towards larger detector arrays, power hungry high performance ROICs, or large cold shields. Another variation is due to different dewar types being used at different IR detector manufacturers. There is a variation of dewar bore diameters, lengths and interface details. Often, dewars a matched to either linear or rotary type cryocoolers. As a result, several cryocooler solutions are needed to support the entire range of advanced IR detectors.

To allow usage of one dewar type with different detectors at different operating temperatures and heat loads AIM developed a modular concept for linear cryocooler series.

A range of standardized Stirling expanders, fitting to most available dewar types like 7", 8mm or 9mm is available. This concept does not only allow flexible usage of linear or rotary cooler technology for the same dewar but also allows selection of a range of linear compressors for the same dewar. A 7" dewar for example can be operated by 5 different linear compressors covering the range from just small heat loads at 150K with a 160g compressor till some hundred Milliwatts at 70K with a 750g compressor.

Technical details and performance data of most relevant combinations between expander and compressor will be presented.

9821-22, Session 8

Development and optimization progress with RICOR cryocoolers for HOT IR detectors

Sergey V. Riabzev, Amiram Katz, Zvi Bar-Haim, Ilan Nachman, Dan Gover, Victor Segal, Avishai Filis, RICOR Cryogenic & Vacuum Systems (Israel)

The world growth in research and development of High Operating Temperature IR detectors impels the development process and the optimization of "HOT" cryocoolers at RICOR.

The development emphasis on the "SWAP³" configuration which is small size, low weight, improved performance, low power consumption and low price, in order to optimize IDDCA for future hand held thermal sights.

This paper will present the progress made with optimization and development of "HOT" cryocoolers, engineering pre-production series and qualified cryocoolers at the FPA temperature range of 130 - 200K for three different cryocooler models based on rotary & linear design concepts.

The paper will also review the progress with development activities that were implemented in the cryocoolers and the electronic control modules in order to minimize "Idle electronic and mechanical losses" hence minimizing the regulated power consumption

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9821-24, Session 8

A high-pressure ratio DC compressor for tactical cryocoolers

Weibo Chen, Mark Zagarola, Benjamin Cameron, Creare, LLC (United States); Sri Narayanan, The Univ. of Southern California (United States)

A high pressure ratio DC compressor is a critical component for many cryocooler cycles. Prior research has focused on the adaptation of commercial compressor technology (scroll, screw, linear with rectification valves, and regenerative) for use in cryogenic applications where long-life and oil-free (i.e., volatile contamination free) are unique requirements that are not typical for commercial compressors. In addition, many cryocooler applications are for cooling imaging instruments, making low vibration an additional requirement. An alternative compressor technology has emerged from the fuel-cell industry that may be ideal for many cryocooler applications. Proton Exchange Membranes (PEMs) are used in fuel cells to separate reactants and transport protons, and these capabilities may be used in cryocoolers to compress hydrogen from low to high pressure. Creare has been investigating the use of PEM compressors for low temperature Joule-Thomson and dilution cryocoolers. These cryocoolers have no moving parts, can operate at temperatures down to nominally 23 K, produce no vibration, and are low cost. Our work on the cycle optimization, cryocooler design, and the development and demonstration of the compressor technology is the subject of this presentation.

9821-25, Session 8

Miniature Stirling cryocoolers at Thales Cryogenics: qualifications results and integration solutions

Roel Arts, Thales Cryogenics B.V. (Netherlands); Jean-Yves Martin, Cédric Seguineau, Thales Cryogénie S.A. (France); Garnt de Jonge, Thales Cryogenics B.V. (Netherlands); Sebastien Van Acker, Julien Le Bordays, Thales Cryogénie S.A. (Netherlands); Tonny Benschop, Thales Cryogenics B.V. (Netherlands)

No Abstract Available

9821-26, Session 8

Overview of RICOR tactical cryogenic refrigerators space missions

Sergey V. Riabzev, Avishai Filis, Dorit Livni, Victor Segal, Dan Gover, RICOR Cryogenic & Vacuum Systems (Israel)

Cryogenic cryocoolers represent a significant enabling technology for Earth and Space science enterprises. Many of the space instruments require cryogenic refrigeration to enable the use of advanced detectors to observe a wide range of phenomena.

RICOR cryocoolers involved in Space programs are overviewed in this paper, starting since 1994 with "Clementine" Moon mission, until the latest "Curiosity" Mars mission in 2012. Many other RICOR cryocoolers were involved in Space missions after passing through flight acceptance, qualification, thermal and life testing.

The adaptation frame of work includes extensive cryocooler characterization and qualification test program to validate a cryocooler reliability, thermal interfacing design with the detector, vibration export control, efficient heat dissipation in vacuum environment, robustness mounting design, compliance with outgassing requirements and strict performances screening.

9821-27, Session 9

Digital cooler drive electronics: status and developments

Ingo N. Rühlich, Andreas Withopf, Sebastian Zehner, AIM INFRAROT-MODULE GmbH (Germany)

Advanced HOT IR detectors aim to achieve best system performance with regard to Size, Weight, Power and Cost (SWaP,C). To meet these requirements, a family of high efficient and compact long life cryocoolers had been developed over the last year. High efficient, compact and flexible cooler drive electronics are needed to get the best out of the cryocooler.

AIM's new digital cooler control electronics series is build up based on state of the art technology to achieve best performance and highest reliability.

For coolers with up to 100W input power the high power electronics DCE100 is suitable. It includes a built-in EMI filter for best system compatibility and temperature stability.

The DCE025 is a high efficient, compact single board electronics for coolers with up to 25W input power. The DCE025 is an ideal choice to operate single piston coolers using a passive balancer as the integrated accelerometer allows easy adjustment of the cooler to achieve lowest exported vibration.

Even smaller size and less power consumption have been the goals for the development of the newest μ DCE025. With an outline dimension of 35 x 40 x 5 mm the electronics can drive coolers with up to 25W with improved temperature stability. All electronics can be accessed thru a flexible and powerful GUI.

9821-28, Session 9

EMC performance of cryocooler control electronics for infrared application

Baoyu Yang, Yinong Wu, Shanghai Institute of Technical Physics (China)

Electromagnetic interference and compatibility of cryocooler subsystem are critical issue in practical application, especially infrared application. The digital cryocooler control electronics has been developed to attenuate the electromagnetic noise. The different filters and shielding methods, including CLC and LC type, were adopted to reduce corresponding ripple of power line and total harmonics distortion of drive line. The parameter design and analysis of H-bridge circuit for driving the linear motor in cryocooler are discussed. Using the control electronics, electromagnetic interference tests, such as CE102, RE102, were successfully completed. Also, the degradation due to EMI was not occurring during the performance testing of infrared sensor coupled with cryocooler.

Conference 9822: Advanced Optics for Defense Applications: UV through LWIR

Sunday - Monday 17-18 April 2016

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9822-1, Session 1

Moldable chalcogenide glasses for multispectral imaging in the visible and the thermal infrared region

Xiang-Hua Zhang, Antoine Brehault, Laurent Calvez, Michel Cathelinaud, Odile Merdrignac-Conanec, Univ. de Rennes 1 (France); Joël Rollin, Marie Duchene, Thales Angénieux S.A. (France); Philippe Adam, Délégation Générale pour l'Armement (France)

Imaging in different spectral regions, in visible and in thermal infrared regions for example, can offer complementary information useful for applications both in commercial and defense fields. As an example, for car driving assistance, visible/SWIR image is better for reading road indications and for detecting the presence of ice on the road. Thermal image is much better for seeing further and pedestrians in foggy condition and during the night. For defense applications, it is, for example, easier to move in the dark with intensified SWIR image and thermal imaging is indispensable to detect hidden hot target.

Today, only the expensive ZnS, obtained by chemical vapor deposition is available for simultaneous transmission in the visible and partially in the thermal infrared region of 8-12 μm . ZnSe offers limited transmission in the visible region. These materials cannot be used alone for the fabrication of high performance multispectral imaging systems.

Chalcogenide glasses have been developed for thermal imaging and the advantages of these materials are associated with the possibility of fabricating complex and efficient optical elements with direct precision molding. Commercial chalcogenide glasses are usually transparent up to 14 μm without significant visible transmission.

In this talk, we will present our last work on the development of chalcogenide-halide glasses with transmission from 0.5 μm up to 12 μm . The objective is to obtain at least two glasses with different chromatic dispersion for simplifying the design of multispectral imaging systems. The optical, properties and the chemical durability will be particularly presented. The feasibility of molded optics will be demonstrated. The performance of multispectral protective and antireflection coatings will also be discussed.

9822-2, Session 1

Manufacturing of transparent ZnS ceramics by powders sintering

Odile Merdrignac-Conanec, Noha Hakmeh, Guillaume Durand, Xiang-Hua Zhang, Univ. de Rennes 1 (France)

There are many optics operating either in the visible/short wave infrared region or in the mid-wave /long wave infrared region. Zinc sulphide is a material of choice for the production of multispectral optics as it combines optical transmission in these two spectral bands and thermal stability and mechanical strength that are required in harsh environmental conditions. ZnS optics are currently available at a high cost as chemical-vapor-deposited (CVD) or hot-isostatic-pressed (HIP) polycrystalline materials (Multispectral ZnS). We report the use of the low cost hot-pressing technique to produce ZnS for multispectral operation, from visible up to 12 μm . There have been many attempts, in the past, to produce transparent ZnS directly by hot-pressing with more or less success. Considerable progress has been obtained by developing efficient powders synthesis procedures. The main emphasis has been on the elaboration of ZnS precursor powders with controlled morphology/chemical composition to

reduce extrinsic scattering and impurities. We were able to produce ZnS parts with visible transparency and transmission in the 8-12 μm range that is comparable to that of Multispectral ZnS. The correlation of processing variables with powders sinterability and optical transmission of the HPed ceramics is discussed.

9822-3, Session 1

Rugged spinel optics for space based imaging systems

Shyam S. Bayya, Guillermo Villalobos, Michael Hunt, Woohong Kim, Simon Plunkett, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

Currently available optical materials for space applications are susceptible to surface and bulk damage due to hypervelocity impacts from dust and debris found in the space environment. Long-term exposure to naturally occurring radiation in the space environment (both solar ultraviolet radiation and ionizing particle radiation from cosmic rays and solar eruptions) also degrades the performance of optical systems. Glasses that are commonly used in imaging systems are subject to the formation of color centers that can significantly reduce their ability to transmit light. NRL is evaluating rugged spinel optics for visible and infrared imaging applications that can withstand the rigors of the space environment and enable long mission lifetimes without compromising performance. The suitability of transparent ceramic spinel will be addressed in this paper.

9822-4, Session 1

Engineering novel infrared glass ceramics for advanced optical solutions

Kathleen A. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and IRadiance Glass, Inc. (United States); Charmayne E. Smith, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Andy Buff, Univ. of Central Florida (United States); Laura Siskin, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); David Musgraves, Peter Wachtel, IRadiance Glass, Inc. (United States); Theresa Mayer, Andrew Swisher, Alexej Pogrebnyakov, Myungkoo Kang, Carlo Pantano, Douglas H. Werner, The Pennsylvania State Univ. (United States); Andrew Kirk, Stephen Aiken, Lockheed Martin Corp. (United States); Clara Rivero-Baleine, Lockheed Martin Corp. (United States) and Univ. of Central Florida (United States)

Advanced photonic devices require novel optical materials that serve specified optical function but also possess attributes which can be tailored to accommodate specific optical design, manufacturing or component/device integration constraints. Multi-component chalcogenide glass (ChG) materials have been developed which exhibit broad spectral transparency with a range of physical properties that can be tuned to vary with composition, material microstructure and form. Specific tradeoffs that highlight the impact of material morphology and optical properties including transmission, loss and refractive index, are presented.

9822-5, Session 1

Infrared optical material refractive index measurements, variations and standards: initial results

Adam M. Phenis, AMP Optics, LLC (United States); John H. Burnett, National Institute of Standards and Technology (United States); Gary E. Wiese, Lockheed Martin Corp. (United States)

The refractive index of infrared (IR) optical materials can vary from manufacturer to manufacturer, batch to batch and within a single batch. Unfortunately, the magnitude of variation is unknown for most IR materials, complicating the design and tolerancing of IR optical systems. This is an industry-wide problem that is typically solved, especially when index tolerances are tight, by having samples measured and modifying the optical design for the as-measured refractive indices. There is an ongoing effort to alleviate this problem by standardizing IR optical material specifications within the United States and eventually at the international level. Currently, there are no standards related to IR materials, but there are standards in development for characterizing the materials (homogeneity, refractive index, striae, sampling, etc.).

The standards development effort has been started with a pilot study to determine the variation of the refractive index within a single batch for several popular IR materials (Ge, Si, ZnSe, multispectral ZnS, CaF₂, BaF₂, IRG26 and GASIR1). Samples have been provided by participating material manufacturers and the measurements are being performed at NIST. The NIST minimum-deviation-angle refractometer facility can characterize the refractive index of materials, within their transmission wavelength range, from 0.12 μm to 14 μm with diffraction-limited accuracy.

The key results of the study will be the magnitude of measured deviations of the refractive index fit (Sellmeier) within the material batch as well as deviations from accepted index resources, such as the Handbook of Optics. Observed intra-batch index variations of 5×10^{-5} or less are on the order of the accuracy of minimum deviation measurements in the IR, and are unlikely to affect the performance of most IR optical systems. Index variations of 1×10^{-3} or larger would be expected to have a noticeable effect on the performance of many IR imaging systems. The measured intra-batch index variations will be used to establish sampling protocols for a future study aimed at measuring multiple batches of material. The pilot study is a long term effort and the materials that have been measured so far will be presented.

Lastly, the future efforts of the standards development and the pilot study will be discussed.

9822-6, Session 1

Designing mid-wave infrared (MWIR) thermo-optic coefficients (dn/dT) in chalcogenide glasses

Benn Gleason, Clemson Univ. (United States); Laura Sisken, Charmayne E. Smith, Kathleen A. Richardson, Univ. of Central Florida (United States)

Seventeen infrared-transmitting GeAsSe chalcogenide glasses were fabricated to determine the role of chemistry and structure on mid-wave infrared (MWIR) optical properties. The refractive index and thermo-optic coefficients of samples were measured at $\lambda = 4.515 \mu\text{m}$ using an IR-modified Metricon prism coupler, located at University of Central Florida. Thermo-optic coefficient (dn/dT) values were shown to range from approximately -40 ppm/°C to +65 ppm/°C, and refractive index was shown to vary between approximately 2.5000 and 2.8000. Trends in refractive index and dn/dT were found to be closely related to the atomic structures present within the glassy network, as opposed to the atomic percentage of any individual constituent. A linear correlation was found between the quantity $(n-3)dn/dT$ and the coefficient of thermal expansion (CTE) of the glass,

suggesting the ability to compositionally design chalcogenide glass compositions with zero dn/dT, regardless of refractive index or dispersion performance. The tunability of these novel glasses offer increased thermal and mechanical stability as compared to the current commercial zero dn/dT options such as AMTIR-5 from Amorphous Materials Inc. For IR imaging systems designed to achieve passive athermalization, utilizing chalcogenide glasses with their tunable ranges of dn/dT (including zero) can be key to addressing system size, weight, and power (SWaP) limitations.

9822-7, Session 2

Chalcogenide material strengthening through lens molding processes

Jayson J. Nelson, Edmund Optics Inc. (United States)

The demand for infrared transmitting materials has grown steadily for several decades as markets realize new applications for longer wavelength sensing and imaging. With this growth has come the demand for new and challenging material requirements that cannot be satisfied with crystalline products alone. Chalcogenide materials, with their unique physical, thermal, and optical properties, have found acceptance by designers and fabricators to meet these demands.

No material is perfect in every regard, and chalcogenides are no exception. A key cause for concern has been the relatively low fracture toughness and the propensity for fracture of the bulk material. This condition is amplified when traditional subtractive manufacturing processes are employed. This form of processing leaves behind micro fractures and sub surface damage, which act as propagation points for both local and catastrophic failure of the material.

Precision lens molding is not a subtractive process, and as a result, micro fractures and sub surface damage are not created. This results in a stronger component than one produced by traditional methods. New processing methods have also been identified that result in an even stronger surface that is more resistant to breakage, without the need for post processing techniques that may compromise surface integrity.

This paper will discuss results achieved in the process of lens molding development at Edmund Optics that result in measurably stronger chalcogenide components. Various metrics will be examined and data will be presented that quantifies component strength for different manufacturing processes.

9822-8, Session 2

Applicability of an annealing coefficient for precision glass molding of As₄₀Se₆₀

Jacklyn Novak, Alan Symmons, LightPath Technologies, Inc. (United States); Spencer Novak, LightPath Technologies Inc (United States); Erik Stover, M3 Measurement Solutions (United States)

Precision glass molding has a well-documented decrease in the index of refraction of the glass during the molding process. This index drop must be taken into account in the optical design in order to accurately determine the optical performance of the final lens. Knowing the annealing coefficient of the glass being molded allows the index to be fine-tuned by adjusting the cooling rate during the molding process. While annealing coefficients are available for visible glasses, the validity of using this method for chalcogenide glasses has not yet been investigated. This paper will determine the annealing coefficient for As₄₀Se₆₀ experimentally, and then verify the results by comparing calculated and experimental refractive index values for other cooling rates.

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9822-9, Session 2

**Molded wafer level optics for long-wave
infrared applications**

John W. Franks, Umicore Electro-Optic Materials (Belgium)

For many years, the Thermal Imaging market has been driven by the high volume consumer market. The first signs of this came with the launch of night vision systems for cars, first by Cadillac and Honda and then, more successfully by BMW, Daimler and Audi. For the first time, simple thermal imaging systems were being manufactured at the rate of more than 10,000 units a year. This step change in volumes enabled a step change in system costs, with thermal imaging moving into the consumer's price range.

Today we see that the consumer awareness and the consumer market continues to increase with the launch of a number of consumer focused smart phone add-ons. This has brought a further step change in system costs, with the possibility to turn your mobile phone into a thermal imager for under \$300.

As the detector technology has matured, the pixel pitches have dropped from 50µm in 2002 to 12 µm or even 10µm in today's detectors. This dramatic shrinkage in size has had an equally dramatic effect on the optics required to produce the image on the detector. A moderate field of view that would have required a focal length of 40mm in 2002 now requires a focal length of 8mm. For wide field of view applications and small detector formats, focal lengths in the range 1mm to 5mm are becoming common.

For lenses, the quantity manufactured, quality and costs will require a new approach to high volume IR manufacturing to meet customer expectations. This, taken with the SwaP-C requirements and the emerging requirement for very small lenses driven by the new detectors, suggests that wafer scale optics are part of the solution. Umicore can now present initial results from an intensive research and development program to mold and coat wafer level optics, using its chalcogenide glass, GASIR.

9822-40, Session 2

**Optimum selection of high-performance
mirror substrates for diamond finishing**

Kenneth S. Woodard, Corning Incorporated (United States); Lovell E. Comstock, Leonard Wamboldt, James S. Sutherland, Corning CSM Advanced Optics (United States)

No Abstract Available

9822-10, Session 3

**Recent advances in joint optical-digital
design for optronics applications**

Marie-Anne Burcklen, Frédéric Diaz, François Leprêtre, Thales Angénieux S.A. (France); Mane-Si Laure Lee-Bouhours, Anne Delboulbé, Brigitte Loiseaux, Philippe Millet, François Duhem, Fabrice Lemonnier, Thales Research & Technology (France); Hervé Sauer, François Goudail, Institut d'Optique Graduate School (France)

Increasing the capture volume of visible cameras while maintaining high image resolutions, low power consumption and standard video-frame rate operation is of utmost importance for hand-free night vision goggles or embedded surveillance systems.

As such imaging systems require to operate at high aperture, their optical design became more complex and critical, and therefore new design alternatives have to be considered.

Among them, wavefront coding changes and desensitizes the modulation transfer function (MTF) of the lens by inserting a phase mask in the vicinity

of the aperture stop. This smart filter is combined with an efficient post-processing that ensures an optimal image quality over a larger depth of field.

In this presentation recent advances will be discussed concerning design and integration of compact imaging system based on wavefront coding.

We will address the design, the integration and the characterization of an HD camera of large aperture (F/1.2) operating in the visible and near infrared spectral range, endowed with wavefront coding. Two home-made six-ring pyramidal and polynomial phase masks have been jointly optimized with their respective deconvolution algorithm in order to meet the best performance along an increased range of focus distances.

Real time deconvolution processing is implemented on a Field Programmable Gate Array. It will be shown that despite high data throughput of an HD imaging chain, the level of power consumption is far below the initial specifications.

Through MTF measurements and image quality assessments we have characterized the performances with and without wavefront coding. Depth-of-field increases up to x2.5 have been demonstrated in accordance with the theoretical predictions.

9822-11, Session 3

**Passive athermalization of infrared lens via
composite phase mask**

Shay Elmalem, Emanuel Marom, Tel Aviv Univ. (Israel)

Until recently, only expensive Infrared (IR) imaging systems were common, mainly for military applications. Lately, IR imaging systems became very wide spread for industrial and civilian applications. Due to such growing market, the need to develop techniques for producing inexpensive IR imaging systems is a necessity.

Most of the IR optical materials have a quite unique drawback- a temperature sensitive refractive index. This issue is most prominent for Germanium (Ge) lenses, used extensively in Long-Wave IR systems, resulting in a temperature-dependent focal length. Many approaches have been developed to solve the thermal focal shift (TFS), leading to 'IR Lens Athermalization', so that the use of IR optical materials would be viable. Several approaches solve the TFS by complex optical design or by using post-processing algorithms. We present a way to treat the TFS as a Depth of Field (DOF) problem, and as such to solve it by using an all-optical DOF phase mask. A DOF composite mask made out of two materials in tandem is designed, obtaining improved imaging performance for broad wavelength band along wide temperature range as well. Several all-optical and passive designs are presented, with different phase-shift behavior (constant or linear), each one leading to improved imaging results with different trade-offs. All of the proposed solutions can be incorporated as an add-on to an existing system, and also can be part of a 'from-scratch' optical design. Simulation results will be presented and discussed.

9822-12, Session 3

**Evaluate depth of field limits of fixed focus
lens arrangements in thermal infrared**

Norbert Schuster, Umicore Electro-Optic Materials (France)

More and more modern thermal imaging systems use uncooled detectors. High volume applications work with detectors that have a reduced pixel count (typically between 200x150 and 640x480). This reduces the usefulness of modern image treatment procedures such as wave front coding. On the other hand, uncooled detectors demand lenses with fast F/ numbers, near F/1.0, which reduces the expected Depth of Field.

What are the limits on resolution if the target changes distance to the camera system? The desire to implement lens arrangements without a focusing mechanism demands a deeper quantification of the Depth of Field problem.

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A new approach avoids the classic “accepted image blur circle” and quantifies the expected Depth of Field by the through focus MTF of the lens. This function is defined for a certain spatial frequency that provides a straightforward relation to the pixel pitch of imaging device.

A certain minimum MTF-level is necessary so that the complete thermal imaging system can realize its basic functions, such as recognition or detection of specified targets. Very often, this technical tradeoff is approved with a certain lens. But what is the impact of changing the lens for one with a different field of view? Narrow field lenses, which give more details of targets in longer distances, tighten the Depth of Field problem.

A first orientation is given by the hyperfocal distance. It depends in a square relation on the focal length and in a linear relation on the through focus MTF of the lens. For closer target distances, the depth of field border is given by relations such as the first order imaging formulas.

The formula of the Diffraction-Limited-Through-Focus-MTF (DLTF) quantifies the physical limit. It shows the contradicting requirements between higher resolution, faster f-number and desired Depth of Field.

A calculation methodology will be presented to transfer depth of field results from an approved lens with a certain focal length and F/number to another lens. Necessary input for this prediction is the through focus MTF of each lens. Practical results will be demonstrated by thermal pictures.

9822-13, Session 3

Characterization of the image quality of a wide angle MWIR f-theta objective lens with means of pixel contrast

Bertram Achtner, Airbus Defence and Space (Germany)

Objective lenses for missile warning systems have typically a wide field of view of about 120° to 180°. In order to get a linear correlation between object angle w [rad] and image height y [mm] they have a f-theta correction, with the focal length f [mm] as correlation factor. Usually the image quality criteria for optical systems are specified with MTF- or Strehl-values. In this case the image quality is indicated as pixel contrast defined by the amount of power from a point source falling on one pixel compared with the amount of power of the same source falling onto the neighboring pixels. The image of a point source from infinity is the Airy disk, which has a circular shape provided that the pupil is also circular. In order to get correct values for quadratic pixels the ensquared energy has to be taken. The values for the diffraction ensquared energy function are approximated from the diffraction encircled energy function. The size of the Airy disk is correlated to the f/number of the optical system and the wavelength. There is an interconnection between dimension of the optical system, f/number, Airy disc and achievable pixel contrast. These dependencies are discussed on a recently developed 168° field of view objective lens.

9822-14, Session 3

Experimental verification of the minimum number of diffractive zones for effective chromatic correction in the LWIR

Jamie Ramsey, Kenneth F. Walsh, Morgan Smith, John P. Deegan, Rochester Precision Optics, LLC (United States)

With the move to smaller pixel sizes in the longwave IR region there has been a push for shorter focal length lenses that are smaller, cheaper and lighter and that resolve lower spatial frequencies. As a result lenses must have better correction for both chromatic and monochromatic aberrations. This leads to the increased use of aspheres and diffractive optical elements (kinoforms). With recent developments in the molding of chalcogenide materials these aspheres and kinoforms are more cost effective to manufacture. Without kinoforms the axial color can be on the order of 15 μ m which degrades the performance of the lens at the Nyquist frequency. The kinoforms are now on smaller elements and are correcting chromatic

aberration which is on the order of the design wavelength. This leads to kinoform structures that do not require large phase changes and therefore have 1.5 to just over 2 zones. The question becomes how many zones are required to correct small amounts of chromatic aberration in the system and are they functioning as predicted by the lens design software?

Through measurement we will evaluate two different lenses, one with a kinoform that has two zones and one without a kinoform. Performance measurements based on MTF, back focal length at multiple, discrete wavelengths, and image resolution, measured monochromatically and broadband, will be used to evaluate the two lenses against their respective design details.

9822-15, Session 4

Design method for a laser line beam shaper of a general 1D angular power distribution

Elad Oved, Amit Oved, Rafael Advanced Defense Systems Ltd. (Israel)

A design method for a refractive beam-shaper for a predefined general 1D angular power distribution is introduced. The method suggests a notion of “Prism Space”, and the surfaces of the beam-shaper are constructed as a continuum of prisms from this space. It is shown that infinitely many different designs are possible for a given power distribution, and we explain how an optimal design is selected among them, based on criteria such as high transmission, low surface slopes, high robustness to manufacturing errors etc. We discuss the case of a periodic beam shaper, desirable for averaging over an unknown or non-repeatable input beam power distribution. An example of a wide angle beam-shaper (100°) with highly non-symmetrical angular power distribution is given.

9822-16, Session 4

Electronic eyebox for weapon sights

Stan Szapiel, Catherine Greenhalgh, Kevin Wagner, Raytheon ELCAN Optical Technologies (Canada)

Operational performance of a weapon sight is critically dependent on the size of its eyebox. Ideally, the eyebox should be much greater than the pupil of the eye - so random movements of the operator’s head will not result in severe vignetting or loss of observable field of view. Strong demand for big eyeboxes is in fundamental conflict with requirements for compactness at larger magnifications.

We propose a solution to this problem, which does not result in significant gains in size and weight of the sighting system. We expand the effective size of the eyebox by following the movements of the operator’s eye with the original small eyebox to create a larger, ‘electronic eyebox’. The original eyebox is dynamically relocated in space so that proper overlap between the iris of the eye and the exit pupil of the device is always maintained. Therefore, the operator will perceive almost the entire field of view of the instrument in a much bigger spatial region than the one defined by the original eyebox. The required transverse relocation of the exit pupil of the device is produced by decentration of a field lens located behind the intermediate image plane and in front of the eyepiece. A pupil tracker registers the offset between the exit pupil and the iris of the eye and provides proper correction feedback to the field lens. Proof-of-the-concept results will be presented for a 4X sight with 2X enlargement of the eyebox along with recommendations for the next phase of development.

9822-17, Session 4

Time-resolved non-sequential ray-tracing modelling of non-line-of-sight picosecond pulse LIDAR

Adam Sroka, Thales UK Ltd. (United Kingdom); Genevieve Garipey, Francesco Tonolini, Heriot-Watt Univ. (United Kingdom); Robert Henderson, The Univ. of Edinburgh (United Kingdom); Jonathan Leach, Daniele Faccio, Heriot-Watt Univ. (United Kingdom); Stephen T. Lee, Thales UK Ltd. (United Kingdom)

The ability to detect motion and to track a moving object that is hidden around a corner or behind a wall provides a crucial advantage when physically going around the obstacle is impossible or dangerous. One recently demonstrated approach to achieving this goal makes use of non-line-of-sight picosecond pulse laser ranging. This approach has recently become interesting due to the availability of single-photon avalanche diode (SPAD) receivers with picosecond time resolution. We present a time-resolved non-sequential ray-tracing model and its application to indirect line of sight detection of moving targets. The model makes use of the Zemax optical design programme's capabilities in stray light analysis where it traces large numbers of rays through multiple random scattering events in a 3D non-sequential environment. Our model then reconstructs the generated multi-segment ray paths and adds temporal analysis. Validation of this model against experimental results is shown. We then exercise the model to explore the limits placed on system design by available laser sources and detectors. In particular we detail the requirements on the laser's pulse energy, duration and repetition rate, and on the receiver's temporal response and sensitivity. These are discussed in terms of the resulting implications for achievable range, resolution and measurement time while retaining eye-safety with this technique. Finally, the model is used to examine potential extensions to the experimental system that may allow for increased localisation of the position of the detected moving object, such as the inclusion of multiple detectors and/or multiple emitters. This document is being exported under Open General Export Licence (Technology for Military Goods) Licence number GBOGE2013/01169

9822-18, Session 4

Novel silicon lenses for long-wave infrared imaging

Gregory J. Kintz, Philip Stephanou, Kurt Petersen, INVIS (United States)

The design, fabrication and performance of a novel silicon lens for long wave infrared imaging are presented. The silicon lenses are planar in nature, and are fabricated using standard silicon processes that can be extended to the wafer level. The silicon processes are used to generate spatially varying phase shifts in the incident light. We will show that the silicon lens designs can be extended to produce lenses of varying focal lengths and diameters, thus enabling IR imaging at significantly lower cost and reduced weight and form factor. We present an optical design program to model the lens performance, process and assembly methods to fabricate the lenses and the IR cameras, and also present characterization results of the fabrication of the lenses. Lenses with focal lengths in the range of 40-50 mm focal lengths were fabricated. The silicon lenses are tested by the focusing the output of a CO2 laser and compared to theoretical focus spot sizes. The silicon lenses are used to produce an image on a VGA micro-bolometer array.

9822-19, Session 4

Expanded IR glass map for multispectral optics designs

Shyam S. Bayya, Daniel J. Gibson, Vinh Q. Nguyen, Guy Beadie, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

There is a strong desire to reduce size and weight of single and multiband IR imaging systems in ISR operations on hand-held, helmet mounted or airborne platforms. NRL is working on developing new IR glasses that expand the glass map and provide compact solutions to multispectral imaging systems. These glasses were specifically designed to have comparable glass molding temperatures and thermal properties to be able to laminate and co-mold the optics and reduce the number of air-glass interfaces (lower Fresnel reflection losses). Our multispectral optics designs using these new materials demonstrate reduced size, complexity and improved performance. This presentation will cover discussions on the new optical materials, multispectral designs, as well fabrication and characterization of new optics.

9822-20, Session 5

Advanced gradient-index lens design tools to maximize system performance and reduce SWaP

Sawyer D. Campbell, Jogender Nagar, Donovan E. Brocker, John A. Easum, The Pennsylvania State Univ. (United States); Jeremiah P. Turpin, E x H, Inc. (United States); Douglas H. Werner, The Pennsylvania State Univ. (United States)

GRADIENT-INDEX (GRIN) lenses have long been of interest due to their potential for providing levels of performance unachievable with traditional homogeneous lenses. While historically limited by a lack of suitable materials, rapid advancements in manufacturing techniques, including 3D printing, have caused renewed interest in GRIN optics in recent years. Further increasing the desire for GRIN devices has been the advent of Transformation Optics (TO) which provides the mathematical framework for representing the behavior of electromagnetic radiation in a given geometry by "transforming" it to an alternative, usually more desirable, geometry through an appropriate mapping of the constituent material parameters. Using TO, aspherical lenses can be transformed to simpler spherical and flat geometries or even rotationally-asymmetric shapes which result in true 3D GRIN profiles. For example, classical GRIN designs such as the Luneberg lens have been revisited in the context of TO and offer an insight to wide field-of-view (FOV) performance that has not been previously achieved with traditional radial- and axial-GRINs. Meanwhile, there is a critical lack of suitable design codes which can effectively evaluate the optical wave propagation through 3D GRIN profiles produced by TO. Current codes also lack modern true multi-objective global optimization algorithms which allow the user to explicitly view the trade-offs between all design objectives such as focus quality, FOV, ?n, and focal drift due to chromatic aberrations. We present an overview of our custom ray-tracing software and TO-enabled GRIN lens design techniques while presenting examples which minimize the presence of mono- and polychromatic aberrations and investigate the potential for maximizing SWaP reduction in various material systems.

9822-21, Session 5

Materials figure of merit for achromatic gradient index (GRIN) optics

Guy Beadie, U.S. Naval Research Lab. (United States); Joseph Mait, U.S. Army Research Lab. (United States);

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Richard Flynn, U.S. Naval Research Lab. (United States);
Predrag Milojkovic, Defense Advanced Research Projects
Agency (United States)

A new figure-of-merit is developed for ranking pairs of materials as candidates for gradient index (GRIN) optics capable of good color correction. The approach leverages recent work (1) which derived a connection in GRIN lenses between the optical properties of constituent materials and the wavelength dependence of the lens power. We extend the analysis to consider a variety of factors which impact the optical performance of an achromatic lens, including bandwidth and lens thickness. We demonstrate the effectiveness of the ranking process by showing a simulated f/3 GRIN lens with diffraction limited performance over the visible spectrum using the top material pair selected out of a database of >5,000 possible candidates. The difference between GRIN materials criteria and standard, homogeneous doublet criteria will be discussed, as well as the implications for how this method can be used to analyze the suitability of materials being developed for GRIN optics in different wavelength bands.

(1) J.N. Mait et al., Opt. Express 23(17) 22069-86 (2015)

9822-22, Session 5

IR-GRIN optics for imaging

Daniel J. Gibson, Shyam S. Bayya, Vinh Q. Nguyen,
Jasbinder S. Sanghera, U.S. Naval Research Lab. (United
States); Mikhail Kotov, Sotera Defense Solutions, Inc.
(United States); Collin McClain, Univ. Research Foundation
(United States)

Graded index (GRIN) optics offer potential for both weight savings and increased performance but have so far been limited to visible and NIR bands (wavelengths shorter than about 0.9 μm). NRL is developing a capability to extend GRIN optics to longer wavelengths in the infrared by exploiting diffused IR transmitting chalcogenide glasses. These IR-GRIN lenses are compatible with all IR wavebands (SWIR, MWIR and LWIR) and can be used alongside conventional materials. The IR-GRIN lens technology, design space and anti-reflection considerations will be presented in this paper.

9822-23, Session 5

**Athermal achromat lens enabled by
polymer gradient index optics**

Richard Flynn, Guy Beadie, U.S. Naval Research Lab.
(United States)

An optical design is shown which provides simultaneous color correction over the visible spectrum and passive thermal compensation, for an f/4 doublet made of a glass and a polymer gradient index (GRIN) element. The design is enabled by a new optical model for the thermally varying GRIN element, which incorporates measured material properties from 20-40°C (limited only by the extent of the measured data set.) This is a particularly important result, because while it has been acknowledged that polymer-based GRIN elements can provide high quality optics, performance at temperatures other than the design temperature has been a concern due to the large thermo-optic and thermal expansion coefficients of polymer. The design is made possible because of the GRIN degrees of freedom available to the material. A color-corrected doublet is most efficient when there is a large ratio of the dispersion strength (Abbe number) between the two materials. To make that doublet athermal, however, there needs to be an equally high ratio between the thermal coefficients. The large ratio of polymer to glass thermal coefficients winds up being a unique advantage for GRIN: the effective GRIN dispersion coefficient can have just as large a ratio to the glass as the thermal coefficients, making for a powerful athermal achromat.

9822-24, Session 5

**An examination of the optical properties
of index gradients created by Fick's Law
diffusion**

Peter L. Marasco, Air Force Research Lab. (United States)

In the last few years, interest in research and development into new ways of creating gradient index optics has increased dramatically. Several new techniques were developed as part of the DARPA-sponsored Manufacturable Gradient Index Optics (M-GRIN) Program. One approach examined in this program was to employ diffusion, governed by Fick's Law, to generate both axial and radial index gradients. However, Fick's Law diffusion tends to yield index gradients that are mathematically uncommon in optical engineering and lens design. The impact of these new gradients on lens aberrations and image quality are not well understood. This paper will examine index gradients that can be described by (makeable by) solving Fick's diffusion laws for both infrared and visible light materials systems. The impact of these gradients in terms of lens modulation transfer function (MTF) will be explored.

9822-25, Session 6

**Transformation optics relay lens design for
imaging from a curved to a flat surface**

Julia Wetherill, The Univ. of Arizona (United States);
Richard S. Lepkowicz, Ramzi N. Zahreddine, The MITRE
Corp. (United States); Mark A. Neifeld, The Univ. of Arizona
(United States)

Monocentric lenses are excellent candidates for compact, broadband, high resolution, wide-field imaging. Traditional monocentric designs produce a curved image surface and have therefore found limited utility. The use of an appropriately machined fiber bundle to relay the curved image plane onto a flat focal plane array (FPA) has recently emerged as a potential solution. Unfortunately the spatial sampling that is intrinsic to the fiber bundle relay can have a negative effect on image resolution, and vignetting has been identified as another potential shortcoming of this solution. In this paper we describe a gradient index (GRIN) optical element that avoids the deleterious effects of sampling and can provide a high-quality image relay from the curved monocentric image surface to a flat FPA. Using quasi-conformal transformation optics (TO) a classical Maxwell's "fish-eye" lens is transformed into a shape with a concave front surface and flat back surface. We will present a study of cost and performance versus lens aperture and thickness. We quantify image quality metrics such as spot size, field of view, and light efficiency along with manufacturing cost metrics such as index contrast and anisotropy. Based on this analysis we identify and fully optimize a monocentric lens in combination with a TO-designed GRIN image relay optic.

9822-26, Session 6

**ALON GRIN optics for visible-MWIR
applications**

Nagendra Nag, Santosh Jha, Surmet Corp. (United States);
Suri Sastri, Lee M Goldman, Surmet Corp (United States);
Pete McCarthy, Greg R Schmidt, Julie L Bentley, Duncan
T Moore, The Institute of Optics, University of Rochester
(United States)

Surmet has continuously striven to introduce novel and trailblazing advanced optical ceramics products for current and future defense and commercial systems. With conventional powder processing techniques, Surmet has progressed its ALON® technology to manufacture large and

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optically transparent armor plates and domes. In addition to transparency at the required wavelengths, many functionalities including EMI shielding, internal heaters, internal antennas and cooling channels etc. have been demonstrated in dimensions that are of interest to many applications.

Surmet is set to commercially offer its newly developed gradient index (GRIN) optics in ALON® for use in the visible through the MWIR bands. Surmet has demonstrated the ability to tailor the refractive index of the ALON® material by either varying its composition or through the addition of dopants. With the development of several enabling process technologies, smooth axial and radial gradient profiles with -0.055 change in refractive index, over depths of 1-8 mm (axial) and over 20 mm radius (radial) have been achieved. Initial design studies with ALON GRIN have shown such elements to provide uniquely advantageous color correction characteristics over multispectral wavebands. Radial gradients in particular, with their optical power contribution, are expected to provide additional degrees of freedom for color correction in broadband imaging systems.

Surmet is continuing to work in maturing the technology of ALON® GRIN elements along with metrology and GRIN optical design development. Surmet is committed to developing manufacturing capability for ALON® GRIN elements and inserting it into novel imaging solutions for military and other commercial systems.

9822-27, Session 6

Raman and CT scan mapping of chalcogenide glass diffusion generated gradient index profiles

George P. Lindberg, Richard H. Berg, John P. Deegan, Robert Benson, Rochester Precision Optics, LLC (United States); Nelson Gross, Bernard A. Weinstein, Univ. at Buffalo (United States); Daniel J. Gibson, Shyam S. Bayya, Jasbinder S. Sanghera, Vinh Q. Nguyen, U.S. Naval Research Lab. (United States); Mikhail Kotov, Sotera Defense Solutions, Inc. (United States)

Metrology of a gradient index (GRIN) material is non-trivial, especially in the realm of infrared and large refractive index. By diffusing chalcogenide glasses of similar composition one can blend the properties in a continuous way. In an effort to measure this we will present data from both x-ray computed tomography scans (CT scans) and Raman mapping scans of the diffusion profiles. We will also present finite element modeling (FEM) results and compare them to post precision glass molded (PGM) elements that have undergone CT and Raman mapping.

9822-28, Session 6

An analytical study of thermal invariance of polymeric nanolayer gradient index optical components

Howard Fein, Michael Ponting, PolymerPlus, LLC (United States)

Specially formulated Gradient-Index polymeric optical materials offer capabilities not possible in conventional GRIN or monolithic optics. A novel technology that enables large scale processing of nanolayered polymer films into real, performance-enhancing lenses and other optical components for Defense-related optical systems is currently being employed.

Polymeric nanoLayer GRIN materials (LGRIN) offer the ability to design and fabricate optics with custom gradient refractive index profiles in optical components up to 90 mm in diameter and approaching 5 cm thick. High performance achromatic singlet lenses were designed using specially developed ZEMAX design tools and exceptionally high quality lenses were fabricated from the LGRIN materials. Optical performance of LGRIN optics is shown to be significantly better than with conventional monolithic optics

while also significantly reducing optical system mass, volume, and optical element count.

Understanding the thermal behavior of such optical components is essential to their operational capability so an experimental study of the effects of elevated operational environments to validate the feasibility of deploying LGRIN optics into real-world operational environments was carried out. This entailed a rigorous thermo-mechanical characterization of LGRIN optics to determine the effect of elevated operating temperature on lens survivability, the optic geometry, and transmission wavefront behavior. PMMA/SAN17 LGRIN optics were interferometrically measured and demonstrated a regular and well understood geometry expansion and exhibit no significant variation in transmitted wavefront aberrations or optical performance over the designed operational thermal range of 30C - 50C. Based on these results, it is evident that the nanolayered polymeric laminate GRIN lenses can be categorized as a traditional polymer lens material with a predictable CTE and optical behavior at elevated operational temperatures.

9822-29, Session 7

HfO2/SiO2 multilayer based reflective and transmissive optics from the IR to the UV

Jue Wang, Gary A Hart, Jean Francois Oudard, Leonard Wamboldt, Brian P Roy, Corning Advanced Optics (United States)

HfO2/SiO2 multilayer based reflective optics enable threat detection in the SWIR/MWIR and high power laser targeting capability in the NIR. On the other hand, HfO2/SiO2 multilayer based transmissive optics empower early threat warning by taking advantage of the extremely low noise light detection in the DUV spectral region where solar irradiation is strongly absorbed by the ozone layer of the earth's atmosphere. The former requires high laser damage resistance, whereas the latter needs a solar-blind property, i.e. high transmission of the radiation below 290 nm and strongly suppression of the solar background from 300 nm above. The technical challenges in both cases are discussed. Applications in both defense and commercial are presented.

9822-30, Session 7

Defect-induced laser damage in dielectric optical coatings

Xinbin Cheng, Jinlong Zhang, Hongfei Jiao, Bin Ma, Tao Ding, Zhengxiang Shen, Zhanshan Wang, Tongji Univ. (China)

Dielectric optical coatings are enabling technology for modern high power laser systems, and their laser-induced damage threshold (LIDT) limits the output power of the laser system and has a big influence on its safe operation. It has been well recognized that localized defects, that are unavoidable in real-world optical coatings, lead to critical LIDT degradation. According to the nature of defects, we classified them into two categories: nano-sized absorbers and micro-sized defects. Off-stoichiometric nano-clusters or high-density electronic defects are thought to be the possible sources for nano-sized absorbers. Whereas, micro-sized defects result from the replication of substrate imperfections or particulates within the coatings by subsequent layers, and they can induce stronger electric-field enhancement, weaken mechanical stability and reduce LIDT. This work reviews the defect-induced laser damage in dielectric optical coatings with an emphasis on our research progress of micro-sized nodular defects.

Nodules are limiting defects for HR coatings working at near infrared region. The difficulty of systematical study of nodular defects lies in their low densities and diverse properties. It is difficult and challenging to achieve reliable experimental studies and to make meaningful comparisons with theoretical models. Artificial nodules whose properties can be well controlled have been used to reveal their damage mechanisms. The fabrication of artificial nodules, laser damage testing, electric-field

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simulations and thermomechanical models has been investigated. With the deepened understanding of nodular damage mechanisms, new processes were developed to improve the LIDT of HR coatings.

9822-31, Session 7
Ultra-narrowband pass filters for infrared applications with improved angle of incidence performance

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Ultra-narrow band pass filters for infrared applications with improve angle of incidence performance.

Ultra-narrow bandpass filters are used in a wide range of infrared applications from LIDAR to gas detection and laser line passband band filters. Significant improvement in notch band pass transmission and the steepness of edge slopes have been reported for NIR sub-nanometer wide bandpass filters(1) . A limitation of these filters is their sensitivity to field of view. This paper presents designs and measured filter results which reduce the angular shift for filter in the near to far infrared spectral region.

All interference filters shift towards shorter wavelength with increased angle of incidence. For ultra-narrow bandwidth filters, the band pass transmission moves out of band with as little as a few degrees angle of incidence. Using design techniques and material choices that are available in the infrared, angle sensitivity can be substantially improved. High effective index and submerging the filter in high index substrates stabilizes the design substantially. Design techniques using an effective negative index can be used to angle stabilized polarized light(2) . This technique uses a multiple material stack to create an effective negative index.

Narrow multi-band pass designs are also demonstrated using rugate or gradient index technology. These filters combine multiple pass bands for discriminating multiple absorption bands within a single filter(3) . Each design study is supported by fabrication results.

9822-32, Session 7
Acousto-optic tunable filter as a notch filter

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An acousto-optic tunable filter (AOTF) is an all solid-state robust device with no-moving parts that has been used in the development of hyperspectral imagers from the ultraviolet to the longwave infrared. Such a device is developed by bonding a piezoelectric transducer on a specially cut prism in a birefringent crystal. When a radio frequency (RF) signal is applied to the transducer, a diffraction grating is set up in the crystal with grating period determined by the applied RF and the diffracted wavelength depends upon the applied RF and the prism parameters. When broadband white light is incident on the prism input facet, two orthogonally polarized diffracted beams at a wavelength with a narrowband bandpass are transmitted. The transmitted wavelength can be tuned by varying the applied RF. This is what is used in a hyperspectral imager design application. An AOTF can also be used with multiple radio frequencies applied at the same time to diffract a number of different wavelengths. This mode can be exploited to design a tunable optical notch filter where multiple RFs are applied simultaneously such that all wavelength in a specific range can transmit except one wavelength with the corresponding RF missing. We designed an optical system using a TeO₂ AOTF operating in the shortwave infrared (SWIR) with a 16-channel RF driver where both the amplitude and frequency can be controlled. We will discuss the optical system, its characterization and present results obtained

9822-33, Session 7
New counter-countermeasure techniques for laser anti-dazzling spectacles

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Brillouin scattering is an effect caused by the $\chi^{(3)}$ nonlinearity of a medium, specifically by that part of the nonlinearity which is related to acoustic phonons. Above a certain threshold power of a light beam in a medium, stimulated Brillouin scattering (SBS) can reflect most of the power of an incident beam. By doing so, the forward power is reduced accordingly. This decreasing of the forward power with increasing incident power is called a limiting effect.

Optical systems as well as the human eye are susceptible to saturation or damage caused by high power lasers. We present a new non-linear, passive optical protection filter based on SBS phenomena. At input powers below SBS threshold, the filter has high transmission over the whole spectral band. However, when the input power exceeds the threshold power, transmission is decreased dramatically. We propose a novel technology for protection of any imaging system, sensors and the human eye against laser threats from the visible and up to the IR.

9822-41, Session 7
Low-loss crystalline coatings for the near- and mid-infrared

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Substrate-transferred crystalline coatings have recently emerged as a groundbreaking new concept in optical interference coatings. Building upon our initial demonstration of this technology, we have recently realized significant improvements in the limiting optical performance of these novel single-crystal GaAs/AlGaAs multilayers. In the near-infrared (NIR), for center wavelengths spanning 1064 to 1560 nm, we have reduced the excess optical losses (scatter + absorption) to less than 5 ppm, enabling the realization of a cavity finesse exceeding 300,000 at the telecom-relevant wavelength range near 1550 nm. Moreover, we demonstrate the direct measurement of sub-ppm optical absorption at 1064 nm. Concurrently, we investigate the mid-IR (MIR) properties of these coatings and observe exceptional performance for first attempts in this important wavelength region.

Specifically, we verify excess losses at the hundred ppm level for wavelengths of 3300 and 3700 nm. Taken together, our NIR optical losses are now fully competitive with ion beam sputtered films, while our first prototype MIR optics have already reached state-of-the-art performance levels for reflectors covering the important fingerprint region for optical gas sensing. Thus, mirrors fabricated via this technique exhibit the lowest mechanical loss (and thus Brownian noise), the highest thermal conductivity, and, potentially, the widest spectral bandwidth of any "supermirror" technology, owing to state-of-the-art levels of scatter and absorption losses in both the near and mid IR, all in a single material platform. Looking ahead, we see a bright future for crystalline coatings in applications requiring the ultimate levels of optical, thermal, and optomechanical performance.

9822-35, Session 8

Exploring the imaging properties of thin lenses for cryogenic infrared cameras

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Designing a cryogenic camera is a good strategy to miniaturize and simplify an infrared camera using a cooled detector. Indeed, the integration of optics inside the cold shield allows to simply athermalize the design, guarantee a cold pupil and release the constraint on having a high focal length for small focal length systems. By this way, cameras made of a single lens or two lenses are viable systems with good optical features and a good stability in image correction. However it involves a relatively significant additional optical mass inside the dewar and thus increased the cool down time of the camera. ONERA is currently exploring a minimalist strategy consisting in giving an imaging function to thin optical plates that are found in conventional dewar. By this way, we could make a cryogenic camera that has the same cool down time as a traditional dewar without an imagery function. Two examples will be presented: the first one is a camera using a dual-band infrared detector made of a lens outside the dewar and a lens inside the cold shield, the later having the main optical power of the system. We were able to design a cold plano-convex lens with a thickness less than 1mm. The second example is an evolution of a former cryogenic camera called SOIE. We replaced the cold meniscus by a plano-convex Fresnel lens with a decrease of the optical thermal mass equal to 3. The performances of both cameras will be compared.

9822-36, Session 8

Foveated optics

Kyle R. Bryant, U.S. Army AMRDEC (United States)

Foveated imaging can deliver two different resolutions on a single focal plane. This could be the way to deliver more capability for less money for military systems. Separate sensors for each field of view are easy and relatively inexpensive, but lead to bulky detector and electronics. Folding and beam-combining of separate optical channels reduces sensor footprint, but induces image inversions and reduced transmission. Entirely common optics provide good resolution, but cannot provide a significant magnification difference between foveal regions. This design study discovered many valuable lessons which can be used for any future design efforts in this area.

9822-43, Session 8

The first order solutions for two configurations of discrete zoom lenses

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Discrete zoom systems are commonly used as laser beam expanders and infrared zoom lenses. They have the advantage over continuous zoom systems for containing fewer elements, thus reducing the weight of the system, and often have more exotic but simpler mechanical movement. In literature there is little information on the first order parameters and starting requirements for discrete systems. This work derives the first order equations for two different discrete zoom systems. The equations are derived from the requirements of first order parameters which define the starting group focal lengths. The two design configurations studied are: one zoom group flipping in and out of the system; one zoom group moving laterally along the optical axis. This work analyzes the first order equations for both configurations and discusses the starting point for the

designs taking into consideration system limitations. Final designs for both configurations are then compared over several parameters: group focal lengths, lens diameters, overall length, number of elements, materials, and performance.

9822-37, Session PSTue

Additive manufacturing using optically transparent quartz

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This paper reports on a system using CO2 laser to print fused quartz for optical/NIR applications. Quartz is attractive for the process because it has lower coefficient of thermal expansion relative to soda-lime or borosilicate glasses. This allows it to be printed without preheating the build platform. Quartz also does not suffer from bubble generation due to the reboil process. However, it has a higher melting temperature and requires more precise control to achieve desired results. A filament (either 0.5 mm rod or optical fiber) is fed into a laser generated melt pool which is moved relative to the workpiece on a precision stage. Complicated geometries, including optical assemblies can be deposited by scanning the workpiece over computer controlled trajectories. In-situ emission spectroscopy is used to provide feedback of the process. The local index of refraction can be varied by mixing multiple filaments in the melt pool. The morphology and optical properties are dependent on the process parameters which determine the temperature distribution in and surrounding the melt pool. This is explored by printing quartz with different feed rates, scan speeds and laser powers and comparing the morphology and emission spectra. The transmission of the printed quartz is measured along with the modulation transfer function of simple windows. These results are compared to control-oriented thermal models of the process.

9822-38, Session PSTue

Fabrications of the free-standing aerogel thin film and optical grating

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Free-standing nanoporous silica thin films were fabricated by peeling-off method or demoulding method, combining with PAMS(poly-?-methyl styrene)-degradation technique. For peeling-off method, silica gel film was deposited on PAMS-coated silicon wafer, aged, dried via supercritical CO2, peeled off from silicon wafer and transfer onto copper grids. Then the free standing aerogel thin film was obtained by eliminating PAMS layer via annealing. For demoulding method, hydrophobic silica gel film was deposited on the PAMS side of PAMS/betaine/glass multilayer substrate, and separated from the glass to prepare SiO2/PAMS film by dissolving betaine layer. After that, free-standing nanoporous silica film was prepared by degrading PAMS. The formation quality of the film synthesized by the first method was greatly depended on the relative viscosity of the silica sol and the optimal viscosity was ranged from 2 to 7 cP. For the samples with bulk density of 100 mg/cm³, the thickness of the film could be adjusted from 50 to 500 nm. The roughness is about 20nm in the area of 600µm x 600µm. Nanoporous thin film prepared by the second method is hydrophobic and avoids the destructive peeling process, indicating its good tolerance. The peak transmittance of the film is 98.47% in the wavelength range of 350-1500 nm, from which the refractive index and the porosity could be calculated as 1.13 and 69% respectively. At last, free-standing optical grating was fabricated via combining the process for preparing photosensitive gel film and optical lithography technique.

9822-39, Session PSTue

Broadband coordinate transformation for Laguerre-Gauss orbital angular momentum modes with metasurfaces

Hossein Alisafae, Mark A. Neifeld, The Univ. of Arizona (United States)

Conventional approaches for multiplexing (mux) and demultiplexing (demux) optical orbital angular momentum (OAM) modes typically employ diffractive phase holograms, complicated interferometers, or free-form astigmatic optical elements. These approaches can suffer from low efficiency and/or result in large/bulky systems. Many of these previous approaches are also limited to monochromatic operation. The challenge to develop a thin, efficient, and broadband OAM mux/demux can be overcome by use of metasurfaces. In this work, we design a Cartesian to Log-polar coordinate transformation system for Laguerre-Gauss optical modes using metasurfaces. These structures are usually thick on the order of a wavelength, hence they allow the realization of more compact systems. Further, metasurfaces enable engineering the spatial distribution of amplitude and phase for manipulation of the wavefront of the light beams at subwavelength dimensions. This feature circumvents the fundamental limitation of diffractive optics by generating only a single diffracted order that carries all the power of the incident light. Besides, this feature could also open new opportunities for enhanced mode isolation in the demux step. The crosstalk occurs due to the diffraction limit and causes blurring of the output. However, with the aid of metasurfaces in order to go beyond the diffraction limit, we study the crosstalk between successive modes to find a possible enhancement method. Finally, we also investigate the upper bound for the number of OAM modes that can be handled simultaneously with the metasurface. This can be useful to find the limits of channel capacity for transmitting the multiplexed OAM modes.

9822-42, Session PSTue

Computing the PSF with high-resolution reconstruction technique

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Point spread function (PSF) is a very important indicator of the imaging system; it can describe the filtering characteristics of the imaging system. The image is fuzzy when the PSF is not very well and vice versa. In the remote sensing image process, the image could be restored by using the PSF of the image system to get a clearer picture. So to measure the PSF of the system is very necessary. Usually we can use the knife edge method, line spread function (LSF) method and streak plate method to get the modulation transfer function (MTF), and then use the relationship of the parameters to calculate the PSF of the system. In the knife edge method, the non uniformity (NU) of the detector would lead an unstable precision of the edge angle; using the streak plate could get a more stable MTF, but it is only at one frequency point in one direction, so it is not very helpful to get a high-precision PSF. In this paper, we measured the impulse response directly by using the image of the point target and combined with the energy concentration to calculate the PSF. First we made a point matrix target board and make sure the point can image to a sub pixel position at the detector array; then we used the centre of gravity to locate the point targets image to get the energy concentration; then we fusion the targets image together by using the characteristics of sub pixel and got a stable PSF of the system. Finally we used the simulation results to confirm the accuracy of the method.

9822-44, Session PSTue

High-accuracy refractive index measurement system for germanium and silicon using the channelled spectrum method in the range of 3 to 15 μm

Hilmar Straube, JENOPTIK Optical Systems GmbH (Germany); Christian Hell, Photonic Sense GmbH (Germany)

The refractive index of Germanium is known only up to the third decimal according to publicly available sources. This data from various authors shows deviations in the order of several 10^{-3} not to be explained by experimental errors of the refractive index measurement. This is a strong indication that there is optically relevant material property variation. We present an interferometric method to measure the refractive index and its temperature dependency on etalon samples, which are cheaper to prepare with high quality than prism samples needed for the classical method of index measurement. Resolution and stability of our method is better than 10^{-4} . The method can be used for both Germanium and Silicon. Our goal is to be able to produce material with optically relevant specifications. This is in contrast to the conventional method of specifying these important IR-optical materials in terms of electrical properties such as dopant type and concentration.

Conference 9823: Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XXI

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9823-1, Session 1

Coil design considerations for a high-frequency electromagnetic induction sensing instrument

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Detection of intermediate electrical conductivity objects, such as Carbon Fiber (CF) and Ammonium Nitrate (AN), are an interest for the US Military because of their use in "smart" bombs and homemade explosives (HME), respectively. Objects in this conductivity range (.1 to 1000 mS/m) exhibit characteristic quadrature response peaks at high frequencies (100 kHz-15 MHz). For traditional frequencies used in metal detection (100 Hz-100 kHz), more wire turns in a transmit coil will produce more magnetic field for an equivalent power source. The extra field will then lead to better signal to noise (SNR) ratios. In the high frequency range, this is not true, because of coil reactance. While target sizes typically do not exceed the Magneto Quasistatic (MQS) approximation, electrical coil lengths with many turns easily will ($\lambda = 20\text{m}$ at 15 MHz). If electrical lengths violate MQS, coil currents will have different phase, which means the spatial distribution of the magnetic field will vary by frequency. This corrupts our sensing scheme, which requires that a target is illuminated by an Alternating Magnetic Field (AMF) proportional to electrical current in the transmitter, for all frequencies. Our previously-introduced High Frequency Electromagnetic Induction (HFEMI) instrument is suited for sensing in both low and high frequency ranges. For best performance, coil turns are individually disconnected and reconnected at different frequencies in the sweep. Care must be taken that disconnected turns themselves are not electrically long, or else these will carry induced currents, and show up in measurement. The instrument also requires calibration by background subtraction and ferrite compensation. This paper discusses engineering tradeoffs for sensing across a broad band of frequencies, particularly coil geometries.

9823-2, Session 1

Improved feedback amplifier for electromagnetic induction sensors

Waymond R. Scott Jr., Georgia Institute of Technology (United States)

Broadband electromagnetic induction (EMI) sensors have been shown to be able to discriminate between certain classes of metallic targets and have shown significant reductions in false alarm rates when compared with traditional metal detectors. To maximize the discrimination capability, the EMI sensor must accurately measure the response of the targets. The accuracy is particularly important when the soil is highly mineralized

because the soil response can be much stronger than the target response. Then, even a small measurement error of the response can cause a significant error in the target response after a soil compensation algorithm is applied.

Making the sensor accurate in the presence of magnetic soil is difficult because the soil changes the inductance of the sensor coils, which causes errors that cannot be removed by a simple calibration. A method using feedback is presented that reduces measurement errors in an EMI sensor. The feedback is directly applied to the receive coils of the system and does not require secondary feedback coils. A simple negative impedance circuit is used to implement the feedback. The method reduces the currents induced in the receive coil which reduces errors introduced by mineralized soils. In addition, the method reduces the coupling between the receive coils in an EMI array which can significantly improve the accuracies of the array. Theoretical and experimental results are presented to show the effectiveness of the feedback over a broad range of frequencies.

9823-3, Session 1

Formulation for a practical implementation of electromagnetic induction coils optimized using stream functions

Mark A. Reed, Waymond R. Scott Jr., Georgia Institute of Technology (United States)

Continuous-wave (CW) electromagnetic induction (EMI) systems generally use separate transmit and receive coils. As a result, the coupling between the two coils must be kept to a minimum. When these systems operate in the presence of magnetic soil, they often encounter issues with the voltage that the soil induces in the receive coil (the soil response). Some of our previous work involved developing a method to represent the two coils using stream functions and optimize the stream functions for improved sensitivity while both controlling the soil response and maintaining minimum mutual coupling between the two stream functions. However, none of this work involved converting the stream functions to wire-wound coils or producing physical coils that could be tested.

A new pair of coils is optimized for the maximum sensitivity attainable while restricting the soil response to acceptable levels and the coupling between the coils to zero. The optimization is performed using an improved version of our stream function optimization approach. The new coils are converted to non-constant, single-sided spirals with a single feed. The coils must be single-sided to ensure that capacitive coupling within the coils is kept to a minimum. Otherwise, the coils may exhibit undesirable resonances. The coils are then produced by winding wire on composite forms. The coils are tested and compared to other common coil types. Experimental results are presented that show the coils' performance.

9823-4, Session 1

Dynamic EMI sensor platform for digital geophysical mapping and automated clutter rejection for CONUS and OCONUS applications

Stephen J. Laudato, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Joe Keranen, Jonathan S. Miller, Gregory Schultz, White River

**Conference 9823: Detection and Sensing of
Mines, Explosive Objects, and Obscured Targets XXI**

Technologies, Inc. (United States)

The implementation of new advanced electromagnetic induction (EMI) sensor surveys at sites containing unexploded ordnance (UXO) and explosive remnants of war (ERW) is an effective method for accurate mapping, but also for discriminating clutter from targets of interest. We present development and integration of a next generation advanced EMI sensor onto a cart-based sensing platform to combine the mapping capability of previous digital geophysical survey instruments with the high-resolution discrimination capability of advanced characterization arrays. The EMI sensor employs a multi-axis receiver configuration to produce data sufficient for anomaly discrimination. We discuss platform design and development, data acquisition and post-processing software development, and results from field tests demonstrating the detection and discrimination capability of the cart-based system. Platform development and design focused on navigation and EMI sensor integration onto a custom, low-noise, metal-free platform. Data acquisition is via an Android application with emphasis on ease-of-use and real-time quality control (QC) of collected data. Post-processing methods emphasize QC, inversion-based anomaly location estimation, and automated or supervised polarizability-based discrimination methods to produce a prioritized dig list. Integration of the detection, clutter rejection and QC methods into the post-processing software module reduces the time required between sensor data collection and generation of a prioritized dig list. System concept of operations (CONOPs), data collection, QC, and data processing procedures, and performance against various clutter objects and targets of interest will also be discussed.

9823-5, Session 1

Test and evaluation of dismantled detection systems

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The use of in-ground (near surface, less than four feet depth) land mines and improvised explosive devices (IEDs) is the primary cause of casualties to our forward deployed operational forces. The ability to locate and defeat the effects of these in-ground threats is a top priority. Mine warfare, including unexploded ordnance (UXO) and IEDs, has warranted the use of multi-sensor detection because it has advanced to items that are no longer subject to strict metal detection, but now also requires ground penetrating radar to detect differences in material densities. The Naval Surface Warfare Center Panama City Division (NSWC PCD) Dismounted Detection Systems (DDS) team evaluates and assesses the operational effectiveness and suitability of lightweight handheld in-ground threat detectors. The NSWC PCD DDS team has developed a premier testing bed for handheld mine detection for both training and testing purposes due to a testing methodology which provides quick and relevant results against a wide variety of threats in multiple soil types. The current manuscript presents the types of testing that are conducted at the NSWC PCD test lanes which include performance testing, suitability testing, equipment evaluation, and first article testing. In addition to types of testing, the current article will discuss the areas that should be focused on in developing sound experimental strategies while measuring performance capabilities of handheld detectors.

9823-6, Session 2

Landmine detection with Bayesian cross-categorization on point-wise, contextual, and spatial features

Jasmin Leveille, Ssu-Hsin Yu, Avinash Gandhe, Scientific Systems Co., Inc. (United States)

Recently developed feature extraction methods proposed in the landmine detection community have yielded many features that potentially provide

complementary information for explosive detection. Finding the right combination of features that is most effective in distinguishing targets from clutter, on the other hand, is extremely challenging due to a large number of potential features to explore. Furthermore, sensors employed for landmine and IED detection are typically sensitive to environmental conditions such as soil properties and weather as well as other operating parameters. In this work, we applied Bayesian cross-categorization (CrossCat) to a heterogeneous set of features derived from EMI sensor time-series for purposes of landmine detection. The set of features used here includes simple, point-wise measurements such as the overall magnitude of the EMI response, contextual information such as soil type, and a new feature consisting of spatially aggregated Discrete Spectra of Relaxation Frequencies (DSRFs). Previous work showed that the DSRF characterizes target properties with some invariance to orientation and position. We have developed a novel approach to aggregate point-wise DSRF estimates. The spatial aggregation is based on the Bag-of-Words (BoW) model found in the machine learning and computer vision literatures and aims to enhance the invariance properties of point-wise DSRF estimates. We considered various refinements to the BoW model for purpose of landmine detection and tested their usefulness as part of a Bayesian cross-categorization framework on data collected from two different sites. The results show improved performance over classifiers using only point-wise features.

9823-7, Session 2

A high-power EMI sensor for detecting and classifying small and deep targets

Fridon Shubitidze, Thayer School of Engineering at Dartmouth (United States); Benjamin E. Barrowes, U.S. Army Engineer Research and Development Ctr. (United States); Kevin A. O'Neil, Thayer School of Engineering at Dartmouth (United States)

Detecting and classifying small (i.e., with calibers ranging from 20 to 60 mm) and deep targets (burial depth more than 11 times targets diameter) till is a challenging problem using current advanced-EMI sensors and signal processing approaches. In order to overcome this problem, the standard time-domain NRL TEMTADS 2x2 electromagnetic induction (EMI) instrument is modified to increase transmitter (Tx) currents from 6 Amperes to 14 Amperes. The instrument has Tx array with four coplanar square coils, together with four tri-axial receivers (Rx) placed at the center of each Tx. Each Rx cube contains three orthogonal coils and thus registers all three vector components of the impinging signals. The Tx coils, with transmitter currents of -14 A, illuminate a buried target, and the target responses are collected with a 500 kHz sample rate after turn off of the excitation pulse. The system operates in both static (cued) and dynamic modes. For cued mode, the raw decay measurements are grouped into 121 logarithmically-spaced "gates" whose center times range from 25 μ s to 24.35 ms with 5% widths. The sensor is placed on a cart which provides a sensor-to-ground offset of 20 cm or less. In this paper, studies for APG Calibration (66 cells), Blind (400 cells), and Small Munitions (300 cells) Grids are presented and analyzed. The areas are arranged in grids of test cells and the cell center positions are known. Each target position is flagged with a non-metallic pin flag using cm-level GPS. The sensor is positioned over each target in turn. With the system positioned over the target, the Tx are activated sequentially and during off the Tx current, all four Rx record data. The capabilities of this sensor platform are rigorously investigated for UXO classification in a cued data collection mode at APG blind and small munitions grids.

9823-8, Session 2

Adaptive coherence estimator (ACE) for explosive hazard detection using wideband electromagnetic induction (WEMI)

Brendan Alvey, Alina Zare, Matthew Cook, Dominic K. Ho,

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Univ. of Missouri (United States)

The adaptive coherence estimator (ACE) estimates the cosine of the angle between a known target vector and a sample vector, in a whitened coordinate space. This space is whitened according to an estimation of the background statistics, which controls the effectiveness of the statistic as a target detector. In this paper, the ACE detection statistic is detect buried explosive hazards in Wideband Electromagnetic Induction (WEMI) sensor. Target signatures are based on a dictionary defined using a Discrete Spectrum of Relaxation Frequencies (DSRF) model. Results are summarized as a receiver operator curve (ROC), and compared to other leading methods.

9823-9, Session 2

Buried object detection using handheld WEMI with task-driven extended functions of multiple instances

Matthew Cook, Alina Zare, Brendan Alvey, Dominic K. Ho, Univ. of Missouri (United States)

Analytically defined dictionaries have been used for some time now for the detection of buried objects and, recently, work has been done in order to learn an optimized dictionary. A few of these dictionary learning algorithms have added supervision to find a more discriminative dictionary. However, when training these algorithms precise knowledge of the training data is required to provide very accurate point-wise labels in the training data, which is not always feasible. This is often true in buried object detection where the size of the objects are not always consistent. In this paper a new multiple instance dictionary learning algorithm for detecting buried objects using a handheld WEMI sensor is detailed that can overcome the requirement of very accurate point-wise labels and still learn a highly discriminative dictionary. Results are then presented and discussed on real-world WEMI data.

9823-10, Session 3

Detection and classification of unexploded ordnance: recent applications in Laos

Laurens Beran, Black Tusk Geophysics (Canada); Stephen Billings, Black Tusk Geophysics (Canada) and Gap EOD Pty (Australia); David Lutes, Leonard R. Pasion, Black Tusk Geophysics (Canada)

Electromagnetic induction (EMI) is the prevailing geophysical method for discriminating buried unexploded ordnance (UXO) from benign metallic clutter. EMI sensors designed for this application illuminate buried targets with primary fields from multiple directions and measure orthogonal components of the secondary field at each receiver. Subsequent processing involves fitting a physical model to observed sensor data and then using the parameters of this model to make inferences about the intrinsic physical properties of a detected target. Recent demonstrations have shown that classification with next generation EMI sensors consistently outperforms conventional monostatic systems.

We present recent applications of advanced EMI sensing of UXO in the Lao PDR. We first consider detection and classification of small cluster munitions dropped in Laos during the Vietnam War. We present the results of a field demonstration conducted with a multi-component EMI system. The small size of the cluster munitions, magnetic soils and local topography combine to make this a challenging problem. We present processing strategies for optimizing classification performance in this scenario.

Secondly, we consider detection of larger munitions buried at depth. In this application we use a large transmitter loop to illuminate deep targets, and a roving receiver array to measure the vector components of the secondary magnetic field. We discuss survey design considerations, magnetic soil effects, and inversion processing.

9823-11, Session 3

Computation of the eddy-current modes of three-dimensional conducting bodies

Jonathan E. Gabbay, Waymond R Scott Jr., Georgia Institute of Technology (United States)

The modes of the three-dimensional eddy current problem are of significant importance for landmine detection using broadband electromagnetic inductions sensors. Detection of a target of interest relies on the availability of an accurate dipole model that is computed based on a precise description of the flow of eddy currents inside the target. Analytical descriptions of the currents are available only for a small subset of targets, such as spherical conductors, that display high degrees of symmetry. Numerical approaches have thus far been limited to bodies of revolution or thin sheets of conducting material. In this paper, a numerical approach is described that may be used to model targets of arbitrary geometry.

The approach is based on the finite integration technique, which is used to model the electromagnetic interaction of the target with an incident magnetic field. The smallest eigenvalues and eigenvectors of the resulting system matrices are found using a Jacobi-Davidson eigenvalue solver. Care is taken to avoid the system's large null space that is a repercussion of choosing a differential computational method. The eigenvalues and eigenvectors of the system are used to create a broadband dipole model for the target that is useful for detection using electromagnetic induction sensors. The analytical modes of a sphere and those obtained by numerical computation will be compared. Additionally, the dipole model for a selection of targets that were previously not computable will be presented.

9823-12, Session 3

Carbon fiber and void detection using high-frequency electromagnetic induction techniques

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Electromagnetic induction instruments have been traditionally used to detect high conductivity discrete targets such as metal unexploded ordnance. The frequencies used for this electromagnetic induction regime have typically been less than 100 kHz. To detect lower conductivity objects like carbon fiber or saturated salts, we use higher frequencies up to the low megahertz range to capture the relaxation response. As a first step, we modeled the response of these intermediate electrically conducting material (IECM) targets using the Method of Auxiliary sources (MAS). We have also fabricated a benchtop high-frequency electromagnetic induction instrument capable of acquiring EMI data up to 15 MHz. We show both modeled and acquired characteristic relaxation signatures from calcium chloride saturated water and from carbon fiber. In addition, we show that the absence of conductivity (a void, e.g. a rock, a piece of wood, rubber, or other insulating material) in an otherwise conducting region can be detected using these high-frequency techniques.

9823-13, Session 3

Improved electromagnetic induction processing with novel adaptive matched filter and matched subspace detection

Charles E. Hayes, James H. McClellan, Waymond R. Scott

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This work introduces two advances in electromagnetic induction (EMI) processing: a novel adaptive matched filter (AMF) and a constant false alarm rate matched subspace detector (CFAR MSD). Both these advances make use of recent work with a subspace SVD approach to separate the signal, soil, and noise subspaces.

The AMF removes the EMI sensor self-response while improving the signal to noise of the EMI data. The AMF builds the filter by optimizing the strength of the signal space while constraining the spatial frequency response of the filter. This allows for easy removal of the self-sensor response by nulling the DC spatial component and also minimizing noise by nulling high spatial frequency components that are not from EMI targets. Unlike previous EMI adaptive spatial filters, this new filter will not erroneously optimize the EMI soil response instead of the EMI target response, because of the subspace projection. The optimization is formulated as a Rayleigh quotient maximization which is well understood.

This work shows how the signal, soil, and noise subspaces are ideal for defining the CFAR MSD. Once this is shown, the CFAR MSD has already been shown to have a generalized likelihood ratio test that is the uniformly most powerful invariant detector. This new EMI detection method will be tested with the proposed AMF, as well as other filters, on field data to compare their effectiveness.

9823-14, Session 4

**Pulsed THz TDS of objects covered by
disordered structure**

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Using both computer simulation and physical experiment we demonstrate principal limitations of standard Time Domain Spectroscopy based on a broadband THz pulse for the detection and identification of substance placed inside the disordered structure. As example of such system under consideration we consider chocolate covered by napkins.

The interaction of a THz pulse with a disordered layered structure was simulated in order to show the influence of the disordered layers on the spectral characteristics of the transmitted and reflected signals. Spectral characteristics of these signals were analyzed in a direct comparison with the incident pulse spectrum. We showed that a disordered structure disturbs the reflected pulse spectrum dramatically. To avoid this, we used the integral correlation criteria in real experiment.

9823-15, Session 4

**Object identification as part of contraband
detection system**

Jeremy Straub, Univ. of North Dakota (United States)

Previous work has discussed a human scanning-based contraband detection system that functions based on anomaly detection. This system compared the expected data to the actual data and assessed the differences to determine whether to pass the subject, request the collection of additional data or identify the presence of contraband. This approach, however, limited its utility in a wide variety of applications as the training data and the presented data had to match (requiring that allowed objects either be consistently present, or removing the potential to have a set of allowed objects altogether).

This work presents and evaluates an augmentation of this system: an identification component. This component can be used in two ways, either to proactively identify allowed objects to prevent them from being flagged as anomalies for further human review or to identify objects that, while still contraband, are of particular interest (e.g., those requiring different handling

or presenting a possible threat to system operators, etc.).

The system includes two components: a scan processing system that creates 'chunks' of data for object matching assessment and a partial membership expert system-based classification system that attempts to determine whether the 'chunks' being presented match any object in the system database. The scan processing system includes a human-size 3D scanner that uses visible light imaging to construct a model of the individual (and/or objects) being scanned, an algorithm that processes this scan data to identify and separate the scanned data into discrete, but interconnected components and a system to reduce the data volume (to speed its processing in the expert system classification system) by smoothing over the small anomalies created by the 3D scanner.

The classification system is comprised of a pattern matching algorithm (which makes rough correlations of data chunk components to known object parts) and an expert system which makes inferences regarding what is present, based on the object parts detected. This partial-membership expert system, in addition to identifying the most likely match, also provides a confidence metric that can be used to trigger additional validation for items with low-confidence identification.

This paper provides an overview of the 3D scanning / contraband detection system and describes how it functions. It then considers, qualitatively and quantitatively, its efficacy for several use case scenarios and compares this to the prospective performance of the prior system (without object identification). From this, the comparative benefits of the two systems are assessed and conclusions about the suitability of both designs for various applications is discussed. The paper concludes with a discussion of next steps that are planned for this project.

9823-16, Session 5

**Curvelet filter based prescreener for
explosive hazard detection in hand-held
ground penetrating radar**

Julie White, Derek T. Anderson, John E. Ball, Mississippi State Univ. (United States); Brian Parker, Mississippi State University (United States)

Buried explosive hazards are a serious threat to both civilians and soldiers alike. As a result, great interest resides in identifying algorithms and systems to detect such threats. Explosive hazard detection (EHD) comes in a number of solutions, for example downward or forward looking vehicle mounted platforms or handheld systems. In addition, robust detection resides in the processing and fusion of various information from different sensing modalities, e.g., radar, infrared, electromagnetic induction, etc. In this article, we focus on the design of a new energy-based prescreener in handheld ground penetrating radar (GPR). First, we Curvelet filter B-scans using either reverse-reconstruction followed by enhancement or selectivity of wedge information in the Curvelet transform. Next, we aggregate the result of a bank of matched filters then run a size contract filter with Bhattacharyya distance. Last, alarms are combined using weighted mean shift clustering. Results are demonstrated in the context of receiver operating characteristic (ROC) curves on data from a U.S. Army test site that contains multiple target and clutter types, burial depths and times of day.

9823-17, Session 5

**Background Adaptive Division Filtering for
Hand-Held Ground Penetrating Radar**

Matthew Lee, Derek T. Anderson, John E. Ball, Julie White, Mississippi State Univ. (United States)

Buried explosive hazards are a serious threat to both civilians and soldiers in current and former conflict zones. As a result, automated explosive hazard detection (EHD) systems have become a high priority. However, robust detection is complicated due to the varied composition and anatomy

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of such hazards and environments. In order to solve this challenge, a number of platforms (vehicle-based and handheld) and sensors (infrared, ground penetrating radar, etc.) are being explored. Herein, we focus on handheld downward looking ground penetrating radar (GPR). The signal enhancement algorithm we explore is motivated by deconvolution. We discuss global, local and adaptive estimation implementations of the core algorithm. Furthermore, we investigate the additional enhancement of the signal in post-processing using Curvelets. Both qualitative and quantitative results, in the context of receiver operating characteristic (ROC) curves, are demonstrated on data from a U.S. Army test site that contains multiple target and clutter types.

9823-18, Session 5

Generalized Dixon Taylor line operator-based features for handheld based explosive hazard detection in ground penetrating radar

John E. Ball, Derek Reeves, Stanton R. Price, Derek T. Anderson, Mississippi State Univ. (United States)

A serious threat to both civilians and soldiers is buried explosive hazards. As a result, there is great interest in developing automated systems to detect such threats. In this article, we explore the use of the generalized Dixon Taylor line operator (GDTLO) in handheld ground penetrating radar (GPR). The DTLO has been used previously in diverse image processing applications such as asbestos fiber counting and digital mammography enhancement and analysis. GDTLO is a very powerful line enhancement algorithm that can bring out very subtle details in imagery. We apply the GDTLO to enhance curvilinear signal features from GPR B-scans to facilitate more robust target detection. Specifically, we form new energy-based, spatial-based, and angle-based features from GPR images enhanced with GDTLO. Results are demonstrated in the context of receiver operating characteristic (ROC) curves on data from a U.S. Army test site that contains multiple target and clutter types, burial depths and times of day.

9823-19, Session 5

On the use of Log-Gabor features for subsurface object detection using handheld ground penetrating radar

Samuel D. Harris, Dominic K. Ho, Alina Zare, Univ. of Missouri (United States)

Handheld ground penetrating radar (GPR) enables the detection of subsurface objects under different terrains and over regions with significant amount of metal debris. The challenge for the handheld GPR is to reduce the false alarm rate and limit the undesirable human operator effect. This paper proposes the use of the log-Gabor features to improve the detection performance. In particular, we apply 36 log-Gabor filters to the B-scan of the GPR data in time domain for the purpose to extract the edge behaviors of a prescreener alarm. The 36 log-Gabor filters cover the entire frequency plane with different bandwidths and orientations. The energy of each filter output forms an element of the feature vector and an SVM is trained to perform target vs non-target classification. Experimental results using the data collected at a government site supports the increase in detection performance from the log-Gabor features.

9823-20, Session 5

Comparative Analysis of Short and Long GPR Pulses for Landmine Detection

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Serkan Aksoy, TÜBİTAK BILGEM (Turkey) and Gebze Institute of Technology (Turkey)

Ground Penetrating Radar (GPR) is one of the most popular subsurface sensing devices. It has a wide range of applications such as landmine detection, archeological investigations, road condition survey and so on. Hardware and software requirements of the GPR system are strongly dependent on type of applications. Principally, lower frequencies provide deeper penetration and low resolution, but higher frequencies are able to detect shallow objects with high resolution. As a fundamental design criterion, there is a trade-off between penetration depth and vertical resolution. In impulse radar, pulse duration (frequency related) is a key parameter because it affects the system detection performance. Specially, optimization of the pulse duration is a challenging problem for landmine detection because the GPR performance has been strongly affected from mine types, varying terrain and environmental conditions. In this work, two GPR systems, having pulse durations of 650 ps and 870 ps are compared for evaluation of their detection performance. The pulses are tested with extensive data sets collected from different soil types by using surrogate mines and other objects. The Receiver Operating Characteristic (ROC) curves of the system are calculated. It seems that the 650 ps pulse duration gives better performance than the 870 ps pulse duration for the shallow landmine detection.

9823-21, Session 5

A label propagation approach for detecting buried objects in handheld GPR data

Graham Reid, Hichem Frigui, Univ. of Louisville (United States)

Landmines and buried objects detection using ground penetrating radar (GPR) has been investigated for almost two decades and several classifiers have been developed. Most of these methods are based on the supervised learning paradigm where labeled target and clutter signatures are needed to train a classifier to discriminate between the two classes. Typically, large and diverse labeled training samples are needed to improve the performance of the classifier by overcoming noise and adding robustness and generalization to unseen examples. Unfortunately, even though unlabeled GPR data may be abundant, labeled data are often available in small quantities as the labeling process is tedious and can be ambiguous for most of the data.

In this paper, we propose an algorithm for detecting landmines and buried objects that uses unlabeled data to help labeled data in the classification process. Our algorithm is graph-based and propagates the nodes' labels to neighboring nodes according to their proximity in the feature space. For labeled data, we use a set of prototypes that are extracted from labeled training samples. For unlabeled data, we use a collection of signatures that are extracted from the vicinity of the alarm being tested. This choice is based on the assumption that many spatially close signatures are expected to have similar features and thus, unlabeled samples can create dense regions that link different regions of the labeled samples and propagate their labels to test samples. In other words, unlabeled samples are explored to create a context for each test alarm.

To validate the proposed label propagation based classifier, we use it to detect buried explosive objects in GPR data collected by a handheld system. This data set corresponds to a diverse set of conventional landmines and other buried explosive objects consisting of varying shapes and sizes. A small subset of the data is labeled and is used to identify few representative prototypes. Each alarm is characterized by an edge histogram descriptor (EHD). We compare the proposed approach to a baseline K-Nearest Neighbor classifier that uses only labeled data. Performance of both methods are analyzed using receiver operating characteristics (ROC) curves. We also investigate the effect of the size of unlabeled samples and identify cases where unlabeled samples improve the performance.

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9823-22, Session 5

Detecting buried explosive hazards with handheld GPR and deep learning

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Buried explosive hazards (BEHs), including traditional landmines and homemade improvised explosives, have proven difficult to detect and defeat during and after conflicts around the world. Despite their various size, shape and construction material, ground penetrating radar (GPR) is an excellent phenomenology for detecting BEHs due to its ability to sense localized changes in electromagnetic properties. Handheld GPR detectors are common equipment for detecting BEHs because of their flexibility (in part due to the human operator) and effectiveness in cluttered environments. With modern digital electronics and positioning systems, handheld GPR sensors can sense and map variation in electromagnetic properties while searching for BEHs. Additionally, large-scale computers have demonstrated an insatiable appetite for ingesting massive datasets and extracting meaningful relationships. This is no more evident than the maturation of deep learning artificial neural networks (ANNs) for image and speech recognition now common place in industry and academia. This confluence of sensing, computing and pattern recognition technologies provides great potential to develop automatic target recognition techniques to assist operators detecting deadly BEHs. In this work we use deep learning ANNs to detect BEHs and discriminate them from harmless clutter. We apply these techniques to a multi-antennae, handheld GPR with centimeter-accurate positioning system that was used to collect data over prepared lanes containing a wide range of BEHs. This work demonstrates that deep learning ANNs can automatically extract meaningful information from complex GPR signatures, complementing existing GPR anomaly detection and classification techniques.

9823-23, Session 6

Subsurface targets detection and classification from survey data sets

Fridon Shubitidze, Thayer School of Engineering at Dartmouth (United States); Benjamin E. Barrowes, U.S. Army Engineer Research and Development Ctr. (United States); Yinlin Wang, Thayer School of Engineering at Dartmouth (United States); Irma Shamatava, Jonathan S. Miller, White River Technologies, Inc. (United States)

In current practices, the best subsurface targets detection and classification performances are achieved in static model, which is very time consuming and expensive task. One of the possible ways to save time and reduce cost is to detect and classify targets directly from survey data sets. Current advanced EMI instruments, such as 2x2 TEMTADS, OPTEMA and MetalMapper provide the rich, diverse and classification level data sets. To take advantage of these high fidelity data, in this paper advanced, electromagnetic induction (EMI) models, such as orthonormalized volume magnetic source (ONVMS), joint diagonalization (JD) and differential evolution (DE) approach, are applied to dynamic data sets collected at South Western Proving ground as a part of ESTCP live-site UXO classification pilot studies program. These advanced EMI models have been developed for cued data sets and successfully applied to the next generation EMI. In this paper, the advanced models are applied to data collected using 2x2 TEMTADS and OPTEMA instruments in dynamic mode. For each anomaly, data are inverted and the targets intrinsic (total volume magnetic source (NVMS) i.e. the size, shape and material properties) and extrinsic (location, depth, orientation) parameters are estimated. The intrinsic parameters are used for classification and a ranked dig-list is generated. The dig-list is submitted to the Institute for Defense Analyses (IDA) for independent scoring. The advanced models classification performances are assessed and documented based on the independent scored results.

9823-24, Session 6

Imaging of concealed metallic objects by means of resonating circuits

Roberta Guilizzoni, Univ. College London (United Kingdom); Joseph C. Watson, AWE plc (United Kingdom); Paul Bartlett, Ferruccio Renzoni, Univ. College London (United Kingdom)

An electromagnetic induction system suitable for 2D imaging of metallic samples of different conductivities has been developed. The system is based on a parallel LCR circuit made up of a ferrite-cored coil, which works both as an inductor and as a sensor, a resistor and a capacitor. The working principle of the system is based on eddy current induction inside a metallic sample when this is introduced into the AC magnetic field generated by a coil. The inductance of the LCR circuit is modified due to the presence of the metallic sample, to an extent which depends on the sample conductivity. Such modification is known to increase when the system is operated at its resonant frequency. Characterizing different metals based on their values of conductivity should then be possible by utilizing a suitable system operated at resonance. Both imaging and material characterization were demonstrated by means of the proposed electromagnetic induction technique. Furthermore, the choice of using a resonating system made it possible to adjust its resonant frequency and decrease it to values that allow penetration of the magnetic field through thick screens. Investigations on the possibility of imaging concealed metals by penetrating through metallic shields have been carried out. Our results demonstrate that the presence of the concealed object can be revealed. The proposed technique was thus proven to be a promising detection tool for security applications.

9823-25, Session 6

Electromagnetic imaging with atomic magnetometers: a novel approach to security and surveillance

Ferruccio Renzoni, Luca Marmugi, Cameron Deans, Sarah Hussain, Univ. College London (United Kingdom)

We give an overview of our research programme on the use of atomic magnetometers to detect conductive objects via electromagnetic induction. The extreme sensitivity of atomic magnetometers at low frequencies, up to seven orders of magnitude higher than a coil-based system, allows their operation at low frequency, thus permitting deep penetration through different media and barriers, and in various operating environments. This eliminates the limitations usually associated with electromagnetic detection. Potential applications in security and surveillance are discussed.

We describe recent developments in our program, in particular describing our new setup for imaging with atomic magnetometers. A weak low frequency primary magnetic field induces eddy currents in the object of interest. The secondary field generated by such eddy currents is then detected by an atomic magnetometer. This allows the detection of the object. Additionally, multiple sets of measurements allow the reconstruction of the object shape. We demonstrate the ability to image conductive objects using magnetic field of different frequencies. The demonstration of imaging at low frequency opens the door to detection and imaging of objects deep underground or underwater. The set-up allows one to perform real-time imaging, and is promising for a variety of applications, from security to surveillance.

9823-26, Session 6

Enhanced buried UXO detection via GPR/EMI data fusion

Matthew P. Masarik, Joseph W. Burns, Brian T. Thelen, Jack

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Kelly, Michigan Tech Research Institute (United States);
 Timothy C. Havens, Michigan Technological Univ. (United States)

This paper investigates the enhancements to detection of buried unexploded ordnances achieved by combining ground penetrating radar (GPR) data with swept-frequency electromagnetic induction (EMI) data. Novel features from both the GPR and the EMI sensors are concatenated as a long feature vector, on which a non-parametric classifier is then trained. The classifier is a boosting classifier based on tree classifiers, which allows for disparate feature values. The fusion algorithm was applied to a government-provided dataset from an outdoor testing site, and significant performance enhancements were obtained relative to classifiers trained solely on the GPR or EMI data. It is shown that the performance enhancements come from a combination of improvements in detection and in clutter rejection.

9823-28, Session 7

Characterization of non-standard and home-made explosives

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Within the analysis of cases relating to the use of explosives for crimes, we have experienced a shift from using industrial explosives towards substances made in amateur and illegal way. Availability of industrial explosives is increasingly limited to a narrow sphere of subjects with a relevant permission. Thus, on the part of perpetrators, terrorists, ever greater attention is paid to illegal production of explosives that are easily made from readily available raw materials. Another alarming fact is the availability of information found on the internet. Procedures of preparation are often very simple and do not require even a deeper professional knowledge. Explosive characteristics are not actually accessible for many of these substances (detonation velocity, sensitivity, working capacity, brisance, physical and chemical stability, etc.). Therefore, a project is being implemented, which on grounds of assessment of individual information available in literature and on the internet, aiming at choosing individual areas of potentially abusable substances (e.g. mixtures of nitric acid (98%) with organic substances, mixtures nitromethane and tetranitromethane with organic substances, mixtures of chlorates and perchlorates of alkali metals with organic substances, chemically individual compounds of organic base type of perchloric acid, azides, fulminates, acetylides, picrates, styphnates of heavy metals, etc.). It is directed towards preparation of these explosives also in non-stoichiometric mixtures, conducting test explosives, determination of explosive characteristics (if they are unknown) and analysis of both primary phases and post-blast residues through available analytical techniques, such as gas and liquid chromatography with mass detection, FTIR, micro-Raman spectrometry, electron microscopy with microanalysis and Raman microspectrometry directly in SEM chamber for analysis at the level of individual microparticles. The received characteristics will be used to extend knowledge database for security forces.

9823-29, Session 7

A comparison of robust principal component analysis techniques for buried object detection in downward looking GPR sensor data

Anthony Pinar, Timothy C. Havens, Joseph S. Rice, Michigan Technological Univ. (United States); Matthew P. Masarik, Joseph W. Burns, Brian T. Thelen, Michigan Tech Research Institute (United States)

Explosive hazards are a deadly threat in modern conflicts, hence detecting them before they cause injury or death is of paramount importance. One method of buried object discovery relies on data collected from ground penetrating radar (GPR) and electromagnetic inductance (EMI) sensors. Threat detection with downward looking GPR is challenging due to large returns from non-target objects and clutter. This leads to a large number of false alarms (FAs), and since the responses of clutter and targets form very similar signatures, classifier design is not trivial. One approach to combat these issues uses robust principal component analysis (RPCA) to enhance target signatures while suppressing clutter and background responses, though there are many versions of RPCA. This work applies many of these RPCA techniques to GPR and EMI sensor data and evaluates their merit using the results of a common detection algorithm. Experimental results on government furnished data show that while many of the RPCA methods yield similar results, there are indeed some methods that outperform others. Furthermore, we show the computation time required by the different RPCA methods varies widely, and we suggest appropriate solutions if real-time implementation is desired.

9823-31, Session 7

Evaluation of a biomimetic optical-filter based chemical sensor for detection of hazardous chemical vapors in the infrared

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Detection of concealed hazardous materials is a pressing need for the global defense community. To address this need, the development of reliable and readily-deployable sensing devices is a key area of research. A multitude of infrared sensing techniques are being studied which allow for reliable sensing of concealed threats. Continued development in this field is working to increase the selectivity of such infrared sensors, while at the same time reducing their complexity, size and cost. We have recently developed a biomimetic optical filter based approach, based on human color vision, that utilizes multiple, broadband, overlapping infrared (IR) filters to clearly discriminate between hazardous target chemicals and interferents with very similar mid-IR spectral signatures. This technique was extensively studied in order to select filters which provide optimum selectivity for specific chemical sets. Using this knowledge, we designed and assembled a gas-phase sensor which uses three broadband mid-IR filters to detect and discriminate between a target chemical, fuel oil, and various interferents with strongly overlapping IR absorption bands in the carbon - hydrogen stretch region of the IR absorption spectrum 2700 - 3300 cm⁻¹ (3.0 - 3.7 μm).

We present an overview of the design and performance of this filter-based system and explore the ability of this system to examine to detect and discriminate between strongly overlapping target and interferent chemicals. The detection results using the filter-based system are compared to numerical methods to demonstrate the operation of this methodology. We present the results of experiments with both target and interferent chemicals present with chemicals both in and out of the detection set, and discuss future field development and application of this approach.

9823-32, Session 8

Laser-Induced X-ray Radar Particle Physics Model

David Lockley, Robert M. Deas, Robert M. Moss, Defence Science and Technology Lab. (United Kingdom); Dean

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The technique of high power laser induced plasma acceleration can be used to generate a variety of diverse effects including the emission of X-rays, electrons, neutrons, protons and radio-frequency radiation. A compact variable source of this nature could provide a wide range of potential applications including single sided through barrier imaging, cargo and vehicle screening, infrastructure inspection, oncology, industrial quality control and structural failure analysis.

This paper presents a validated particle physics model which replicates recent results from experiments conducted at the Central Laser Facility at Rutherford Appleton Laboratory, Didcot, UK. The experiment demonstrated the generation of backscattered X-rays from a benign material through the bremsstrahlung of an incident relativistic electron beam produced by Laser Wakefield Acceleration.

A key initial objective of the model was to inform the experimental planning phase on the predicted magnitude of the backscattered X-rays associated with objects present in the scene. This was achieved and used to show the viability of the proposed concept. At the more advanced stages of the experimental planning phase the model was used to gain critical knowledge of where it would be technically feasible to locate key diagnostic equipment within the experiment.

The experiment successfully demonstrated the concept of X-ray radar imaging achieved through the accurate timing information of the backscattered X-rays relative to an ultra-short laser pulse driven plasma source. This involved using fast responding detectors to derive range information of objects in a scene. An X-ray radar image was produced from experimental results by combining traces of backscatter X-ray intensity with respect to time/range for various test objects for a single horizontal line scan. The same post-processing was applied to the output of the particle physics model. The results of the developed model show good agreement with the experimental temporal and spatial responses of the backscattered X-rays.

The model has also been used to extend the data set beyond line scan measurements to simulate scanning over an area to obtain full 3D information of the scene. Range gating was applied to the simulated 3D data to show how significant signal to noise ratio enhancements could be made to resulting 2D images compared to a conventional backscatter X-ray image.

Further predictions have been made by the model including the energy distribution of the generated X-rays, multi-path and scatter effects not measured in the experiment. Multi-path effects were shown to be the primary contributor of undesirable image artefacts observed in the simulated images. The model allowed the sources of these artefacts to be identified and highlighted the importance of effective mitigation of these effects in the experiment. These predicted effects could be explored and validated in future experiments.

The validated model has shown to be successful in confirming the assumed underlying principle of the experimental technique to produce time resolved backscatter X-ray images. Additionally the model has provided insight into potential performance limitations and the importance of mitigation of multi-path effects. Further model developments will include simulating a more realistic electron beam energy distribution and incorporating representative detector characteristics.

9823-33, Session 8

X-ray backscattering inspection of dangerous materials based on lobster-eye objective with large field of view

Jie Xu, Xin Wang, Baozhong Mu, Qi Zhan, Qing Xie, Yaran Li, Yifan Chen, Yanan He, Tongji Univ. (China)

In order to defend drug-related and terrorist crimes effectively, and to safeguard homeland security as well as public safety, it is important to inspect drugs, explosives and other contraband quickly and accurately from

the express, luggage, vehicles and other objects.

In this paper, we will discuss X-ray backscattering inspection system based on a novel lobster-eye X-ray optical system, which is an effective inspection technology for drugs, explosives and other contraband inspection. Low atomic number materials, such as drugs and explosives, occurs strong Compton scattering after irradiated by X-ray, which is much stronger than high atomic number material, such as common metals, etc. By detecting the intensity of scattering signals, it is possible to distinguish between organics and inorganics. The lobster-eye X-ray optical system imitates the reflective eyes of lobsters, which field of view can be made as large as desired and it is practical to achieve spatial resolution of several millimeters for finite distance detection. A novel lobster-eye X-ray optical system is designed based on modifying Schmidt geometry by using multi-lens structure, so as to reduce the difference of resolution between the meridional and sagittal directions. The demonstration experiments of X-ray backscattering imaging were carried out, organic objects hidden in a steel can were imaged by the lobster-eye X-ray optical system. The results show that this X-ray backscattering inspection system can get a resolution of less than five millimeters under the FOV of more than two hundred millimeters with -0.5 meter object distance, which can still be improved.

9823-34, Session 8

Image enhancement and ROI extraction for x-ray backscattering inspection of dangerous materials

Qi Zhan, Xin Wang, Baozhong Mu, Jie Xu, Qing Xie, Yaran Li, Yifan Chen, Yanan He, Tongji Univ. (China)

The inspection of dangerous materials, such as explosives and drugs, has significant impact on the prohibition of related crimes and the spread of dangerous materials. Lobster-eye optical imaging system is a kind of dangerous materials inspection device which mainly takes advantage of backscattering x-ray. The strength of the system is its applicability to access only one side of an object, and to detect dangerous materials without disturbing the surroundings of the target objects.

The device uses Compton scattered x-rays to create digital image of suspected objects during security inspection process. Due to the grid structure of the bionic lobster-eye objective, grids contributes to the main image noise during the imaging process. At the same time, when used to inspect structured or dense materials, the image is plagued by superposition artifacts and limited by attenuation and noise. With the goal of achieve high quality images which could be used for dangerous materials inspection and further analysis, we developed effective image process methods applied to the system. The first aspect of the image process is the ROI-image extraction, which extracts the region of interest (ROI) in the image, which could be used to help identifying dangerous materials mixed with complex backgrounds. The second aspect is the denoising and enhancing edge contrast process, in order to achieve high quality images, we apply deconvolution algorithm to remove the grids and other noises. After image processing, we achieve high signal-to-noise ratio image with ROI-image extraction. The methods demonstrated in the paper have the potential to improve the sensitivity and quality of x-ray backscatter system imaging.

9823-35, Session 8

NQR detection of explosive simulants using RF atomic magnetometers

Jeffrey K. Okamitsu, Mark Monti, Dimitri Alexson, NIITEK, Inc. (United States)

Nuclear Quadrupole Resonance (NQR) is a highly selective spectroscopic method that can be used to detect and identify a number of chemicals of interest to the defense, national security, and law enforcement community. In the past, there have been several documented attempts to utilize NQR to detect nitrogen bearing explosives using induction sensors to detect

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the NQR RF signatures. We present here our work on the NQR detection of explosive simulants using optically pumped RF atomic magnetometers. RF atomic magnetometers can provide an order of magnitude (or more) improvement in sensitivity versus induction sensors and can enable mitigation of RF interference, which has classically been a problem for conventional NQR using induction sensors. We present the theory of operation of optically pumped RF atomic magnetometers along with the result of laboratory work on the detection of explosive simulant material. An outline of ongoing work will also be presented along with a path for a fieldable detection system.

9823-36, Session 8

Polarization enhanced NQR detection of explosive simulants

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Nuclear Quadrupole Resonance (NQR) has long been demonstrated for detection of nitrogen (or quadrupolar nuclei) containing explosives. Application of a material specific radio-frequency (RF) pulse (~400 kHz to 6 MHz) excites a response typically detected with a wire-wound antenna. NQR is non-contact and material specific. However, it is an inherently signal limited method, making demonstration of practical utility challenging. Although external magnetic fields are not required, polarization of hydrogen in an applied magnetic field and its transfer to the nitrogen when field is removed can enhance the NQR signal by an order of magnitude or more. Atomic magnetometers (AM) have been shown to improve detection sensitivity beyond a conventional antenna by a similar amount. AM sensors are immune to piezo-electric effects that hamper conventional NQR, and can be combined as a gradiometer for effective RF noise cancellation. In principle, combining polarization enhancement (PE) with AM detection should yield improvement in signal-to-noise ratio that is the product of the two methods, 100-fold or more over conventional NQR. However, both methods are even more exotic than traditional NQR, and have never been combined due to challenges in operating a large magnetic field and ultra-sensitive magnetic field sensor in proximity. Here, we present NQR on explosive simulant material with and without PE using a conventional antenna. We also present the first NQR measurements combining PE with AM detection of explosive simulants. Experimental methods and future applications are discussed.

9823-37, Session 8

Explosive hazard detection using a portable high-flux neutron generator

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Explosive hazards (IEDs, mines, and UXO) pose one of the greatest threats to the American warfighter today. Successful defense against these hazards requires the capability to rapidly detect and classify the hazard at safe standoff ranges. A neutron-based detection system is a viable technology solution, as described in this paper. When neutrons interact with matter, gamma radiation is emitted with characteristic energy levels that provide signature information about the elemental composition of the object being interrogated. This radiation can be detected and rapidly analyzed via a computer algorithm to generate an alert that an explosive threat is nearby and further analyzed to identify the composition of the explosive material. The speed and standoff distance of detection is directly tied to the neutron source strength, and PNL's very intense neutron generator allows neutron-based explosive detection to be a practical solution.

In this study, PNL performed a quantitative analysis to determine how its 1xE11 n/s DD neutron generator would improve upon past explosive

detection performance. The analysis focused on the use of the Thermal Neutron Analysis (TNA) technique. TNA uses the absorption of neutrons via the (n,λ) reaction of thermal neutrons (approximately 0.025 eV) and identifies the activated material with the energy of the gamma-ray signature. TNA is a common strategy for neutron-based explosives detection because of the large cross section for thermal neutrons versus fast neutrons. The analysis was primarily performed using the MCNP (Monte Carlo N-Particle) code. The five parameters evaluated include explosive type and composition, explosive depth, distance from neutron source to explosive, and soil composition.

9823-38, Session 8

Effectiveness of laser sources for contactless sampling of traces of explosives

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A comparative study of effectiveness of laser sources to initiate desorption has been performed for traces of paranitrotoluene (PNT), trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), pentaerythritol tetranitrate (PETN), cyclotetramethylenetetranitramine (HMX) on various surfaces at vacuum and atmospheric pressure. YAG:Nd³⁺ nanosecond (τ_{pulse}=6 ns, λ=266, 532, 1064 nm), and picosecond (τ_{pulse}=300ps, λ = 266, 532 nm) lasers and continuous wave laser (λ = 440nm) were used. Substrates of quartz, paper, aluminum or polyethylene with traces of explosives were located in a special vacuum-impenetrable laser rod. The rod was inserted into a mass-spectrometer and samples were exposed radiation, followed by desorption of explosives. The same measurements have been fulfilled at ambient conditions.

Quantitatively, it is shown the most effective source is a nanosecond laser with λ =266 nm. The desorbed quantities achieved dozens nano-grams for TNT, RDX, PETN per single pulse. The desorption efficiency under nanosecond (λ=532nm) radiation was comparable to that of ultraviolet radiation for TNT, RDX, PETN even in the case of optically thin samples at the same laser intensity.

A dissociation product - nitric oxide (NO) was registered during desorption of all studied explosives. The possible mechanisms of NO formation are discussed.

Desorption of HMX is possible for a series of 50 or more laser pulses only.

The nanosecond (λ =1064 nm) and picosecond radiation (λ=266, 532 nm) were not effective for initiating desorption at any available laser intensities.

The desorption efficiency at ambient pressure exceeds the same at vacuum.

A possibility to create an effective contactless portable (~2kg) sampling system is discussed.

9823-39, Session 8

Digital micromirror devices in Raman trace detection of explosives

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Tunable filter based imaging Raman spectroscopy is a verified technique to detect single explosives particles at stand-off distances. However inherent in the design are the large light losses due to sequential imaging at different wavelengths, leading to effective transmission often well below 1%. High performance tunable filters are expensive and only available for certain wavelength regions, thus limiting the flexibility.

The use of digital micromirror devices (DMD) in imaging Raman explosive trace detection can improve light throughput and add significant flexibility

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compared to existing systems. DMDs also allow for fast switching of tailored coded apertures in the light collection path. The present work focus on the ways DMDs can be used when applying imaging Raman spectroscopy to stand-off explosives trace detection and evaluate the possible performance in terms of light throughput, reconstruction accuracy and ultimately detection limits.

With two discrete reflection orders for the DMD real time imaging with a 2nd camera is possible. This allows continuous target monitoring, possible input for the image reconstruction as well as adaptive rejection of highly fluorescent regions in the target scene. This type of setup also permits the use of compressive sensing techniques which in turn makes possible combining imaging with non-spatially resolved fluorescence suppression techniques, such as Kerr gating.

The system presented consists of a 2nd harmonics Nd:YAG laser with 2.3 W average output at 1000 Hz for sample excitation, collection optics, DMD, CMOS-cameras and a spectrometer with ICCD camera for signal gating and detection.

9823-40, Session 9

Improving the detection of explosive hazards with LIDAR-based ground plane estimation

Andrew Buck, James M. Keller, Mihail Popescu, Univ. of Missouri (United States)

Detecting buried explosive hazards while driving requires accurate road recognition from reasonable stand-off distances. On unpaved roads in arid desert environments, this can be difficult due to the similarity in color and texture of the on-road and off-road regions. Furthermore, shadows from roadside shrubs and irregular terrain caused by washouts can be troublesome for image-based systems. In this paper, we show how fine-grained elevation data from an onboard LIDAR system can improve the road detection accuracy of our previous image-only system. We first coregister the image data with the 3D point cloud and then determine the texture of the terrain directly in front of the vehicle. We then locate regions in the image with similar texture and estimate which pixels are likely to be on-road. This allows us to update a parametric road model that is robust against variations in lighting and terrain. Our algorithm is tested on an unpaved desert road at an arid U.S. Army test site.

9823-41, Session 9

3D Environment Modeling and Location Tracking Using Off-The-Shelf Components

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The remarkable popularity of smartphones over the past decade has led to a technological race for dominance in market share. This has resulted in a flood of new processors and sensors that are cheap, low power and high performance. These sensors include accelerometers, gyroscope, barometers and most importantly cameras. This sensor suite, coupled with multicore processors, allows a new community of researchers to build small, high performance platforms for low cost. This paper describes a system using off-the-shelf components to perform position tracking as well as scene modeling. The system relies on tracking using stereo vision and inertial navigation to determine movement of the system as well as create a model of the scene sensed by the system.

9823-42, Session 9

Road detection in arid environments using uniformly distributed random based features

Pooparat Plodpradista, James M. Keller, Mihail Popescu, Univ. of Missouri (United States)

The capability of detecting the road in arid environments can greatly enhance an explosive hazard detection system. One approach is to segment out the off-road area and the area above the horizon, which is considered to be an irrelevant area. Segmenting out irrelevant areas, such as the region above the horizon, allows the explosive hazard detection system to process a smaller region in a scene, allowing a more complex and expensive approach for the remainder. However, the road detection algorithm cannot be so computationally expensive as to outweigh its benefit. In this paper, we propose the use of random projection and random selection on image patches to map them into much lower dimensional spaces to speed up detection algorithms. Both methods are computationally low-cost and can be used to compress the data to lower dimensions while approximately preserving pairwise distances (in probability). This allows any classifier used in our proposed algorithm to consume fewer resources. Furthermore, by applying the random projections directly to intensity patches, there is no costly feature extraction computation. The data used in our proposed algorithm are from sensors on board a U.S. Army countermine vehicle. The experiments are designed to compare both random projection and random selection, as well as another popular method, Principal Component Analysis (PCA).

9823-43, Session 10

Integrated use of field spectroscopy and satellite remote sensing for defence and security applications in Cyprus

George Melillos, Cyprus Univ. of Technology (Cyprus)

'Underground structures' can affect their surrounding landscapes in different ways such as vegetation vigour. This latter indicator is often observed on the ground as a crop mark; a phenomenon which can be used to denote the presence of underground structures. This paper focuses results obtained from a field spectroscopy campaign on 'buried' underground structures in Cyprus. A SVC-1024 field spectroradiometer was used and in-band reflectances were determined for a variety of medium and high resolution satellite sensors. Several vegetation indices such as NDVI and SAVI were obtained from the spectroradiometric measurements. A 'smart indices algorithm' was developed aiming for the detection of military underground structures following the assessment of the existing vegetation indices or other available band combinations algorithm. Test areas were identified, analyzed and modeled. The areas have been analyzed and tested in different scenarios such as: (a) the 'natural state' of the underground structure (b) the different type of crop over the underground structure and imported soil (c) the different types of non-natural material over the underground structure. A reference target in the nearby area was selected. Controllable meteorological and environmental parameters were acquired and monitored. As well, an unmanned aerial vehicle (UAV) was also used to survey the area with visible and near-infrared cameras in order to generate NDVI values for comparison to the in-situ spectroradiometric measurements.

9823-44, Session 10

Roadside IED Detection Using Subsurface Imaging Radar and Rotary UAV

Yexian Qin, LR Technologies (United States); Jones

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Modern improvised explosive device (IED) and mine detection sensors using microwave technology are based on ground penetrating radar operated by a ground vehicle. Operation of such sensors is limited by vehicle size, road conditions, and obstacles along the troop marching direction. This paper presents a new conceptual design using a rotary unmanned aerial vehicle (UAV) to carry a subsurface imaging radar for roadside IED detection. We have built a UAV flight simulator with the subsurface imaging radar running in a laboratory environment and tested it with non-metallic and metallic IED-like targets. From the initial lab results, we can detect the IED-like target 15-cm below road surface while carried by a UAV platform.

One of the challenges is to design the radar and antenna system for a very small payload (less than 3 lb). The motion compensation algorithm is also critical to the imaging quality. In this paper, we also demonstrate the algorithm simulation and experimental imaging results with different target materials, sizes, and clutters.

9823-45, Session 10

Integration of micro-fabricated atomic magnetometers on military systems

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A new generation of ultra-high sensitivity magnetic sensors based on innovative micro-electromechanical systems (MEMS) are being developed and incorporated into military systems. Specifically, we are currently working to fully integrate the latest generation of MicroFabricated Atomic Magnetometers (MFAMs) developed by Geometrics on defense mobility systems such as unmanned systems, military vehicles and handheld units. Recent reductions in size, weight, and power of these sensors has enabled new deployment opportunities for improved sensitivity to targets of interest, but has also introduced new challenges associated with noise mitigation, mission configuration planning, and data processing. Our work is focused on overcoming the practical aspects of integrating these sensors with various military platforms. Implications associated with utilizing these combined sensor systems in working environments are addressed in order to optimize signal-to-noise ratios, detection probabilities, and false alarm mitigation. Specifically, we present collaborative work that bridges the gap between commercial specialists and operation platform integration organizations including magnetic signature characterization and mitigation as well as the development of simulation tools that consider a wide array of sensor, environmental, platform, and mission-level parameters. We discuss unique deployment concepts for explosive hazard target geolocation, and data processing. Applications include configurations for undersea and underground threat detection - particularly those associated with stationary or mobile explosives and compact metallic targets such as munitions, subsea threats, and other hazardous objects. We show the potential of current and future features of miniaturized magnetic sensors including very high magnetic field sensitivities, bandwidth selectivity, and array processing.

9823-46, Session 11

Attribute-driven transfer learning for detecting novel buried threats with ground-penetrating radar

Kenneth A. Colwell, Leslie M. Collins, Duke Univ. (United States)

Ground-penetrating radar (GPR) technology is an effective method of detecting buried explosive threats. The system uses a binary classifier to distinguish "targets", or buried threats, from "nontargets" arising from system prescreener false alarms; this classifier is trained on a dataset of previously-observed buried threat types. However, the threat environment is not static, and new threat types that appear must be effectively detected even if they are not highly similar to every previously-observed type. Gathering a new dataset that includes a new threat type is expensive and time-consuming; minimizing the amount of new data required to effectively detect the new type is therefore valuable. This research aims to reduce the number of training examples needed to effectively detect new types using transfer learning, which leverages previous learning tasks to accelerate and improve new ones. Further, new types have attribute data, such as composition, components, construction, and size, which can be observed without GPR and typically are not explicitly included in the learning process. Since attribute tags for buried threats determine many aspects of their GPR representation, a new threat type's attributes can be highly relevant to the transfer-learning process. In this work, attribute data is used to drive transfer learning, both by using attributes to select relevant dataset examples for classifier fusion, and by extending a relevance vector machine (RVM) model to perform intelligent attribute clustering and selection. Classification performance results for both the attribute-only case and the low-data case are presented, using a dataset containing a variety of threat types.

9823-47, Session 11

Detecting very deeply buried threats in ground penetrating radar data

Daniel Reichman, Jordan M. Malof, Leslie M. Collins, Duke Univ. (United States)

Ground penetrating radar (GPR) is a popular remote sensing modality for buried threat detection. Many algorithms have been developed to distinguish buried targets from subsurface clutter. This work proposes a new detection approach that improves the detection of very deeply buried targets, and interestingly, also improves the detection of targets buried at more shallow depths. First, it is shown that the appearance of target signal response over time (the target "signature"), is very well localized in time, and well correlated with target burial depth. This motivates the proposed approach, to split the GPR data into two disjoint subsets based on time and to process each subset of data separately. This split separates the data into an early and late portion corresponding to the time at which target signatures for shallow and deep targets, respectively, are expected to appear. Experiments are conducted on real GPR data using the previously published HOG prescreener: a fast supervised processing method operated on histogram of oriented gradient (HOG) features. The results show substantial improvements in detection of very deeply buried targets (4.1% to 17.2%) and in overall detection performance (81.1% to 83.9%). These results suggest that other methods may benefit from depth-based processing as well.

9823-48, Session 11

Enhancements to GPR buried UXO detection using the apex-shifted hyperbolic Radon transform

Matthew P. Masarik, Brian T. Thelen, Ismael Xique, Michigan Tech Research Institute (United States)

This paper investigates the use of the apex-shifted hyperbolic Radon transform to improve detection of buried unexploded ordnances with ground penetrating radar (GPR). The forward transform, motivated by physical signatures generated by targets, is defined and implemented. The adjoint of the transform is derived and implemented as well. The transform and its adjoint are used to filter out responses that do not exhibit the hyperbolic structure characteristic of GPR target responses. The filtering procedure is based on using a regularized least-squares inversion algorithm,

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and is applicable for both real and complex GPR data. The effectiveness of filtering off clutter via this hyperbolic Radon transform filtering procedure is demonstrated qualitatively on several examples of GPR B-scan imagery from a government-provided dataset collected at an outdoor testing site. Furthermore, a quantitative assessment of the utility within a detection algorithm is given in terms of improved ROC curve performance on the same dataset.

9823-49, Session 11

A Fisher vector representation of GPR data for detecting buried objects

Andrew Karem, Amine Ben Khalifa, Hichem Frigui, Univ. of Louisville (United States)

We present a new method, based on the Fisher Vector (FV), for detecting landmines using ground-penetrating radar (GPR) data. The Fisher Vector is a generalization of the standard Bag of Words (BoW) method, which provides a framework to map a set of local descriptors to a global feature vector. Typically, potential GPR targets, flagged by the prescreener for further discrimination, are large and cover areas wider and deeper than the targets of interest. Thus, to effectively classify a new signature, we extract features from multiple depths (patches). In particular, we extract dense SIFT features from a grid covering the regions of interest (ROIs). ROIs are identified as regions with high-energy along the (down-track, depth) dimensions of the 3-D GPR cube, or with high-energy along the (cross-track, depth) dimensions.

Fisher vector's patch aggregation mechanism is based on the Fisher Kernel. The Fisher Kernel characterizes a patch by its deviation from a generative model. The deviation is the gradient of the patch log-likelihood with respect to the generative model parameters. The vectorial representation of all the deviations is called the Fisher Vector (FV). The FV is more efficient to compute than the BoW since it relies on a significantly smaller dictionary ("visual vocabulary"). In addition, mapping a GPR signature into one global feature vector using this technique makes it more efficient to classify using simple and fast linear classifiers such as Support Vector Machines..

The proposed approach is applied to the real world problem of detecting buried explosive objects using GPR data. The selected data were accumulated across multiple dates and multiple test sites by a vehicle mounted mine detector (VMMD) using ground penetrating radar (GPR) sensor, and correspond to a diverse set of conventional land mines and other buried explosive objects consisting of varying shapes, metal content, and underground burial depths. Performance of the proposed approach is analyzed using receiver operating characteristics (ROC) and is compared to the feature-based Edge Histogram Discriminator (EHD). Preliminary analysis indicates that the FV approach significantly outperforms the EHD in detecting both conventional landmines and buried explosive objects and in reducing the number of false alarms.

9823-50, Session 11

KLMS based prescreener approach on landmine detection and fusion with various types of prescreener algorithms

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In this paper, a decision level fusion of multiple pre-screener algorithms on Ground Penetrating Radar (GPR) data for the detection of buried landmines is presented. The purpose of the project is to propose a pre-screener that can work in real time with lower false alarm rate and higher true detection rate. The data used in the experiments were collected from the test area of IPA Defense, Ankara, Turkey; using GPR developed by NIITEK mounted on ASELNAN's Kaplan UGV. The test area contains four different soil types at

separated lanes; in which targets of several shapes, sizes and materials are buried. Each lane in the test area is 25m long and 2m wide. The pre-screener algorithms tested on this data include the Q-Scan, Kernel Least Mean Square (KLMS), Edge Histogram Descriptor (EHD), Robust PCA (RPCA) and Blob Filter. Among these, despite the well-spread use of the LMS algorithm, KLMS is a novel algorithm for landmine detection with GPR. In this study, the aforementioned prescreeners as well as KLMS and LMS are compared. Q-Scan, RPCA and EHD algorithms are applied through Down-Track B-scan data. KLMS and Blob Filter are applied through depth bins. In addition, to increase reliability of the proposed KLMS algorithm, decision level fusion is applied using the other prescreeners. In doing so, we succeeded in getting high detection rates in several different situations. The full algorithm including pre-processing and object classification will be presented.

9823-51, Session 11

Preprocessing of A-scan GPR data based on energy features

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There is an increasing demand for noninvasive detection and classification of objects buried in soil or hidden behind walls. Ground penetrating radars (GPRs) are effective sensors to recognize landmines, underground pipes etc. Real-time mine detection/classification must be completed within short processing time periods with high accuracy and low false-alarm rates. The process is divided into two phases; preprocessing phase to detect the presence of buried objects, and classification phase to figure out if it is a real threat. While classification phase involves more challenging signal/image processing techniques, the preprocessing phase must be computationally simple, inexpensive and fast. This paper presents an efficient and novel preprocessing method based on the computation of energy features of down-looking GPR A-scan data to detect buried targets.

The traditional approach of GPR B-scan preprocessing involves the removal of air-ground reflections, down shifting/alignment and data normalization. In the suggested preprocessing approach however, only air-ground reflections are removed from the raw A-scan signals to preserve the target depth/geometry information and the original spectral content of the data which are needed for subsequent target feature extraction steps of classification. While cumulative energy curves of an A-scan signal can be used to eliminate ground-reflected signals, total energy levels of A-scan signals are used to compute ground clutter thresholds. Total energy values exceeding the clutter thresholds indicate the presence of buried targets. Then, the instantaneous energy curve of the A-scan signal can be used to estimate the target depth.

9823-52, Session 12

Anomaly detection using classified eigenblocks in GPR image

Min Ju Kim, Seong Dae Kim, KAIST (Korea, Republic of); Seung-eui Lee, Hanwha Thales Co., Ltd. (Korea, Republic of)

Automatic landmine detection system using ground penetrating radar has been widely researched. For the automatic mine detection system, the system speed is an important factor. Many techniques for mine detection are developed based on statistical background. Among them, a detection technique employing Principal Component Analysis (PCA) is mainly used for clutter reduction and anomaly detection. However, the PCA technique has not provided any advantages in terms of system speed, because of large basis dimension and a numerous number of inner product operations. In order to overcome this problem, we propose a fast anomaly detection system using 2D DCT and PCA.

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To reduce the number of bases, our proposed system is trained with positive and negative angle anomaly signals separately. We construct a set of positive and negative angle bases of anomaly signals with PCA. Before construction, we employ 2D DCT to take advantage of its characteristic of compact representation. PCA followed by coefficient selection in DCT domain reduces the basis dimension.

In testing phase, we transform an input by means of 2D DCT. A pre-screener is then applied to 2D discrete cosine transformed test patch. The directional characteristic of patch can be estimated from the ratio of vertical edge coefficient power and horizontal edge coefficient power. The pre-screener categorizes the patches as positive angle spot, negative angle spot, or background spot candidates. For positive and negative angle spot candidate patches, we calculate the difference between the original block and its approximation computed with basis blocks. The spot is classified as positive/negative angle spot if the difference is less than some threshold. However, this kind of positive/negative angle signal appears in not only anomaly but also the ground surface. To remove unwanted clutters, we employ the fact that the recurrent signals appear repeatedly under the anomaly spot.

Our experiments use the data obtained from a test site that include anti-tank and anti-personnel mines. The result shows that the proposed system performs much better than the conventional PCA systems from the viewpoint of speed.

9823-53, Session 12

Multiple kernel based feature and decision level fusion of iECO individuals for explosive hazard detection in FLIR imagery

Stanton R. Price, Bryce Murray, Lequn Hu, Derek T. Anderson, Mississippi State Univ. (United States); Timothy C. Havens, Michigan Technological Univ. (United States); Robert H. Luke III, U.S. Army RDECOM CERDEC NVESD (United States); James M. Keller, Univ. of Missouri (United States)

Explosive hazards are a serious threat to both civilians and soldiers. Algorithms, sensors and systems that can automatically detect such threats are of great interest. A number of approaches are currently being explored for explosive hazard detection (EHD), for example hand-held, downward-looking and forward-looking vehicle mounted platforms. In addition to platform, multiple sensors (and their fusion) are being explored to tackle this extreme problem. Herein, we investigate the utility of feature and decision-level fusion of learned signal/image Improved Evolution-CONstructed (iECO) features for forward-looking EHD in infrared imagery. Specifically, we demonstrate different ways to fuse learned features pre- and post-classification. We explore feature-level fusion using genetic algorithm based multiple kernel learning and support vector machine (GAMKLP-SVM) classification and decision-level fusion using fuzzy integral based multiple kernel learning and SVM (DeFIMKL-SVM) classification. Performance is assessed in the context of receiver operating characteristic (ROC) curves on data from a U.S. Army test site that contains multiple target and clutter types, burial depths and times of day.

9823-55, Session 12

Seismic wave identification estimation using robust principal component analysis for buried target detection

Miles Crosskey, CoVar Applied Technologies, Inc. (United States); Kenneth D. Morton Jr., CoVar Research (United States)

We introduce an algorithm for buried target detection in the presence of induced seismic waves. Ground fluctuations are measured over time and space with an array of laser Doppler vibrometers (LDVs) and the resulting data is used to estimate the presence of buried objects. Buried targets often cause scattering of the subsurface waves, resulting in anomalies in the LDV measurements of the travelling wave. The seismic wave response through the ground depends upon many factors that are rarely known in advance, most importantly the physical properties of the soil. Characterization of buried target signatures using time or frequency features of the raw data is problematic, as the features are strongly influenced by the travelling wave. We introduce a statistical method that identifies the travelling wave, and anomalies in its propagation. The proposed algorithm adapts Robust Principal Component Analysis (RPCA), a well-known algorithm for anomaly detection in video processing, to the seismic anomaly detection problem. Our algorithm assumes that the signature of the traveling waves is low-rank as a function of angle from the seismic source and that anomalies are sparse in time and space. Once identified, the travelling wave can be subtracted from the raw data, leaving behind only residual signatures belonging to anomalies. Using standard pattern recognition algorithms and a variety of characterizing features, target detection performance is shown to be improved on the residual data versus the raw data.

9823-56, Session 13

A feature learning and bag of words approach for classifying buried threats in forward-looking ground penetrating radar data

Joseph A. Camilo, Jordan M. Malof, Leslie M. Collins, Duke Univ. (United States)

The forward-looking ground penetrating radar (FLGPR) is a remote sensing modality that has recently been investigated for buried threat detection. The FLGPR considered in this work uses a stepped frequency sensing followed by filtered backprojection to create images of the ground, where each image pixel corresponds to the radar energy reflected from the subsurface at that location. Typical target detection processing begins with a prescreening operation where a small subset of spatial locations are chosen to consider for further processing. Image statistics, or features, are then extracted around each selected location and used for training a machine learning classification algorithm. A variety of features have been proposed in the literature for use in classification. Thus far, however, predominantly hand-crafted or manually designed features from the computer vision literature have been employed (e.g., HOG, Gabor filtering, etc). Recently, it has been shown that image features learned directly from data can obtain state-of-the-art performance on a variety of problems. In this work we employ a feature learning scheme using k-means and a bag-of-visual-words model to learn effective features for target and non-target discrimination in FLGPR data. Experiments are conducted using several lanes of FLGPR data and learned features are compared with several previously proposed static features. The results suggest that learned features perform comparably, or better, than existing static features. Similar to other feature learning results, the features consist of edges or texture primitives, revealing which structures in the data are most useful for discrimination.

9823-57, Session 13

Convolutional neural network based sensor fusion for forward looking ground penetrating radar

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Forward looking ground penetrating radar (FLGPR) is an alternative buried threat sensing technology designed to offer additional standoff compared to downward looking GPR systems. Due to additional flexibility in antenna configurations, FLGPR systems can accommodate multiple antennas sampling at different frequencies and signal polarizations. The different antenna configurations present challenges in both developing informative feature extraction methods, and fusing sensor information in order to obtain the best discrimination performance. This work presents the use of convolutional neural networks in order to jointly learn features across all antenna configurations and perform feature level fusion by optimizing a single network. This joint optimization is possible by modifying the traditional image-based convolutional neural network configuration to have independent sets of filters not shared between antenna configurations. The filters generated by this process create a learned feature extraction method that is optimized to provide the best discrimination performance when fused. This paper presents the results of applying convolutional neural networks on this multi-sensor platform and compares these results to the use a variety of expert-designed features. This paper also compares performance of this method to traditional convolutional neural networks architectures to show the benefit of convolutional network based sensor fusion.

9823-58, Session 13

Q-MSM: a modeling approach to design, and guide research for, multi-modality buried target detection systems

Jordan M. Malof, Leslie M. Collins, Duke Univ. (United States)

Many remote sensing modalities have been developed for buried target detection (BTD), each one offering relative advantages over the others. There has been interest in combining several modalities into a single BTD system that benefits from the advantages of each constituent sensor. Recently an approach was developed, called multi-state management (MSM), that aims to achieve this goal by separating BTD system operation into discrete states, each with different sensor activity and system velocity. Additionally, a modeling approach, called Q-MSM, was developed to quickly analyze multi-modality BTD systems operating with MSM. This work extends previous work by addressing two goals. The first goal is to experimentally demonstrate the benefits of BTD systems operating with MSM. Experiments are conducted using real, field-collected data, showing the performance benefits of a system that combines a forward looking infrared camera (FLIR) with a GPR, operating with MSM. The second goal is to demonstrate how Q-MSM modeling can be used to design BTD systems operating with MSM, and to guide research to yield the most performance benefits. Experiments are conducted using Q-MSM modeling, to evaluate the performance impact of improvements made to individual system components, such as the processing time of algorithms, or the detection performance of each modality (e.g., FLIR or GPR). Q-MSM permits fast analysis that can determine where system improvements will have the greatest impact, and can therefore help guide BTD research.

9823-60, Session 13

Sequential feature selection for detecting buried objects using forward looking ground penetrating radar

Darren A. Shaw, Kevin E. Stone, Dominic K. Ho, James M. Keller, Univ. of Missouri (United States); Robert H. Luke III, Brian P. Burns, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Forward looking ground penetrating radar (FLGPR) has the benefit of detecting objects at a significant standoff distance. The FLGPR signal is radiated over a large area and the radar signal return is often weak.

Improving detection, especially for buried on road targets, while maintaining an acceptable false alarm rate remains to be a challenging task. Various kinds of features have been developed over the years to increase the FLGPR detection performance. This paper focuses on investigating the use of as many features as possible for detecting buried targets and applying the sequential feature selection technique to automatically choose the features that contribute most for improving performance. Experimental results using data collected at a government test site will be presented.

9823-61, Session 13

Spectral diversity for ground clutter mitigation in forward-looking GPR

Adam J. Webb, Timothy C. Havens, Timothy J. Schulz, Michigan Technological Univ. (United States)

The operational constraints associated with a forward-looking ground-penetrating radar (GPR) limit the ability of the radar to resolve targets in the dimension orthogonal to the ground. As such, detection performance of buried targets is greatly inhibited by the relatively large response due to surface clutter. The response of buried targets differs from surface targets due to the interaction at the boundary and propagation through the ground media. The electromagnetic properties of the media, interrogation frequency, depth of buried target, and location of the target with respect to the the sensing platform all contribute to the shape, position, and magnitude of the point spread function (PSF). The standard FLGPR scenario produces a wide-band data set collected over a fixed set of observation points. By observing the shape, position, and amplitude behavior of the PSF as a function of frequency and sensor position (time), energy resulting from surface clutter can be separated from energy resulting from buried targets. There are many possible ways by which this simple relationship between attenuation and frequency might be exploited. The approach considered here is to perform an independent components analysis on a set of sub-banded GPR images produced from a single frame. The primary component is interpreted as the ground clutter component while subsequent components are interpreted as buried targets.

9823-62, Session 14

Multiple instance learning for buried hazard detection

Joseph S. Rice, Anthony Pinar, Timothy C. Havens, Michigan Technological Univ. (United States); Adam Webb, Michigan Technological University (United States) and Michigan Tech Research Institute (United States); Timothy J. Schulz, Michigan Technological Univ. (United States)

Buried explosives hazards are one of the many deadly threats facing our Soldiers, thus the U.S. Army is interested in the detection and neutralization of these hazards. One method of buried target detection uses forward-looking ground-penetrating radar (FLGPR), and it has grown in popularity due to its ability to detect buried targets at a standoff distance. FLGPR approaches often use machine learning techniques to improve the accuracy of detection. We investigate an approach to explosive hazard detection that exploits spatiotemporal features to discriminate between hazardous and non-hazardous returns in FLGPR data. One challenge this problem presents is a high number of clutter and non-target objects relative to the number of targets present. Our previously investigated detection techniques have imaged the radar data by using backpropagation to integrate each frame into a single output image. The approach discussed in this paper integrates sequential overlapping subsets of frames into individual images representing observations from multiple locations and angles. For each potential target, we extract features from each image at the corresponding location. Using these collected features, we learn an in situ model of the spatiotemporal signatures of potential targets and confuser objects in order to classify alarms as either targets or false alarms. We demonstrate our method on test data collected at a U.S. Army test site.

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9823-63, Session 14

**Multiple-modality Program for Standoff
Detection of Roadside Hazards**

Kathryn Williams, Seth Middleton, Ryan Close, Robert H Luke III, Rajiv Suri, U.S. Army RDECOM CERDEC NVESD (United States)

The U.S. Army RDECOM CERDEC Night Vision and Electronic Sensors Directorate (NVESD) Countermine Division has developed a program to investigate the use of multiple sensor modalities to detect roadside hazards. The first phase of the program is a two-year effort spanning FY15 and FY16 to investigate the capability of existing radar, acoustic, lidar, and electro-optical/infrared (EO/IR) sensors to detect unconcealed or lightly concealed roadside hazards. Conclusions about phenomenology, feature extraction, and potential sensor fusion will be drawn from analysis of data from collections, modeling and simulation, and laboratory experiments. Modeling and simulation will also be used to investigate optimal sensor configurations. The second phase of the program will focus on developing a technology demonstrator combining the most effective sensor(s) with autonomous detection algorithms.

Phase I of the program is currently underway. To date, relevant sensor systems have participated in four data collections, in varying terrains and environmental conditions. The data collections were designed to understand the capabilities and limitations of each sensor modality, as well as to capture target signature data in multiple configurations. Current data analysis is focused on quantifying detection capabilities, developing feature extraction methods, analyzing the consistency and repeatability of features, and determining each sensor's ability to penetrate concealment. This paper will describe the strategy, data collections, analysis, modeling and simulation, and future work involved with this program.

9823-64, Session 14

**Advances in ground vehicle-based LADAR
for standoff detection of roadside hazards**

Jim Hollinger, Land Air Sea Autonomy LLC (United States); Alyssa Vessey, LSA Autonomy (United States); Ryan R. Close, Seth Middleton, Kathryn Williams, Ronald R. Rupp, Son Nguyen, U.S. Army RDECOM CERDEC NVESD (United States)

Commercial sensor technology has the potential to bring cost-effective sensors to a number of U.S. Army applications. By using sensors built for a widespread commercial application, such as the automotive market, the Army can decrease costs of future systems while increasing overall capabilities. Additional sensors operating in alternate and orthogonal modalities can also be leveraged to gain a broader spectrum measurement of the environment. Leveraging multiple phenomenologies can reduce false alarms and make detection algorithms more robust to varied concealment materials. In this paper, this approach is applied to the detection of roadside hazards partially concealed by light-to-medium vegetation. This paper will present advances in detection algorithms using a ground vehicle-based commercial LADAR system. The benefits of augmenting a LADAR with millimeter-wave automotive radar and results from relevant data sets are also discussed.

9823-65, Session 14

**Explosive hazard detection using synthetic
aperture acoustics sensing**

Eric Brewster, Kevin E. Stone, James M. Keller, Mihail Popescu, Univ. of Missouri (United States)

In this paper, we develop an approach to detect explosive hazards designed to attack vehicles from the side of a road, using a side looking synthetic aperture acoustic (SAA) sensor. This is done by first processing the raw data using a back projection algorithm to form images. Next, an RX prescreener creates a list of possible targets, each with a designated confidence. Initial experiments are performed on libraries of the highest confidence hits for both target and false alarm classes generated by the prescreener. Image chips are extracted using pixel locations derived from the target's easting and northing. Several feature types are calculated from each image chip, including: local binary pattern (LBP), histogram of oriented gradients (HOG), and generalized column projection features where the column aggregator takes the form of the minimum, maximum, mean, median, mode, standard deviation, variance, and one-dimensional fast Fourier transform (FFT). A support vector machine (SVM) classifier is then utilized to evaluate feature type performance during training and testing in order to determine whether the two classes are separable. This will be used to build an online classifier system for testing on lane based data.

9823-66, Session 14

**Comparison of spatial frequency domain
features for the detection of side attack
explosive ballistics in synthetic aperture
acoustics**

Joshua L. Dowdy, Derek T. Anderson, Mississippi State Univ. (United States); Robert H. Luke III, U.S. Army RDECOM CERDEC NVESD (United States); John E. Ball, Mississippi State Univ. (United States); Timothy C. Havens, Michigan Technological Univ. (United States); James M. Keller, Univ. of Missouri (United States)

Explosive hazards in current and former conflict zones are a serious threat to both civilians and soldiers alike. As a result, much effort has been dedicated to identifying automated algorithms and systems to detect such threats. However, robust detection is complicated due to factors like the varied composition and anatomy of such hazards. In order to solve this challenge, a number of platforms (vehicle-based and handheld) and sensors (infrared, ground penetrating radar, acoustics, etc.) are being explored. In this article, we explore the detection of side attack explosive ballistics via a vehicle-mounted acoustic sensor. In particular, we explore different spatial frequency domain transformations and features on digitally beamformed acoustic data and also on the raw acoustic returns. These features are explored in the context of feature-level fusion using GAMKLP-SVM, a genetic algorithm-based multiple kernel learning technique and support vector machine-based classifier. Performance is assessed in the context of receiver operating characteristic (ROC) curves on data from a U.S. Army test site that contains multiple target and clutter types, burial depths and times of day.

9823-67, Session 14

**Detection of landmines and UXO using
advanced synthetic aperture radar
technology**

Markus Peichl, Eric Schreiber, Andreas Heinzl, Stephan Dill, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

A main problem of effective landmine and UXO decontamination is efficient and reliable detection and localization of suspicious objects in reasonable time. This requirement demands for fast sensors investigating large areas with sufficient spatial resolution and sensitivity. Ground penetrating radar (GPR) is a suitable tool and is considered as a complementing sensor since nearly two decades. However, most GPRs operate in very close distance to ground in a rather punctual method of operation. In contrast, synthetic aperture radar (SAR) is a technique allowing fast and laminar stand-off

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investigation of an area.

TIRAMI-SAR is imaging radar at lower microwaves for fast close-in detection of buried and unburied objects on a larger area. This allows efficient confirmation of a threat by investigating such regions of detection by other sensors. For proper object detection sufficient spatial resolution is required. Hence the SAR principle is applied. SAR for landmine/UXO detection can be applied by side-looking radar moved on safe ground along the area of interest, being typically the un-safe ground. Additionally, reliable detection of buried and unburied objects requires sufficient suppression of background clutter. For that purpose TIRAMI-SAR is using several antennas in multi-static configuration and wave polarization together with advanced SAR processing. The radar system and main results of the project are illustrated in the paper.

9823-68, Session 15

**Statistically normalized coherence for
coherent change detection in synthetic
aperture sonar imagery**

Tesfaye G-Michael, James D. Tucker, Naval Surface Warfare Ctr. Panama City Div. (United States); Rodney G. Roberts, Florida State Univ. (United States)

Coherent Change Detection (CCD) is a process of highlighting an area of activity in scenes (seafloor) under survey and generated from pairs of synthetic aperture sonar (SAS) images of approximately the same location observed at two different instances. The problem of CCD and subsequent anomaly feature extraction is complicated due to several factors such as the presence of random speckle pattern in the images, changing environmental conditions, and platform instabilities. These complications make the detection of weak target activities even more difficult. Typically, the degree of similarity between two images measured at each pixel locations is the coherence between the complex pixel values in the two images. Higher coherence indicates little change in the scene represented by the pixel and lower coherence indicates change activity in the scene. Such coherence estimation scheme based on the pixel intensity correlation is an ad-hoc procedure where the effectiveness of the change detection is determined by the choice of threshold which can lead to high false alarm rates.

In this paper, we propose a novel approach for anomalous change patterns using the statistical normalized coherence. This method may be used to highlight change patterns against a background of normal activities. Test results of the proposed methods on a data set of SAS images will be presented illustrating the effectiveness of the normalized coherence will be presented in terms statistics from various seafloor sediment types. A comparison will also be made to current change detections techniques for SAS.

9823-69, Session 15

**Optimized passive sonar placement to
allow improved interdiction**

Bruce A. Johnson, Cameron Matthews, Naval Surface Warfare Ctr. Panama City Div. (United States)

The Art Gallery Problem (AGP) is the name given to a constrained optimization problem meant to determine the maximum amount of sensor coverage while utilizing the minimum number of resources. The AGP is significant because a common issue among surveillance and mining systems is obtaining an understanding of the optimal position of sensors and weapons in advance of enemy combatant maneuvers. The implication that an optimal position for a sensor to observe an event or for a weapon to engage a target autonomously is usually very clear after the target has passed, but for autonomous systems the solution must at least be conjectured in advance for deployment purposes. This abstract applies the AGP as a means to solve where best to place underwater sensor nodes such that the amount of information acquired about a covered area is maximized

while the number of resources used to gain that information is minimized. By phrasing the ISR/mining problem this way, the issue is addressed as an instance of the AGP.

The AGP is a member of a set of computational problems designated as non-deterministic polynomial-time (NP)-hard. As a member of this set, the AGP shares its members' defining feature, namely that no one has proven that there exists a deterministic algorithm providing a computationally-tractable solution to the AGP within a finite amount of time. At best an algorithm meant to solve the AGP can asymptotically approach perfect coverage with minimal resource usage but providing perfect coverage would either break the minimal resource usage constraint or require an infinite amount of time. No perfectly-optimal solution yet exists to the AGP, however, approximately optimal solutions to the AGP can approach complete area or barrier coverage while simultaneously minimizing the number of sensors and weapons utilized. A minimal number of underwater sensor nodes deployed can greatly increase the Mean Time Between Operational Failure (MTBOF) and logistical footprint. The resulting coverage optimizes the likelihood of encounter given an arbitrary sensor profile and threat from a free field statistical model approach. The free field statistical model is particularly applicable to worst case scenario modeling in open ocean operational profiles where targets do not follow a particular pattern in any of the modeled dimensions.

We present an algorithmic testbed which shows how to achieve approximately optimal solutions to the AGP for a network of underwater sensor nodes with or without effector systems for engagement while operating under changing environmental circumstances. The means by which we accomplish this goal are three-fold: 1) Develop a 3D model for the sonar signal propagating through the underwater environment 2) Add rigorous physics-based modeling of environmental events which can affect sensor information acquisition 3) Provide innovative solutions to the AGP which account for the environmental circumstances affecting sensor performance.

9823-70, Session 15

**Risk-based scheduling of multiple search
passes for UUVs**

John G. Baylog, Thomas A. Wettergren, Naval Undersea Warfare Ctr. (United States)

This paper addresses selected computational aspects of collaborative search planning when multiple search agents seek to find hidden objects (i.e. mines) in local operating environments where the detection process is prone to false alarms. In this paper, we examine the impact of fixed and spatially variable validation criteria as they pertain to search agent scheduling. In particular, we discuss the properties of the risk-based objective function in terms of submodularity and its impact on scheduling algorithms.

We apply an agnostic Receiver Operator Characteristic (ROC) calculation indicative of undersea search performance to construct a Bayesian cost objective function that weighs and combines the risk of missed detection and false alarm probabilities. The Bayesian risk is developed as a function of the planned distribution of search effort over the search space, the selected ROC operating points and the validation requirement on the number of observed detections. It is shown that for any fixed combination of ROC operating point and validation criterion, an interval exists in the number of conducted search passes over which the risk objective function is submodular; that is, monotone in its marginal values (i.e., discrete derivatives). We show that this property is not retained over the boundary between intervals signifying a change in the validation criterion.

The impact of these properties on search agent scheduling is discussed. We develop the conditions under which a simple greedy algorithm can be applied to determine cell visitations within a discrete search model. We investigate the use of a double greedy algorithm for schedule optimization under more general operating conditions including the transition between validation criteria. Details of its application within a broader search planning context are discussed and numerical results are provided to demonstrate the effectiveness of the approach on overall search performance.

9823-71, Session 15

1D edge detection of tones in high noise littoral environments

Cameron Matthews, Naval Surface Warfare Ctr. Panama City Div. (United States); Pierre-Philippe Beaujean, Florida Atlantic Univ. (United States)

littoral regions typically present as a high noise acoustic environment to passive sensors, particularly with respect to port and harbor regions where tidal variation, often characterized as pink, mixes with reverberation from on-shore business and commercial shipping, often characterized as white noise. Some fish in these regions, in particular epiphenalius Guttatus, or more commonly the red hind grouper, emit relatively narrowband tones in low frequencies to communicate with other fish in such regions. The impact of anthropogenic noise sources on the red Hind and other fish is a topical area of interest for wildlife fisheries, private sportsmen and military offices are not considered here; the fact that fish species continue to populate and communicate in these regions in the presence of high noise content lends some study to the signal content and modeling of a potential receiver structure. A model is presented which considers the cyclostationary aspects of a tone of amplitude varying between 0 and 1 in the presence of variably colored noise models normalized to the voltage reading of a hypothetical passive transducer. The model applies a Mel Frequency Cepstral (MFC) analysis to derive time gated local power estimates that can then be analyzed for statistical noise variations both in the individual coefficient frame and frame to frame transitions, resulting in a 2-feature statistical signal processing data fusion routine for detection of the modelled tone in noise. The algorithm is then tested against recorded fish signals for exemplar outputs.

9823-72, Session 15

Multi-input multi-output waveform optimization for synthetic aperture sonar

Bradley Marchand, Naval Surface Warfare Ctr. Panama City Div. (United States)

Multi-input multi-output (MIMO) sonar is an emerging technology that has significant potential for advancing the state-of-the-art of modern sonar. Unlike standard sonar, which transmits scaled versions of a single waveform, a MIMO sonar system can transmit, via multiple transmitters, multiple probing signals through the use of waveform diversity. The MIMO sonar forms an Expanded Real Aperture Sonar, which can improve detection capability, enhance array gain, and improve spatial resolution without increasing system time-bandwidth requirements. A principle requirement for MIMO is that the transmission signals have narrow auto-correlation, for good resolution, and low cross-correlation for low signal to signal interference. An additional requirement for Synthetic Aperture Sonar (SAS) application is that the signals share the same time/frequency band for coherent SAS imaging. In this paper, we introduce an optimization method for designing signals for SAS imaging. We also demonstrate the performance of our signals through simple SAS platform simulations.

Conference 9824: Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XVII

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9824-1, Session 1

Chemical and biological sensing applications of integrated photonics with an introduction to the American Institute for Manufacturing Integrated Photonics (AIM Photonics)

Justin R. Bickford, U.S. Army Research Lab. (United States); Jason A. Guicheteau, U.S. Army Edgewood Chemical Biological Ctr. (United States)

Integrated photonics affords an opportunity to explore novel sensing and lab-on-a-chip concepts. It offers a route to high sensitivity, high selectivity, and low SWaP-C test systems that can be operated autonomously or by minimally-trained field personnel. We'll introduce the topic, discuss possible sensing modalities, and highlight the advantages and limitations of this technology. We'll also introduce the recent American Institute for Manufacturing Integrated Photonics (AIM Photonics), give an overview of its vision and capabilities, how to utilize its Electronic-Photonic Design Automation (EPDA) tools and its Multi-Project Wafer and Assembly (MPWA) services, how to engage in its roadmapping efforts, and how to become a contributing member. We'll host a discussion session later to engage the audience regarding chemical and biological sensing and lab-on-a-chip applications of photonic integrated circuit systems. The discussion will include the important packaging issues as well as the pros, cons, and requirements of the two implementation categories: wholly integrated systems and throw away diagnostic kits.

9824-2, Session 1

Integrated mid-infrared photonic circuits for label-free biochemical sensing

Pao Tai Lin, Texas A&M Univ. (United States)

A mid-infrared (mid-IR) spectrometer for label-free on-chip chemical sensing was developed using an engineered nanofluidic channel consisting of a Si-liquid-Si slot-structure. Utilizing the large refractive index contrast ($n_1 - n_2$) between the liquid core of the waveguide and the Si cladding, a broadband mid-IR lightwave can be efficiently guided and confined within a nanofluidic capillary (≤ 100 nm wide). The optical-field enhancement, together with the direct interaction between the probe light and the analyte, increased the sensitivity for chemical detection by 50 times when compared to evanescent-wave sensing. This spectrometer distinguished several common organic liquids (e.g., n-bromohexane, toluene, isopropanol) accurately and could determine the ratio of chemical species (e.g., acetonitrile and ethanol) at low concentration ($< 5 \mu\text{g/mL}$) in a mixture through spectral scanning over their characteristic absorption peaks in the mid-IR regime. The combination of CMOS-compatible planar mid-IR microphotronics, and a high-throughput nanofluidic sensor system, provides a unique platform for chemical detection.

9824-3, Session 1

Raman spectroscopy of trace gases using functionalized waveguides

Todd H. Stievater, Dmitry A. Kozak, Marcel W. Pruessner,

William S. Rabinovich, R. Andrew McGill, U.S. Naval Research Lab. (United States); Scott A. Holmstrom, The Univ. of Tulsa (United States); Jacob B. Khurgin, Johns Hopkins Univ. (United States)

We report the measurement of Raman spectra of several chemical species reversibly sorbed into a hypersorbent polymer coated onto a highly evanescent silicon nitride waveguide. The waveguides are composed of a 175-nm thick silicon nitride core deposited on a silicon dioxide bottom cladding. Above the core, we deposited a sorbent top cladding designed to strongly partition hydrogen-bond basic vapors to the waveguide, including phosphonate esters and other hazardous chemicals. This enables strong interactions between the pump mode and dilute chemical species along a photonic integrated circuit waveguide. In waveguide-based Raman spectroscopy the pump field continuously generates Raman scattering over the entire waveguide length, enhancing the overall efficiency compared to conventional Raman spectroscopy by approximately the ratio of the waveguide length to the wavelength. The generated Raman signal is captured by the waveguide and dispersed by an off-chip spectrometer. We have measured the Raman spectra of dimethyl sulfoxide, methyl salicylate, and ethyl acetate at levels of 140 ppb, 3.4 ppm, and 3900 ppm, respectively. These spectra represent the first measurement of trace-gas Raman scattering within integrated photonic structures.

9824-4, Session 1

A label-free optical biosensor for serotyping unknown influenza viruses

Benjamin L. Miller, Hanyuan Zhang, Univ. of Rochester Medical Ctr. (United States); Carole Henry Dunand, Patrick Wilson, The Univ. of Chicago (United States)

The ability to accurately serotype influenza viruses is critical to understanding patterns of infection, vaccine efficacy, and to the process of developing new vaccines. Unfortunately, influenza serology is hampered both by the virus' ability to undergo antigenic drift and shift (rendering it a "previously unknown" strain), and by technological limitations. In an effort to overcome these challenges, we have developed a label-free human monoclonal antibody array for flu serology, using a pattern recognition approach to assign virus serotype. The array is built on the Arrayed Imaging Reflectometry (AIR) platform. AIR relies on the creation of a near-perfect antireflective condition on the surface of a silicon chip. When this antireflective condition is perturbed because of binding to an antibody spot (or other immobilized probe molecule), binding may be sensitively and quantitatively detected as an increase in reflected light. We will describe fabrication and characterization of the array, and testing with both single-cycle and native influenza viruses. We anticipate that this approach may be extended to other viruses by expansion of the array.

9824-5, Session 1

Low-cost optical platform for digital detection of biomarkers

M. Selim Ünlü, Boston Univ. (United States)

Interferometric Reflectance Imaging Sensor (IRIS) provides the ability to detect single nanoscale particles in a simple and low-cost instrument. In single-particle modality of IRIS (SP-IRIS), the interference of light reflected from the sensor surface is modified by the presence of particles

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producing a distinct signal that reveals the size of the particle. The dielectric layered structure acts as an optical antenna optimizing the elastic scattering characteristics of nanoparticles for sensitive detection and analysis. By extending single-particle IRIS to in-liquid dynamic imaging, we demonstrated real-time digital detection of individual viral pathogens as well as single molecules labeled with Au nanoparticles.

With this technique we demonstrate real-time simultaneous detection of multiple targets in a single sample. This approach promises to simplify and reduce the cost of rapid diagnostics at very high sensitivity and specificity, providing a robust and versatile platform, ideal for point-of-care diagnostics applications.

9824-6, Session 2

Photon-sparse microscopy: visible light imaging using infrared illumination (*Invited Paper*)

Miles J. Padgett, Reuben S. Aspden, Peter A. Morris, Univ. of Glasgow (United Kingdom)

Ghost imaging systems use down-conversion sources that produce twin output beams of position-correlated photons to produce an image of an object using photons that did not interact with the object. One of these beams illuminates the object and is detected by a single pixel detector while the image information is recovered from the second, spatially correlated, beam. We utilise this technique to obtain images of objects probed with 1.5µm photons whilst developing the image using a highly efficient, low-noise, photon-counting camera detecting the correlated photons at 460nm. The efficient transfer of the image information from infrared illumination to visible detection wavelengths and the ability to count single-photons allows the acquisition of an image while illuminating the object with an optical power density of only 100 pJ cm⁻² s⁻¹. We apply image reconstruction techniques based on compressive sensing to reconstruct our images from data sets containing far fewer photons than conventionally required. This wavelength-transforming ghost imaging technique has potential for the imaging of light-sensitive specimens or where covert operation is desired.

9824-8, Session 2

Quantum noise limited nanoparticle detection and the holographic optical tweezer (*Invited Paper*)

Lars Madsen, The Univ. of Queensland (Australia)

Biology is an important and longstanding frontier for quantum metrology, with quantum-noise limited sensitivity allowing higher signal to noise or reduced optical intensities, leading to a reduction in specimen damage[1]. In this talk, I will give an overview of efforts underway in the Queensland Quantum Optics Laboratory to apply quantum-noise limited detection to biological measurements and to enhance optical trapping.

We demonstrate a quantum noise limited nanoparticle sensor capable of trapping and detecting the motion of single unlabelled biomolecules with radius as small as 5 nm. These nano-particles are illuminated with a probe laser through a microscope objective and the scattered light is collected by the tapered fibre. Here it interferes with a local oscillator and we obtain a quantum-noise limited detection down below 10 Hz. This noise performance opens for direct observation of certain biomolecular movements avoiding large biomarkers which might influence the motion.

We also present a new holographic optical tweezer which makes silica spheres work as a beamsplitters imparting much higher momentum kick per photon compared with Gaussian beams. The achieved stiffness is up to 27.5±4.1 times higher than was possible using Gaussian traps for 3.5–10.0 µm silica spheres, as well as a two-orders-of-magnitude higher measured signal-to-noise ratio of their thermally driven motion [2]. The increased stiffness for large particles will amongst other allow manipulation of larger cells and

particles in aerosols, which have been inaccessible with Gaussian traps.

References

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9824-9, Session 2

Absorption spectroscopy beyond the shot-noise limit using single-photon states (*Invited Paper*)

Rebecca Whittaker, Alex Neville, Javier Sabines-Chesterking, Patrick Birchall, Monica Berry, Christopher Erven, Jeremy L. O'Brien, Hugo V. Cable, Jonathan C. Matthews, Univ. of Bristol (United Kingdom)

Quantum mechanics tells us that there are limits in precision in measurement — a fundamental limit as to how small an error can be on a set of estimates as a function probe being used to perform a measurement. In the case of measurements made with lasers, the best precision achievable is the shot noise limit, irrespective of the detector technology or the system being measured. This is because of the quantum state of a laser being desired by a poisson distribution of different photon number. Using different optical probes can give us access to better precision. We demonstrate that single photon states can achieve the predicted "ultimate limit" in precision in measuring absorption. We use spontaneous parametric downconversion in a periodically polled PPKTP crystal to generate pairs of single photons. While these are randomly generated in time, we use one of the photons to herald the generation of a single photon. We then use this heralded single photon to obtain the binomial statistics in absorption estimation. To indicate practical use, we tune the wavelength of the heralded photons (by tuning the temperature of the PPKTP crystal) to perform spectral absorption measurements. With the current iteration of our setup in, we report up to a 30% increase in precision per photon detected, beyond the shot noise limit and at the ultimate quantum limit. We will discuss near term and practical approaches to improve this performance.

9824-10, Session 2

Plasmonic hot carrier injection in wide bandgap nitride semiconductors (*Invited Paper*)

Prineha Narang, California Institute of Technology (United States) and Northrop Grumman Corp. (United States)

Despite more than a decade of intensive scientific exploration, new plasmonic phenomena continue to be discovered, including quantum interference of plasmons, observation of quantum coupling of plasmons to single particle excitations, and quantum confinement of plasmons in single-nm scale plasmonic particles. Simultaneously, plasmonic structures find widening applications in integrated nanophotonics, biosensing, photovoltaic devices, single photon transistors and single molecule spectroscopy. Decay of surface plasmons to hot carriers is a new direction that has attracted considerable fundamental and application interest, yet a theoretical understanding of ultrafast plasmon decay processes and the underlying microscopic mechanisms remain incomplete.

Recently we analyzed the quantum decay of surface plasmon polaritons and found that the prompt distribution of generated carriers is extremely sensitive to the energy band structure of the plasmonic material. A theoretical understanding of plasmon-driven hot carrier generation and relaxation dynamics at femtosecond timescales is presented here. We report the first ab initio calculations of phonon-assisted optical excitations in metals, which are critical to bridging the frequency range between

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resistive losses at low frequencies and direct interband transitions at high frequencies. We also present calculations of energy-dependent lifetimes and mean free paths of hot carriers, accounting for electron-electron and electron-phonon scattering, lending insight towards transport of plasmonically-generated carriers at the nanoscale. We will discuss calculations for multiplasmon and nonlinear processes in the ultrafast regime from the mid-IR to visible and in different geometries. Employing a Feynman diagram approach here has been critical to determine the relevant processes.

Finally we combine first principles calculations of electron-electron and electron-phonon scattering rates with Boltzmann transport simulations to predict the ultrafast dynamics and transport of carriers in real materials. In particular, we calculate the distributions of hot carriers generated by plasmon decay and their transport in aluminum and noble metal nanostructures. We also predict the evolution of electron distributions in ultrafast experiments on noble metal nanoparticles from the femtosecond to picosecond time scales, using a modified two-temperature model as well as a full time-dependent Boltzmann equation with ab initio collision integrals. We find that the positions of the d bands and the energy dependence of the electron-phonon matrix elements substantially alter the effective electronic heat capacity and electron-lattice coupling compared to previous simplified theoretical approaches and are important for interpreting high-power ultrafast optical measurements on plasmonic nanoparticles.

9824-11, Session 3

High sensitivity stand-off detection and quantification of chemical mixtures using an active coherent laser spectrometer (ACLaS) (Invited Paper)

Neil A. MacLeod, Damien Weidmann, STFC Rutherford Appleton Lab. (United Kingdom)

High sensitivity detection, identification and quantification of chemicals in a stand-off configuration is a highly sought after capability across the security and defence sector. Specific applications include assessing the presence of explosive related materials, poisonous or toxic chemical agents, and narcotics.

Real world field deployment of an operational stand-off system is challenging with stringent requirements: high detection sensitivity, stand-off ranges from centimetres to hundreds of meters, eye-safe invisible light, near real-time response and a wide chemical versatility encompassing both vapour and condensed phase chemicals. Additionally, field deployment requires a compact, rugged, power efficient, and cost-effective design.

To address these demanding requirements, we have developed the concept of the Active Coherent Laser Spectrometer (ACLaS), which can be described as a middle infrared hyperspectral coherent lidar. Combined with robust spectral unmixing algorithms inherited from retrievals of high resolution space-based sounding data, ACLaS has been demonstrated to fulfil the above-mentioned needs.

ACLaS prototypes have been developed using quantum cascade lasers (QCL's) to exploit the fast frequency tuning capability of these solid state sources. Using distributed feedback (DFB) QCL's, demonstration and performance analysis were carried out on narrow-band absorbing chemicals (N₂O, H₂O, H₂O₂, CH₄, C₂H₂ and C₂H₆) at standoff distances up to 50 m using realistic non cooperative targets such as wood, painted metal, and bricks. Using more widely tunable external cavity QCL's, ACLaS has also been demonstrated on broadband absorbing chemicals (dichloroethane, HFC134a, ethylene glycol dinitrate and 4-nitroacetanilide solid) and on complex samples mixing narrow-band and broadband absorbers together in a realistic atmospheric background.

9824-12, Session 3

Stand-off detection of explosives and precursors using compressive sensing Raman spectroscopy

Mattias Svanqvist, Henric Östmark, Martin Glimtoft, Matilda Ågren, Markus Nordberg, FOI-Swedish Defence Research Agency (Sweden)

Compressive sensing spectroscopy using coded apertures can under certain conditions give a large increase in light collection compared to standard slit based configurations [1] or filter-based solutions. This can in turn, for example, be used to reduce measurement times, increase measurement distances, or increase sensitivity in stand-off imaging Raman systems [2] designed to detect threat substances like explosives or other hazardous chemicals.

We investigate the possible benefits of using compressive sensing and digital micromirror devices (DMD) applied to imaging Raman spectroscopy for stand-off detection of trace amounts of explosives. In doing so we have built an experimental setup designed to test compressive sensing concepts in realistic scenarios.

Measurements are done using the second harmonic of an Nd:YAG laser giving 6 ns pulses of 2.3mJ at 532 nm with a repetition rate of 1 kHz. The laser pulses illuminates samples of ammonium nitrate particles of different sizes (1 µg - 1mg) at a distance of 3 meters. A lens is used to image the Raman scattered light emitted from the samples onto a DMD. The light then reflected off the DMD is scrambled by focussing it into a tapered Light Pipe to remove vignetting effects. The light from the last light pipe is directed into a round-to-slit fiber connected to a commercial spectrometer. A gated ICCD camera is used in the spectrometer as a detector. Image reconstruction the hyperspectral data is done based on the TVAL3 algorithm [3].

The first experimental results will be presented here.

[1] S.T. McCain et al, Applied Spectroscopy 60(6), 2006

[2] S. Wallin et al, Proc. of SPIE 8358(8358OP), 2012

[3] J. Zhang et al, IEEE ISCAS 2836, 2013

9824-13, Session 3

Ultraviolet Raman scattering from persistent chemical warfare agents

Fredrik Kullander, Pär Wästerby, Lars Landström, FOI-Swedish Defence Research Agency (Sweden)

Laser induced Raman scattering at excitation wavelengths ranging from 210 to 410 nm was examined using a pulsed tunable laser based spectrometer system. Neat droplets of chemical warfare agents, with a volume around 1 µl, were placed on a silicon surface and irradiated with sequences of laser pulses. The Raman scattering from Tabun (GA), Mustard Gas (HD) and VX were studied with the aim of finding the optimum parameters and the requirements for a detection system. A particular emphasis was put on VX that has been previously shown to yield relatively weak Raman scattering in this excitation band.

9824-14, Session 3

Recent development of two new UV Raman standoff explosive detection systems

Robert D. Waterbury, Robert D. Babnick, Justin Cooper, Alan Ford, Francisco Herrera, Adam J. Hopkins, Ken Pohl, Alakai Defense Systems, Inc. (United States); Luisa Profeta, Alakai Defense Systems Inc. (United States); Juan

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Sandoval, Darius Vunck, Alakai Defense Systems, Inc.
(United States)

Alakai Defense Systems has created two new user-friendly, short range UV Raman standoff explosive detection sensors called the Critical Infrastructure Protection System (CIPS) and Portable Raman Improvised Explosive Detection System (PRIED). Both these systems are designed to detect near-trace quantities of explosives and homemade explosives at standoff ranges of 10 cm and 1-10 m respectively within practical analysis times. A short description of the instruments, design trades, and CONOPS of each design is presented along with collected data for a wide variety of explosives, precursors, TIC/TIM's, narcotics, and CWA simulants.

9824-15, Session 3

**Trace material detection of surfaces via
single-beam femtosecond CARS**

Sherrie B. Pilkington, Stephen D. Roberson, Paul M. Pellegrino, U.S. Army Research Lab. (United States)

There is a significant need for the development of optical diagnostics for rapid and accurate detection of chemical species in convoluted systems. In particular, chemical warfare agents and explosive materials are of interest, however, identification of these species is difficult for a wide variety of reasons. Low vapor pressures, for example, cause traditional Raman scattering to be ineffective due to the incredibly long signal collection times that are required. Multiplex Coherent Anti-Stokes Raman Scattering (MCARS) spectroscopy generates a complete Raman spectrum from the material of interest using a combination of a broadband pulse which drives multiple molecular vibrations simultaneously and a narrow band probe pulse. For most species, the complete Raman spectrum can be detected in milliseconds; this makes MCARS an excellent technique for trace material detection in complex systems. In this paper, we present experimental MCARS results on solid state chemical species in complex systems. The 40fs Ti:Sapphire laser used in this study has sufficient output power to produce both the broadband continuum pulse and narrow band probe pulse simultaneously. A variety of chemical species, concentrations, and mixtures have been determined, showing the flexibility of this system. The Raman gain factor of MCARS versus spontaneous Raman scattering has been determined. Additionally, a limit of detection study of the amount of signal averaging required for species detection for the materials of interest was conducted and is discussed.

9824-16, Session 4

**Applications of spatially offset Raman
spectroscopy to defense and security
(Invited Paper)**

Jason A. Guicheteau, U.S. Army Edgewood Chemical Biological Ctr. (United States); Rebecca J. Hopkins, Defence Science and Technology Lab. (United Kingdom)

Defense and Security applications typically require positive and non-destructive detection and identification of samples to enable the responder to make effective decisions and preserve potential evidence. Over the past 30 years, Raman Spectroscopy has proven the effectiveness of vibrational spectroscopy as an analytical technique in defense research and applications. Spatially Offset Raman Spectroscopy (SORS) allows for sub-surface and through barrier detection and has applications in drug analysis, cancer detection, forensic science, as well as security and defense. This paper reviews previous efforts in SORS and other through barrier Raman techniques and presents a discussion on current research in defense and security applications.

9824-17, Session 4

**New sampling methods for Raman
handheld instruments (Invited Paper)**

Keith Carron, Snowy Range Instruments (United States)

Raman scattering is an instantaneous event. A photon from the excitation laser source hits the target molecule and simultaneously bounces off with a lower energy. The difference between the energy of the incident photon and the scattered photon is equivalent to the energy need to make bonds in the target molecule vibrate. The key to understanding the hybrid Raman spectroscopies: ORS, DRS, and OARS is the instantaneous photon events which create Raman scattering.

ORS – Orbital Raster Scanning

The typical configuration for Raman scattering is to focus the excitation laser beam onto the sample. A small focal point is desired since the diameter of the focal spot determines the resolution of the Raman spectrum. The smaller the spot the higher the resolution. The small laser spot can be problematic for many samples:

- dark samples might be deteriorated by the high laser intensity in such a small spot
- heterogeneous samples will not be clearly represented by a small focal point that misses the average composition of the sample

This problem could be solved with a larger focal spot, but that would decrease the resolution of the Raman system.

The solution is to maintain a small focal spot and to move it rapidly over the sample. This rapid movement of the laser spot will prevent damage to the sample and, by making the movement over the area faster than the system's acquisition time, it will average over the heterogeneity of the sample. Our systems have a special collinear design that transmits the laser beam along the same path that Raman scattered light returns through the spectrograph. When this is the case, the laser beam can be rotated on the sample with an off-axis mirror to raster over the sample. Since the Raman process is instantaneous there is no delay between the excitation and scattering; the Raman scattering will return along the same path as the excitation regardless of the location of the laser beam on the sample. The motion produced by an off-axis mirror represents an orbit around the mirrors center. This led to our terminology of ORS – Orbital Raster Scanning.

DRS – Dynamic Raman Scattering

DRS again relates to the instantaneous nature of Raman scattering. We have developed two types of DRS spectroscopy for liquids and for solids.

Liquid DRS

Particles with submicron size stay suspended in solution through Brownian motion; where Brownian motion is the random movement imparted on particles by collisions with solvent molecules. If the laser excitation beam in a Raman experiment passes through a solution with a low concentration of particles the observed Raman spectrum will be composed of the solvent spectrum and that of the particles. This leads to a problem of material identification:

- it is impossible to distinguish the features of the particles and the solvent in the spectrum

However, if, instead of taking one long acquisition, a series of short acquisitions are acquired then it becomes possible to separate the events created by the particles propelled by Brownian motion passing through the beam and the continuous background of solvent materials. The separation occurs by observing the statistically unusual particle events from the average spectrum. If for example, 1000 short integration time spectra are acquired the average of the 1000 spectrum is composed almost entirely of the solvent spectrum. The variance is composed of the fluctuations created by the rare particle motion through the laser beam. These two measurements permit the particle spectrum to be distinguished from the solvent.

Solid – DRS

If ORS is combined with DRS then it becomes possible to observe particles in the background of a matrix. The concept is similar to liquid DRS; in this case, we want to observe a small concentration of a material in the presence

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of a majority of another material. For example, we might want to observe an API (Active Pharmaceutical Ingredient) in the presence of a filler material. Conventional Raman systems would:

- miss the API due to their small laser spot size
- ORS would see an average spectrum which is dominated by the filler material

If the ORS speed is slowed and multiple spectra are taken within a single raster pattern then the same statistical methods would produce spectra of the API. The average of the multiple spectra would represent the filler and the variance would be the API.

OARS – Off-Axis Raman Scattering

Conventional Raman systems use a col-linear laser excitation and Raman collection path. This convention leads to very simple point and shoot sampling with the Raman scattering originating where the laser hits the sample. All other optical signals are removed by the spatial filter of the spectrograph. The spatial filter is a small aperture that allows only the Raman scattering from the laser beam through to the spectrograph. The problem of this configuration is:

- material in front of the sample will contribute to the Raman spectrum
- fluorescence from the material in front of the sample will interfere with the Raman spectrum

If the condition of co-linearity is relaxed and the laser beam combines with the Raman scattered light's collection path the potential of removing top layers of a sample occurs. The top layer's Raman and fluorescence is removed by the spatial filter and only the Raman scattering from the target that is co-linear with the sample will be observed.

9824-18, Session 4

Bottled liquid explosive scanner by near infrared

Hideo Itozaki, Osaka Univ. (Japan)

A bottled liquid explosive scanner has been developed using near infrared technology. It has been already certified by ECAC as a detector which can be used at airport security. It was tested at Narita International airport to check passengers' bottles successfully.

It uses 0.8 to 1 micron of near infrared wave length. Because this region can avoid a strong absorbance of water which is main content in almost of beverage carried by passengers, and can catch a small absorbance peak of water. There are some other absorbance by not safety liquid, too. There are almost no influence by color of bottles in this wave length region if spectra are treated by the second derivative, because colors of bottles come from a visible light region such as less than 0.6 microns.

The equipment is constructed simply by a tungsten halogen lamp as a light source and a silicon spectrometer and a PC. Spectra of more than 500 various liquids are collected as data base. Spectrum of a sample is checked with this data base. The most highly correlated liquid is identified as a sample liquid. Detection time is depend on transparence of liquid sample. It almost less than a second. Failure rate is quite low and detection rate is very high by ECAC test and feasibility tests in Narita airport.

9824-19, Session 4

Application of the modified transient plane source technique for early detection of liquid explosives

Adam Harris, C-Therm Technologies, Ltd. (Canada)

A strong proof of principle is presented on application of the MTPS transient thermal property measuring in the early-screening of liquid explosives. The work demonstrates a significant sensitivity to distinguishing a wide range of

fluids based on their thermal properties through a barrier material. The work covers various complicating factors to the longer-term adoption of such a method including the impact of carbonization and viscosity. While some technical challenges remain - the technique offers significant advantages in complimenting existing detection methods in being able to penetrate reflective metal containers (e.g. aluminum pop cans) with ease.

9824-20, Session 4

Differential excitation spectroscopy for detection of industrial chemicals: benzene and chlorinated solvents

Jason Cox, Boyd V. Hunter, Kestrel Corp. (United States); Michael A. Miller, Robert A. McIntosh, Southwest Research Institute (United States); Paul Harrison, William P. Walters, Kestrel Corp. (United States)

Differential Excitation Spectroscopy (DES) is a new pump-probe detection technique which characterizes molecules based on a multi-dimensional parameterization of the rovibrational excited state structure, pump and probe interrogation frequencies, as well as the lifetimes of the excited states. Under appropriate conditions, significant modulation of the ground state can result. DES results provide a unique, simple mechanism to validate and understand various molecules in support of relevant science. In addition, the DES multi-dimensional parameterization provides an identification signature that is highly unique and has demonstrated high levels of immunity from interferences, providing significant practical value for high-specificity material identification.

Benzene and various chlorinated solvents have been used as degreasing agents in many industrial and military facilities and have often contaminated groundwater and been dispersed from their original locations by plumes in the groundwater. The vapors from these solvents then show up under previously uncontaminated facilities. A current challenge is to provide continuous monitoring of vapors in potentially contaminated facilities to ensure workplace safety. Molecular similarity makes spectroscopic determination a challenge. To meet this difficulty, a DES gas-phase testbed was constructed and ab initio modeling calculations were performed on benzene, dichloroethylene, trichloroethylene, tetrachloroethane, and chloroform; subsequent validation demonstrated the very specific DES responses to be used to provide the signatures needed for continuous monitoring as well as to establish limits of detection for the technique.

This work was funded by US Air Force contract #FA9302-13-C-0002.

9824-21, Session 4

Characterization and control of tunable quantum cascade laser beam parameters for stand-off detection of trace explosives and hazardous chemicals

Robert Furstenberg, Christopher A. Kendziora, Michael R. Papantonakis, Viet Nguyen, R. Andrew McGill, U.S. Naval Research Lab. (United States)

Infrared active stand-off detection techniques often employ high power tunable quantum cascade lasers (QCLs) for target illumination. Due to the distances involved, any fluctuation of the laser beam direction and/or beam profile is amplified at the sample position and, if not accounted for, leads to diminished performance (both sensitivity and selectivity) of the detection technique as a direct result of uncertainties in laser irradiance at each imaged pixel of the sample. This is especially true for detection approaches which illuminate a relatively small footprint at the target since the laser beam profile spatial fluctuations are often comparable to the (focused) laser spot size. Also, there is often a necessary trade-off between high output QCL power and beam quality. Therefore, precise

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characterization of the laser beam profile and direction as a function of laser properties (tuning wavelength, current and operating mode: pulsed or CW) is imperative. We present detailed measurements of beam profiles, beam wander and power fluctuations and their reproducibility as function of laser wavelength and standoff distance. We also investigate mode hops in QCLs and how they affect laser beam properties at the sample. Detailed mode-hop stability maps were measured for selected lasers. Finally, we present potential strategies for improving beam quality by either compensating for fluctuations using motorized mirrors and lenses or removing those through the use of spatial filters and optical fibers.

9824-22, Session 5

Standoff photoacoustic detections with high-sensitivity microphones and acoustic arrays (Invited Paper)

Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States); Chen-Chia Wang, Brimrose Corp. of America (United States); Jacob B. Khurgin, Johns Hopkins Univ. (United States); Alan C. Samuels, U.S. Army Edgewood Chemical Biological Ctr. (United States); Sudhir B. Trivedi, Brimrose Corp. of America (United States); Deepa Gupta, Univ. of Maryland, Baltimore County (United States)

Standoff detection of dangerous chemicals like explosives, nerve gases, and harmful aerosols has continuously been an important subject due to the serious concern about terrorist threats to both overseas and homeland lives and facility. Compared with other currently available standoff optical detection techniques, like Raman, photo-thermal, laser induced breakdown spectroscopy,...etc., photoacoustic (PA) sensing has the advantages of background free and very high detection sensitivity, no need of back reflection surfaces, and 1/R instead of 1/R² signal decay distance dependence. Furthermore, there is still a great room for PA sensitivity improvement by using different PA techniques, including lock-in amplifier, employing new microphones, and microphone array techniques. Recently, we have demonstrated standoff PA detection of isopropanol vapor, solid phase TNT and RDX at a standoff distance. To further calibrate the detection sensitivity, we use nerve gas simulants that were generated and calibrated by a commercial vapor generator. For field operations, array of microphones and microphone-reflector pairs can be utilized to achieve noise rejection and signal enhancement. We have experimentally demonstrated signal enhancement and noise reduction using an array of 4 microphone/4 reflector system as well as an array of 16-microphone/1 reflector. In this work we will review and compare different standoff techniques and discuss the advantages of using different photoacoustic techniques. We will also discuss new advancement of using new types of microphone and the performance comparison of using different structure of microphone arrays and combining lock-in amplifier with acoustic arrays. Demonstration of out-door real-time operations with high power mid-IR laser and microphone array will be presented.

9824-23, Session 5

Development of a LaBr₃-based associated particle imaging system for contraband detection and bulk materials analysis

Jarrold C. Marsh, U.S. Army Research Lab. (United States) and Oak Ridge Associated Univ. (United States); Marc S. Litz, James J. Carroll, Martin G. Shetty, U.S. Army Research Lab. (United States); Christopher J. Chiara, U.S. Army Research Lab. (United States) and Oak Ridge Associated Univ. (United States)

Fast neutron-induced gamma-ray emission with neutron tagging is an emerging technology for non-destructive materials analysis and contraband detection. The physics underpinning the approach has been well established for decades; however, it was not until recently that gamma-ray detectors with sufficiently good properties (light yield, energy resolution, timing resolution) have become available. Previous attempts concentrated on using low-cost crystal scintillators (NaI, CsI) for detection of gamma rays produced during neutron exposure. Associated Particle Imaging (API) is a technique where gamma particles produced in a deuterium-tritium reaction are tagged with a position-sensitive photodetector, giving the time and direction of the associated back-to-back 14.1 MeV neutrons. Time-of-flight calculations then suppress background by only recording data during the time window in which a corresponding gamma ray should arrive. This paper reports on the design and development of a LaBr₃-based API system built around a Versa Module Europa (VME) data acquisition system and Thermo Scientific API120 electronic neutron generator. VME is a digital backplane communication standard popular in nuclear physics for its high data transfer rates. Modern systems can utilize gigabit Ethernet or USB 3.0 speeds to create truly impressive amounts of data. This systems uses Struck SIS3153 and Wiener VM-USB controllers, a Mesytec MADC-32 peak sensing ADC, and a Mesytec MTDC-32. Current system performance is demonstrated, with a goal of detecting a 1% change in material composition.

9824-24, Session 5

Standoff photoacoustic sensing of trace chemicals by laser Doppler vibrometer

Yu Fu, Qi Hu, Huan Liu, Nanyang Technological Univ. (Singapore)

Photoacoustic spectroscopy (PAS) is a useful technique that suitable for trace detection of chemicals and explosives. Normally high-sensitive microphone or quartz tuning fork is used to detect the signal in photoacoustic cell. In recent years, laser Doppler vibrometer (LDV) is proposed to remote-sense photoacoustic signal on various substrates. It is a high-sensitivity sensor with a displacement resolution of <10pm. In this research, the photoacoustic effect of various chemicals is excited by a quantum cascade laser (QCL) with a scanning wavelength range of 7.3μm to 10.6 μm. A home-developed LDV at 1550nm wavelength is applied to detect the vibration signal. After normalize the vibration amplitude with QCL power, the photoacoustic spectrum of various chemicals can be obtained. Different factors that affect the detection accuracy and sensitivity have also been discussed. The results show the potential of the proposed technique for standoff detection of trace chemicals and explosives.

9824-25, Session 5

Spectral imaging of chemical compounds using multivariate optically enhanced filters integrated with InGaAs VGA cameras

Ryan J. Priore, CIRTEMO (United States); Niels F. Jacksen, SCD.USA, LLC (United States)

Infrared hyperspectral imagers (HSI) have been fielded for the detection of hazardous chemical and biological compounds, tag detection (friend versus foe detection) and other defense critical sensing missions over the last two decades. Low Size/Weight/Power/Cost methods of identification of chemical compounds spectroscopy has been a long term goal for hand held applications. We describe a new HSI concept for low cost / high performance InGaAs SWIR cameras chemical identification for military, security, industrial and commercial end user applications.

Multivariate Optical Elements (MOEs) are thin-film devices that encode a broad band, spectroscopic pattern allowing a simple broadband detector to generate a highly sensitive and specific detection for a target analyte. MOEs can be matched 1:1 to a discrete analyte or class prediction. Additionally,

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MOE filter sets are capable of sensing an orthogonal projection of the original sparse spectroscopic space enabling a small set of MOEs to discriminate a multitude of target analytes.

This paper identifies algorithms and broad band optical filter designs that have been demonstrated to identify chemical compound using high performance InGaAs VGA detectors. It shows how some of the initial models have been reduced to simple spectral designs and tested to produce positive identification of such chemicals. We also are developing pixilated MOE compressed detection sensor for the detection of a multitude of chemical targets in challenging backgrounds/environments for both commercial and defense/security applications. This MOE based, real-time HSI sensor will exhibit superior sensitivity and specificity as compared to currently fielded HSI systems.

9824-26, Session 6

Chemical and explosive detection with long-wave infrared laser induced breakdown spectroscopy

Feng Jin, Sudhir B. Trivedi, Brimrose Corp. of America (United States); Clayton S. Yang, Battelle East Science and Technology Ctr. (United States); Ei E. Brown, Eric Kumi-Barimah, Uwe H. Hommerich, Hampton Univ. (United States); Alan C. Samuels, U.S. Army Edgewood Chemical Biological Ctr. (United States)

Conventional laser induced breakdown spectroscopy (LIBS) mostly uses silicon-based detectors and measures the atomic emission in the UV-Vis-NIR region of the spectrum. It can be used to detect the elements in the sample under test, such as the presence of lead in the solder for electronics during RoHS compliance verification. This wavelength region, however, does not provide sufficient information on the bonding between the elements, because the molecular vibration modes emits at longer wavelength region. Measuring long-wave infrared spectrum (LWIR) in a LIBS setup can instead reveal molecular composition of the sample, which is the information sought in applications including chemical and explosive detection and identification. This talk will present the work and results from the collaboration of several institutions to develop the methods of LWIR LIBS for chemical/explosive/ pharmaceutical material detection/identification, such as DMMP and RDX, as fast as using a single excitation laser pulse. In our latest LIBS setup, both UV-Vis-NIR and LWIR spectra can be collected at the same time, allowing more accurate detection and identification of materials.

9824-27, Session 6

Photoacoustic Spectroscopy for Trace Vapor Detection and Standoff Detection of Explosives

Ellen L. Holthoff, Logan S. Marcus, Paul M. Pellegrino, U.S. Army Research Lab. (United States)

Infrared (IR) spectroscopy encompasses a diverse collection of sensing paradigms. Photoacoustic spectroscopy (PAS) is one of the more flexible IR spectroscopy variants, and that flexibility allows for the construction of sensors that are designed for specific tasks. We discuss the evaluation of a PAS sensor that has been designed around increasing operator safety during detection and identification of explosive materials by performing sensing operations at a standoff distance. We investigate a standoff variant of PAS based upon an interferometric sensor by examining the characteristic absorption spectra of PETN, RDX, and TNT collected at 1 meter.

9824-28, Session 6

Bioaerosol detection using single particle triggered LIBS

Annelie Karlsson, Anders Larsson, Lars Landström, FOI-Swedish Defence Research Agency (Sweden)

A prototype LIBS system, measuring on single aerosol particles sampled from ambient air, has been evaluated for BWA detection purposes. Library data was obtained by measurements on dispersions of various simulant bioaerosols as well as interferents. In addition, the possibility to further discriminate measurement sampling, fluorescence trigger stage was incorporated. The 405 nm induced fluorescence was also monitored to give additional data to classification/alarm algorithms. The impact of chosen variables (emission lines, scattered light, and fluorescence) on classification models was investigated via multivariate statistical methods.

9824-29, Session 6

Progress in bread board sized photo-acoustic spectroscopy (PAS) system with comparison of results to laboratory sized system

John F. Schill, Paul M. Pellegrino, Mark M. Giza, U.S. Army Research Lab. (United States)

In the past we have reported on the design of a photo-acoustic spectroscopy (PAS) system that could be reduced to a 12" x 12" breadboard size by implementing the lock-in amplifier on a field programmable gate array (FPGA). In this paper we present the results of comparison testing between our design and laboratory sized systems using several different analytes. In addition, we present a new design implemented on a much larger FPGA which allows us to implement a 32 bit microcontroller on the FPGA along with larger filters allowing us to improve the performance of the PAS system as well as providing significant gains in size reduction. This new design will allow us to control the system from the FPGA and process the data on board removing the need for a laptop to perform these functions.

9824-47, Session PSTue

Infrared laser induced breakdown spectroscopy (LIBS) emissions from energetic materials using an eye-safe laser at 1.57 μm

Ei E. Brown, Uwe H. Hömmerich, Hampton Univ. (United States); Clayton S. Yang, Battelle East Science and Technology Ctr. (United States); Feng Jin, Sudhir B. Trivedi, Brimrose Corp. of America (United States); Alan C. Samuels, U.S. Army Edgewood Chemical Biological Ctr. (United States)

Laser-induced breakdown spectroscopy (LIBS) is a powerful diagnostic tool for detection of trace elements by monitoring the atomic and ionic emission from laser-induced plasmas. Besides those elemental emissions in conventional UV-Vis LIBS, signature molecular vibrational LIBS emissions of the target compounds were clearly observed in the long-wave infrared (LWIR) region in recent studies. Most current LIBS studies employ fundamental Nd:YAG laser which has extremely low eye-damage threshold. Thus, eye-safe LIBS are of critical importance in many applications such as standoff detection of chemical, biological, and explosive (CBE) materials, laser radar, remote sensing, rangefinding, and laser countermeasures. In this work, comparative LWIR-LIBS emissions studies using traditional 1.064 μm pumping and eye-safe laser wavelength at 1.574 μm were performed

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for energetic materials for potential applications in CBE sensing. A Q-switched Nd:YAG laser operating at 1.064 μm and the 1.574 μm output of a pulsed Nd:YAG pumped Optical Parametric Oscillator were employed as the excitation sources. The IR LIBS emissions within the hot plasma were focused onto the entrance slit of a 0.15 m grating spectrometer in conjunction with a single element liquid nitrogen cooled Mercury Cadmium Telluride (MCT) detector. The IR signature spectral region between 4 - 12 μm was mined for the appearance of LWIR-LIBS emissions that are directly indicative of oxygenated breakdown products as well as partially dissociated and recombination molecular species. The observed molecular emission bands show strong correlation with FTIR absorption spectra of the studied materials. Eye-safe LIBS emission studies using a MCT linear array system will also be presented at the conference.

9824-48, Session PSTue

Research and development of laser sensors for environmental monitoring of sulphur

Alexsandr S. Grishkanich, Sergey Kascheev, Aleksandr Zhevnikov, ITMO Univ. (Russian Federation); Igor Sidorov, Univ. of Eastern Finland (Finland); Artem Pinigin, ITMO Univ. (Russian Federation)

The presence of YAG-Nd laser working at wavelengths of 266 and 532 nm – the second and fourth harmonics of this laser determines the choice of method of Raman scattering to monitor particle of sulfur dioxide. Use for excitation of the fourth harmonic of neodymium laser glass allows the use of resonant methods; the radiation with such wavelength is not strongly absorbed by the lower layers of the atmosphere and falls into a spectral region with negligible luminosity of the sky. So are available round-the-clock observation, which is extremely important in practice. This method has some drawbacks. At high concentrations of corrosive gases are actively forms in the atmosphere by chemical sprays, which luminescent under the action of laser radiation, obliterating the useful Raman scattering signals. Small cross section of Raman scattering impose restrictions on determination of low concentrations. In order to improve the accuracy of the devices use lasers with large energy output pulse and interference filters or polychromator with high spectral resolution. In connection with the dispersion of harmful particles of the atmosphere, need local measurement of gas concentrations in the air. The selected method for remote optical sensing of spontaneous Raman scattering allows us to monitor small concentrations, smaller maximum permissible concentrations of pollutants.

Studies have confirmed the effectiveness of the method of spontaneous Raman scattering to create a modern lidar for monitoring of sulfur dioxide emissions from the local sources that originate from fuel combustion in areas of emission control.

This device can be used in ports to monitor emissions from thermal installations of ships, in particular from their main thrust engines and additional equipment at the entrance to the harbour. As for process, monitoring of production processes in the petrochemical and energy associated with the formation and release of sulfur dioxide.

9824-49, Session PSTue

Remote sensing technologies

Ramesh C. Sharma, Laser Science and Technology Ctr. (India)

The paper is focused on development of measurement technique and processing of signal for the detection of chemical, explosive, biological agents and its simulants using Engineered Quartz Enhanced Laser Photoacoustic Spectroscopy (QE-LPAS) technique. Hazardous materials like Sarin, TATP (Tri acetone tri-peroxide) and their simulants like DMMP (Dimethyl Methyl Phosphonate) Acetone, CH₄ were detected in 7 to 12 μm wavelength band from a standoff distance of up to 30 meters in gases / vapour and aerosols based on retro-reflector in ~2.0 ppm concentration.

Hazardous biomolecules like Tryptophan and DPA are detected on diffuse aluminum adsorbed surface plate. Explosive and its simulants TNT on adsorbed surface and DMMP, Nitrobenzene, Acetone were detected in liquid form.

A dedicated single screen, single user, user friendly Graphical User Interface (GUI) for controlling the entire system, acquisition and processing of the incoming signal and demonstration of results has been developed with the help of Laboratory Virtual Instrument Engineering Workbench (LABVIEW). The phase sensitive data acquisition for hazardous biological, chemicals and explosive detection is developed. An engineered tripod mounted LPAS system has been developed which give alarms for hazardous biological, chemicals and explosive and pollutant gases in atmosphere (like green house gases) using the developed software. In tripod mounted, Engineered LPAS system Lockin amplifier instrument box and function Generator box are replaced by lockin amplifier card, function generator card, in a small volume, weight and size. In the case, gold coated ellipsoidal receiver mirror of aperture size 20cm is used.

Figure 1, shows the block diagram of the standoff LPAS detection which shows the various electro-optical components that are required for successful detection of the biological, explosives, chemicals, pollutant gases. Tunable Quantum cascade laser radiations (QCL) beam is falling to the target via the folding gold coated mirror and aligned by visible diode laser. Both beams are collinear falling to sample target. Diode laser beam is used only for reference / alignment with Mid-IR beam. Mid-IR radiation absorbed by the sample and back reflected from the target. Back reflected radiations are captured by the receiving gold coated mirror optics and focus to the QCTF detector. Detector signal is processing using the pre-amplifier and phase sensitive lock in amplifier and Data acquisition for detection and identification of Hazardous molecules. Tripod mounted system is developed and shown in Figure 2. Standoff Quartz Enhance Quantum Cascade Laser Photoacoustic Spectroscopy is a highly selectivity, highly sensitive, eye safe in mid IR wavelength region technique. The major advantage of this technique it will work in solar back ground. There is not interference of any ambient light / Solar light and any background electronic frequency. It is applicable in the laser spectroscopic technique.

All results will be discussed in full paper.

9824-30, Session 8

Detection of gaseous plumes in airborne hyperspectral imagery

Eyal Agassi, Eitan Hirsch, Israel Institute for Biological Research (Israel); Martin Chamberland, Marc-André Gagnon, Telops (Canada); Holger Eichstaedt, Digital Mapping Hong Kong Pty. Ltd. (Hong Kong, China)

The capability of an airborne detection of gaseous plumes offers some advantages over ground based remote sensing. It enables fixed (and usually shorter) detection ranges, less interference from atmospheric effects, a high and sufficient thermal contrast, and a lack of any obscurants. However, it poses a significant challenge since airborne sensing usually yields only a single "shot" of a scene, with no availability of any clear background, or temporal analysis. A gas detection algorithm with such capabilities was introduced and proven to be highly efficient (Hirsch and Agassi, 2007), and therefore has a high potential to be used for airborne sensing as well. In order to test this hypothesis, we have conducted a field test, in which a thermal hyperspectral sensor (Hyper-Cam) was mounted on a light aircraft and measured continuous releases of several atmospheric tracers from a height of 2 km. The algorithm was operated over the acquired data with excellent detection results. However, some issues still need some refinement – especially achieving good estimation of the ground level air temperature which is an essential input parameter for the detection algorithm. The data-cubes were acquired in a "target mode", which is a unique method of operation of the Hyper-Cam sensor. This method provides multiple views of the plume which can be exploited to enhance the detection performance. These encouraging results demonstrate the utility of airborne LWIR hyperspectral imaging for efficient detection and mapping of effluent gases for environmental monitoring.

9824-31, Session 8

Hyperspectral image analysis for standoff trace detection using IR laser spectroscopy

Jan P. Jarvis, Frank Fuchs, Stefan Hugger, Quankui K. Yang, Ralf Ostendorf, Christian Schilling, Wolfgang Bronner, Rachid Driad, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

In the recent past imaging infrared laser backscattering spectroscopy has been shown to be a promising technique for standoff trace detection of harmful substances. In this work we present a mobile hyperspectral image sensor for measurement distances of up to 25 m based upon this principle, using External Cavity Quantum Cascade Lasers (EC-QCLs) as spectrally selective illumination sources. We focus on the application specific data analysis algorithms and present measurement results that prove system applicability in real world conditions.

The sensor presented in this work produces a hyperspectral image of the surface to be analyzed. Two tunable EC-QCLs serve as illumination sources providing a total spectral measurement range of 300 cm⁻¹ from 7.7 μm to 10 μm. A high performance Mercury-Cadmium-Telluride infrared camera is used to collect the diffusely backscattered light. The resulting measurement data forms a hyperspectral image, where each pixel vector contains the backscattering spectrum of a specific location in the scene. We show that the obtained backscattering spectra are well comparable to FTIR spectra if appropriate preprocessing steps are applied. Using state of the art target detection algorithms, traces of various explosive substances like e.g. PETN, TNT and RDX, as well as explosive precursors like Ammonium Nitrate can be reliably detected. The sensor system has proven to be operational under real world conditions, and has been shown to be able to successfully identify the explosive used for fabrication of an improvised explosive device in a post blast scenario.

9824-32, Session 8

Analysis of analytic nonresonant background removal algorithm for MCARS spectra

Stephen D. Roberson, Sherrie B. Pilkington, Paul M. Pellegrino, U.S. Army Research Lab. (United States)

Multiplex Coherent Anti Stokes Raman Spectroscopy (MCARS) has been shown to generate a complete Raman spectrum of a material on a millisecond time scale which allows for rapid identification of a wide variety of molecular targets. Along with the desired resonant spectrum due to the vibrational Raman spectroscopy of the analyte, MCARS is known to simultaneously generate a nonresonant spectrum that can obscure the desired Raman spectrum which hinders detection. Extracting the desired resonant Raman signal from the overall MCARS signal analytically has proven difficult without having prior knowledge of the analyte. We have developed an algorithm that utilizes a combination of the maximum entropy method in conjunction with advanced Fourier filtering to analytically remove the nonresonant background from our MCARS spectra without having prior knowledge of the vibrational spectrum of the analyte. In this report, we will report on the theoretical background for this algorithm as well as our experimental work testing this algorithm under various nonresonant spectra conditions for a number of analytes. We will systematically vary the amount of nonresonant background generated in the sample by changing the temporal overlap of the two beams necessary to generate the MCARS signal. Additionally, we place the analyte into increasing concentrations of water to generate increasing amounts of nonresonant background spectra to test the algorithm's effectiveness. Finally, we compare the analyte vibrational spectral output from the algorithm to the Raman spectrum measured with the spontaneous Raman system in the laboratory of the same sample in an effort to ascertain accuracy of the output spectra.

9824-33, Session 8

Standoff detection of explosive and hazardous molecules for defense applications

Ramesh C. Sharma, Hari B. Srivastava, Deepak Kumar, Saurabh Kumar, Subodh Kumar, R. K. Jain, Laser Science and Technology Ctr. (India)

The paper is focused on development of measurement technique and processing of signal for the detection of chemical, explosive, biological agents and its simulants using Engineered Quartz Enhanced Laser Photoacoustic Spectroscopy (QE-LPAS) technique. Hazardous materials like Sarin, TATP (Tri acetone tri-peroxide) and their simulants like DMMP (Dimethyl Methyl Phosphonate) Acetone, CH₄ were detected in 7 to 12 μm wavelength band from a standoff distance of up to 30 meters in gases / vapour and aerosols based on retro-reflector in -1.0 ppm concentration.

Hazardous bio-molecules like Tryphatophan and DPA are detected on diffuse aluminum adsorbed surface plate. Explosive and its simulants TNT on adsorbed surface and DMMP, Nitrobenzene, Acetone were detected in liquid form.

A dedicated single screen, single user, user friendly Graphical User Interface (GUI) for controlling the entire system, acquisition and processing of the incoming signal and demonstration of results has been developed with the help of Laboratory Virtual Instrument Engineering Workbench (LABVIEW). The phase sensitive data acquisition for hazardous biological, chemicals and explosive detection is developed. An engineered tripod mounted LPAS system has been developed which give alarms for hazardous biological, chemicals and explosive and pollutant gases in atmosphere (like green house gases) using the developed software. In tripod mounted, Engineered LPAS system Lockin amplifier instrument box and function Generator box are replaced by lockin amplifier card, function generator card, in a small volume, weight and size. In the case, gold coated ellipsoidal receiver mirror of aperture size 20cm is used.

9824-34, Session 8

Stand-off detection: distinction of bacteria by hyperspectral laser induced fluorescence

Arne Walter, Frank Duschek, Lea Fellner, Karin M. Grünewald, Anita Hausmann, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Sandra Julich, Friedrich-Loeffler-Institut (Germany); Carsten Pargmann, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Herbert Tomaso, Friedrich-Loeffler-Institut (Germany); Jürgen Handke, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

The detection of hazardous bioorganic materials at a very high sensitivity as well as a rapid identification with low false alarm rates are essential topics in defense and security. A single method can hardly achieve these tasks. Point sensors collect and identify materials but they have to be positioned at the correct location in advance of an attack. Laser based standoff detection, however, can immediately classify released hazardous material and provide information on its position and propagation. The coupling of both methods may be a promising solution to optimize the acquisition and identification of hazardous substances.

While the capability of the hyperspectral laser induced fluorescence (LIF) technique as a fast detection and online classification method for biological hazardous materials has already been proven at the DLR Lampoldshausen test facility last year, the next step is to verify the distinguishing capability of this technique for various bacterial strains. Closely as well as more distantly related bacterial strains are selected according to their phylogenetic relation. The bacterial suspensions are irradiated at 22 m standoff distance

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by excitation wavelengths of 280 nm and 355 nm in alternating mode. A gated ICCD spectrometer system records spectrally resolved fluorescence data. Studies are performed at living bacteria as well as at those deactivated by different methods.

9824-35, Session 8

Analysis of continuum generation in bulk materials with a femtosecond Ti:Sapph laser

Sherrie B. Pilkington, Stephen D. Roberson, Paul M. Pellegrino, U.S. Army Research Lab. (United States)

There is a significant need for the generation of highly stable continuum beams for a wide variety of optical diagnostic techniques. Of particular interest to this group are those techniques being used for chemical detection, such as Multiplex Coherent Anti-Stokes Raman Scattering (MCARS), stimulated Raman scattering, two-photon absorption spectroscopy, and techniques involving ultrafast optical parametric amplifiers (OPAs). While photonic crystal fibers (PCFs) are popular and provide an ample method for continuum generation under very specific conditions, they are not particularly stable in unfavorable conditions such as with difficult orientation of the light and damage thresholds too low for high power femtosecond lasers. They can exhibit energy fluctuations and lack of coherence. Bulk solid materials, commonly sapphire or YAG crystals, can provide incredibly broad and smooth spectra with better temporal and spatial coherence. In this study, we present an in-depth analysis of femtosecond continuum generation in sapphire and YAG crystals of varying thicknesses (0.5 mm – 5 mm) using a 40fs Ti:Sapphire laser. Beam size, pump pulse energy, beam profile, and a variety of focusing conditions are considered. In addition, an analysis of the aberration theory required for collimation of the continuum beam has been conducted and experimentally verified.

9824-36, Session 9

Scintillator applications in radiological and nuclear detection (*Invited Paper*)

Zane W. Bell, Oak Ridge National Lab. (United States)

Scintillation detection systems have become widely available for vehicular and pedestrian portal monitoring and for use by fire, police, and emergency response personnel. They operate in spectroscopic and pulse counting modes and can determine the location of a source and identify the isotopes present. Some systems operate as sensitive dosimeters or as directional detectors. Because all these instruments have, at their cores, scintillators and photosensors, and must operate in environments very different from those found in traditional counting/spectroscopy laboratories and physics experiments, special care must be taken to select the correct scintillator for outdoor and indoor environments, and instruments that transition between them. We will review the commonly used scintillators and the implications of their properties for the behavior of detector systems. The radiation fields that can reasonably be expected from various industrial and medical sources and backgrounds, and the effects of source self-shielding and shielding by vehicles, cargo, and people will be discussed. We will also touch on the pros and cons of selected isotope identification and detection algorithms.

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9824-37, Session 9

Design and growth of novel compounds for radiation sensors: multinary chalcogenides and chalcogenides

Narsingh B. Singh, Univ. of Maryland, Baltimore County (United States); Ching-Hua Su, NASA Marshall Space Flight Ctr. (United States); Bradley Arnold, Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

There is a strong need for the high performance and low cost variety of hand held and other large radiation sensors. The material is the biggest road block for this technology. We present novel class of materials to meet this demand.

9824-38, Session 9

Tritium-powered radiation sensor network

Marc S. Litz, Johnny A. Russo, James J. Carroll, U.S. Army Research Lab. (United States); Dimosthenis C. Katsis, Athena Energy Corp. (United States)

The most compelling reason to use isotope power sources is the long lifetime capability for remotely located or unattended sensors. Isotope-based power sources specifically enable extended lifetime operation. While chemical-based power sources are inexpensive, application independent, and ubiquitous, chemical energy conversion does not enable field operation for 15-100 years of remotely located sensors, infrastructure embedded sensors, or communications nodes.

The radiation observations with communications (ROC) sensor can operate on limited 100- μ W power supply with energy management tools provided by both the microcontroller and sensor peripherals. The power consumption is reduced to a minimum by 1) use of a minimum set of components, and 2) high efficiency hardware chosen specifically to minimize power requirement from each component, and 3) software taking advantage of low-power component modes. A low-power microcontroller is powered by a lithium ion battery (energy reservoir/storage maintained by the isotope power source). The size of the lithium ion battery is based on the trickle charge rate of the isotope battery (on the order of 10 J per day at 100 μ W). For the ROC (Generation 3) sensor design, the lowest power sleep mode requires only 0.22 μ A at 3.3V. The MSP430 microcontroller offers external interrupts capable of wake up from sleep mode. When in normal operation (data collection and transmission), the microcontroller draws 3.34 mA at 3.3V. With our 100- μ W battery, we can operate for ~30 minutes a day with limited data volume. Table 1 shows how long the microcontroller runs on 8.64 J per day when each mode is used.

9824-39, Session 9

Remote monitoring of radioactive nuclides by using laser methods

Aleksandr S. Grishkanich, Sergey Kascheev, Aleksandr Zhevlakov, ITMO Univ. (Russian Federation); Igor Sidorov, Univ. of Eastern Finland (Finland)

Laser sensing can serve as a highly effective method of searching and monitoring of radioactive contamination. Its advantages over traditional, such as physico-chemical (sampling), or the standard radiometric (radiometers and spectrometers): remote, possibility of continuous areal and profile scanning with simultaneous determination of a wide range radioactive elements and compounds, as well as highly sensitive and fast detection. The method of remote detection a radionuclide in atmosphere from container burial places and in places of recycling the fuel waste of the atomic power station is elaborates. Raman scattering and fluorescence

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analysis carried out the experiments. Preliminary results of investigation show the real possibility to register of leakage of a radionuclide with concentration U235O₂, U238O₂ at level of 10⁻⁸-10⁻⁹ cm⁻³ by Raman-scattering circuit, and concentration Sr 90 and ¹³⁷Sr at level of 10⁻¹³-10⁻¹⁵ on a safe distance (100 m) from the contaminated object.

9824-40, Session 9

Solid state thermal neutron detector for personal radiation detection

Jia-Woei Wu, Rajendra P. Dahal, Adam Weltz, Erik English, Mona M. Hella, James J. Q. Lu, Yaron Danon, Ishwara B. Bhat, Rensselaer Polytechnic Institute (United States)

The development of high efficiency solid state thermal neutron detectors at low cost is critical for a wide range of civilian and defense applications. The use of present neutron detector system for personal radiation detection is limited by the cost, size, weight, power requirements, and performance of the system. Chip scale solid state neutron detector based on silicon technology would provide significant benefits in terms of cost, volume, and allow for wafer level integration with charge preamplifier and readout electronics. In this paper, we will present the performance of silicon based solid state thermal neutron detectors that can be fabricated at low cost, but with thermal neutron detection efficiency exceeding 25%. The detector utilizes three dimensional trench silicon micro-structures fabricated by silicon wet etching. The silicon microstructures with continuous p+-n junction diode incorporates enriched boron (99% of 10B) as a converter material for thermal neutron detection. These detectors use custom built charge pre-amplifier and shaping for data acquisition.

9824-41, Session 9

Raman spectroscopy for analysis of thorium compounds

Yin-Fong Su, Timothy J. Johnson, Khri B. Olsen, Pacific Northwest National Lab. (United States)

The thorium fuel cycle is an alternative to the uranium fuel cycle in that when ²³²Th is irradiated with neutrons it is converted to ²³³U, another fissile isotope. There are several chemical forms of thorium which can be used in the Th fuel cycle. Recently, Raman spectroscopy has become a very portable and facile analytical technique with many applications, including determining chemical composition of different materials such as for thorium compounds. The technique continues to improve with the development of more sensitive instrumentation and better software. Using a laboratory Fourier-transform (FT)-Raman spectrometer with a 785 nm wavelength laser, we were able to obtain Raman spectra from a series of thorium-bearing compounds of unknown origin. These spectra were compared to the spectra of in-stock-laboratory thorium compounds including ThO₂, ThF₄, Th(CO₃)₂ and Th(C₂O₄)₂. The unknown spectra showed very good agreement to our known standards. If one includes trace element impurity analysis to the analytical scheme, the trace element and spectroscopic techniques in combination can be used to e.g. confirm source attribution of unknown materials.

9824-42, Session 10

Real-time short-wave infrared hyperspectral conformal imaging sensor for the detection of threat materials

Matthew P. Nelson, Nathaniel R. Gomer, Patrick J. Treado, ChemImage Corp. (United States)

Hyperspectral imaging (HSI) systems can provide sensitive and specific detection and identification of high value targets in the presence of complex backgrounds. However, current generation sensors are typically large and costly to field, and do not usually operate in real time. Sensors that are capable of real time operation have to compromise on the number of spectral bands, image definition, and/or the number of targets being detected. Additionally, these systems command a high cost and are typically designed and configured for specific mission profiles, making them unable to adapt to multiple threats within often rapidly evolving and dynamic missions.

Despite these shortcomings, HSI-based intelligence has proven to be a valuable tool, thus resulting in increased demand for this type of technology. A cost-effective sensor system that can easily and quickly adapt to accomplish significantly different tasks in a changing environment is highly desirable. The capability to detect and identify user-defined targets in complex backgrounds under a range of varying conditions with an easily reconfigured, automated, real-time, portable HSI sensor is a critical need.

CISSTM is developing a novel real-time, adaptable, compressive sensing short-wave infrared (SWIR) hyperspectral imaging technology called the Reconfigurable Conformal Imaging Sensor (RCIS) that will address many shortcomings of current generation systems and offer improvements in operational agility and detection performance, while addressing sensor weight, form factor and cost requirements. This paper will provide an overview of SWIR hyperspectral imaging, discuss the development of the RCIS system, and discuss its application in various use scenarios.

9824-43, Session 10

Airborne pipeline leak detection: UV or IR?

François Babin, Jean-François Y. Gravel, Martin Allard, INO (Canada)

Detecting small leaks from underground liquid petroleum product pipelines is done or proposed to be done in a number of ways. There are those that require installing a permeable tube or optical fiber along the length of the pipeline and those that use acoustic detection pigs that travel within a pipeable pipeline. Then there are those that use above ground platforms (especially airborne) that travel along the surface and measure the effects of the leaks. This is a successful approach for natural gas pipelines. This paper will present a study of different approaches to the measurement of the above ground vapor plume created by the spill caused by a small 0.1 l/min (or less) leak in an underground liquid petroleum pipeline. The initial scenarios are those for the measurement from an airborne platform. The usual approach is that of IR absorption, but in the case of liquid petroleum products, there are drawbacks that will be discussed, especially when using alkanes to detect a leak. The optical measurements studied include UV enhanced Raman lidar, UV fluorescence lidar, UV absorption and IR absorption integrated path lidars. The breadboards used for testing the different approaches will be described along with the different testing set-ups (for leak simulation). The set-ups include a long horizontal open path cell and a large compacted sand container with piping for simulating a leak. The set-ups include tubing for underground and above ground reference measurements of the vapor concentration and content. Although IR absorption would intuitively be the most sensitive, it is shown that UV absorption could be the best choice. When using the very broad alkane signature in the IR, the varying ground spectral reflectivities are a problem. Benzene and toluene are much less abundant in the vapor plume but are immune to varying ground spectral reflectivities. It is also determined that integrated path measurements are preferred, the UV enhanced Raman measurements showing that the vapor plume stays very close to the ground.

9824-44, Session 10

A method to control the polymorphic phase of RDX-based explosives

Brittney L. Argirakis, Transportation Security Lab. (United States) and The Pennsylvania State Univ. (United States); John J. Brady, Alexander D. Gordon, Transportation Security Lab. (United States) and Signature Science, LLC (United States); Richard T. Lareau, Barry T. Smith, Transportation Security Lab. (United States)

The effect of mass loading, solvent and sample deposition on the polymorphic phase of 1,3,5-trinitro-1,3,5-triazine (RDX) was examined using Raman spectroscopy. Vibrational modes in the obtained spectra for the "drop and dry"-deposited and the aerosol-deposited samples at high mass loadings were indicative of concomitant polymorphism as both the α and β -RDX phases were present. At low mass loadings, only β -RDX was observed regardless of solvent or mass loading. However, when the standards underwent a sample preparation method known as dry transfer, only the desired bulk phase (i.e., α -RDX) was observed regardless of mass loading or the initial deposition solvent. The data reported here demonstrates that the use of the dry transfer preparation method can be used to successfully prepare RDX-based standards with the desired bulk phase regardless of the initial solvent used to dissolve the sample, the initial deposition technique, or the mass loading.

9824-45, Session 10

Persistence of explosives particles under real world conditions

Robert Furstenberg, U.S. Naval Research Lab. (United States); Thomas Fischer, Bundesamt für Ausrüstung, Informationstechnik und Nutzung der Bundeswehr (Germany); Andrew Howard, American Society for Engineering Education (United States); Katy Adams, Oak Ridge Institute for Science & Education (United States); Michael R. Papantonakis, Christopher A. Kendziora, R. Andrew McGill, U.S. Naval Research Lab. (United States)

Particles of explosives deposited by fingerprint transfer provide an evidentiary trail for detection and forensic applications. Particle persistence on a substrate is therefore of specific interest in security areas. The particle lifetimes are limited by three main phenomena: a) sublimation, b) dissolution and c) detachment/lift off. These three controlling aspects are influenced by a wide range of factors including: 1) vapor pressure, 2) particle geometry, 3) substrate geometry, 4) temperature, 5) airflow velocity, 6) areal coverage, 7) particle field area, 8) relative humidity, 9) condensation/solubility, 10) inclusion chemicals, 11) adlayers, 12) exposed light and, in some instances, 13) the substrate material type. We are working towards a complete particle persistence model which captures the relative importance of these effects to allow the user, with known environmental conditions, to predict particle lifetimes for explosives or other chemicals. In this work, particles of explosives are deposited on smooth glass substrates by sieving and their sublimation or liftoff is monitored in situ by photo/video-microscopy. Particle sizes and loadings were selected to compare with those found in fingerprints. A custom airflow cell, with a window for in situ optical microscopy, allows control of cell height, flow, humidity and temperature. Analysis of 2D micrograph images is used to track the size, as the radial sublimation velocity, of each particle in an ensemble. In this paper we expand the set of environmental conditions used, from our previous studies, to include a range of relevant humidities and temperatures and include some preliminary sebum oil adlayer experiments.

9824-46, Session 10

A new approach for detection of explosives based on ion mobility spectrometry and laser desorption/ionization on porous silicon

Yury Kuzishchin, Igor L. Martynov, Dmitriy S. Dovzhenko, Gennadii E. Kotkovskii, Alexander A. Chistyakov, National Research Nuclear Univ. MPhI (Russian Federation)

A new approach for detection of ultralow concentration of explosives has been proposed. It combines ion mobility spectrometry (IMS) and a promising method of laser desorption/ionization on silicon (DIOS) at ambient conditions. DIOS is widely used in mass spectrometry due to high sensitivity and a possibility of detection of small molecules. It is known that IMS based on laser ion source is a powerful method for the fast detection of ultralow concentration of organic molecules.

The investigation of laser desorption/ionization on porous silicon (pSi) surface has been carried out for trinitrotoluene (TNT) and cyclotrimethylenetrinitramine (RDX) using IMS and mass spectrometry. It is shown that TNT ion formation in a gas phase under ultraviolet laser action is a complicated process including both an electron emission from a (pSi) surface with subsequent ion-molecular reactions in a gas phase and a proton transfer tween (pSi) surface and TNT molecule. The specially elaborated laser DIOS ion source for IMS detector provides effective ionization of explosives for the following parameters of laser radiation: $\lambda=266$ nm, E pulse = 50 μ J, I = 10^7 W/cm². The achieved IMS detection threshold is equal to 100 pg for TNT traces with signal-to-noise ratio 10. The low energy of laser pulse decreases laser source requirements significantly and allows one to construct both compact and high sensitive device for analyzing gas and liquid probes. The further prospects of the proposed technique are analyzed.

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9825-1, Session 1

Non-lethal technologies: state of art and challenges for future (*Invited Paper*)

David B. Law, Joint Non-Lethal Weapons Directorate (United States)

No Abstract Available

9825-2, Session 1

Hyperspectral analysis of explosive formed penetrator

Paul J. Yun, U.S. Army Armament Research, Development and Engineering Ctr. (United States)

No Abstract Available

9825-3, Session 1

Shooter position estimation with muzzle blast and shockwave measurements from separate locations

David Grasing, U.S. Army Research, Development and Engineering Command (United States)

No Abstract Available

9825-4, Session 1

A novel class of MEMS accelerometers for very high-G munitions environment

Jahangir Rastegar, Dake Feng, Omnitek Partners, LLC (United States)

The state of the art in shock resistant MEMS accelerometer design is to reduce the size of the proof mass, thereby reducing the generated forces and moments due to shock loading. Physical stops are also provided to limit proof mass motion to prevent damage to its various moving components. The reduction of the proof mass size reduces the sensor sensitivity. In addition, to increase the sensor dynamic response, proof mass motion needs to be minimally damped, resulting in a significant sensor settling time after experiencing a high acceleration level such as those experienced by gun-fired munitions during firing. The settling time is particularly important for accelerometers that are used in gun-fired munitions and mortars for navigation and guidance.

This paper describes the development of a novel class of accelerometers that are provided with the means of locking the sensor proof mass in its "null" position when subjected to acceleration levels above those that are intended to sense during its normal operation, thereby protecting the

moving parts of the accelerometer during very high shock loading events. In munitions applications, the proof mass is thereby locked in its null position during the firing and released during the flight to begin to measure flight acceleration with minimal settling time. The paper describes details of the design and operation of an accelerometer developed for high precision measuring of accelerations of up to 20 Gs but that can survive accelerations of up to 100,000 Gs. Prototyping of the accelerometers and results of their testing are presented. The application of the developed technology to other types of inertial sensors and devices is discussed.

9825-5, Session 1

Small arms advanced technology development at ORNL

Slobodan Rajic, Oak Ridge National Lab. (United States)

No Abstract Available

9825-6, Session 1

Remote detection of vital signs by radio- and ultrasonic location systems

Sergey I. Ivashov, Bauman Moscow State Technical Univ. (Russian Federation); Alexander S. Bugaev, Moscow Institute of Physics and Technology (Russian Federation); Fedar Severin, Roman G. Maev, Univ. of Windsor (Canada)

The recent advantages of developing methods and equipment for heartbeat detection with microwave-radar technology can be extended to the ultrasonic location and diagnostics of the live persons behind an obstacle. Periodic movement in the human body due to cardiac activity and breathing causes spectral distortion of the reflected signal. Whereas microwave devices can provide high sensitivity at significant distances, ultrasound is safe for continuous operation and can penetrate through metal walls. These factors are especially valuable for the routine prevention of human trafficking at railroad and automotive border crossings.

Specific signatures of the signals from cardiac muscle contractions and respiration were analyzed in various physical conditions of the person. Cross-correlation functions of different kinds of the multifrequency probing signals, modelling optimum processing of impulses are compared in view of resolution, levels of lateral lobes and presence of diffractive maxima. The time and frequency features obtained by different demodulation methods of backscattered signals are considered. Special attention was paid to algorithms for discrimination of interfering reflections from surrounding objects and reverberations for signals with stepwise frequency modulation.

The results may be used in various remote probing applications varying from searches of live humans trapped under rubble to the detection of people and their movements inside of buildings in the course of antiterrorist operations. An estimation of emotional and physical conditions provides the means for persons screening during latent or open checks, at airports for example (remote lie detector). Medical applications include the measurement of heartbeat and breath parameters for patients where contact gauges are objectionable.

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9825-7, Session 1

Distributed micro-radar system for detection and tracking of low-profile, low-altitude targets

Ashok Gorwara, Planar Monolithic Industries, Inc. (United States); P. Molchanov, Consultant (United States)

No Abstract Available

9825-8, Session 1

using convolutional neural networks for human activity classification on micro-Doppler spectrograms

Tyler S. Jordan, Sandia National Labs. (United States) and Stanford Univ. (United States)

This paper explores the possibility of using single-chip radar technology to detect micro-gestures in humans for the purpose of predicting potentially violent behavior. Micro-Doppler processing enables several cm/s resolution even through optically opaque materials such as clothing and even walls. This technology could be used to assist soldiers, law-enforcement officers, and other personnel in potentially violent situations to provide warning in real-time of a possible attack.

Data is collected by a single-chip radar operating at 24 GHz aimed at the test subject performing various activities including typical actions such as walking and running, as well as more subtle actions like answering a cell phone or drawing a weapon. The data gathered from these activities, performed by various people, is segmented into a training set and a testing set where various machine learning algorithms are applied. Several feature extraction methods are evaluated such as using the raw or compressed data from the real cepstrum, the spectrogram, and range-Doppler processing. Heuristically-chosen features are automatically extracted from the aforementioned data such as signal energy, average Doppler frequency, average bandwidth, and gait cycle period. The gathered features are fed into various machine learning algorithms including support vector machines, Gaussian mixture models, and neural networks. These algorithms, once properly trained with appropriately chosen features extracted from the training set, classify the various human activities from the testing set into their corresponding categories. A comparison of the effectiveness of each algorithm with respect to correctly classifying potentially violent activities is given and the corresponding accuracies are reported.

9825-9, Session 1

Real-time threat detection using magnetometer arrays

Mark D. Prouty, Mikhail Tchernychev, Geometrics, Inc. (United States)

In this paper we present the results of using an array of atomic magnetometers to locate the presence of ferrous materials, such as concealed weapons, in real time.

Ferrous materials created magnetic field anomalies. In order to determine the location of such objects, readings from many positions must be analyzed. This field inversion is typically done in post processing, once readings over a survey area or region of interest have been gathered.

With the recent development of small and low power sensors, the dozen or so required to provide information for magnetic field inversion may be deployed. We have built such an array and present here the results of using a real-time inversion algorithm.

The inversion algorithm accurately determines target properties at rates of

10 times per second as objects move past the array. Accuracies are as good as those obtained in post processing methods.

What is especially interesting is the behavior of the array in real-time when observing multiple targets. Closely spaced targets are difficult to interpret in data post processing because one must adjust the inversion algorithm according to how many targets are expected. Determining the number of targets to use can be quite difficult.

An array used in real time, however, greatly improves this process. The array tends to lock onto the nearest target as it passes by. System software can readily observe a series of locations given by the array and determine the locations of several targets. We will present quantitative summaries of this process.

9825-10, Session 2

Antisoiling transparent superhydrophobic coatings

Panos G. Datskos, Oak Ridge National Lab. (United States)

No Abstract Available

9825-11, Session 2

Enabling homeland security missions with in-space 3D printing

Thomas McGuire, Michael P. Hirsch, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

This paper considers the utility of space-based 3D printing for homeland security applications. Agencies with homeland security focuses may benefit from the use of orbital assets to collect data to facilitate the detection of a variety of occurrences of interest. These include everything from prospective acts of terrorism, to invasion, to natural disasters. This paper presents multiple prospective homeland security applications for an in-space 3D printing technology. These applications are then evaluated using case studies which consider different approaches to achieving the desired aim and compare the efficacy of the solution including in-space 3D printing to other prospective approaches.

The in-space 3D printing technology is based on using solar energy to heat a printing material (e.g., aluminum or other metals) to its melting point. It is then extruded and deposited in the desired location on an object under construction. Because spacecraft structure fabrication occurs entirely in space, materials (and various electronic component supplies) can be brought to orbit in a more compact raw form, reducing the required volume and, thus, launch costs. Structures can also be developed to sustain only orbital conditions (instead of having to be built to withstand terrestrial gravity, launch stresses and include mechanisms to transition between storage and deployed modes), reducing their mass and facilitating the creation of certain structures that could not be produced on Earth.

More specific to the needs of homeland security agencies, the technology facilitates the fabrication, refurbishment and repair of orbital craft on-demand. This not only allows the decision as to what types of craft are best suited to changing national security needs to be deferred until closer to the point of need, it also facilitates mission longevity.

One prospective deployment approach for the technology – for homeland security purposes – would be as a mothership for a sensor net constellation. Under this approach, the primary (printer) spacecraft would have sensing capabilities. When it detected a phenomena of interest, it would either task an existing craft to monitor it (if one was available and properly positioned and suitably equipped) or construct a new one. The spacecraft deployed could be configured to specifically match the sensing requirements of the phenomena of interest. For example, the aperture size of a remote sensing spacecraft or the antenna size of a communications intercept spacecraft could be specifically configured in response to a particular concern or

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threat. These spacecraft could be placed in orbits that maximize temporal (or spatial, etc.) coverage of the phenomena.

With multiple mission types considered and benefits ranging from volume and mass reduction to paradigm change presented and assessed, the paper's focus then turns to the technologies required to enable the described solutions. The required technical advances are discussed and a pathway forward is presented.

9825-13, Session 2

Infrared computer tomography (IR-CT) spectroscopy for chemical characterization

Philip R. Bingham, Oak Ridge National Lab. (United States)

No Abstract Available

9825-14, Session 2

Advanced Fingerprint Verification Software

Aryaz Baradarani, Univ. of Windsor (Canada); Jason R. B. Taylor, McGill Univ. (Canada); Fedar Severin, Roman G. Maev, Univ. of Windsor (Canada)

We have developed an advanced fingerprint software in commercial scale. The software and processing units implement new algorithms competing with current best available systems. Development of this technology has been in line with the design and prototype of our ultrasonic fingerprinting scanners. The system has been successfully tested on available databases FVC2000, 2000, 2004 as well as on commercial fingerprint databases.

Main contributions include:

- i) Unique algorithm to remove illumination artifacts and shaded areas from raw fingerprint images via selective subband filtering of double-density dual-tree complex wavelet transform (DD-DTCWT).
- ii) To reduce disparity between features, adapted version of successive mean quantization transform (SMQT) has been employed to render details in case of poor fingerprints.
- iii) For feature extraction and matching, our system compensates deformation of the fingertip skin pressed against a sensor. This compensation occurs at both the local feature level and at the larger scale matching level. The system also accounts for variations in local image quality, represented by feature uncertainty in the matching stage, matching local features in a probabilistic manner.
- iv) A new minutia-based feature for fingerprints is introduced: for a given minutia, adaptive kernel density estimation is used to calculate a 3D distribution of the likelihood of a neighboring minutia at each relative direction and location within a fixed-radius neighborhood.
- v) A new spectral graph-theoretic 1-to-1 fingerprint matching is introduced, using a pairwise inter-minutia constraint network and quality-weighted nodes.
- vi) Solid and robust performance is achieved for misplaced and low quality fingerprints because of PIRI's pressure-invariant and rotation-invariant features.

9825-15, Session 2

Deep layer fingerprint imaging with high-speed ultrasonic system

Fedar Severin, Aryaz Baradarani, Roman G. Maev, Univ. of Windsor (Canada)

Personal identification by fingerprint matching is the traditional although

still developing technique. Widely used ink-and-paper, optical or most of other sophisticated methods for fingerprint reading have significant drawbacks. They are focused on the skin surface profile and can be easily tampered with. The present work is aimed at the development of ultrasonic 3D imaging of the finger pads, including the underskin region along with surface topology. Registration of the internal skin structure increases the amount of useful information obtained, and allows for the reconstruction and verification of ridge patterns. This makes the method more precise, foolproof and insensitive to surface contaminations. Obtained data is backward compatible with existing databases, i.e. implementation can be easy and inexpensive.

A prototype of a system was designed and built based on preliminary research. A unique cylindrical scanner optimized for the finger geometry provides a helical spiral motion of multiple sequentially operating focused transducers. This configuration reduces vibration and allows constant data flow at a maximal rate. The device provides a high resolution scan of the fingerprint area almost "nail to nail" (2.5 x 2.5 cm) with a depth up to 2 mm. Controlling software stores data in the form of a 3D cube for subsequent processing which includes compensation of transducers' misplacement, amplitude leveling and noise reduction. The resulting fingerprint image combines all levels of information including surface fingerprint pattern, sweat porous locations and dermis structures. This ultrasonic method can also detect blood motion using the Doppler effect. Its sensitivity to skin tissue reactions may be indicative of a person's health or psychological state

9825-16, Session 2

Analysis of Turkey's contribution to NATO ballistic missile defense system

Hasan Alperen Karali, Turkish Air Force Academy (Turkey)

Ballistic Missiles are one of the most serious threats to both Turkey and NATO member countries. These circumstances proposed question that what NATO members can do against these threats as a precaution. The fact that these missiles will be expected from Eastern region will eventually result in establishing defense systems in eastern countries of NATO Alliance Members. Because of its location, Turkey is the closest country to threat as a NATO member. In this study, probability of self-defense of NATO against ballistic missiles in a situation in which Turkey has ABMs (Anti-Ballistic-Missiles) is analyzed. Having a NATO's X-Band radar system in Turkey provides a great deal of advantages to the allies about detecting missiles even after seconds from launching. Currently, there is no ABM capability of Air Defense System in Turkey but Turkey has an ongoing Project named T-LORAMIDS (Turkish Long Range Air and Missile Defense System). In accordance with this study, potential impacts of establishing all these necessary defense systems and integrating these systems to the NATO will be foreseen. At the end of this study, some suggestions are proposed in terms of Ballistic missiles protection and NATO's security.

9825-40, Session 2

The benefits and harms of patriot air defense systems of the Turkish Air Force in the defense of the country against regional threats

Selamettin Dirik, Turkish Air Force Academy (Turkey)

The Middle East has been the address of the conflicts and wars throughout history. Particularly, it has turned into a seething cauldron since the Gulf War. After this war in this region, Iraq War, the Syrian crisis and the other big and small problems has broken out. Turkey which has been one of the major actors in this region, was regarded as an ally especially by the US and European countries and has played a supporting role for peace in the Middle-East. But in this last period of time, the Syrian crisis and the ISIS that exploits this crisis environment, has become a major threat to Turkey. Against this threat the NATO, of which also Turkey is a member, got involved

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with the situation and expressed that whenever Turkey wants, they would have the necessary assistance for Turkey. "During this crisis, what are the benefits or harms of the PATRIOT air defense missile systems that were sent by the allies to protect the territory of Turkey and Turkish airspace against the countries that especially have the ballistic missiles which range from short, medium, long and intercontinental distance and can carry a conventional or nuclear warheads?" Survey question was identified as the problem.

In this study, the status of the Patriot deployment in Turkey, the ballistic missile power of the governments around Turkey, the activity and amount of these missiles, the status of alternative air defense systems and the countries that use them, the historical background of the development of regional states in terms of these systems and for the USA, Russia and China as global players earnings/losses of the placement of these air defense systems to Turkey, are examined.

9825-17, Session 3

Command and control of collaborative assets at the tactical edge (*Invited Paper*)

Jean-Charles Lede, Defense Advanced Research Projects Agency (United States)

No Abstract Available

9825-18, Session 3

Target-oriented binary sensor sets in C3I systems

Tomasz P. Jansson, Volodymyr Romanov, Thomas C. Forrester, Wenjian Wang, Andrew A. Kostrzewski, Physical Optics Corp. (United States); Ranjit Pradhan, Physical Optics Corp (United States)

In this paper, Single-Target Oriented (STO) Binary Sensor Sets are introduced and analyzed for C3I applications. These STO Bayesian Binary Sensor Set Systems (B2S3) are diversified multi-sensors (such as: CCD camera, IR camera, LIDAR, etc.), standardized into the binary sensor format. By increasing k-number of sensors within STO paradigm, we increase target predictability, thus, increasing Bayesian inference strength of B2S3. The B2S3 can be not only ISR multi-sensors, but also cybersensor sets, the latter ones working as Decision Generation Tools, for example. They constitute a kind of homeostat working as heterogeneous learning machine.

In this paper, Single-Target Oriented (STO) Binary Sensor Sets are introduced and analyzed for C3I applications. These STO Bayesian Binary Sensor Set Systems (B2C3) such as: ISR, medical, software (cybersensors), etc., are multi-sensors standardized into the binary sensor format. This format includes such basic elements as: object, target, and binary alarm, (i.e., alarm and no-alarm). By increasing number of sensors within STO paradigm, we increase Bayesian inference strength of B2C3. The B2Cs can be not only ISR multi-sensor, or other physical multi-sensor, but also cyber-multi-sensor, the latter one working as Decision Generator Tool, for example. Such compound cybersensors constitute a kind of homeostat, working as heterogeneous learning machine (integrating human and artificial intelligence).

The decision process can be done either through Figure of Merit (FoM) weighted average, or by JPPV (Joint Positive Predictive Value) formulas, creating a kind of hard or soft decision paradigm. All these decision processes use constant and continuous Bayesian Truthing (BT) experimental validating and complimentary Bayesian statistics.

The FoMs should balance false-positives and false-negatives as a function of asymmetricity factor (rare targets in object space).

The long-term benefits: sensors' performance can be evaluated in more uniform, standardized way, invariant to specific sensing median (such as ISR, optical, medical, QC, security, cybersensing).

Applications include: Homeland Security, Law Enforcement, ISR, medical, QC, military command and control, cybersecurity, social media.

9825-20, Session 3

Entropy as a Metric in Critical Infrastructure Situational Awareness

Markus Klemetti, Samir Puuska, Jouko Vankka, The Finnish Defence Forces (Finland)

In this paper, we expand our previously proposed critical infrastructure (CI) model with time dependent stochastic elements, and conduct software simulations to assess the resulting framework. We explore the possibility of using Shannon's entropy as a support tool for CI modelling and analysis.

In the model, CI is presented as a directed graph, where each vertex is a discrete system. Edge directions represent dependency relations between the systems. Each node is associated with a finite state machine (FSM) which represents the status (health, capability etc.) of the system in question. In this paper we expand the model by associating a probability distribution to each FSM, which accounts for the flow of time and previous confirmed sensor reading. As time passes, the uncertainty about the state of the system increases. By relying on statistical probabilities that have been previously observed or are known, it is possible to make predictions about the current state of CI.

Attached to each FSM is a status function S. By observing the expected value $E(S(X))$, it is possible to estimate the status of the system in question. The entropy of the random variable X informs us of the reliability of the estimate. The interlinked FSM structure guarantees that the dependencies between systems are taken into account.

We believe that the proposed model improves CI situational awareness by taking into account the increasing uncertainty created by the passage of time.

9825-21, Session 3

Hilbertian sine as absolute measure of Bayesian inference in ISR, homeland security, medicine, and defense

Tomasz P. Jansson, Wenjian Wang, Juan F. Hodelin, Thomas C. Forrester, Physical Optics Corp. (United States); Volodymyr Romanov, Physical Optics Corp (United States); Andrew A. Kostrzewski, Physical Optics Corp. (United States)

In this paper, Bayesian Binary Sensing (BBS) is discussed as an effective tool for Bayesian Inference (BI) evaluation in diversified areas such as: ISR (and, C3I), Homeland Security, QC, Medicine, Defense, and many others. In particular, Hilbertian Sine (HS) as absolute measure of the BI, is introduced, while avoiding relativity of decision threshold identification, as in the case of traditional relative measures of the BI. The Hilbertian Sine (or, cosine) is derived from formalism of Hilbertian vector algebra. Due to the HS, we avoid relativity of the threshold value which next must balance false positives versus false negatives.

In this paper, Hilbertian Sine as absolute Measure of Bayesian Inference in the Bayesian Binary Sensing (BBS) is introduced. In general, we have relative and absolute measure of Bayesian Inference (BI) in the binary sensors. Typically, in the case of the BBS, we apply relative measure as a natural generalization of signal theory, or, rather Signal Detection Theory (SDT) where decision threshold is applied, in the presence of signal and (Gaussian) noise. However, said threshold introduces relativity in such a sense that higher threshold value lower false positives while higher false negatives; and vice versa. To avoid such relativity, in this paper, we introduce the absolute measure of the BI, based on Hilbertian vector algebra (rather than Hilbert vector analysis, as in quantum mechanics).

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Since, each Single-Target Oriented Bayesian Binary Sensor Set System (B2S3), (as discussed in other paper) has the BBS scale, any sensor readout, after Bayesian Truthing, is identified as target, or non-target, with a given BBS scale value. Then, all target values create a vector (same with non-targets). The scalar product of these two (unit) vectors can be interpreted as cosine, while equivalent positive value is Hilbertian Sine.

The long-term benefits: Bayesian inference can be evaluated in absolute way, independently on (relative) threshold value. This is especially important in the case of weak BBS, when Bayesian inference of each component single sensor can be very weak.

9825-22, Session 3

Development of unmanned vehicle cross domain command and control

M. Incze, Naval Undersea Warfare Ctr. (United States)

No Abstract Available

9825-23, Session 4

Interactive analysis of geodata based intelligence

Boris Wagner, Ralf Eck, Gabriel Unmüßig, Elisabeth Peinsipp-Byma, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

Introduction

In disaster management, the effective management of spatiotemporal intelligence data is essential. Especially different specialists and increasingly non-governmental organizations (NGOs) have to work together. Due to their varying technological and educational background, a metaphorical basis has to be found that creates a bridge in between them. We think, digital maps have this ability. When a spatiotemporal events happens, multi-source intelligence data is gathered to understand the problem, and strategies for solving the problem are investigated. The difficulties arising from handling spatial and temporal intelligence data represent the main problem.

Solution

For the analysis of geodata based intelligence data, a software was developed that combines geodata with optimized ergonomics. The interaction with the common operational picture (COP) is essentially facilitated. The composition of the COP is based on geodata services, which are normalized by international standards of the Open Geospatial Consortium (OGC). The geodata are combined with intelligence data from images (IMINT) and humans (HUMINT), stored in a NATO Coalition Shared Data Server (CSD, STANAG 4559). These intelligence data can be combined with further information sources, i.e., live sensors to build a COP. This allows the users to work interactively with the COP, i.e., searching with an on board CSD client for suitable intelligence data and integrate them into the COP. This allows intelligence services to contribute effectively to the process.

Applications

The developed software runs on various hardware. It was ranked effectively in several military exercises. Civil disaster management forces decided to use the system for their intelligence analysis.

9825-24, Session 4

Comparison and Evaluation of Datasets for Off-angle Iris Recognition

Osman M Kurtuncu, Meliksah University (Turkey); Gamze N. Cerme, Mahmut Karakaya, Meliksah Univ. (Turkey)

Recent works prove that iris is one of the most accurate, distinctive,

universal, and reliable biometric system to confirm or determine the identity of an individual. However, the accuracy of iris recognition system bases on a well-designed and controlled experimental setup. Standoff iris recognition system is one of the new areas of research in biometrics where the identity of both cooperative and non-cooperative individuals from an image or video sequence. Therefore, their recognition performance is degraded by several factors including off-angle, occluded, and dilated iris images which explain several challenging issues for iris recognition system. Impact of these challenging issues must be taken into account to develop more accurate and reliable iris recognition system. However, the datasets in the literature is limited or incomplete for the research in stand-off iris biometrics.

In this paper, we first investigated the publicly available iris recognition datasets and their data capture platforms to figure it out if it is suitable for the stand-off iris recognition research. There are NIST Iris Challenge Evaluation (ICE) iris dataset, Chinese Academy of Sciences (CASIA) iris dataset, West Virginia University (WVU) iris dataset, Oak Ridge National Laboratory (ORNL) iris dataset. Majority of these datasets only include frontal iris images. WVU dataset has off-angle iris images from 0°, 15° and 30° in gaze angles. ORNL off-angle iris dataset includes images from -50° to 50° in angle. However, iris images are captured by using only one camera by moving the camera from 50° to 50° in image acquisition angle. Therefore, the frontal and off-angle iris images are not captured at the same time. The comparison of the frontal and off-angle iris images produce results not only for the gaze angle difference but also change in pupil dilation and accommodation. In order to observe the effect of the challenging issues including the gaze, pupil, and accommodation, the frontal and off-angle iris images are supposed to be captured at the same time by using two different cameras. For this purpose, we create an image acquisition platform by using a stepper motor, rotary table, Stepper Bee + control board, limit switches, sigma profile and two cameras. One camera is placed at fixed arm and second camera is placed at the moving arm. Each camera captures 10 iris images for every 10° degree from -50° to 50°. For each subject, 220 iris images are captured per eye from frontal and off-angle cameras. There are totally 113 subjects in our dataset where 66 males and 57 females with an average of 26. We compared the hamming distance of the frontal and off-angle iris images in two-camera-setup and one-camera-setup. We observed that hamming distance in two-camera-setup is less than one-camera-setup approximately 0.05-0.001 in range. This results shows that in order to have an accurate results in the stand-off iris recognition research, two-camera-setup is necessary in order to distinguish the challenging issues from each other.

9825-25, Session 4

Carrier frequency offset estimation for an acoustic-electric channel using 16 QAM modulation

Leonard Anderson, Gary J. Saulnier, Henry A. Scarton, Michael Cunningham, Soumya Chakraborty, Kyle R. Wilt, Rensselaer Polytechnic Institute (United States)

Acoustic-electric channels can be used to send data through metallic barriers, enabling communications where electromagnetic signals are ineffective. This paper considers an acoustic-electric channel that is formed by mounting piezoelectric transducers on metallic barriers that are separated by a thin water layer. The transducers are coupled to the barriers using epoxy and the barriers are positioned to axially-align the PZT's, maximizing energy transfer efficiency. The electrical signals are converted by the transmitting transducers into acoustic waves, which propagate through the elastic walls and water medium to the receiving transducers. The reverberation of the acoustic signals in these channels can produce multipath distortion with a significant delay spread that introduces inter-symbol interference (ISI) into the received signal. While the multipath effects can be severe, the channel does not change rapidly which makes equalization easier. Here we implement a 16-QAM system on this channel, including a method for obtaining accurate carrier frequency offset (CFO) estimates in the presence of the quasi-static multipath propagation. A raised-power approach is considered but found to suffer from excessive data noise resulting from the ISI. An alternative approach that utilizes a

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pilot tone burst at the start of a data packet is used for CFO estimation and found to be effective. The autocorrelation method is used to estimate the frequency of the received burst. A real-time prototype of the 16 QAM system that uses a Texas Instruments MSP430 microcontroller-based transmitter and a personal computer-based receiver is presented along with performance results.

9825-26, Session 4

Interoperability of heterogeneous distributed systems

Christian Zschke, Barbara Essendorfer, Christian Kerth, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

To achieve knowledge superiority in today's operations interoperability is the key. Budget restrictions as well as the complexity and multiplicity of threats combined with the fact that not single nations but whole areas are subject to attacks force nations to collaborate and share information as appropriate.

Multiple data and information sources produce different kinds of data, real time and non-real time, in different formats that are disseminated to the respective command and control level for further distribution. The data is most of the time highly sensitive and restricted in terms of sharing. The question is how to make this data available to the right people at the right time with the right granularity.

The Coalition Shared Data concept aims to provide a solution to these questions. It has been developed within several multinational projects and evolved over time. A continuous improvement process was established and resulted in the adaptation of the architecture as well as the technical solution and the processes it supports.

Coming from the idea of making use of existing standards and basing the concept on sharing of data through standardized interfaces and formats and enabling metadata based query the concept merged with a more sophisticated service based approach.

The paper addresses concepts for information sharing to facilitate interoperability between heterogeneous distributed systems. It introduces the methods that were used and the challenges that had to be overcome. Furthermore, the paper gives a perspective how the concept could be used in the future and what measures have to be taken to successfully bring it into operations.

9825-27, Session 5

Quantifying and measuring cyber resiliency (Invited Paper)

George Cybenko, Thayer School of Engineering at Dartmouth (United States)

No Abstract Available

9825-28, Session 5

Near-optimal sequential methods for detecting network intrusions

Xinjia Chen, Frederick W. Lacy, Patrick Carriere, Southern Univ. and A&M College (United States)

In this paper, we propose new sequential methods for detecting port-scan attackers which routinely perform random "portscans" of IP addresses to find vulnerable servers to compromise.

In addition to rigorously control the probability of falsely implicating benign remote hosts as malicious, our method performs significantly faster

than other current solutions. Moreover, our method guarantees that the maximum amount of observational time is bounded.

Further, we have established explicit bounds on the average detection time of the proposed detection procedure. Such bound implies that the average detection time of proposed scheme is very closest to the least possible bound.

9825-29, Session 5

A preliminary analysis of quantifying computer security vulnerability exposure in "the wild"

K. A. Farris, Thayer School of Engineering at Dartmouth (United States); Sean R. McNamara, Adam Goldstein, Dartmouth College (United States); George Cybenko, Thayer School of Engineering at Dartmouth (United States)

A system of computers, networks and software has some level of vulnerability exposure that puts it at risk to criminal hackers. Presently, most vulnerability research uses data from software vendors,

and the National Vulnerability Database (NVD). We propose an alternative path forward through grounding our analysis in data from the operational information security community, i.e. vulnerability data from "the wild". In this paper, we propose a vulnerability data parsing algorithm and an in-depth univariate and multivariate analysis of the vulnerability arrival and deletion process (also referred to as the vulnerability birth-death process). We find that vulnerability arrivals are best characterized by the log-normal distribution and vulnerability deletions are best characterized by the exponential distribution. These distributions are the priors for future bayesian analysis. We also find that over 22% of the deleted vulnerability data has a rate of zero, and that the arrival vulnerability data is always greater than zero. Finally, we quantify and visualize the dependencies vulnerability deletions have on vulnerability arrivals through a bivariate scatterplot and statistical observations.

9825-30, Session 5

Autonomous cyber warfare system

Jeremy Straub, Univ. of North Dakota (United States)

The growing prevalence of cyber threats and a prospective capability for attacks to be launched autonomously drives a need for an autonomous system to defend against them. Requiring a human in the loop (or, in some cases, even 'on' the loop) may make a response to slow to prevent damage to a critical asset or create the fear of retaliatory damage necessary to deter certain attacks (i.e., a form of cyber mutually assured destruction). An autonomous system is required to provide a rapid response capability at a speed paralleling prospective attackers. Similarly, for cases when it may be desirable to attack the interests of an adversary, a system capable of performing at or above the speeds of the opponent's autonomous defense system is required.

This paper presents one aspect of an autonomous warfare system based on the Blackboard Architecture that focuses specifically on cyber threat defense and attack capabilities. The work presented focuses on command decision making, leaving the specifics of prospective attack and defense tools and mechanisms to other work. Specifically, the system utilizes a blackboard to model the relationships between the various parties (adversaries, allies, neutral parties, parties with unknown interests, etc.) and the cyber assets that they control. A second blackboard is utilized to store a decision making framework for determining how to act in various scenarios (i.e., rules, protocols and heuristics of engagement). A third blackboard stores information on specific tactics and their utility against various forms of attack and defense on certain systems.

Mechanisms for replicating this information across multiple decision

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making centers and coordinating a loosely controlled attack are discussed. Additionally, techniques for coordinating these actions across an untrusted medium are also considered. Finally, overall system operations are presented and evaluated. The proposed approach is evaluated both qualitatively and quantitatively, based on several scenarios that are presented and under which performance is analyzed.

9825-31, Session 5

efficient inference of hidden Markov models from large observation sequences

Benjamin W Priest, George Cybenko, Thayer School of Engineering at Dartmouth (United States)

No Abstract Available

9825-32, Session 5

A theory of stopped random walk and its applications to detection of network intrusions

Xinjia Chen, Southern Univ. and A&M College (United States)

In this paper, we establish a connection between stopped random walk and the problem of detecting network intrusions. We demonstrate that many adaptive sequential techniques can be cast into the general framework of stopped random walk. We develop tight bounds and asymptotic results for average stopping times and distributions of relevant statistics. Such theory can be applied to investigate the average detection time and false-alarm probabilities of existing detection algorithms. In particular, we have used the proposed techniques to investigate the well-known Threshold Random Walk Algorithms for detecting port scanners.

9825-33, Session 6

Atmospheric properties and propagation characteristics determined by Raman lidar
(Invited Paper)

C. Russell Philbrick, North Carolina State Univ. (United States)

No Abstract Available

9825-34, Session 6

Physics-based atmospheric modeling near marine boundary

J. Olson, Naval Undersea Warfare Ctr. (United States)

No Abstract Available

9825-35, Session 6

High-order computerized improvements in characterization of nonlinear systems by signal processing exploitation

Albert H. Nuttall, Naval Undersea Warfare Ctr. (United States)

No Abstract Available

9825-36, Session 6

3 band Raman laser developments for atmospheric characterization as meteorological tool

J. Olson, Naval Undersea Warfare Ctr. (United States)

No Abstract Available

9825-37, Session 6

Data requirements for modeling, analysis, and understanding of laser beam propagation in marine boundary

Richard Katz, Naval Undersea Warfare Ctr. (United States)

No Abstract Available

9825-38, Session 6

Optical properties of salt aerosols with and without inclusions as a function of relative humidity

Margaret E Greenslade, Dept. of Chemistry, University of New Hampshire (United States); Alexis R Attwood, Droplet Measurement Technologies (United States); Tyler Galpin, Dept. of Chemistry, University of New Hampshire (United States)

No Abstract Available

9825-39, Session 6

Field assessment of optical transparency in the low-level marine boundary layer: preliminary data from coastal New England measurement sites

Margaret E Greenslade, Univ. of New Hampshire (United States); Hui Feng, Institute for the Study of Earth Oceans and Space, Univ. of New Hampshire (United States); Douglas Vandemark, The Univ. of New Hampshire (United States)

No Abstract Available

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9826-1, Session 1

OS Friendly Microprocessor Architecture: Hardware Level Computer Security

Patrick Jungwirth, U.S. Army Research, Development and Engineering Command (United States); Patrick La Fratta, Micron Technology, Inc. (United States)

We present an introduction to the patented OS Friendly Microprocessor Architecture (OSFA) and hardware level computer security. Conventional microprocessors have not tried to balance hardware performance and OS performance at the same time. Conventional microprocessors have depended on the Operating System for computer security and information assurance. The goal of the OS Friendly Architecture is to provide a high performance and secure microprocessor and OS system. We are interested in cyber security, information technology (IT), and SCADA control professionals reviewing the hardware level security features and information assurance features.

The OS Friendly Microprocessor Architecture implements hardware level computer security by extending Unix file permission bits down to each cache bank and each memory address. The permission bits provide for a simple and convenient way to implement hardware based cyber/computer security. The cache bank permission bits provide a hardware level sandbox to isolate all processes.

The OS Friendly Microprocessor Architecture's cache memory pipeline configuration provides hardware features for hardware level context switching. For light-weight threads, the memory pipeline configuration provides near instantaneous context switching times. The architecture's parallelism allows context switching operations, and the microprocessor's execution pipeline to both run in parallel. The cache bank memory pipeline also provides for low overhead I/O and memory management.

9826-2, Session 1

Risk analysis and control for malware spreading and evolution

Hasan Cam, U.S. Army Research Lab. (United States)

A holistic risk analysis requires not only observation and detection of all events of attackers, intrusions, and vulnerabilities, but also analysis of their interactions, causality, temporal and spatial orderings in real time. In order to accurately assess and control exploit likelihood and impact of vulnerability exploitations during malware spreading and evolution, this paper presents a dynamic causality-based approach to analyzing and modeling the interactions of cyber events as malware keeps spreading and influencing. In this approach, malware epidemics, causal interactions of events, and Petri nets are first used to characterize the context of malware spreading, estimate risk parameters, and then control risk by limiting malware spreading or influence, with the help of real-time sensor measurements.

9826-3, Session 1

Image encryption based on ghost imaging via quantum walks

Nitin Rawat, Gwangju Institute of Science and Technology (Korea, Republic of)

An image encryption combined with ghost imaging (GI) and Quantum walks (QW) is encoded in Fresnel domain. The computational version of GI emulates the optical propagation through a bucket detector whereas QW can serve as an excellent key generator due to its inherent nonlinear chaotic dynamic behavior. First, a spatially coherent monochromatic laser beam

passes through an SLM, which introduces an arbitrary phase-only mask. The modified beam is collected by a single-pixel detector. Further, the intensity is multiply with the QW digitally. In contrast to previous techniques, the encrypted version of the object image is not a complex-valued matrix but simply an intensity vector, which noticeably reduces the number of bits sent by the sender to the receiver. QW shows high sensitivity to system parameters, unpredictability, stability and non-periodicity whereas GI is capable of encrypting and transmitting the data. Only applying the correct keys, the original image can be retrieved successfully. Simulations and comparisons show the proposed method to be secure enough for image encryption and outperforms prior works. The proposed method opens the door towards introducing GI and quantum computation into image encryption and promotes the convergence between our approach and image processing.

9826-4, Session 1

Network reconstruction via graph blending

Rolando Estrada, Teledyne Scientific Co. (United States)

Relational data is crucial in cyber-security applications. However, graphs estimated from empirical data are often noisy and incomplete due to the difficulty of monitoring all the components (nodes and edges) of the true graph. This problem is exacerbated in large networks where the number of components may far exceed available surveillance capabilities.

Errors in the observed graph include missing/spurious components, as well as fused (multiple nodes are merged into one) and split (a single node is misinterpreted as many) nodes. Traditional reconstruction methods, however, can only handle missing/spurious errors. Thus, we developed a novel graph blending framework that allows us to cast the full estimation problem as a simple edge addition/deletion problem.

There are two main sources of information (or features) for reconstructing a graph: topological (i.e. graph connectivity) and intrinsic (domain-specific properties of the represented object). We empirically tested the performance of various topological and intrinsic features on the full estimation problem using both synthetic data and a set of graphs derived from Wikipedia. For the topological features, we analyzed four existing link prediction algorithms, as well as three global features that encapsulate the overall statistics of the graph. We modeled the intrinsic features in the Wikipedia graphs using textual analysis (LSA, LDA) and WordNet semantic similarity.

Our experimental results suggest that topological features consistently hinder reconstruction accuracy, while intrinsic features only help if their fidelity exceeds a threshold given by the graph's sparsity. We provide an initial theoretical analysis of these phenomena and suggest several avenues for improvement.

9826-5, Session 1

Identifying compromised systems through correlation of suspicious traffic from malware behavioral analysis

Ana E. F. Camilo, National Institute for Space Research (Brazil); Andre R. A. Gregio, Ctr. de Tecnologia da Informacao Renato Archer (Brazil); Rafael D. Coelho dos Santos, Instituto Nacional de Pesquisas Espaciais (Brazil)

Malicious programs are one of the greatest threats to Internet-connected systems, compromising public and private organizations. Mutants, or variants, are versions of the same malware that may exhibit the same infection behavior, but with different instructions to deceive defensive mechanisms. Antiviruses are the first defense against malware, but they do not provide sufficient protection when the malicious program is an

unidentified variant (without a detection signature/heuristic rule) or sophisticated enough to evade the engine. Moreover, thousands of variants are created and spread on a daily basis. One way to accomplish malware detection is through the analysis of the network traffic produced during malware infection, as well as their interaction with the target operating system. To do so, researchers usually leverage dynamic analysis systems (automated execution environments tightly controlled), which are used to run malware samples and extract their behavior. By definition, all network traffic produced during malware execution is suspicious. This traffic may represent malware accessing an external compromised system, either to steal sensitive data from the victim (users credentials, information from the target operating system) or to fetch other malicious artifacts (configuration files, additional modules, commands etc.). Thus, correlating information from suspicious network traffic gathered during malware execution in dynamic analysis systems can provide useful information about the role of servers and other computer systems owned by malicious adversaries. In this work, we propose a visualization tool to identify compromised systems based on correlation graphs of malware-generated network connections and IP address-related geolocation data. To evaluate our tool, we used over 10 thousand unique network traffic files captured during distinct malware analyses in our behavioral-based dynamic system. The graphs created can be used to observe different malware connecting to the same compromised server, thus allowing us to identify malicious campaigns. We are also able to verify if a compromised server is being used as a point of download of malicious artifacts or as a point of collection for stolen data. Furthermore, analyzing the structures of our graphs we may identify malicious programs that behave in a similar fashion (from the point of view of exfiltrating to or fetching objects from the compromised server), but with varying IP addresses or hostnames. Hence, our discussion about the results can help security analysts, researchers, and incident responder to identify behavioral patterns aiming at the detection of malicious network activity and creation of countermeasures that improve systems security.

9826-13, Session 2

Securing your assets from espionage

Stacey Banks, National Institute for Standards and Technology (United States)

Budget cuts to the left of us, layoffs to the right. Who, and what, is left to protect the intellectual property? The cost to conduct business espionage is decreasing while the cost of containment is rising. With all these constraints, to do more with less, we need to readdress the issues in our current security compliance posture to refocus our capabilities.

Espionage at its root is a security concern and espionage is a reality that every organization faces whether they are a business or government agency. The attack principals are utilized to gain knowledge that can be used for business leverage, identity theft, or financial theft. Consider how many of your competitors are using your knowledge to cut their costs? Economic espionage includes a multitude of tactics used to gain your trade secrets, competitive knowledge, sources, and more.

As with any security issue the key aspect of security being a success or failure is in our human assets. In order to secure our systems we must train and secure our personnel. We will explore the issue from both the insider and outsider perspectives and review what steps can be taken to better protect against this continuing threat.

9826-14, Session 2

Multispectral very wide-view sensing concept

Anatolia Boryssenko, Nuvotronics, Inc. (United States)

No Abstract Available

9826-15, Session 2

Optimization of RF components in omnidirectional sensor

Anatolia Boryssenko, Nuvotronics, Inc. (United States)

No Abstract Available

9826-16, Session 2

Evaluating cyber security persistence in a connected internet of things heterogeneous networks

Bassam S. Farroha, U.S. Dept. of Defense (United States)

No Abstract Available

9826-6, Session 3

Hybrid sentiment analysis utilizing multiple indicators to determine temporal shifts of opinion in OSNs

Joshua S. White, SUNY Polytechnic Institute (United States); Robert T. Hall, Rsignia Inc. (United States); Jeremy Fields, SUNY Polytechnic Institute (United States); Holly M. White, American College of Education (United States)

Utilization of traditional sentiment analysis for predicting the outcome of an event on a social network depends on: precise understanding of what topics relate to the event, selective elimination of trends that don't fit, and in most cases, expert knowledge of major players of the event. Sentiment analysis has traditionally taken one of two approaches to derive a quantitative value from qualitative text. These approaches include the "bag of words model", and the usage of "NLP" to attempt a real understanding of the text. Each of these methods yield very similar accuracy results with the exception of some special use cases. To do so, however, they both impose a large computational burden on the analytic system. Newer approaches have this same problem. No matter what approach is used, SA typically caps out around 80% in accuracy. However, accuracy is the result of both polarity and degree of polarity, nothing else. In this paper we present a method for Hybridizing traditional SA methods in order to better determine shifts in opinion over time within social networks. This hybridization process involves augmenting traditional SA measurements with contextual understanding, and knowledge about the writers demographics. Our goal is to not only to improve accuracy, but to do so with minimal impact to computation requirements.

9826-7, Session 3

Social relevance: toward understanding the impact of the individual in an information cascade

Robert T. Hall, Rsignia Inc. (United States); Joshua S. White, Jeremy Fields, SUNY Polytechnic Institute (United States)

Information Cascades (IC) through a social network occurs due to the decision of users to disseminate content. We define this decision process as User Diffusion. IC models typically describe an information cascade by treating a user as a node within a social graph, where a node's acceptance of an idea is represented by some activation state. The probability of activation then becomes a function of a node's connectedness to other activated nodes as well as, potentially, the history of activation attempts. We enrich this Coarse-Grained User Diffusion (CGUD) model by applying

actor type logics to the nodes of the graph. The resulting Fine-Grained User Diffusion (FGUD) model utilizes prior research in actor typing to generate a predictive model regarding the future influence a user will have on an Information Cascade. Furthermore, we introduce a measure of Information Resonance that is used to aid in predictions regarding user behavior.

9826-8, Session 3

Application of actor-level social characteristic indicator selection for the precursory detection of bullies in online social networks

Holly M. White, American College of Education (United States); Jeremy Fields, SUNY Polytechnic Institute (United States); Robert T. Hall, Rsignia Inc. (United States); Joshua S. White, SUNY Polytechnic Institute (United States)

Bullying has become a national problem for our schools and the economy. Social and professional lives of victims are affected, along with quality of work. Early detection of bullies can therefore mitigate the destructive effects of bullying. Our previous research has found that given specific characteristics of an actor, actor logics can be developed utilizing input from natural language processing and graph analysis. Given that bullies have similar characteristics, in this paper we present the creation of actor logics specific to bullies and apply these to a select social media dataset to identify bullies.

9826-9, Session 3

Self-structuring data learning approach

Igor V. Ternovskiy, James T. Graham, Daniel J. Carson, Air Force Research Lab. (United States)

No Abstract Available

9826-10, Session 3

Visualizing output for a data learning algorithm

Igor V. Ternovskiy, Daniel J. Carson, James T. Graham, Air Force Research Lab. (United States)

No Abstract Available

9826-11, Session 3

Implementing a self-structuring data learning algorithm

Igor V. Ternovskiy, James T. Graham, Daniel J. Carson, Air Force Research Lab. (United States)

No Abstract Available

9826-12, Session 3

Behavior-based network management (BBNM): a unique model-based approach to implementing cyber superiority

Jocelyn M. Seng, Air Univ. (United States)

Behavior-Based Network Management (BBNM) is a technological and a strategic approach to mastering identification and control of behavior, both programmatic as well as human, in a digital battle space during the engagement period. As all five AF mission areas rely upon the cyber domain to support, enhance and execute (SEE) their mission, BBNM leads to better understanding the degree of reliance we can place upon a digital capability and ability to determine the risk at which we operate the capability. The objective of BBNM is a holistic ability to ensure compliance with cyberspace policies, such as access, security, monitoring, provisioning, utilization management, allocation to support mission sustainment, and change control. Using a Vector Relational Data Modeling (VRDM) approach to leverage the power of non-apparent relationships between data objects (digital transactions), operators can more quickly detect and counter malicious behavior. Initial research configurations provide executable BBNM models through a combination of normalizing behavior-based network management architecture, threat vectors, and definitions of "good" behavior. The Global Network Information Architecture (GINA) technology allows cyber domain subject matters experts (SMEs) to flexibly develop, test and employ solutions to persistent and evolving cyber threats. Information models are inherently transparent allowing domain SME ability to navigate through models and model components for deep understanding, lending to rapid model extension, reconfiguration, and data reuse.

9826-17, Session 3

New generation of war preemptive strike on cyber space

Fatih Aksoy, Turkish Air Force Academy (Turkey)

As an important force factor, electronic and cyber warfare instruments are becoming more and more integrated with the existing weapon systems. It is considered that international conflict will intensify on the cyber - state area therefore information systems will be an integral part of the national and international security.

Cyber, as our new war domain, has some differences from the other war domains. The very basic characteristic of cyber-attack is its asymmetric feature. In other words; bigger impacts can be achieved with little effort. In the war domains other than the cyber; you must have sophisticated and expensive weapon systems to dominate to adversary. But in cyber, with a cyber-weapon, developed by a few cyber experts using little resource could interrupt logistics activity and fire support of armies, target detection systems and mission computers might be made nonfunctional and ongoing orders might be changed with the cyber-attack to military systems. A cyber-attack to communication system influences all users at all levels. A country to surrender without any struggle by means of cyber-attacks on critical substructure as SCADA (Supervisory Control and Data Acquisition) systems. Besides all these provided damages, cyber-attack capability is relatively a low cost but this capability identifies countries' virtual war provision and operational advantages.

Faster processors, high sensitivity image sensing systems, strong password breakers, frequency mixers, and designing and producing high-security communications satellites define cyber war capabilities and operational advantages of countries. During the war, considering the cost of creating front-line and loss of human, creating a virtual front-line with electronic attack as the concept of self-defense is a strategy that in many respects superior. Physical response to the attacks of virtual armies is like fighting against windmills, in award, it requires virtual response to virtual attack.

In this study; the development in electronic environment, increasing dependence on cyber space, information security and cost issues, definition of cyber-security, critical infrastructures, tools and objectives of cyber threats, viruses, SCADA systems, state-sponsored cyber-attacks, cyber security policies implemented in the world and active defense issue are considered as the elements of a solution domain and cyber defense policies are analyzed.

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9827-1, Session 1

Integration of a laser Doppler vibrometer and adaptive optics system for acoustic-optical detection in the presence of random water wave distortions

Phillip Land, Dennis J. Robinson, James Roeder, T. Dean Cook, Arun K. Majumdar, Naval Air Warfare Ctr. Weapons Div. (United States)

A new technique has been developed using a laser Doppler vibrometer (LDV) and an adaptive optics (AO) system consisting of a fast steering mirror, deformable mirror, and Shack-Hartmann Wavefront Sensor for mitigating surface water distortions and recording underwater acoustics. The LDV is used to make non-contact vibration measurements of a surface via a two beam laser interferometer. We have demonstrated the feasibility of this technique in a laboratory tank to overcome the water distortions generated on the surface of the water. The LDV beam penetrates the surface of the water down to an underwater speaker and records the returned beam. The reflected or returned beam is then recorded by the LDV as a vibration wave measurement. An acoustic wave is sent to the underwater speaker. The LDV identifies the acoustic wave while the AO mitigates the water wave distortions. The results show the Strehl ratio, the measure of the quality of optical image formation, which is recorded by the AO system and detection of an underwater acoustical wave which is recorded by the LDV. The open-loop and closed loop of the AO control system clearly demonstrated the utility of the AO-based LDV for many applications.

9827-2, Session 1

Demonstration of adaptive optics for mitigating laser propagation through a random air-water interface

Phillip Land, Arun K. Majumdar, Naval Air Warfare Ctr. Weapons Div. (United States)

This paper describes a new concept of mitigating signal distortions caused by random air-water interface using a Laser Doppler Vibrometer (LDV) and adaptive optics (AO) system. This is the first time the concept of using an AO for mitigating the effects of distortions caused by a random air-water interface. We have demonstrated the feasibility of correcting the distortions using AO in a laboratory water tank for investigating the propagation effects of a laser beam through an air-water interface. The AO system consisting of a fast steering mirror, deformable mirror, and a Shack-Hartmann Wavefront Sensor for mitigating surface water distortions has a unique way of stabilizing and aiming a laser onto an object underneath the water. Essentially the AO system mathematically takes the complex conjugate of the random phase caused by air-water interface allowing the laser beam to penetrate through the water by cancelling with the complex conjugates. The results show the improvement of a number of metrics including Strehl ratio, a measure of the quality of optical image formation for diffraction limited optical system. These are the first results demonstrating the feasibility of developing a new sensor system utilizing an LDV and AO for mitigating surface water distortions.

9827-3, Session 1

Statistical Characterization of the Optical Interaction at a Supercavitating Interface

Gage Walters, Timothy J. Kane, The Pennsylvania State Univ. (United States)

The optical characteristics of an air/water interface have been widely studied for natural interface formations. However, the creation and management of artificial cavities creates a complicated interaction of gas and liquid that makes optical sensing and communication through the interface challenging. A ventilated cavity can reduce friction in underwater vehicles, but the resulting bubble drastically impedes optical and acoustic propagation. The complicated interaction at the air-water boundary yields surface waves and turbulence that make the optical properties difficult to model and compensate for.

Our experimental approach uses a narrow laser beam to probe the surface of the interface and measure the beam deflection and lensing effects. Using a vehicle model with a cavitator in a water tunnel, a laser beam is propagated through the boundary and projected onto a target grid. The beam projection is captured using a high-speed camera, allowing us to measure and analyze beam shape and deflection. This approach has enabled us to quantify the temporal and spatial periodic variations in the cavity boundary. This information has allowed us to characterize the cavity surface and determine the scale, shape, roughness, and periodicity of its features.

9827-4, Session 1

Measurements of optical underwater turbulence under controlled conditions

Andrey V. Kanaev, U.S. Naval Research Lab. (United States); Szymon Gladysz, Rui Almeida de Sá Barros, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany); Silvia C. Matt, Gero A. Nootz, Damien Josset, Weilin W. Hou, U.S. Naval Research Lab. (United States)

Laser beam propagation underwater is becoming an important research topic because of high demand for its potential applications. Namely, ability to image underwater at long distances is highly desired for scientific and military purposes, including submarine awareness, diver visibility, and mine detection. Optical communication in the ocean can provide covert data transmission with much higher rates than that available with acoustic techniques, and it is now desired for certain military and scientific applications that involve sending large quantities of data. Unfortunately underwater environment presents serious challenges for propagation of laser beams. Even in clean ocean water, the extinction due to absorption and scattering theoretically limit the useful range to few attenuation lengths. However, extending the laser light propagation range to the theoretical limit leads to significant beam distortions due to optical underwater turbulence. Experiments show that the magnitude of the distortions that are caused by water temperature and salinity fluctuations can significantly exceed the magnitude of the beam distortions due to atmospheric turbulence even for relatively short propagation distances. We are presenting direct measurements of optical underwater turbulence in controlled conditions of laboratory water tank using two separate techniques involving wavefront sensor and LED array. These two independent approaches will enable development of underwater turbulence power spectrum model based directly on the spatial domain measurements and will lead to accurate predictions of underwater beam propagation.

9827-5, Session 1

Dynamic control of coherent orbital-angular-momentum beams in turbid environments

Kaitlyn Morgan, Keith Miller, Clemson Univ. (United States); Brandon Cochenour, Naval Air Systems Command (United States); Eric G. Johnson, Clemson Univ. (United States)

Dynamic control of the intensity profile of a beam is desirable for sensing, detection, and characterization of underwater turbid environments. This work explores the manipulation of phase in coherent orbital-angular-momentum modes to temporally control the beam shape through the use of an RF signal. The beam shaping capabilities demonstrated are explored as an alternative to amplitude modulation of a visible light source in determining underwater channel properties. The setup utilizes a blue-green laser source. Different orbital-angular-momentum modes are generated by passing the coherent beams through diffractive vortex phase plates. The beams are then superimposed using a mach-zehnder interferometry setup. Various beam profiles are presented and compared with simulation results. These beams are then sent through a controlled underwater environment. The propagation of these dynamic orbital-angular-momentum beams under various turbid conditions is examined. The use of coherent beams enables the detection of alternative channel properties where amplitude modulation is ineffective or lacks precision. This data provides the foundations necessary to develop a method for channel characterization of underwater communication links with these dynamically controlled coherent orbital-angular-momentum modes.

9827-6, Session 1

The influence of underwater turbulence on optical phase measurements

Brandon Redding, US Naval Research Lab (United States); Allen Davis, Clay Kirkendall, Anthony Dandridge, U.S. Naval Research Lab. (United States)

Emerging underwater optical imaging and sensing applications rely on phase-sensitive detection to provide added functionality and improved sensitivity. However, underwater turbulence introduces spatio-temporal variations in the refractive index of water which can degrade the performance of these systems. Although the influence of turbulence on traditional, non-interferometric imaging has been investigated, its influence on the optical phase remains poorly understood. Nonetheless, a thorough understanding of the spatio-temporal dynamics of the optical phase of light passing through underwater turbulence are crucial to the design of phase-sensitive imaging and sensing systems. To address this concern, we combined underwater imaging with high speed holography to provide a calibrated characterization of the effects of turbulence on the optical phase. By measuring the modulation transfer function of an underwater imaging system, we were able to calibrate varying levels of optical turbulence intensity using the Simple Underwater Imaging Model (SUIM). We then used high speed holography to measure the spatial and temporal dynamics of the optical phase of light passing through varying levels of turbulence. Using this method, we measured the variance in the amplitude and phase of the beam, the temporal and spatial correlation of the optical phase, and recorded the turbulence induced phase noise as a function of frequency. By bench marking the effects of varying levels of turbulence on the optical phase, this work provides a basis to evaluate the real-world potential of emerging underwater interferometric sensing modalities.

9827-7, Session 2

Remotely operated compact underwater temporally encoded imager: CUTEI

Derek M. Alley, Linda J. Mullen, Brandon Cochenour, Naval Air Systems Command (United States)

Optical imaging is a very powerful tool for maritime exploration and defense. Currently, maritime imaging technology is dominated by SONAR systems. SONAR propagates very easily through water, but cannot achieve the same spatial resolution of optical systems, such as CCD cameras. Although cameras are capable of achieving very high resolution, the performance of a CCD camera quickly deteriorates in degraded visual environments (DVE) such as turbid coastal waters and dirty harbors. To fill this capability gap, laser-based sensors have been developed to enhance optical imaging in DVEs. However, since traditional approaches require that the laser and receiver are located on the same platform, the size, weight, and power requirements are incompatible with remotely operated vehicles (ROV).

Researchers at NAVAIR have developed a low cost optical imager that uses a bistatic geometry where the laser and receiver are mounted on separate, smaller platforms. The transmitter uses a modulated laser beam and a microelectromechanical (MEMS) scanner to sequentially illuminate an underwater object. A distant receiver collects the object reflected laser light and reconstructs the imagery. Communications information, including a synchronization sequence, is encoded onto the modulation to assist the receiver in piecing the image back together. Lab tests have shown this sensor is able to overcome the limitations of the CCD camera in turbid conditions while preserving image resolution. The laser illuminator is currently being integrated into a small remotely operated vehicle (ROV) to create a very compact, remotely operated optical imager that is useful for ocean exploration, harbor defense, and more in turbid water conditions.

9827-8, Session 2

Experimental study of the compressive line sensing imaging system in a turbulence test tank

Bing Ouyang, Harbor Branch Oceanographic Institute (United States); Weilin W. Hou, U.S. Naval Research Lab. (United States); Cuiling Gong, Texas Christian Univ. (United States); Frank M. Caimi, Fraser R. Dalgleish, Anni K. Vuorenkoski, Harbor Branch Oceanographic Institute (United States)

The Compressive Line Sensing (CLS) active imaging system has been demonstrated to be effective in scattering mediums, such as coastal turbid water, fog and mist, through simulations and test tank experiments. The CLS prototype hardware consists of a CW laser, a DMD, a photomultiplier tube, and a data acquisition instrument. CLS employs whiskbroom imaging formation that is compatible with traditional survey platforms. The sensing model adopts the distributed compressive sensing theoretical framework that exploits both intra-signal sparsity and highly correlated nature of adjacent areas in a natural scene. During sensing operation, the laser illuminates the spatial light modulator DMD to generate a series of 1D binary sensing pattern from a codebook to "encode" current target line segment. A single element detector PMT acquires target reflections as encoder output. The target can then be recovered using the encoder output and a predicted on-target codebook that reflects the environmental interference of original codebook entries.

In this work, we investigated the effectiveness of the CLS imaging system in the turbulence environment. Turbulence poses challenges in many atmospheric and underwater surveillance applications. A series of experiments were conducted in the Naval Research Lab's optical turbulence test facility with the target subjected to turbulence. The preliminary experimental results showed that the current imaging system was able

to recover target information through various turbulence strengths. The challenges of acquiring data in NRL's turbulence test facility and future enhancements of the system will be discussed.

9827-9, Session 2

Wide bandwidth optical signals for high range resolution measurements in water

Justin K. Nash, Robert C. Lee, Linda J. Mullen, Naval Air Systems Command (United States)

Measurements with high range resolution are needed to identify underwater threats, especially when two-dimensional contrast information is insufficient to extract object details. The challenge is that optical measurement are limited by scattering phenomena induced by the underwater channel. Back-scatter results in transmitted photons being directed back to the receiver before reaching the target of interest which induces a clutter signal for ranging and a reduction in contrast for imaging. Multiple small-angle scattering (forward-scatter) results in transmitted photons being directed to unintended regions of the target of interest (spatial spreading), while also stretching the temporal profile of a short optical pulse (temporal spreading). Spatial and temporal spreading of the optical signal combine to cause a reduction in range resolution in conventional laser imaging systems. NAVAIR has investigated ways in which wide bandwidth optical signals can be utilized to improve ranging and imaging performance in turbid water environments. These optical signals include traditional short pulses as well as longer pulses that are intensity modulated with wideband RF waveforms such as frequency chirps and phase-shift keyed Barker codes. Experimental and modeling efforts have been conducted to investigate channel effects on the propagated frequency content, as well as different filtering and processing techniques on the return signals to maximize range resolution and 3D image quality. Of particular interest for the modulated pulses are coherent detection and signal processing techniques employed by the radar community, including methods to reduce sideband clutter and increase signal-to-noise. The paper will summarize NAVAIR's work and show that wideband optical signals, in combination with the various detection and processing techniques, can indeed provide enhancements to range resolution and 3D imagery in turbid water environments.

9827-10, Session 2

Enhanced oil spill detection sensors in low-light environments

Toomas H. Allik, Active EO Inc. (United States); Len Ramboyoung, Night Vision & Electronic Sensors Directorate (NVESD) (United States); Mark Roberts, Mark Walters, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Thomas J. Soyka, U.S. Army RDECOM CERDEC NVESD (United States); Roberta E. Dixon, CACI International Inc. (United States); Jay Cho, Bureau of Safety & Environmental Enforcement (United States)

Although technological advances have been made in the remote detection of oil spills, many sensors do not work well at night or low visibility. This presentation addresses the results of a joint program between BSEE and NVESD to enhance remote sensing techniques to determine oil thickness in a marine environment that leverages current military and state-of-the-art night vision sensors. Laboratory experiments, calibration techniques and field tests at Fort Belvoir Virginia, Santa Barbara California, and the Ohmsett Test Facility in Leonardo, New Jersey are presented. Weathered crude oils were studied spectroscopically and characterized with LWIR, SWIR, and low light level visible/NIR cameras. For this project, we designed and fabricated an oil emulsion thickness calibration cell for spectroscopic laboratory measurements and a buoy for ground truth field measurements. Digital night vision cameras, provided useful imagery and were able to detect and recognize oil from full sun to partial moon light. The LWIR camera provided

quantitative oil analysis (identification) for >1 mm thick crude oils both day and night. Two filtered SWIR cameras were used to determine whether oil thickness could be measured in real time. Spectroscopic results revealed that oil emulsions vary with location and weathered state and some crudes (e.g. ANS and Santa Barbara seeps) do not show the spectral rich features from archived Deep Water Horizon hyperspectral data. Multi-sensor imagery collected during the 2015 USCG Airborne Oil Spill Remote Sensing & Reporting Exercise and the design of a compact, multiband imager will be presented.

9827-11, Session 2

Automated sea floor extraction from underwater video

Lauren Kelly, Mark D. Rahmes, James A. Stiver, Michael P. McCluskey, Harris Corp. (United States)

This project's objective was to develop a workflow to automatically extract metadata from marine video and create image optical and elevation surface mosaics. Three developments made this possible. First, optical character recognition by means of two-dimensional correlation using a known character set allows for the capture of metadata from image files. The second method introduced image mosaicking, exploiting the metadata's latitude, longitude, heading, camera angle and depth readings. Metadata allowed for the determination of location and placement of the image frame in mosaic from the map coordinates and sensor perspective data. Image registration was used to improve the accuracy of mosaicking. Finally, the third contribution involved the use of overlapping data to infer height information. A disparity map was created using the parallax from overlapping viewpoints of a given area and the relative height data was utilized to create a three-dimensional, textured elevation map. Ocean floor mapping using video is a method to simply and cost-effectively record large areas of the seafloor. Obtaining visual and elevation models have noteworthy applications in search and recovery missions. Hazards to navigation are abundant and pose a significant threat to the safety, effectiveness, and speed of naval operations and commercial vessels.

9827-12, Session 3

Probability density function analysis for optical turbulence with applications to underwater communications systems

Marius Bernotas, Charles Nelson, U.S. Naval Academy (United States)

Underwater optical systems have significant potential in the domain of wireless underwater communications. However, the underwater optical channel has yet to be fully characterized. Specifically, the effects of optical turbulence due to such factors as temperature gradient and salinity are not well understood.

Probability Density Functions (PDFs) are commonly used to model laser beam propagation in free space, but comparatively little PDF research has been conducted for the underwater channel. Accurate knowledge of the probability density function for the irradiance of an optical beam on a receiver allows better prediction of performance of the communication link, as it informs the bit error rate of the link.

The Weibull and Exponentiated Weibull distributions have been examined for the free space regime using heuristically derived shape and scale parameters. This paper extends the current literature for free space to the underwater channel and explores use of experimentally derived shape and scale parameters. Data were gathered in a short range underwater turbulence and channel emulator, and analysis was conducted using a nonlinear curve fitting methodology to optimize the shape parameters and find a best-fit curve. This method using a short range, low cost emulator provides insight into the scaled effects of underwater optical turbulence on a long range link. Shape and scale parameters derived for brackish

water from the Severn River at the US Naval Academy were compared to parameters derived from water from other sources. This may yield a general set of equations for determining the PDF for an underwater communications link in many types of water around the world.

9827-13, Session 3

Underwater-detector array for optical communication and laser beam diagnostics

Shachak Pe'eri, Firat Eren, May-Win Thein, Yuri Rzhanov, Matthew Birkeback, The Univ. of New Hampshire (United States)

Underwater optical propagation is used in many marine applications, such as airborne lidar bathymetry (ALB), subsurface navigation and communication. Previous studies on performance evaluation of underwater applications involving laser propagation have been heavily dependent on simulations that provide an approximation to the direct measurement of the laser beam. Results from light propagation simulations that attempt to include complex effects such as multiple scattering may differ significantly. In this paper, we present two experimental designs of underwater detectors using a 6-by-6 array of photodiodes. The design of the array is based on considerations of the performance of the photodiodes and potential noise sources within the associated hardware. Performance evaluation tests for the two array detectors are conducted in the Ocean Engineering Tank Facilities at the University of New Hampshire. The study presented in this paper also includes geometric beam path diagnostics for a green (532 nm) laser source. The test measurements take into account the source light field and explore the effects of variable environmental conditions in water column scattering (turbidity) and seafloor reflectance.

9827-14, Session 3

Boundary layer effects on optical turbulence: a limiting factor in underwater communications

Silvia C. Matt, Weilin W. Hou, Wesley Goode, U.S. Naval Research Lab. (United States); Samuel Hellmann, Dantec Dynamics Inc. (United States)

Boundary layers around moving underwater vehicles or other platforms can be a limiting factor for optical communication. Turbulence in the boundary layer of a body moving through a stratified medium can lead to small variations in the index of refraction, which impede optical signals. We investigate this boundary layer effect on underwater optics in the Rayleigh-Bénard laboratory tank at the Naval Research Laboratory Stennis Space Center. The tank is set up to generate temperature-driven, i.e., convective turbulence, and allows control of the turbulence intensity. This controlled turbulence environment is complemented by computational fluid dynamics simulations to aid sensor placement, as well as visualize and quantify multi-scale flow patterns. The boundary layer dynamics in the laboratory tank are quantified using high-resolution Acoustic Doppler Velocimeter profilers (Nortek Vectrino), designed to be pointed at boundaries. In addition, a state-of-the-art Particle Image Velocimetry (PIV) system is used to examine the boundary layer velocities and turbulence parameters. Laser-Induced Fluorescence (LIF), a novel method using the PIV setup for temperature measurements, is used to visualize temperature fluctuations in the boundary layer. The LIF data is validated by fast thermistor probes and novel next-generation fiber-optics temperature sensors. This multi-level approach to studying boundary layer effects on optical turbulence, combining in-situ measurements, optical techniques, and numerical simulations, provides new insights into the effect of temperature variations in turbulent boundary layers on underwater optics and can aid mitigate turbulence impacts on underwater optical signal transmission.

9827-15, Session 3

Blue-light digital communication in underwater environments utilizing orbital angular momentum

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Underwater optical communication has recently become the topic of much investigation as the demands for underwater data transmission have rapidly grown in recent years. The need for reliable, high-speed, secure underwater communication has turned increasingly to blue-light optical solutions. As has been shown, the blue-green wavelength window provides an attractive answer to the problem of underwater transmission thanks to its low attenuation, where traditional RF solutions used in free-space communications collapse. Beginning with GaN laser diodes as the optical source, this work explores various methods of increasing underwater data rates using a variety of electrical and optical approaches. Given the challenges presented in an underwater environment, such as the mechanical and optical turbulences that make proper alignment difficult to maintain, it is desirable to achieve extremely high data rates on a point-to-point basis in order to allow the time window of alignment between the transmitter and receiver to be as small as possible. In this paper, work is done to increase underwater data rates through the use of orbital angular momentum combined with various encoding formats designed to create arrays of parallel channels. Analysis is performed on the retention of data quality as information propagates through the underwater channel medium, and optimization techniques are explored via the use of orthogonal frequency division multiplexing. Results are shown for a range of data rates across a variety of channel types ranging in turbidity from that of a clear ocean to a dirty harbor.

9827-16, Session 4

Airborne lidar bathymetry (ALB) waveform analysis for bottom return characteristics

Firat Eren, Shachak Pe'eri, Yuri Rzhanov, The Univ. of New Hampshire (United States)

In modern hydrography (ocean surveying), an uncertainty value is required with each depth measurement. This value is required for all survey technology. Airborne Lidar Bathymetry (ALB) waveforms provide a time log for the interaction of the laser pulse with environment along its ray-path geometry. Using the water surface return and the bottom return, it is possible to calculate the water depth. In addition to bathymetry, the bottom return can provide information on the performance of the systems as well as the bottom characteristics. The main environmental factors that contribute to the response function of the bottom return are: slope, roughness, vegetation, and mineral composition of the surface geology. In this study, the bottom return of the ALB waveform was investigated spatially (i.e., area contributing to the return) and temporally (i.e., the shape of the return) using an Avalanche Photodiode (APD) detector array and photomultiplier tube (PMT). The empirical measurements taken from a variety of bottom characteristics that represent different coastal environments in United States were compared to simulated waveforms. The simulations were generated using hardware parameters typical in commercial ALB systems. The results were used to evaluate bottom detection of the ALB system and the uncertainty associated with the measurements. Bathymetry and backscatter collected by multibeam echosounder were used as reference measurements.

9827-17, Session 4

Underwater impulse response measurements using a diode-based chaotic lidar sensor

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Wideband chaotic lidar sensors offer high resolution measurement of channel impulse responses. An underwater chaotic lidar sensor developed at Clarkson University operates in the blue-green optical spectrum, and provides nanosecond temporal resolution when properly calibrated. Because the sensor is based on small, lightweight, and power-efficient laser diodes and fiber optic devices, its form factor is compatible with deployment on small platforms and unmanned vehicles.

This paper will investigate use of this transmitter for sensing in turbid waters, with a focus on water scattering measurements. Impulse responses, and corresponding modulation depth spectra, will be measured for a variety of water conditions and system geometries.

Quasi-monostatic (reflective) measurements will be made, such as might inform the design of ranging and imaging systems. Bistatic (transmissive) measurements will also be attempted such as might inform the design of a communications link, and will be included if results of widespread interest are obtained. (The current hardware should be sufficient for at least 10 attenuation length communications path measurements, but bistatic testing has not yet been performed.)

9827-18, Session 4

Independent component analysis for underwater lidar clutter rejection

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Linda J. Mullen, Naval Air Systems Command (United States)

Lidar-based sensors offer the possibility for high-resolution, high-accuracy ranging in the underwater environment. Such optical systems experience an exponential propagation loss due to the properties of the underwater channel, namely absorption and scattering. Absorption reduces received signal power, while scattering produces a "clutter" signal that can mask the return from submerged objects in the scene. One approach to suppressing the backscatter clutter is the hybrid lidar-radar technique, in which a laser is intensity-modulated with a radar signal. In this approach, backscatter is observed to have a lowpass filter characteristic due to the channel physics, motivating the use of frequency-domain filtering techniques to suppress the backscatter. New approaches are being explored in which signal processing approaches are used to reject the backscatter clutter.

This work will demonstrate the use of independent component analysis (ICA) to separate the clutter from the object return in a statistical-domain, which should extend the operating range of underwater lidar rangefinders in scatter-limited environments. ICA is a statistical signal processing technique used to separate a mixture of signals into their independent source components based on underlying statistical differences. As backscattered photons never reach the submerged object, it is reasonable to assume independence of the clutter and object returns. This motivates the use of ICA in this work to separate the object return from the clutter. Backscatter and object return distributions will be modeled using an optical propagation simulator, from which statistical parameters will be extracted. ICA will be tailored to use metrics observed to be sufficiently different between the backscatter and object distributions. Some statistical metrics commonly used with the ICA approach include skewness, kurtosis, entropy, and mutual information, each of which may be investigated in this work. The utility of each metric for separating components of underwater lidar returns will be investigated for wideband modulation waveforms. Results from laboratory experiments will be presented and compared to model predictions, as well as to the frequency-domain filtering approach.

9827-32, Session PSTue

Lidar for monitoring methane hydrate in the arctic

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Development and application of new physical methods the detection sensitivity of a nonlinear augmentation allows you to use versatile and powerful method of laser sensing as part of very effective and competitive method of Aero-geochemical search methane emissions in the Arctic environment. In comparison with traditional indirect methods. For example, physico-chemical, this method has the following advantages: remoteness, contactlessness, the possibility of continuous areal and profiled scanning in combination with simultaneous determination of a wide set of chemical elements and compounds, and high the sensitivity and speed of detection (10-6 sec). Automated airborne laser scanning allows assessment methane emissions intensity, as well as evaluation qualitative and quantitative parameters of methane anomalies. The use of Airborne geochemical survey data will be to allow the placement of zones of methane accumulation and promptly monitoring levels of methane concentration changes, thus acquiring all the data needed for climate modelling and estimate of the rate of global warming. In addition, this lidar can be used to assess environmental and engineering conditions in the design, construction and operation of bore wells.

9827-33, Session PSTue

Structural characterization of wind-sheared turbulent flow using self-organized mapping

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A nonlinear cluster analysis algorithm is used to characterize the cross-wind structure of a wind-sheared turbulent flow obtained from the direct numerical simulation (DNS) of the three dimensional temperature and momentum field. This data, obtained from a numerical experiment performed at the United States Naval Research Laboratory, is used as a proxy for hyperspectral imagery. For the three Reynolds numbers of 150, 180, and 220, self-organized mapping is successful in the extraction of boundary layer streaky structures from the turbulent temperature and momentum fields. In addition, it preserves the cross-wind scale structure of the streaks exhibited in both fields which loosely scale with the inverse of the Reynolds number. Self-organizing mapping of the along wind component of the helicity density shows a significant layer of the turbulence field which is spotty and which gets thinner as the Reynolds number increases. This suggests that a layer may exist where there is significant direct coupling between the large scale and small scale turbulent structures. The spatial correlation of the temperature and momentum fields allows for the possibility of the remote extrapolation of momentum structure from thermal structure. The similarity in the high dimensional structure between DNS data, and hyperspectral and multispectral data suggests that the methodology can be applied to the extraction of anomalous structures such as underwater obstacles and depleted coral reefs.

9827-34, Session PSTue

Impact of MODIS SWIR band calibration improvements on Level 3 atmospheric products.

Andrew Wald, Global Science & Technology, Inc. (United States)

States); Robert C. Levy, NASA Goddard Space Flight Ctr. (United States); Amit Angal, Xu Geng, Science Systems and Applications, Inc. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States); Kurt E. Hoffman, Science Systems and Applications, Inc. (United States)

The reflective solar bands (RSB) of the MODIS instruments are characterized on-orbit using regular solar diffuser (SD) observations, with the SD's on-orbit bi-directional reflectance factor change tracked using solar diffuser stability monitor (SDSM) observations. In order to account for the SD's degradation at wavelengths beyond 0.94 μm , the MODIS Characterization Support Team (MCST) developed a long-term correction using earth-scene targets. This correction has been implemented in the MODIS Collection 6 for the 1.24 μm band of Terra MODIS over the entire mission, and is also applied to the 1.37 μm band of Terra MODIS in the forward processing. As the instruments continue to operate beyond their design lifetime of five years, a similar correction is also planned for other SWIR bands of both MODIS instruments.

The SWIR bands play an important role in deriving some key Level-2 (L2) atmosphere products, including aerosol optical thickness, atmospheric water vapor, physical and radiative properties of clouds and profiles of atmospheric temperature and moisture. The correction in Terra bands 5 and 26 impacts the retrieval of these atmosphere products. Using both corrected and uncorrected Terra MODIS Level 1B (L1B) calibration, several L2 atmosphere products are assessed for improvements. A similar evaluation for Aqua MODIS is also performed.

9827-19, Session 5

Present status and future enhancements to ACSPO SST products at NOAA *(Invited Paper)*

Alexander Ignatov, NOAA National Environmental Satellite, Data, and Information Service (United States); Yury Kihai, Maxim Kramar, NOAA National Environmental Satellite, Data, and Information Service (United States) and Global Science & Technology, Inc. (United States); Prasanjit Dash, NOAA National Environmental Satellite, Data, and Information Service (United States) and Cooperative Institute for Research in the Atmosphere (United States); Irina Gladkova, NOAA National Environmental Satellite, Data, and Information Service (United States) and The City College of New York (United States) and Global Science & Technology, Inc. (United States); Boris Petrenko, John Stroup, NOAA National Environmental Satellite, Data, and Information Service (United States) and Global Science & Technology, Inc. (United States); Xingming Liang, NOAA National Environmental Satellite, Data, and Information Service (United States) and Cooperative Institute for Research in the Atmosphere (United Kingdom); Xinjia Zhou, NOAA National Environmental Satellite, Data, and Information Service (United States) and Cooperative Institute for Research in the Atmosphere (United States); Feng Xu, Ctr. for Satellite Applications and Research (United States) and Fudan Univ. (China) and GST, Inc. (United States); Yaoxian Huang, Ctr. for Satellite Applications and Research (United States) and Cooperative Institute for Research in the Atmosphere (United States); John Sapper, NOAA NESDIS Office of Satellite and Product Operations (United States)

NOAA produces several operational SST products (from S-NPP/VIIRS and multiple AVHRRs onboard NOAA and Metop satellites) using the NOAA Advanced Clear Sky Processor for Oceans (ACSPO) SST system. Several experimental products from Himawari-8/AHI and Terra and Aqua MODIS are also routinely produced and analyzed. In 2016, GOES-R will be launched with ABI onboard which is similar to AHI, and in 2017 JPSS-1 with VIIRS is scheduled for launch. All SST products are routinely monitored and validated in the NOAA monitoring system, and distributed to users. Major progress since 2015, current status and future plans are discussed.

9827-21, Session 5

Near real time SST retrievals from Himawari-8 data with ACSPO at NOAA

Maxim Kramar, Yury Kihai, Global Science & Technology, Inc. (United States) and National Oceanic and Atmospheric Administration (United States); Alexander Ignatov, National Oceanic and Atmospheric Administration (United States); Prasanjit Dash, Cooperative Institute for Research in the Atmosphere (United States) and National Oceanic and Atmospheric Administration (United States); Boris Petrenko, Global Science & Technology, Inc. (United States) and National Oceanic and Atmospheric Administration (United States)

The Advanced Himawari Imager (AHI) onboard recently launched Himawari-8 geostationary satellite provides observations with an unprecedented combination of spatial and spectral resolutions and spectral coverage. Full disk (FD) (5500x5500 pixels, with 2 km resolution at nadir) are available every 10 minutes in five SST bands centered at 3.9, 8.6, 10.4, 11.2, and 12.3 microns.

The NOAA Advanced Clear-Sky Processor for Ocean (ACSPO) has been adapted to process AHI data. Experimental near real time production of L2 SST with native AHI spatial and temporal resolution has been commenced at NOAA/STAR on July 6, 2015, and data from 11 June 2015 - present are processed and posted at ftp://ftp.star.nesdis.noaa.gov/pub/sod/sst/acspo_data/l2/ahi/. Normally, there are ~142 FD ACSPO granules per day in GDS2 format (~45 Gbytes/day).

The product is routinely monitored and validated against in situ data in the NOAA SST Quality Monitor (SQUAM; www.star.nesdis.noaa.gov/sod/sst/squam/GEO/). The 10-min validation statistics show a typical bias within about ± 0.2 K and standard deviation within ~ 0.6 K.

Work is underway to generate a reduced volume ACSPO AHI SST product (L2C - collated in time, e.g. 1hr, in the original swath projection, or L3C - collated in time and gridded in space by interpolating/approximating SST L2 data) and archive with NASA PO.DAAC and NOAA NCEI. The same ACSPO algorithms will be applied to the data from the Advanced Baseline Imager (ABI; a sister sensor to AHI) onboard the US new generation GOES-R satellite (to be launched in late 2016), and similar SST products will be generated.

9827-22, Session 5

Preliminary evaluation of AHI clear-sky ocean radiances by comparisons with VIIRS and MODIS for accurate SST retrievals

Xingming Liang, Alexander Ignatov, NOAA National Environmental Satellite, Data, and Information Service (United States); Maxim Kramar, Global Science & Technology, Inc. (United States); Fangfang Yu, ERT, Inc. (United States)

Clear-sky brightness temperatures (BT) in five bands of the Advanced Himawari Imager (AHI) onboard Himawari-8 satellite centered at 3.9, 8.6, 10.4, 11.2 and 12.3 μm (denoted as IR37, IR86, IR10, IR11 and IR12, respectively) are used in the NOAA Advanced Clear-Sky Processor over Ocean (ACSP) SST system. Here, AHI BTs are preliminarily evaluated for stability and checked for consistency with the corresponding VIIRS and MODIS BTs, using the sensor Observation minus Model simulation (O-M) biases. The objective is to ensure accurate and consistent SST products from the polar and geo sensors, and to prepare for the launch of the GOES-R satellite in 2016. All AHI bands are found biased negatively relative to the VIIRS and MODIS (which are found stable and consistent, except for Terra IR86, which is biased low by 1.5 K). Also, the longwave AHI bands IR10-IR12 are less stable. Work is underway to add AHI analyses in the NOAA Monitoring of IR Clear-Sky Radiances over Oceans for SST (MICROS) system, and to improve AHI BTs by collaborating with the sensor calibration Team.

9827-23, Session 5

Exploring new bands in modified multichannel regression SST algorithms for the next-generation polar and geostationary infrared sensors at NOAA

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Multichannel regression algorithms are widely used to retrieve sea surface temperature (SST) from infrared observations with satellite radiometers. Theoretical foundation for these algorithms was laid during the era of the Advanced Very High Resolution Radiometer – specifically, the AVHRR/2 and /3 flown onboard multiple NOAA satellites since 1981. These instruments have three channels centered at 3.7, 11 and 12 μm and suitable for SST. Many existing forms of the SST algorithms employ these three bands at night and only two bands at 11 and 12 μm during the daytime. Newer radiometers, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) flown on Aqua and Terra satellites, the Visible Infrared Imager Radiometer Suite (VIIRS) flown onboard the Suomi National Polar-orbiting Partnership (S-NPP) and follow-on Joint Polar Satellite System (JPSS) satellites, the Advanced Baseline Imager (ABI) which will be onboard the future Geostationary Operational Environmental Satellites – R Series (GOES-R), and its close proxy, the Advanced Himawari Imager (AHI) flown onboard the Japanese Himawari-8 (and to be flown onboard Himawari-9) satellites, carry a number of additional window bands located near 4 μm , 8.5 μm or 10 μm , which can be used for SST. Exploring these new bands may require modifications to the currently used Multi-Channel and Non-Linear SST (MCSST and NLSST) equations. In this presentation, we discuss constructing SST regression equations using an arbitrary number of radiometric bands and explore the information content of the sets of radiometric channels available from the presently flown S-NPP VIIRS and Himawari-8 AHI sensors, and the future GOES-R ABI.

9827-24, Session 6

Improving AVHRR calibration in SST bands

Kai He, NOAA National Environmental Satellite, Data, and Information Service (United States) and Global

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AVHRR clear-sky brightness temperatures (BTs) over ocean and derived sea surface temperatures (SSTs) are produced at NOAA from several polar and geostationary sensors, including AVHRR/3s onboard US NOAA and European MetOp satellites. Analyses in the Monitoring of IR Clear-sky Radiances over Oceans for SST system (MICROS; www.star.nesdis.noaa.gov/sod/sst/micros/) suggest that artifacts in SSTs are strongly linked to anomalies in BTs. Recently, another online system, Sensor Stability for SST (3S; www.star.nesdis.noaa.gov/sod/sst/3s/) has been developed aiming to link BT anomalies to sensor calibration and orbital configuration.

The 3S system reveals that the calibration coefficients are closely linked with the thermal regime of the sensor. In short term, the thermal regime and consequently the calibration coefficients, are more stable over the part of an orbit when the satellite is in the Earth shadow, and more variable when the satellite is in direct Sun. In long term, the thermal regime is associated with orbit drift, so that the sensors spending more time in the Earth shadow, during some periods, are more thermally stable than some others. In the 3S, the equator crossing time (EXT) is computed and modeled to better understand and characterize such an evolution. For thermally stable sensors, improvements to AVHRR calibration are more likely using the dark part of the orbit, rather than following the current line-by-line approach. Improved quality control and smoothing algorithms are developed to produce new calibration coefficients for SST bands in 3S.

9827-25, Session 6

Regional validation and potential enhancements to NOAA polar ACSP SST products

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The Advanced Clear-Sky Processor for Ocean (ACSP) sea surface temperature (SST) products are produced at NOAA from multiple polar platforms and sensors. In addition to the continuous global validation of the ACSP products in the SST Quality Monitor (SQUAM), a regional monitoring system is being developed with a focus on areas interesting to SST users (e.g., coastal and internal waters, high-latitudes, and cloudy regions where coverage is sparse). Those regions are often challenging for SST producers, in terms of SST retrievals (e.g., algorithm may retrieve different values at different view zenith angles) or cloud screening (e.g., dynamic ocean areas are often confused with cloud). For instance, in the high-latitudes, the ACSP clear-sky mask is known to overly conservative, especially in the day/night transition region.

In addition, the regional monitor would help us in obtaining high-quality gridded L3C products (original swath data are mapped on a uniform spatial scale and averaged over daytime and nighttime). However, the collation of multiple observations of the same area during the day requires addressing

some difficulties like the diurnal warming/cooling, and variable cloud conditions and view zenith angles.

This presentation discusses some preliminary results of validating the ACSPO SSTs in the high latitudes and coastal and dynamic regions. We check the data from different passes and satellites for consistency, taking into account various view zenith angles, cloud conditions, and observation times which affect the retrieved SST due to the diurnal cycle.

9827-26, Session 6

Recent improvements to the NOAA iQuam system

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The quality of in situ sea surface temperatures (SSTs) is critical for calibration and validation of satellite SSTs. NOAA has established the in situ SST Quality Monitor (iQuam; www.star.nesdis.noaa.gov/sod/sst/iquam) to support a wide range of its SST Cal/Val responsibilities. The iQuam performs three major functions: 1) quality controls (QC) in situ SSTs (using Bayesian reference and buddy checks in addition to basic screenings, such as duplicate removal, geo-location check, platform track, and SST spike checks); 2) monitors QCed SSTs online in near-real time; and 3) serves them with QC flags and indicators appended, to downstream NOAA applications (SQUAM) and to external users.

Based on experience accumulated with version 1, iQuam is being upgraded to version 2 which includes several major updates. In addition to four in situ data types (drifters, ships, and tropical and coastal moorings) from 1991-pr, four more platform types have been added. The historical data is extended back to Sep 1980 to cover the full satellite era. The iQuam2 now employs two L4 SST references, Reynolds and CMC 0.2 (compared with only Reynolds SST in version 1). In addition to monthly statistics reported in iQuam1, the webpage now additionally displays daily statistics, to help check for data interruptions and abnormalities. QCed data are now served online via iQuam2 website in NetCDF4 format, and report all layers originally included in raw data (including all original QC flags and indicators), as well as additional layers of QC flags and indicators, generated in iQuam2.

9827-27, Session 7

Impact of surface forcing and satellite SST observations on the forecast skill of NCOM-4DVAR

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The quality of the satellite SST observations used in the assimilation along with the accuracy of the surface heat flux used to force the ocean prediction system can have a significant impact on the system's overall prediction skill, especially in coastal regions where the flow can have the tendency to be more ageostrophic. In this study, four one-year-long experiments (May 2013 - April 2014) were performed with the Navy Coastal Ocean Model 4-Dimensional Variational Assimilation (NCOM-4DVAR) system along the coast of southern California. NCOM-4DVAR is an analysis and forecasting tool that employs the representer method to assimilate temperature, salinity and sea surface height observations from satellites, buoys, gliders, and drifters in all 4 dimensions; NCOM is then used to propagate a forecast from the analysis. The experiments differ in which SST satellites are used and the source of the surface forcing; each experiment is forced with surface fluxes

from one of the following different sources: 1) Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), 2) Navy Global Environmental Model (NAVEM), 3) COAMPS with NFLUX corrections, and 4) NAVEM with NFLUX corrections. NFLUX (NRL Ocean Surface Flux System) is a tool that uses 2DVAR to blend a range of satellite observations of surface air temperature, moisture, wind speed, solar and longwave radiation with model forecasts to provide corrections to the model's estimation of the surface heat fluxes. The forecast skill will be computed for these different experiments using independent data, and the model variability resulting from the different surface forcing and SST observations will be analyzed.

9827-28, Session 7

Sensitivity of modeled ocean heat content to errors in short wave radiation and its attenuation with depth

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Short wave radiation (SWR) and its attenuation with depth has a major impact on the vertical distribution of the oceanic water temperature, dynamical processes, and ocean-atmosphere interactions. In numerical modeling of oceanic processes, the SWR usually comes from the atmospheric model predictions, while the short wave attenuation schemes are internally prescribed (estimated) inside the oceanic dynamical model. It has been reported that atmospheric models show a tendency to overestimate the shortwave radiation due to underestimation of predicted low-level clouds. Most existing schemes to specify the attenuation of SWR with depth in numerical models are based on: the Jerlov (1976) water-types classification; climatological estimates of attenuation coefficients or from the biological model predictions of light-absorbing and scattering water constituents. All of the above attenuation schemes are prone to introducing errors in the attenuation of short wave radiation with depth. As a result, we have to deal with two types of errors in the oceanic modeling: those due to the incorrect specification of the magnitude of SWR at the surface (from the atmospheric model), and those due to inaccurate vertical attenuation of SWR (prescribed in the oceanic model). We have developed an approach for estimating errors in the oceanic model heat budget due to errors in surface values of SWR and in its attenuation with depth. Based on this approach, we present examples illustrating sensitivities of the heat budget of the water column to the changes in specification of surface SWR and its attenuation.

9827-29, Session 7

Investigating the potential impact of the Surface Water and Ocean Topography (SWOT) altimeter on ocean mesoscale prediction

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NASA's Surface Water and Ocean Topography (SWOT) satellite, scheduled for launch in 2020, will provide sea surface height anomaly (SSHA) observations with a wider swath width and higher spatial resolution than current satellite altimeters. It is expected that this will help to further constrain ocean models in terms of the mesoscale circulation. In this work, this expectation is investigated by way of twin data assimilation experiments using the Navy Coastal Ocean Model Four Dimensional Variational (NCOM-4DVAR) data assimilation system using a weak constraint formulation. Here, a nature run is created from which SWOT observations are sampled, as well as along-track SSHA observations from simulated Jason-2 tracks. The simulated SWOT data has appropriate spatial coverage, resolution, and noise characteristics based on an observation-simulator program provided by the SWOT science team. The experiment is run for a three-month period during which the analysis is updated every 24 hours and each analysis is used to

initialize a 96 hour forecast. The forecasts in each experiment are compared to the available nature run to determine the impact of the assimilated data. It is demonstrated here that the SWOT observations help to constrain the model mesoscale in a more consistent manner than traditional altimeter observations. The findings of this study suggest that data from SWOT may have a substantial impact on improving the ocean model analysis and forecast of mesoscale features and surface ocean transport.

9827-30, Session 7

Chlorophyll fluorescence and the polarized underwater light field: comparison of polarized radiative transfer simulations and multangular hyperspectral polarization field measurements

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For some years we have been studying multiangular hyperspectral polarization characteristics of underwater scattered light, using a Stokes vector polarimeter developed by us to measure underwater Stokes parameters to retrieve information on the characteristics of non - algal particle (NAP), scattering as well as other IOPs. Prior work by us on the un-polarized nature of chlorophyll fluorescence had provided insights on its expected impacts on the polarized underwater light field. Recent availability to us of the RayXP vector radiative transfer program (VRTE) permits a comprehensive analysis of the relationship of chlorophyll fluorescence to the hyperspectral polarized underwater light field by comparing VRTE simulations using WETLabs package measured IOPs and hyperspectral polarized field measurements for various coastal water conditions. The underwater degree of polarization is markedly reduced in the fluorescence spectral range by addition of the unpolarized fluorescence component. Using measured IOPs and VRTE simulations were made for expected underwater polarized light fields for several locations. Theoretical relationships were developed between fluorescence magnitude and the expected reduction of polarization. These analytically derived relationships were then applied to polarization field measurements to derive the magnitude of the fluorescence component. For comparison purposes, the IOPs were then used in the Hydrolight radiative transfer program to derive the unpolarized elastic underwater water radiance (i.e. without the fluorescence component). This elastic component is then subtracted from the measured total water leaving radiance (in an approach previously reported by us) to retrieve the fluorescence component. Comparisons of these fluorescence components with those using RAYXP simulations and the polarized light field measurements generally show good agreement of the two methods.

9827-31, Session 7

Estimating Terra MODIS polarization effect using ocean data

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Terra MODIS has been known since pre-launch to have polarization sensitivity, particularly in short-wavelength Bands 8 and 9. The MODIS Characterization Support Team (MCST) previously developed a vicarious approach based on measured reflectance from a single pseudo-invariant desert site to track on-orbit polarization sensitivity. Here we extend the monitoring to multiple ocean sites distributed over latitude. The Mueller matrix derived individually from each of the ocean sites can be compared with desert site results to examine the robustness of the derived instrument polarization parameters. These single-site estimates, whether of desert or ocean, necessarily combine measurements taken over a significant fraction of a year to allow the sun's annual change in declination to change the illumination conditions, and thus combining measurements over many months into one Mueller matrix may apparently minimize the annual variation in the Mueller matrix. Therefore in this study we also derive the Mueller matrix row by combining near-simultaneous multiple-latitude ocean measurements allowing the Mueller matrix row to be estimated from a much shorter time series of data. Polarization is not accounted for in MODIS Collection 6 Level 1B calibration, and a good estimate of its effect is required for many MODIS science products.

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9828-1, Session 1

ISR systems: Past, present, and future (Invited Paper)

Daniel J. Henry, Rockwell Collins, Inc. (United States)

Intelligence, Surveillance, and Reconnaissance (ISR) systems have been in use for thousands of years. Technology and CONOPS have continually evolved and morphed to meet ever-changing information needs and adversaries. Funding constraints and procurement philosophies have also evolved, requiring cost-effective innovation to field marketable products which maximize the effectiveness of the Tasking, Capture, Processing, Exploitation, and Dissemination (TCPED) image chain.

9828-2, Session 1

A framework for autonomous and continuous aerial intelligence, surveillance, and reconnaissance operations

Christopher Korpela, Philip Root, U.S. Military Academy (United States); Jinho Kim, Univ. of Maryland, Baltimore County (United States); Stephen A. Wilkerson, U.S. Army Research Lab. (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

We propose a framework for intelligence, reconnaissance, and surveillance using an aerial vehicle with multiple sensor payloads to provide autonomous and continuous security operations at a fixed location. A control scheme and a graphical user interface between the vehicle and operator is strictly mandated for tasks requiring remote and unattended inspection. By leveraging existing navigation and path planning algorithms, the system can autonomously patrol large areas, automatically recharge when required, and relay on-demand data back to the user. This paper presents recent validation results of the system and its sensors using the proposed framework.

9828-3, Session 1

An analysis of air balloon usage for intelligence, surveillance, reconnaissance and location stabilization

Emre Bakan, Turkish Air Force Academy (Turkey)

In the last centuries, humankind became very curious about sky and to learn it, we made lots of researches. To use it for our benefit, we built and developed lots of vehicles. Researches about air systems grow with a great acceleration and huge complex systems equipped with high technology invented in this period of time. Although all this technological development today we still use same simple vehicles like as air balloon.

Air balloons are systems which gain altitude with gases in it less heavy than air such as Helium and Hydrogen. This system which most frequently used for meteorological guesses isn't common in military areas but the altitude we have with balloons can easily pass the altitude which we can make visual observation. Even if we design a simple camera system, mount it to balloon, drop a few balloon simultaneously we can earn more intelligence than satellites in easier and cheaper way.

Balloon system's earning altitude, in another way balloon system's being uncontrollable in vertical way is the biggest disadvantages for its usage. There is no a well detailed research about how can we prevent this disadvantages but there is a way to make balloons more reliable and handfull. With the project which mentioned overall in the article we will not only be able to use balloons for intelligence or scientific researches but also stabilize the altitude.

9828-4, Session 1

Particle flow filter-based airborne-SLAM

Erol Duymaz, Turkish Air Force Academy (Turkey)

SLAM has been a popular research topic in the field of robotics for many years. Moreover, its applications on land vehicles are still going on intensively. SLAM is relatively easy to implement in robotics compared to air vehicles. Since robots and land vehicles move at lower speeds in a 2D area, necessary mathematical model is developed in two dimensions only. In contrast, UAVs which move much faster than robots or land vehicles need more complex mathematical models in a 3D environment. This further complicates the application of SLAM technique on UAVs, which is known as Airborne SLAM (A-SLAM). Moreover, kinematic model of a UAV results in a set of nonlinear equations which brings additional complexity.

As the result Simultaneous Localization and Mapping (SLAM) is a good choice for UAV navigation when both UAV's position and region map are not known. Expectedly due to nonlinearity of kinematic equations of a UAV Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are employed whereas in this study, not just EKF and UKF based A-SLAM concepts are reviewed but also particle flow filter based A-SLAM discussed in details by presenting the formulations and MATLAB Simulink model with simulation results. The UAV kinematic model and state-observation models for these filter based A-SLAM methods are developed to analyze the filters' consistencies. Results supports the superiority of particle flow filter in recursive state estimation in A-SLAM problem in spite of its some drawbacks.

9828-5, Session 1

An aerial 3D printing test mission

Michael P. Hirsch, Thomas McGuire, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

This paper proposes, evaluates and presents results from an aerial, high altitude balloon (HAB)-based test mission for plastic 3D printing. The proposed mission will demonstrate the capability of the fused deposition modeling plastic printing technique for use in low-temperature, low-pressure and volatile environments. Over the course of the mission (with pressure and temperature decreasing on ascent and increasing on descent), performance under multiple temperature / pressure / volatility conditions will be able to be assessed. A mission design is presented and assessed. Particular focus is paid to the visible light sensing system that will be used to assess the performance of the onboard 3D printer.

A solar balloon (where lift is provided by the sun heating the air inside the balloon to be hotter than the surrounding air) will be used for this test mission. This balloon will be made of black Mylar sheeting which is formed into the inverted pyramid design of the balloon using masking tape. The payload housing is connected to this using a string line. A small and lightweight 3D printer is located inside this housing. The housing has limited

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ventilation to prevent a pressure difference from building up; however, it is designed to prevent materials from escaping and to provide limited thermal insulation. A cut-down and recovery system is also included which will detach the payload from the solar balloon and facilitate a parachute-controlled descent.

To assess the performance of the 3D printer in this environment, multiple types of data will be collected. Temperature, pressure and inertial measurement data will be collected and time-correlated to visual imagery of the 3D printing process. Additionally, the resulting object will also be assessed for completeness and structural durability.

The imaging system will be comprised of a Raspberry Pi single-board computer and a Raspberry Pi camera. This unit will be powered by an attached battery unit. The camera will be mounted at an angle to the printer to facilitate imaging of both the printer mechanism as well as the object being printed. The design and configuration of this system will be discussed in detail.

By demonstrating the efficacy of 3D printing in the aerial environment, the mission demonstrates the potential to create or augment aerial craft from an aerial platform. Previously, aerial platforms were used as aircraft carriers for manned craft. The aerial printing technology could enable a similar mission concept for unmanned aerial vehicles enabling numerous sensing (or other) mission-on-demand capabilities. The carrier craft would be equipped with the raw materials and electronic components needed to fabricate multiple craft (and, prospectively, multiple types of craft). These materials and supplies would require less volume than pre-fabricated craft as well as allowing the decision of what type of craft to use to be deferred to during the mission.

The paper concludes with a discussion of the current state of the technology and the future steps to enabling high-quality 3D printing performance in the aforementioned aerial environment

9828-6, Session 1

**Providing over-operability in advanced
ISR systems by a high-level networking
technology**

Peter Sapaty, National Academy of Sciences of Ukraine
(Ukraine)

With the world dynamics increasing rapidly, during the last weeks and days especially, the advanced ISR technologies are becoming of enormous importance to predict, analyse, and withstand unexpected situations and conflicts. Traditional parts-to-whole interoperability principles in organizing distributed ISR systems may not always be adequate in rapidly changing environments, and more holistic approaches may be needed. A new high-level distributed control technology will be presented that can effectively integrate scattered ISR facilities of international forces into global-goal-driven systems providing overall awareness and domination. It pursues so called "overoperability" philosophy allowing us to grasp large distributed systems by dynamically creating holistic, gestalt-inspired, operational infrastructures in them in a parallel virus-like mode. Due to full interpretation and mobility in distributed networked environments, the technology has high level or ubiquity, stealthiness, and self-recovery especially in asymmetric situations, always fulfilling local and global objectives.

9828-7, Session 2

**Laser-based satellite communication
systems stabilized by non-mechanical
electro-optic scanners**

Michael Ziemkiewicz, Scott R. Davis, Scott D. Rommel,
Derek Gann, Benjamin Luey, Joseph D. Gamble, Michael H.
Anderson, Vescent Photonics Inc. (United States)

Laser communications systems provide numerous advantages for

establishing satellite-to-ground data links. As a carrier for information, lasers are characterized by high bandwidth and directionality, allowing for fast and secure transfer of data. These systems are also highly resistant to RF influences since they operate in the infrared portion of the electromagnetic spectrum, far from radio bands. In this paper we will discuss an entirely non-mechanical electro-optic (EO) laser beam steering technology, with no moving parts, which we have used to form robust optical data connections through air. This technology will enable low cost, compact, and rugged free space optical (FSO) communication modules for small satellite applications. The EO beam-steerer at the heart of this system is used to maintain beam pointing as the satellite orbits. It is characterized by extremely low values for size, weight and power consumption (SWaP) – approximately 300 cm³, 300 g, and 5 W respectively, which represents a marked improvement compared to heavy, and power-consuming gimbal mechanisms. It is capable of steering a 500 mW, 1 mm short wave infrared (SWIR) beam over a field of view (FOV) of 30° x 6°. Polarization gratings (PG's) have been used to extend the FOV by 2°N for N PG's per axis. We have integrated this device into a communication system and demonstrated the capability to lock on and transmit a high quality data stream by modulation of SWIR power.

9828-8, Session 2

**Piezo-based miniature high resolution
stabilized gimbal**

Nir Karasikov, Gal Peled, Roman Yasinov, Rita Yetkariov,
Nanomotion Inc. (United States)

Piezo motors are characterized by higher mechanical power density, fast response and direct drive. These features are beneficial for miniature gimbals.

A gimbal based on such motors was developed. Diameter is 58 mm, weight is 160 gram. The gimbal carries two cameras. A Flir Quark and an HD day camera. The dynamic performance is as high as 2.5 rad/sec velocity and 90 rad/sec² acceleration. A 2 axes stabilization algorithm was developed, yielding 80 micro radian stabilization. Further a panoramic image capture at a rate of 6 stabilized field of view per second was developed.

The presentation will review the motor features; gimbal structure and open architecture, allowing adaptation to other cameras (SWIR etc.); the algorithm and, further, will review experimental results of stabilization and of panoramic view taken on a vibration platform and on a UAV.

Further miniaturization is feasible and will be discussed as well.

9828-9, Session 2

**Break diffraction limit using nearest
neighbour pixel modified optical transfer
function**

Yu Wang, GDS Optics (United States); YuJing Lu, NBXtech
(China)

For single frame images taken by a diffraction limited optical system with regularly spaced pixel detector, if the pixel pitch of the detector is much small than the diffraction pattern, then the spatial resolution of the images can be enhanced with nearest neighbour pixel modified optical transfer function method. This method rewrites PSF in terms of nearest pixel model and develops a modified optical transfer function using shift theory of Fourier Transform. Theoretical simulation shows that this method is able to enhance resolution of single frame images beyond the diffraction limit. Initial experiment results have good agreement with the theory.

9828-11, Session 3

The eyes of LITENING

Eric Moser, Northrop Grumman Electronic Systems (United

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States)

LITENING is an airborne system-of-systems providing long-range imaging, targeting, situational awareness, target tracking, weapon guidance, and damage assessment, incorporating a laser designator and laser range finders, as well as non-thermal and thermal imaging systems, with multi-sensor boresight. Robust operation is at a premium, and subsystems are partitioned to modular, swappable line-replaceable-units (LRUs) and shop-replaceable-units (SRUs). This presentation will explore design concepts for sensing, data storage, and presentation of imagery associated with the LITENING targeting pod.

The “eyes” of LITENING are the electro-optic sensors. Since the initial LITENING II introduction to the US market in the late 90s, as the program has evolved and matured, a series of spiral functional improvements and sensor upgrades have been incorporated. These include laser-illuminated imaging, and more recently, color sensing. While aircraft displays are outside of the LITENING system, updates to the available viewing modules have also driven change, and resulted in increasingly effective ways of utilizing the targeting system. One of the latest LITENING spiral upgrades adds a new capability to display and capture visible-band color imagery, using new sensors. This is an augmentation to the system’s existing capabilities, which operate over a growing set of visible and invisible colors, infrared bands, and laser line wavelengths. A COTS visible-band camera solution using a CMOS sensor has been adapted to meet the particular needs associated with the airborne targeting use case.

9828-12, Session 4

Precision optical navigation guidance system

Dmitry S. Starodubov, Kyle McCormick, Pete Nolan, Leo Volfson, Torrey Pines Logic, Inc. (United States)

In our paper we present the results of PRecision Optical Navigation Guidance (PRONG) system development. The problem addressed by our development is the U.S. Navy’s need for a non-RF system that will provide precision ship-relative navigation (PS-RN) data to manned and unmanned aircraft to support aided or autonomous landing on aircraft carriers and other U.S. Navy ships.

The system provides continuous, high quality range and bearing data to fixed wing aircraft during landing approach to an aircraft carrier. The PRONG system uses infrared optical communications with advanced modulation and coding to measure range between ship and aircraft with accuracy and precision better than 1 meter at ranges more than 7.5 km (4 nm). The system includes an innovative electro-optical receiver design which measures bearing from aircraft to ship with accuracy and precision better than 0.5 mRad (0.03 degrees). The PRONG system provides real-time range and bearing updates to multiple aircraft at rates up to several kHz, and duplex data transmission between ship and aircraft.

The PRONG system will benefit the Navy in many ways: it will reduce pilot workload during carrier landings under adverse sea and weather conditions, and will enable fully autonomous landings of unmanned aerial vehicles on both aircraft carriers and small-deck Navy ships. The PRONG system provides the same benefits for fixed and mobile land-based platforms and autonomous vehicles. Among the many commercial applications are civilian aircraft and UAVs, and self-driving smart vehicles.

The effort is supported by Navy STTR program and executed in collaboration with University of Southern California.

9828-13, Session 4

Pattern of life analysis for diverse data types

Clay Spence, Ben Southall, Alex Tozzo, Jun Hu, Thomas Kover, Joseph Ferraro, Hui Cheng, SRI International Sarnoff (United States)

Navy and Marine commanders are responsible for conducting missions such as non-combatant evacuation, humanitarian aid or disaster relief. It is vital for them to have as much relevant information about the Area of Operations as possible in the mission planning. Understanding the normal Pattern of Life and thus recognizing anomalies are both very important steps in the initial assessment and planning phase.

SRI has developed a prototype system which is capable of automatically analyze the Pattern of Life of ports, routes and vessels from big collections of AIS data. The Pattern of Life of these entities are characterized into a set of semantic attributes which are intuitive to understand and easy to query. Further, the prototype system provides an interface to ingest other types of information such as iTRACE (Lockheed-Martin’s Integrated Trending, Recognition, & Assessment of Current Events) to augment the knowledge it can extract of the Area of Operations. In addition, the prototype system can interact with the commanders by answering questions and simulating what-if scenarios to keep human in the processing loop.

9828-14, Session 4

Automated image quality measurement based on manmade object detection in video frames

Andrew Kalukin, National Geospatial-Intelligence Agency (United States); Joshua D. Harguess, Space and Naval Warfare Systems Ctr. Pacific (United States); Andrew John Maltenfort, National Geospatial-Intelligence Agency (United States); John M. Irvine, Draper Lab. (United States); C. Algire, National Geospatial-Intelligence Agency (United States)

Image quality is often assessed using the National Imagery Interpretability Rating Scale (NIIRS). When sensor specifications, atmospheric conditions, and collection parameters are well characterized, NIIRS can be predicted analytically with high accuracy. However, in many cases, atmospheric conditions and noise degrade image products in ways that are hard to predict or characterize. For these cases, it may be useful to measure image quality based on in-scene information; for example, trained analysts can accurately assess image quality based on the utility of the image product for identifying targets in the scene.

This presentation will show how automated methods of detecting in-scene events and objects such as moving cars and pedestrians can be used for automated image quality assessment. The detected targets can be used to focus on areas of activity in images, identify features to compare with the NIIRS scale, or select edges and surfaces for which image sharpness and noise can be evaluated. Though the research is currently focused on video image quality, the techniques for object detection, image registration, and change detection can be applied to image products from most sensors.

9828-15, Session 4

A study of the effects of degraded imagery on tactical 3D model generation using structure-from-motion

Leslie Bolick, Joshua D. Harguess, Space and Naval Warfare Systems Ctr. Pacific (United States)

An emerging technology in the realm of airborne intelligence, surveillance, and reconnaissance (ISR) systems is structure-from-motion (SfM), which enables the creation of three-dimensional (3D) point clouds and 3D models from two-dimensional (2D) imagery. There are several existing tools, such as VisualSfM and open source project OpenSfM, to assist in this process, however, it is well-known that pristine imagery is usually required to create meaningful 3D data from the imagery. In military applications, such as the use of unmanned aerial vehicles (UAV) for surveillance operations, imagery

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is rarely pristine. Therefore, we present an analysis of structure-from-motion packages on imagery which has been degraded in a controlled manner, such as adding noise and/or resolution changes. Also, we consider two platforms for imagery collection (a fixed-wing UAV and a quadcopter) and their effect on the quality of the 3D model generation. The 3D models generated from each of the scenarios and degradations are evaluated qualitatively and quantitatively and recommendations are given for practical considerations when collecting imagery for 3D model generation.

9828-16, Session 5

Development of a real-time neural network estimator to improve defense capabilities of HEO satellites

Barry M. Gross, Sam Lightstone, Fred Moshary, Moshe Fink, The City College of New York (United States)

The need to observe thermal targets from space is crucial for monitoring both natural events and hostile threats. Defense satellites choose high sensitivity with a small number of spectral channels. This limitation makes atmospheric contamination due to water vapor a significant problem that cannot be determined from the satellite itself. For this reason, we show how it is possible to ingest meteorological satellite data using a neural network to allow for the compensation of water absorption and re-emission in near-real time.

Model atmospheres were created by collecting radiosonde sounding data, and using these profiles in MODTRAN. MODTRAN numerically solves the radiative transfer equation, and outputs band radiation and band transmission.

The complete sounding data would be too cumbersome to use as inputs for the neural network; therefore, the vertical profiles for the temperature, water vapor, and pressure were interpolated into three levels of temperature and three levels of water vapor. Other inputs for the training of the neural network included: surface pressure, surface type (Boolean inputs for desert, farm, and forest), and zenith angle.

Rapid Refresh vertical profiles were injected into the neural network and transmission maps over the continental United States were generated. These maps showed an inverse relationship between water vapor and transmission proving that the neural network results are physical.

To further prove the accuracy of the neural network, Rapid Refresh data matching a Modis overpass was injected into the neural network. A regression analysis shows 88% accuracy for matching the radiance with satellite data.

These results show that in near real-time, a neural network can compensate for water absorption and re-emission missing from satellite data. Further training of the neural network with more locations and longer time periods will certainly improve the results.

9828-17, Session 5

NeuroDSP accelerator for embedded human detection application

Michel Paindavoine, Univ. de Bourgogne (France); Olivier Boisard, Univ. de Bourgogne (France) and GlobalSensing Technologies (France); Alexandre Carbon, Jean-Marc Philippe, CEA LIST (France); Olivier Brousse, GlobalSensing Technologies (France)

Visual recognition of familiar objects in natural environments is easily done by a human subject. Executing the same task on a “classical” computer requires complex and costly algorithms in terms of computing power. Thus, “Neuro-Inspired” approaches, based on models from biology, can be good candidates to reduce computational complexity. In this context, the Hmax model proposed by T. Serre, built on work of T. Poggio, shows that the

recognition of an object in the visual cortex mobilizes V1, V2 and V4 areas. From the computational point of view, V1 corresponds to the area of the directional filters (for example Gabor or wavelet filters). This information is then processed in the V2 area in order to obtain local maxima which are then sent to a classifier such as an artificial neural network. This neural processing module corresponds to V4 area of the visual cortex and is intended to categorize objects in a scene.

To realize autonomous vision systems embedding such processing (with focus on low-power consumption), a new Neural Processor architecture named NeuroDSP was investigated. It is based on clusters of 32 elementary processors working in parallel. Implementation of this new processor has been considered using TSMC 45nm ASIC technology.

We introduce in this paper the original Hmax model and we then show how to optimize it to decrease the amount of calculations in the context of human detection application. Finally, we describe the implementation of the optimized Hmax model using the new NeuroDSP accelerator in the context of this application.

9828-18, Session 5

Automatic construction of aerial corridor for navigation of unmanned aircraft systems in Class-G airspace using lidar

Dengchao Feng, North China Institute of Aerospace Engineering (China); Xiaohui Yuan, Univ. of North Texas (United States)

According to the airspace classification by the Federal Aviation Agency, Class G airspace is typically the airspace 1,200 feet or less to the ground, which is beneath class E airspace and between class B-D cylinders around towered airstrips. Since radio communication is not required in class G airspace, it is completely uncontrolled. With the rapid development of unmanned aerial systems (UASs), it enables a booming market for various applications from parcel delivery to public security. However, the lack of flight supervision mechanism in this airspace, UAS missions poses many safety issues, e.g., collision, etc. Collision avoidance and route planning for UASs in class G airspace is critical for broad deployment of UASs in commercial and security applications. Yet, unlike road network, there is no stationary marker in airspace to identify corridors that are available and safe for UASs to navigate. The complex airspace that is full of restrictions makes it a great need, but a challenge as well, to have the aerial corridor automatically developed.

In this paper, we present an automatic LiDAR-based airspace corridor construction method for navigation in class G airspace and a method for route planning to minimize collision and intrusion. Our idea is to combine LiDAR and high-resolution remote sensing imagery to automatically identify ground objects that pose navigation restrictions such as airports and high-rises. Normalized digital surface model (nDSM) is derived from LiDAR point cloud to provide an altitude-based class G airspace description. Without terrain elevation, ground is leveled and the altitude upper limit of class G airspace is applied. In addition, nDSM precisely characterizes the man-made above-ground structures. However, among these man-made structures, the airspace above some of them is classified as restricted airspace in different types. Hence, classification and recognition of such ground objects are needed. LiDAR data provide elevation and reflectivity properties of the ground objects. However, factors such as atmospheric moisture induce errors in LiDAR measurements, which make it highly challenging to classify certain land objects of interest with satisfactory performance. High-resolution remote sensing images are hence used to provide complementary information. Features from images and point clouds are extracted to characterize different restriction-related ground objects, e.g., airports, national security areas, etc. A boosting-based classification method is used to learn from these features to make robust classification. Following the FAA Aeronautical Information Manual, the ground objects that define the restricted airspaces are used together with digital surface model derived from LiDAR data to construct the aerial corridor for navigation of UMSs.

Our method is evaluated with data from major metropolitan areas, e.g. Houston, and mid-sized cities, e.g., New Orleans. Preliminary results

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demonstrate competitive performance and the construction of aerial corridor can be automated with much great efficiency.

9828-19, Session 5

**High-performance image deinterlacing
using optical flow and artifact post-
processing on GPU/CPU for surveillance
and reconnaissance tasks**

Thomas Müller, Fraunhofer-Institut für Optronik,
Systemtechnik und Bildauswertung (Germany)

The necessity to process interlaced images in surveillance, reconnaissance, or further computer vision areas should be a topic of the past. But, for different reasons, it is not. So, there are situations in practice, in which interlaced images have to be processed. Since a lot of algorithms strongly degrade when working with such images directly, a usual method is to double or interpolate image lines in order to discard one of the two included image frames. This is efficient but leads to weak results, in which half of the original information is lost. Alternatively, a lot of valuable computation time has to be spent to solve the highly complex deinterlacing task in order to improve the results significantly. In this paper, an efficient algorithm is presented to solve this dilemma. First, the algorithm solves the complex 2-D mapping problem using the best state-of-the-art optical flow method that could be found for this purpose. But, of course, for different physical reasons there are regions which cannot properly be handled by optical flow by itself. Therefore, an efficient post-processing method detects and removes remaining artifacts afterwards, which is the main contribution of this paper. This method is based on color interpolation incorporating local image structure. The presented results document the overall performance of the approach with respect to obtained image quality and calculation times. The method is easy to implement and offers a valuable pre-processing for a lot of computer vision tasks.

9828-20, Session 5

**Use of higher-order moments to detect
dim moving targets in clutter**

Shannon R. Young, Air Force Institute of Technology
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Technology (United States) and Oak Ridge Institute for
Science & Education (United States); Bryan J. Steward, Air
Force Institute of Technology (United States)

The proliferation of imaging sensors is creating a volume of motion imagery that exceeds processing and analysis capacity. A robust, efficient method to automate detection of dim point-like targets in motion imagery is required. Current automated processing methods are effective for targets with high SNR (over about 6), but fail or are computationally costly and slow at low SNR. AFIT has previously demonstrated the higher-order moments anomaly detection (HOMAD) algorithm, which is computationally efficient and effective in reducing the detection threshold for moderate SNR targets. The present effort extends this idea to improve detection rates of dim signals (less than about 5). This briefing will present initial results of several AFRL and AFIT developed methods, and the strengths and weaknesses of each will be assessed.

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9829-1, Session 1

Automatic polar ice thickness estimation from SAR images

Maryam Rahnemoonfar, Texas A&M Univ. Corpus Christi (United States)

Global warming has caused serious damage to our environment in recent years. Accelerated loss of ice from Greenland and Antarctica has been observed in recent decades. The melting of polar ice sheets and mountain glaciers has a considerable influence on sea level rise and altering ocean currents, potentially leading to the flooding of the coastal regions and putting millions of people around the world at risk. Synthetic aperture radar (SAR) systems are able to provide relevant information about subsurface structure of polar ice sheets. Manual layer identification is prohibitively tedious and expensive and is not practical for regular, long-term ice-sheet monitoring. Automatic layer finding in noisy radar images is quite challenging due to huge amount of noise, limited resolution and variations in ice layers and bedrock. Here we propose an approach which automatically detects ice surface and bedrock boundaries using distance regularized level set evolution. In this approach the complex topology of ice and bedrock boundary layers can be detected simultaneously by evolving an initial curve in radar imagery. Using a distance regularized term, the regularity of the level set function is intrinsically maintained that solves the reinitialization issues arising from conventional level set approaches. The results are evaluated on a large dataset of airborne radar imagery collected during IceBridge mission over Antarctica and Greenland and show promising results in respect to hand-labeled ground truth.

9829-2, Session 1

Exploiting synthetic aperture radar imagery for retrieving vibration signatures of concealed machinery

Francisco Pérez, Justin B. Campbell, The Univ. of New Mexico (United States); Monica Jaramillo, The Univ. of New Mexico (United States) and Sandia National Labs. (United States); Ralf Dunkel, General Atomics Aeronautical Systems, Inc. (United States); Thomas D. Atwood, Armin W. Doerry, Sandia National Labs. (United States) and The Univ. of New Mexico (United States); Walter H. Gerstle, Balu Santhanam, Majeed M. Hayat, The Univ. of New Mexico (United States)

It has been demonstrated that the instantaneous acceleration associated with vibrating objects directly imaged by synthetic aperture radar (SAR) can be estimated through the application of the discrete fractional-Fourier transform (DFRFT) to the complex SAR image. In general, vibration signatures may include, for example, the number of chirped sinusoids as well as their respective base frequencies and chirp rates. By further processing the DFRFT-processed data for clutter-noise rejection by means of pseudo-subspace methods, the SAR-vibrometry method can be reliable as long as the signal-to-noise ratio (SNR) of the slow-time SAR signal at the range-line of interest exceeds 15dB. The Nyquist theorem dictates that the maximum measurable vibration frequency is limited by half of the pulse-repetition frequency. This paper focuses on the detection and estimation of vibrations generated by concealed machinery. This is a challenging task in general because the vibration signatures of the source are typically altered by their housing structure; moreover, the SNR at the surface of the housing structure tends to be reduced. Here, experimental results for three different vibrating targets, including one concealed target, are reported using complex SAR images acquired by the General Atomics Lynx radar. The concealed vibrating

target is a servo motor with an off-balance weight attached to it, which was housed in wooden housing. The vibrations of the motor were transmitted to a chimney that extended above the housing. Using the SAR vibrometry approach, it was shown that it is possible to distinguish among the three vibrating objects based on their vibration signatures.

9829-4, Session 1

Multistatic passive coherent location using multilateration techniques

Sean A. Kaiser, The Pennsylvania State Univ. (United States); Andrew J. Christianson, Naval Surface Warfare Ctr. Crane Div. (United States); Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Passive Coherent Location (PCL) is a developing radar field, in which the system processes reflections from opportunistic illumination sources in the environment for detection and tracking. Many developments and improvements of PCL implement pseudo-monostatic and bistatic radar configurations, however, with the proliferation of commercial communication systems, the spectrally dense environment proves to be in favor of a multistatic PCL system. In the multistatic case, it can be shown that geolocation of a target is a unique extension of multilateration algorithms. In multilateration, the receiver location is unknown and calculated by exploiting the intersections of distance from receiver to transmitters; in multistatic PCL, an object location is unknown and the intersection of transmitter distance to receiver and reflection distance to receiver are utilized. Multilateration is a well-studied topic where there are many developed techniques that can be applied after the reflection distance is derived electromagnetically.

The framework for a time of arrival based multistatic PCL is provided using time difference of arrival as a measure of propagation time and path length. A nonlinear multilateration solver using a least means square algorithm calculates the geolocation of the object within a tolerable error. Using a frequency modulated (FM) test signal, simulated results show comparable results to a bistatic PCL system using angular measurements for geolocation. Furthermore, introducing error in time for a multistatic multilateration system is more tolerant than a bistatic system with angular inaccuracy. The developed multistatic PCL system is realized and verified using an FM signal.

9829-5, Session 1

Frequency notching effects on GPR imagery while operating in crowded spectrum scenarios

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Over the past decade the RF spectrum in which radar, telecommunication, navigational, and other systems operate has become increasingly crowded. We have developed a Stepped-Frequency Radar (SFR) which can avoid areas of the RF spectrum in which systems are already operating; this allows for mitigation of RFI on the radar, as well as reducing the interference impinged on other systems from the radar. This paper addresses the impact of frequency notching on GPR imagery, and methods of mitigating negative effects.

The SFR operates over 300–2000 MHz, with a minimum frequency step-size of 1 MHz. The radar transmits and receives in pulsed intervals, allowing for receiver blanking of close-in targets. The SFR is vehicle mounted and utilizes two dual-polarized Tx horn antennas on either end of the Rx antenna aperture, which consists of 16-Vivaldi slot antennas (which can be rotated to either H or V polarization). The radar is capable of completing a sweep over its entire operating band in <200 μ Sec (with 200 nsec pulses and 5 MHz steps). Furthermore, the radar is capable of averaging directly on the FPGA in which it stores the digitized Rx channels, thereby increasing data collection times while improving coherency between averages.

9829-6, Session 2

Context-sensitive design and human interaction principles for usable, useful, and adoptable radars

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Over the past two decades, Synthetic Aperture Radar (SAR) systems have become increasingly easy to build, integrate and deploy on a wide range of remote sensing platforms. As SAR systems get smaller and lighter, and as the image formation and data exploitation algorithms continue evolving, there should be rapid growth in the adoption and implementation of SAR across a wide range of remote sensing challenges, from time-critical search and rescue operations to pattern-of-life analysis in strategic operations. However, experienced SAR advocates in government, industry and academia express concern about the underutilization of SAR's unique capabilities, particularly in relation to other remote sensing systems.

This paper draws on several years' worth of interactions and design studies in the SAR community to identify and characterize the issues mitigating against the adoption and application of SAR systems in near-real time operational environments. We enumerate organizational and human-oriented design challenges related to the acquisition and integration of SAR systems into mission platforms and operational workflows. For SAR systems to realize their remote sensing potential in today's tactical and operational environments, SAR advocates and stakeholders should be adopting frameworks and methods from the interdisciplinary fields of contextual and human-oriented design. This paper presents several examples of system integration problems in real-world SAR domains and explains how established design practices support SAR system usability, utility and adoptability in operational settings.

9829-7, Session 2

Second generation of AVTIS FMCW millimeter wave radars for mapping volcanic

David G. Macfarlane, Duncan A. Robertson, Scott L. Cassidy, Univ. of St. Andrews (United Kingdom)

We report on the design and deployment of the second generation of the All-weather Volcano Topography Imaging Sensor (AVTIS) ground-based millimeter wave radar instruments designed for the routine and timely monitoring of the changing topography of volcanic lava domes. The AVTIS2 and AVTIS3 instruments are solid state 94 GHz FMCW radars which can record returns from natural terrain at ranges of up to ~7 km with a range resolution of ~0.5 m. These second generation instruments were designed to operate ten times faster than the prototype AVTIS1 whilst reducing power consumption to a level suitable for sustained battery powered, portable use as well as installation at a remote site under solar power. They were designed for surveying the lava dome at the Soufrière Hills Volcano (SHV), Montserrat, W.I.. AVTIS2 is a rapidly deployed field survey instrument whereas the AVTIS3 radar is a telemetered monitoring station installed at SHV since May 2011. However, no significant topographical activity associated with SHV has occurred since February of 2010. We therefore examine the performance of the new AVTIS radar as a tool for monitoring

static topography over time and shall report on the operational statistics of the AVTIS3 radar both as a radar sensor and as a means of generating digital elevation maps. We also report on localized rain measurements made as a data by-product that may be useful for flood monitoring.

9829-8, Session 2

94GHz pulsed coherent radar for high power amplifier evaluation

Duncan A. Robertson, Robert I. Hunter, Univ. of St. Andrews (United Kingdom); Thomas F. Gallacher, Aalto Univ. (Finland)

Novel vacuum tube technologies are emerging which will advance the state-of-the art in high power amplification at millimeter wave frequencies, notably the gyro-travelling wave amplifier (gyro-TWA) with helically corrugated interaction region. Such amplifiers will open new possibilities for high power, wideband, millimeter wave radars for applications such as remote sensing (e.g. cloud profiling) and space debris monitoring using inverse synthetic aperture radar (ISAR) techniques.

We will present the design and characterization of a 94 GHz pulsed coherent radar to be used for the evaluation and demonstration of a gyro-TWA wideband, high power amplifier. The radar is designed to be fully coherent and exploits a low phase noise architecture to maximize Doppler performance. The pulse characteristics of the radar will be fully characterized at low power prior to adding the gyro-TWA so that the effect of the high power amplifier can be assessed.

For outdoor demonstrations the radar has been designed with 0.5 m diameter transmit and receive antennas. We selected to use horn-fed Fresnel zone plate lens antennas (FZPs) with 4-level phase quantization as a low cost method of realizing such large aperture antennas. We will show that the measured performance of these FZPs agrees closely with the design predictions and exceeds that obtainable with a Cassegrain of equivalent size.

9829-9, Session 2

Eye-safe single aperture laser radars for 3D acquisition

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In this paper we present the new exciting development of the novel single aperture laser radar design that we presented at 2015 DSS conference. The upgrade transforms the design into a real time 3D imaging solution. The single aperture implementation of laser radars in combination with beam scanning solutions enables low cost, compact and efficient laser systems for 3D acquisition. The design benefits include the lack of dead zones; improved stability and compact footprint for the system implementation with simultaneous scanning of transmit and receive channels using the single scanning aperture. The continuation of modular design approach implementation for the system provides a wide range of operating parameters, sizes and costs of the systems. In our presentation we will compare the trade-offs of various scanning solutions based on mechanical and solid state designs. The overview of requirements for various 3D applications is used to define the benefits of the selected scanning approaches from high performance coherent airborne systems to low cost commercial applications. The unique opportunity for a low cost commercial 3D imaging solution based on an eye safe laser and low cost single aperture scanner will be presented with consideration of manufacturability and demand in the new markets including driverless cars, airborne drones and computer gaming. A brief overview of the technology implementation for defense and security applications is presented. The solutions for meeting challenging reliability and performance requirements of airborne implementations are discussed.

9829-10, Session 2

FlexSAR: demonstrating cost effective agile adaptive radar

Chad Knight, Mark D. Jensen, Brent Haslem, Space Dynamics Lab. (United States)

The FlexSAR radar system was designed to be a high quality, low-cost, flexible research prototype instrument. Radar researchers and practitioners often desire the ability to prototype new or advanced configurations, yet the ability to enhance or upgrade existing radar systems can be cost prohibitive. A flexible radar system that can be extended easily, with minimal cost and time expenditures, is critical to reduce the resources required for developing and validating new advanced radar modalities. It also can foster innovation and provide risk reduction since actual data can be collected in the appropriate mode, processed, and analyzed. This allows for an accurate, detailed understanding of the corresponding trade space. This paper is a follow-on to last year's paper and discusses the advancements that have been made in the FlexSAR system design. Two additional receive/transmit phase centers have been incorporated in the FlexSAR system, generating a total of four transmit/receive phase centers (a number that is easily extendable). Multiple examples demonstrating the flexible nature of the FlexSAR system are discussed and analyzed. For instance, the FlexSAR system is configured to perform a multistatic multiple input multiple output (MIMO) along track interferometry (ATI) collect, as well as an interferometric (IF) SAR collect. The results are presented and discussed. Additionally, system design considerations (radio frequency, digital, and software) are discussed with a focus and emphasis towards flexibility and reuse.

9829-11, Session 3

Polarization differences in ground penetrating radar performance in the presence of disturbed earth

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Over the past two decades, the U.S. Army has conducted multiple research and development studies investigating the feasibility of radar detection of buried targets. The Army Research Laboratory (ARL) has contributed to many of these programs by performing system simulations, as well as experimental data collections and processing. These ground penetrating radar (GPR) studies included airborne, vehicle and handheld radar platforms. In many scenarios, it has been noticed that the target burial sites can be identified primarily by the presence of disturbed soil placed on top of the targets. Previous studies have considered the change in ground surface roughness properties as the cause for the change in radar response.

In this paper, we create a new model which accounts for the different dielectric properties of the disturbed soil as compared to the background. The target (in our case, a landmine) is buried under the disturbed soil volume, while a rough air-ground interface provides the background clutter. The simulations consider an airborne, ultra-wideband (UWB) synthetic aperture radar (SAR) operating in a frequency range between 0.5 and 3 GHz. The target is detected based on the difference in radar response between the background clutter and the combined signature of the target and disturbed soil. We are particularly interested in the radar response differences between V-V and H-H polarizations, for various depression angles, with the goal of predicting the configuration which offers the highest signal-to-background-clutter ratio and therefore the best radar performance.

9829-12, Session 3

Alignment of visible, thermal infrared, harmonic radar, and linear radar for hidden object detection

Philip J. Saponaro Jr., Univ. of Delaware (United States); Kyle A. Gallagher, The Pennsylvania State Univ. (United States); Kelly D. Sherbondy, U.S. Army Research Lab. (United States); Chandra Kambhamettu, Univ. of Delaware (United States)

This paper presents the detection of a hidden main charge and initiator type (electronic) devices using the fusion of stereo color, stereo thermal, harmonic radar imagery, and linear radar imagery. A harmonic/linear radar system has been developed at the Army Research Lab in Adelphi, MD. The radar utilizes 16 receive antennas spaced 3 inches apart across a total aperture length of 4 feet and a single transmit antenna. A 16:1 switching network allows a single radar receiver to collect data from each of the 16 receive antennas. A back-projection algorithm is used to form co-boresight linear and harmonic radar image. The harmonic radar is able to detect and classify electronic devices through obscurement, but the imagery contains artifacts due to ground bounces and coupling. We propose fusion between the four modalities using a homography to align the imagery and a linear combination for displaying the fused imagery. The homography is calculated once for a static environment using manually obtained image correspondences. We used a custom built sensor platform to record 100 trials using 5 classes of electronic objects in different locations and orientations in an indoor environment. The targets were placed on average 12m away from the sensor platform to mimic real standoff distances. We created a graphical user interface for displaying the fused modalities and to demonstrate how the resulting fused image can make hidden objects easily visible to the user.

9829-13, Session 3

Segmenting and extracting terrain surface signatures from fully polarimetric multilook SIR-C data

Jorge V. Geaga, Consultant (United States)

We report results from the segmenting and study of terrain surface signatures of fully polarimetric multilook L-band and C-band SIR-C data. Entropy/alpha/anisotropy decomposition features are available from single multilook pixel data. This eliminates the need to average data from several pixels. Entropy and alpha are utilized in the segmentation along with features we have developed primarily from the eigenanalysis of the Kennaugh matrices of multilook data. We have previously reported on our algorithm for segmenting fully polarimetric single look TerraSAR-X, multilook SIR-C and 7 band Landsat 5 data featuring the iterative application of a feedforward neural network with one hidden layer. A comparison of signatures from simultaneously recorded data at L and C bands are presented. The terrain surfaces surveyed include the ocean, lakes, lake ice, bare ground, desert salt flats, lava beds, vegetation, sand dunes, rough desert surfaces, agricultural and urban areas

9829-14, Session 3

A millimeter-wave reflectometer for whole-body hydration sensing

Weidong Zhang, Elliott R. Brown, Wright State Univ. (United States)

In recent years skin hydration has become a more common factor in evaluating human health, approaching the importance of a "vital sign" in

some circumstances. Through the use of THz sensing, hydration contrast has been the basis for imaging burns and skin carcinomas. And more recently, the remarkable hydration sensitivity of the THz reflectivity has been pursued for corneal health assessment. A drawback in most of these applications has been sensor detection or image acquisition time, which is usually measured in minutes. In the present work we have developed and demonstrated a contact hydration sensor that can be manually scanned over large regions of the body. It is based on a simple millimeter-wave reflectometer centered in W Band (94 GHz) and incorporating a Gunn oscillator, a waveguide ferrite circulator, a Schottky rectifier, and a pyramidal horn having a flexible transparent window. A double amplitude-modulation and synchronous-detection scheme allows for measurements of the skin reflectance with an accuracy of $\pm 2\%$, a spot size of ~ 1 cm, and a modulation bandwidth of ~ 10 kHz. Large areas of the torso, arms, and legs can be manually mapped in less than one minute, and accurate calibration performed with soft-tissue surrogates. The system is demonstrated on human subjects and shown to correlate with their known hydration levels.

9829-15, Session 3

Microwave image reconstruction method using a circular antenna array cooperating with a transmitter inside a capsule

Huiyuan Zhou, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Ilangko Balasingham, Norwegian Univ. of Science and Technology (Norway)

Small intestinal tumors, being non-specific in clinical symptoms and lacking ideal examination methods for anatomical reasons, are difficult to diagnose, especially tumors of jejunum and ileum, with a low preoperative diagnosis rate. New methods of examining small intestinal tumors have been explored in recent years. Due to the complicated structure and high water-contained tissues around the intestine, the conventional microwave imaging method cannot supply proper results. In this paper, we present a new system combining an RF transmitter within an endoscopic capsule and external circular antenna arrays around the body. The antennas around the body act as both transmitter and receiver respectively, and communicate with the transmitter inside the capsule to collect additional data which cannot be obtained using the conventional system. In this paper, the synthetic data are collected from the circular phantom and Billie phantom using CST software. For the image reconstruction, we employ the Levenberg-Marquardt algorithm, which is a kind of Newton inversion method to reconstruct the dielectric profile of the object. The imaging process involves two parts. The first part uses a relatively low frequency signal to obtain the average dielectric constant of entire object, which is used as pre-information for the second step of the imaging process. In this second part, we reconstruct the high resolution dielectric image around the intestinal region by choosing a smaller discretization of the object and a higher frequency. The results show that the new system using the two step imaging algorithm can achieve a high resolution image for detecting and imaging small tumors.

SUBMITTED TO SPECIAL SESSION ON MEDICAL RADAR

9829-16, Session 4

Fractal characteristics for binary noise radar waveform

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Noise radar has attracted many researchers recently due to its advantages over conventional radars. The performance of noise radar is determined by its waveform characteristics. Therefore investigating characteristics of noise radar waveforms has significant value for evaluating noise radar performance. In this paper, we use binomial distribution theory to analyze general characteristics of binary phase coded (BPC) noise waveforms. We also develop Monte Carlo framework to explore the characteristics that

are difficult to describe analytically. Through Monte Carlo experiments, we reveal the Fractal relationship of BPC noise waveforms between their lengths and their maximum side lobes, and propose using fractal dimension to measure noise waveform performance.

Noise radar is random signal radar with noise waveform. It has significant advantages over traditional radars: unambiguous on Doppler and range measurement, high immune to noise, and very low probability of intercept (LPI). Noise radar also has high electro-magnetic compatibility, good electronic counter countermeasure (ECCM) and good counter electronic support measure (CESM) capability, and ideal "thumbtack" ambiguity function. One of the key performance factors for noise radar is its noise waveforms. There are two types of noise waveforms: amplitude changing and amplitude constant. In this paper, we will focus on amplitude constant noise waveform: BPC noise waveform

First, we show that the side lobes of BPC noise waveforms follow symmetric binomial distribution. From this distribution, we prove that for the aperiodic autocorrelation of noise waveform, the closer to the main lobe, the higher probability to have high side lobes. We derive a formula to compute entropy of side lobes and demonstrate from this formula that when we move away from the main lobe, the entropy of side lobes decreases monotonically. Using central limit theorem, we show that for the waveform that has large length, the probability of its side lobes near its main lobe follows Gaussian distribution.

For the maximum side lobes of BPC noise waveforms which are critical to noise radar performance, but difficult to formulate analytically, we develop Monte Carlo methods to estimate their average values. We use random number generation and logistic mapping chaotic system to generate independent Bernoulli trial for noise waveform generation. Then we conduct Monte Carlo simulation tests and discover that maximum side lobes and BPC noise waveform length form Fractal relationship, and its fractal dimension is 0.648. This fractal dimension provides measurements on how fast side/main ratios of noise waveform increase as we increase noise waveform lengths, and is an important parameter to measure BPC noise waveform performance.

9829-17, Session 4

High frequency oscillators for chaotic radar

Aubrey N. Beal, Jonathan N. Blakely, Ned J. Corron, U.S. Army Research, Development and Engineering Command (United States); Robert N. Dean Jr., Auburn Univ. (United States)

Approaches for extending the operating frequency of chaotic oscillators while preserving system parameters are presented. This work focuses on implementing a class of exactly solvable chaotic oscillators at speeds that allow real world radar applications. The implementation of a chaotic radar using a solvable system has many advantages due to the generation of aperiodic, random-like waveforms that exhibit an analytic solution. These advantages include high range resolution, no range ambiguity, and spread spectrum characteristics. These systems allow for optimal detection of a noise-like signal by the means of a linear matched filter using simple and inexpensive methods. Recently, it has been shown that chaotic waveforms are optimal candidates for use with a simple, second order matched filter. This motivates the construction of a ranging system based on chaotic signals and their corresponding matched filters. These exactly solvable chaotic systems consist of mixed signal electronics that implement interval stretching and folding mechanisms necessary for chaotic behavior. As the increase in frequency of these systems promotes new applications, non-ideal electronic effects must be accommodated to preserve the system's closed form solution. Particularly, the use of a Negative Impedance Converter (NIC) introduces frequency dependent behavior causing distortion in the chaotic waveforms. This paper outlines the use of exactly solvable chaos in ranging systems, while addressing electronic design issues related to the frequency dependence of the system's stretching function introduced by the use of NICs.

9829-18, Session 4

Ad hoc array collaborative beam-forming using ultra-wideband noise signals

David B. Alexander, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Braham Himed, Air Force Research Lab. (United States)

In many applications, noise waveforms are attractive options for implementation into radar surveillance systems. Furthermore, recent developments have increased the viability of using antenna arrays with elements randomly distributed in space to collaboratively form a radiation beam pattern. To study the effectiveness of these systems, signals were transmitted from and received by the generated network and the correlation between the signals was computed. The performance of ultra-wideband noise waveforms in these networks was compared to that of other signal types.

Computer simulations were programmed for ad sensor networks with nodes located randomly in space. The nodes were generated within a circular area, and the individual positions were taken from a uniform random distribution. Different signal types – including band-limited Gaussian noise, simple sinusoidal pulse waveforms, and frequency-swept cosine waveforms – were implemented to compare the performance. The waveform incident on the target was obtained by applying amplitude attenuation and phase shift to the transmitted signal based on the properties of the random array, and by accounting for atmospheric absorption effects. Similar considerations were made for the incident waveform to obtain the received signal. The correlation between the transmitted and received signals was computed to estimate the performance of the system.

9829-19, Session 4

Investigation of target and ground clutter reflections on the correlation between transmitted and received noise signals

Joshua M. Allebach, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Braham Himed, Air Force Research Lab. (United States)

The use of noise waveforms for radar has been popular for many years; however, not much work has been done to extend their use to long range applications. To study the usefulness of noise signals in discriminating between targets of interest and ground clutter, the correlation values between transmitted and received signals was investigated. Reflections from these different surfaces are dependent on the frequency of operation and other characteristics such as polarization which may impact noise waveforms in a different manner than traditional waveforms.

To study the use of noise waveforms on different target types, a signal was modified in both its amplitude and phase in a manner dependent on the operational frequency. The amplitude of the signal was modified based upon known radar backscatter values for different target and clutter types. These values were adjusted to be proportional to voltage as opposed to the standard power relationships for the radar cross sections. Similarly, the phase shift introduced to the signal from target reflections was an assumed distribution with respect to frequency. If clutter was being illuminated, a random phase was introduced due to the random nature of surface variations and so path lengths. Utilizing these assumptions, a direct comparison between noise waveforms reflecting off of various targets and traditional waveforms was made.

9829-21, Session 5

Efficient sidelobe ASK based dual-function radar-communications

Aboulnasr Hassanien, Moeness G. Amin, Villanova Univ. (United States); Yimin D. Zhang, Temple Univ. (United States); Fauzia Ahmad, Villanova Univ. (United States)

Sidelobe control based dual-function radar-communication (DFRC) systems enable information embedding into the radar-emission via modulating the sidelobe of the instantaneous beampattern. The radar operation usually dictates that the leakage of the transmit power within the sidelobe region be minimized. Therefore, the number of distinct sidelobe levels that can be used to reliably deliver information is small. The state of the art methods for DFRC employ sidelobe amplitude-shift keying (ASK) and multiple orthogonal waveforms to embed one bit of information per waveform. However, dividing the transmitted power evenly among the waveforms being used yields low signal-to-noise ratio (SNR) at the communication receiver. In this paper, we propose a new signaling strategy for enhancing the SNR leading to an improvement in the communication delivery performance. The proposed method employs one reference waveform and simultaneously transmits a number of orthogonal waveforms equals to the number of 1's in the binary sequence being embedded. The proposed method enables achieving close to 3 dB SNR gain as compared to existing sidelobe ASK methods. In addition, the employed waveform diversity can be used to enhance the radar performance. The effectiveness of the proposed information embedding strategy is verified using simulations examples.

9829-22, Session 5

Computationally efficient beampattern synthesis for dual-function radar-communications

Aboulnasr Hassanien, Moeness G. Amin, Villanova Univ. (United States); Yimin D. Zhang, Temple Univ. (United States)

The essence of amplitude-modulation based dual-function radar-communications is to modulate the sidelobe of the transmit beampattern while keeping the main beam, where the radar function takes place, unchanged during the entire processing interval. The number of distinct sidelobe levels (SLL) required for information embedding grows exponentially with the number of bits being embedded. Existing DFRC techniques realize the required number of SLLs via synthesizing a number of transmit beampatterns that is equal to the number of SLLs. Unfortunately, for high data rates, the computational complexity and the memory size needed for synthesizing the beampatterns and storing the corresponding weight vectors is very expensive. In this paper, we propose a simple and computationally cheap method for transmit beampattern synthesis which requires designing and storing only two beamforming weight vectors. The proposed method first designs a principal transmit beamforming weight vector based on the requirements dictated by the radar function of the DFRC system. Then, a second weight vectors is obtained by projecting the principal weight vector onto the orthogonal space of the steering vectors associated with the intended communication directions. This projection introduces deep nulls towards the communication directions without noticeable effect on main radar beam. Additional SLLs can be realized by simply taking weighted linear combinations of the two available weight vectors. The effectiveness of the proposed method for beampattern synthesis is verified using simulations examples.

9829-23, Session 5

Effects of fluctuation in refractive index of atmosphere on synthetic aperture radar images

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SAR image formation methods ignore atmospheric absorption and assume that the speed of electromagnetic (EM) waves is equal to the speed of light in vacuum, i.e., the refractive index of the background medium is simply 1. However, atmospheric absorption may attenuate incident power. If not properly compensated, absorption may induce artifacts in the form of systematic variations in ground reflectivity. Fluctuations in the speed of EM waves introduce phase errors that lead to mispositioning of scatterers in reconstructed images. We are interested in quantitatively analyzing the artifacts induced by atmospheric absorption and fluctuations in the background wave speed.

To model atmospheric absorption, we consider scalar wave equation with complex wave-number. We present the SAR received signal model when the background medium has a complex-valued refractive index. To model variations in wave speed, we assume that the real part of the refractive index deviates from 1. In the image formation, we use an imaging operator derived based on the assumption that the refractive index of the atmosphere is 1. We analyze errors in the reconstructed image induced by this mismatch. Our analysis shows that, including an imaginary component to wave-number results in exponential decay in the incident and scattered waves modulated by the range of the antenna to scatterers in fast-time frequency domain. When this term is not properly compensated by filtering, it results in an undesirable point spread function that induces systematic variations in the ground reflectivity. However, ignoring absorption does not result in mispositioning of targets. Fluctuations in the speed of EM waves, on the other hand, result in mispositioning of scatterers. We perform numerical simulations to verify our theoretical analysis. The artifacts in SAR images due to changes in the atmosphere conditions have been reported in [1-5]. In the final paper, we will present our analysis and compare our results with those presented in [1-5].

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9829-24, Session 5

Radar-centric scattering of possible targets for orbital debris remediation

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Decades of international launches and various space expeditions in the low Earth orbit (LEO) have caused it to become littered with man-made objects and debris. With over 22,000 objects larger than a softball, and hundreds

of thousands in smaller size existing, remediation efforts must take place to minimize the likelihood of on-orbit debris collisions with either civilian, or military assets. While many conceptual techniques for debris remediation exist, an active form of engagement will most likely be necessary. In regards to the debris itself, smaller objects become difficult to track, and require more onboard resource consumption for engagement. Conversely, larger bodies, such as rocket bodies, offer a greater volume for removal with less required space-based operations. Robust sensor packages required to detect, track, and engage these targets would most likely include an onboard microwave remote sensing system such as Radar. To assist in the architectural design of these sensors, relevant a priori Radar-centric scattering knowledge of these large freely tumbling bodies is essential. This paper focuses on the scattering phenomenology from possible large bodied orbital debris, such as rocket bodies, whose geometries are publically available. Particular emphasis is placed on the exhaust nozzle as this is a commonly reoccurring feature between rocket configurations, which could be utilized a grappling, interlocking, or interfacing structure. Radar required, and producible, data will be analyzed with considerations for extracting the nozzle feature from the bodies themselves presented. Radar Cross Section (RCS) distributions, tumbling body analysis, and other related scattering parameters will be assessed and discussed.

9829-25, Session 6

Phase responses of harmonics reflected from radio-frequency electronics

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The phase responses of nonlinear-radar targets illuminated by stepped frequencies are studied. Data is presented for an experimental radar and two commercial electronic targets at short standoff ranges. The amplitudes and phases of harmonics generated by each target at each frequency are captured over a 100-MHz-wide transmit band. As in the authors' prior work, target detection is demonstrated by receiving at least one harmonic of at least one transmit frequency. In the present work, experiments confirm that the phase of a harmonic reflected from a radio-frequency electronic target at a standoff distance is linear versus frequency. Similar to traditional wideband radar, the change of the reflected phase with respect to frequency indicates the range to the nonlinear target.

9829-26, Session 6

Harmonic magnitude and phase progression for an amplifier at the input and output ports

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The amplitudes of the second and third harmonics generated by an amplifier are well documented. These are known as the second and third order intercept points, IP2 and IP3, respectively. Traditionally, IP2 and IP3 measurements are taken at the output port of nonlinear devices. The IP2 and IP3 points are not well established for the input ports of nonlinear devices. This paper examines both the magnitude and phase of the second and third harmonics generated by an amplifier. Measurements are taken at the input and output ports of the amplifier. A good understanding of

how the harmonic phase changes with respect to the input phase of the fundamental frequency is crucial for developing a harmonic radar system and accurately characterizing its performance.

9829-27, Session 6

Waveform design for cognitive radar: target detection in heavy clutter

Benjamin H. Kirk, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Anthony F. Martone, Kelly D. Sherbondy, U.S. Army Research Lab. (United States)

In many applications of radar systems, detection of targets in environments with heavy clutter and interference is difficult. It may be desired for example that a radar system detect targets with a low radar cross-section (RCS) at a further range in order to insure safety as well as be able to detect these targets with very few false negative or positive readings. In a cognitive radar system there are ways that these negative effects can be mitigated and target detection can be significantly improved. Cognitive radar offers solutions to issues using a priori knowledge of targets and environments as well as real time adaptations. Within a complex cognitive radar system algorithms and approaches are needed that exploit knowledge of the environment and targets.

This paper explores the ability of cognitive radar to adapt and optimize the transmitted waveforms for various target and clutter spectral response characteristics. Cognitive radar allows for this capability with the incorporation of digital arbitrary waveform generators (DAWGs) and memory database for quick access. A database is used to hold a priori and dynamic knowledge of the operational environment and targets, such as clutter characteristics and target RCS estimations. The transmitted waveform is next tailored using knowledge of the target-to-clutter ratio (TCR) in order to maximize the mutual information between the target and received signal for enhancing target detectability. Results show that these methods provide significant improvement in distinguishing target signatures from clutter or interference. This allows for the possibility to increase the range of the system as well as reduce missed detections.

9829-28, Session 6

A dynamic spectrum analysis solution for the characterization of the UHF spectrum

Richard O. Pooler, The Pennsylvania State Univ. (United States); Anthony F. Martone, U.S. Army Research Lab. (United States); Kyle A. Gallagher, The Pennsylvania State Univ. (United States); Kelly D. Sherbondy, U.S. Army Research Lab. (United States); Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Today's radio frequency (RF) spectrum is increasingly an overcrowded environment of commercial and military RF systems due in part to the exponentially increasing number of RF applications (Wi-Fi, Bluetooth, cell phones, etc.) along with the equally increasing bandwidth required to use these applications. The ever expanding need for more bandwidth within the already congested RF spectrum calls for an understanding of the spectrum opportunity (or lack thereof) in the electromagnetic environment for the purpose of RF allocation and usage. In order to gain a strong understanding of the RF spectrum activity, an advanced spectrum sensing hardware and software system is required. In particular, the spectrum sensing equipment presented in this paper requires high resolution, high sampling rates, a large dynamic range, high speed processing abilities, and large storage capacity.

The proposed Spectral Analysis Solution (SAS) is a multichannel superheterodyne signal analyzer with the intended applications of RF research, radar verification, and general purpose spectrum sensing primarily in the Ultra-wideband (UWB) range of Ultra High Frequency (UHF) to S band. The SAS features one direct current (DC) to 1.8 GHz wideband

channel with eight narrowband channels that have adjustable instantaneous bandwidths ranging from less than 1 MHz to 100 MHz. The wideband channel provides a large picture of the spectrum while the narrowband channels allow for high resolution and a high spurious free dynamic range (SFDR) capabilities. An adaptive graphic user interface (GUI) has been implemented for the system that actively pulls and processes the system data in real time. This paper will show the low and high level analysis of the system along with system validation and implementation results.

9829-29, Session 7

An overview of the Air Force Research Laboratory's sensor directorate and selected radar research topics (*Invited Paper*)

Tony C. Kim, Air Force Research Lab. (United States)

No Abstract Available

9829-30, Session 7

Pathfinder radar development at Sandia National Laboratories (*Invited Paper*)

Steven P. Castillo, Sandia National Labs. (United States)

Sandia National Laboratories' Airborne Intelligence, Surveillance and Reconnaissance (ISR) systems enable a new product paradigm in radar capabilities and modalities. With the ability to shrink sensor size, increase resolution, raise image quality, and advance real-time on-board processing, Sandia has been dedicated to producing the continuous cycle of next generation systems for nearly three decades. Sandia specializes in the full system design of exquisite Synthetic Aperture Radar (SAR), Ground Moving Target Indicator (GMTI), target recognition and other sensor systems for the Department of Defense, Other Government Agencies and industry partners.

9829-31, Session 7

Radar research at the U.S. Army Research Laboratory (*Invited Paper*)

Eric D. Adler, U.S. Army Research Lab. (United States)

No Abstract Available

9829-32, Session 7

Three-dimensional radar imaging techniques and systems for near-field applications (*Invited Paper*)

David M. Sheen, Thomas E. Hall, Douglas L. McMakin, A. M. Jones, Jonathan R. Tedeschi, Pacific Northwest National Lab. (United States)

No Abstract Available

9829-33, Session 7

Ultra-wideband radar research at Lawrence Livermore National Laboratory (*Invited Paper*)

Neil R. Beer, Steven W. Bond, David H. Chambers, Peter Haugen, Jae Jeon, Lawrence Livermore National Lab. (United States); David W. Paglieroni, Christian T. Pechar, Lawrence Livermore National Lab. (United States)

No Abstract Available

9829-34, Session 8

Heartbeat detection using UWB radar with through the wall sensing applications

David Boutte, Vince Radzicki, Allan R. Hunt, AKELA, Inc. (United States)

Remote sensing of people through walls and other optically impenetrable obstructions is an important problem in defense, security and disaster recovery areas. Mapping the inside of room during a hostage crisis from a safe distance or reliably locating victims in a disaster are examples of challenging and unsolved problems in these areas. Low frequency radar (UHF - L band) is well suited address these challenges. It can easily penetrate walls while still producing a sufficient return signal from objects and people inside the building. Discriminating people from clutter objects in the room requires the exploitation of heartbeat, breathing and other human biometric signatures. A portable ultra-wideband stepped frequency radar has been developed operating between 375 - 6000MHz and has previously demonstrated detections and spatial location of humans inside buildings up to 25m away using gross target motion. The wide frequency bandwidth allows for sufficient range resolution to discriminate closely spaced objects.

This paper discusses system hardware and details algorithm development and sensing phenomenology to extract higher order biometric signals (such as target heartbeat) from experimental data collected using the UWB system. The algorithm relies on extracting time-frequency information from single frequencies sampled during radar operation. The motion due to the heartbeat introduces small Doppler frequency variations on the sampled continuous wave (CW) radar waveform. These deviations show up as a unique return in the time-frequency plane. This technique is able to remove a significant amount of static clutter present in the radar scene.

Experimental results are presented detailing sensing phenomenology and comparing results using the UWB system and an extremely low phase noise CW source. This comparison is useful to quantify system performance since system phase noise is a limiting characteristic when sensing small frequency variation close to the carrier. Results show detections of heartbeats both in line of sight and behind a wall.

9829-35, Session 8

Feature analysis for indoor radar target classification

Travis D. Bufler, Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Machine learning models having the ability to separate human targets from indoor clutter show great promise in through-wall radar applications. Typically, indoor scenarios contain a large amount of clutter that interferes with the radar's ability to distinguish and classify targets. The paper investigate the application of SVM (Support Vector Machines) and feature selection algorithms for the classification of stationary human targets and indoor clutter via spectral features through simulated and experimental data.

Using Finite Difference Time Domain (FDTD) techniques allows us to examine the radar cross section (RCS) of humans and indoor clutter objects by utilizing different types of computer models. FDTD allows for the spectral characteristics to be acquired over a wide range of frequencies, polarizations, aspect angles, and materials. The acquired target and clutter RCS spectral characteristics are then investigated in terms of their potential for target classification using SVMs. Based upon variables such as frequency and polarization, a SVM classifier can be trained to classify unknown responses as a human or clutter.

9829-36, Session 8

Through-wall MIMO radar detection of multiple targets

Evan T. Gebhardt, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Sean P. Broderick, U.S. Army CERDEC Intelligence and Information Warfare Directorate (United States)

Multiple widely separated antennas offer improved target detectability and can detect more unique targets than a phased array can detect alone. MIMO radar can also suppress returns from complex clutter through signal processing techniques. By processing each transmit and receive positions independently and fusing them improved target identification and clutter suppression can be achieved. These features of MIMO radar make it attractive for through the wall detection applications because clutter returns are high and the number of targets is unknown.

Data from multiple transmit and receive antennas arranged in linear positions showed improved resolution and target detection as the number of bistatic positions increased. Calibration techniques were considered to account for different electrical lengths between different bi static positions. Data were taken of a calibration target and compared against the theoretical return of an ideal point target to create a calibration coefficient. By applying these calibration techniques, the resolution was seen to improve. Data have been collected of targets through walls in high clutter environments. The antennas are positioned at known positions along the walls of rooms. Data will be collected from 1, 2, 3, or 4 walls of a single room to reflect different real world scenarios. The data will then be compared to single antenna case and linear MIMO case to see what improvements exist.

9829-57, Session PSTue

Antenna phase center locations in tapered aperture subarrays

Armin W. Doerry, Douglas L. Bickel, Sandia National Labs. (United States)

Antenna apertures that are tapered for sidelobe control can also be parsed into subapertures for Direction of Arrival (DOA) measurements. However, the aperture tapering complicates phase center location for the subapertures, knowledge of which is critical for proper DOA calculation. In addition, tapering affects subaperture gains, making gain dependent on subaperture position. Techniques are presented to calculate subaperture phase center location, and algorithms for equalizing subapertures' gains. Sidelobe characteristics and mitigation are also discussed.

9829-58, Session PSTue

Representing SAR complex image pixels

Armin W. Doerry, Sandia National Labs. (United States)

Complex pixel values for Synthetic Aperture Radar (SAR) images of uniform distributed clutter can be represented as either real/imaginary (also known as I/Q) values, or as Magnitude/Phase values. Generally, these component

values are integers with limited number of bits. For clutter energy well below full-scale, Magnitude/Phase offers lower quantization noise than I/Q representation. Further improvement can be had with companding of the Magnitude value.

9829-59, Session PSTue

Comments on airborne ISR radar utilization

Armin W. Doerry, Sandia National Labs. (United States)

In modern multi-sensor multi-mode Intelligence, Surveillance, and Reconnaissance (ISR) platforms, the plethora of options available to a sensor/payload operator are quite large, leading to an over-worked operator often down-selecting to favorite sensors and modes. For example, Full Motion Video (FMV) is justifiably a favorite sensor at the expense of radar modes, even if radar modes can offer unique and advantageous information. The challenge is then to increase the utilization of the radar modes in a manner attractive to the sensor/payload operator. We propose that this is best accomplished by combining sensor modes and displays into 'super-modes'.

9829-60, Session PSTue

Index for surface coherence (ISC): a method for calculating change susceptibility

Jonathan Tran, Sandia National Labs. (United States)

Coherent change detection (CCD) provides a way for analysts and detectors to find ephemeral features that would otherwise be invisible in traditional synthetic aperture radar (SAR) imagery. However, CCD can produce false alarms in regions of the image that have low SNR and high vegetation areas. The method proposed looks to eliminate these false alarm regions by creating a mask which can then be applied to change products. This is done by utilizing both the magnitude and coherence feature statistics of a scene. For each feature, the image is segmented into groups of similar pixels called superpixels. The method then utilizes a training phase to model each terrain that the user deems as capable of supporting change and statistically comparing superpixels in the image to the modeled terrain types. Finally, the method combines the features using probabilistic fusion to create a mask that a user can threshold and apply to a change product for human analysis or automatic feature detectors.

9829-64, Session PSTue

3D ultra-scale + network-on-chip MPSoC antenna phased-array sounder for radar astronomy

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the first results from the development of a new antenna phased-array digital sounder for radar astronomy applications. The prototype offers an unprecedented variety of scientific observations. It features state-of-the-art all-digital Computer Architecture design methodologies that expedite the high-performance signal processing requirements of the system. At this stage of the project, a portable low-power antenna phased array sounder is considered, suitable for both standalone installations and remote scientific campaigns. The system features a multi-frequency, multi-bandwidth, multi-dynamic range, multi-antenna mode and multi-polarization scheme to empower the implementation of various techniques for Radar Astronomy sounding.

9829-65, Session PSTue

Instantaneous, stepped-frequency, nonlinear radar part 2: experimental confirmation

Kenneth I. Ranney, U.S. Army Research Lab. (United States); Gregory J. Mazzaro, The Citadel-The Military College of South Carolina (United States); Kyle A. Gallagher, The Pennsylvania State Univ. (United States); Anthony F. Martone, U.S. Army Research Lab. (United States); Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Last year, we presented the theory behind the "instantaneous stepped-frequency, non-linear radar". We demonstrated through simulation that certain devices (when interrogated by a multi-tone transmit signal) could be expected to produce a multi-tone output signal near harmonics of the transmitted tones. This hypothesized non-linear (multi-tone) response was then shown to be suitable for pulse compression via standard stepped-frequency processing techniques. At that time, however, we did not have measured data to support the theoretical and simulated results.

In what follows we present laboratory measurements confirming our initial hypotheses. We begin with a brief description of the experimental system, and then describe the data collection exercise. Finally, we present measured data demonstrating the accurate ranging of a non-linear target.

9829-66, Session PSTue

Urban-area extraction from polarimetric SAR image using combination of target decomposition and orientation angle

Bin Zou, Da Lu, Zhilu Wu, Harbin Institute of Technology (China); Zhijun G. Qiao, The Univ. of Texas Rio Grande Valley (United States)

This paper will present an improvement to an urban-area extraction scheme for the accurate mapping in urban by polarimetric synthetic aperture radar (SAR) image.

The polarimetric target decomposition (PTD) theory expresses the average mechanism as the sum of independent elements in order to associate a physical mechanism with each component in each resolution cell. Land-cover classification can be achieved by using features extracted from PTD. However, in urban areas, a large change in scattering intensity is found, if the urban buildings are not parallel to SAR platforms, double-bounce scattering becomes weak and volume scattering components become dominant. In this case, it is difficult to distinguish volume scattering mechanisms from forest areas and urban areas for accurate classification because of similar polarimetric responses.

A new urban extraction scheme is proposed by implementing a rotation of the covariance matrix to improve accurate results that oriented urban areas are recognized as double-bounce objects from volume scattering first and, subsequently, taking randomness of orientation angle into account for further restriction of urban area. This method is carried out subject to fully polarimetric SAR data sets and enables the discrimination of oriented urban blocks versus vegetation as different scattering objects which previously were difficult to be discriminated. Before applying the extraction, the orientation angle which can be used to reduce the dependence of the components on the relative azimuth is calculated by minimizing the cross-polarized term. Then, by rotating the polarimetric covariance matrix with orientation angle, it can distinguish vegetation from oriented urban areas. At last, calculate the randomness of the orientation angle and refine the extraction result. For grassland area and orthogonal urban area, the angle distribution of the orientation angle is concentrated around zero degree; the angle of forested area is distributed rather randomly and the angle of urban area is nearly homogeneous because of the majority of buildings are

aligned in the same direction. So the urban extraction result can be refined by selecting regions whose orientation angle is homogeneous.

ESAR L-band PolSAR data of the Oberpfaffenhofen Test Site Area will be used to validate the proposed algorithm.

9829-67, Session PSTue

Fully polarimetric data from the ARL RailSAR

Getachew A. Kirose, Kenneth I. Ranney, U.S. Army Research Lab. (United States); Brian R. Phelan, The Pennsylvania State Univ. (United States); Kelly D. Sherbondy, U.S. Army Research Lab. (United States)

No Abstract Available

9829-68, Session PSTue

Distributed transmit beamforming using high-accuracy microwave wireless positioning

Thomas Comberiate, Johns Hopkins Univ. Applied Physics Lab., LLC (United States); Kojo S. Zilevu, Praemittias Systems, LLC (United States); Jason E Hodkin, Jeffrey A. Nanzer, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

Research in distributed transmit beamforming (DTB) has been fueled by the cost concerns and performance limitations associated with a single transmitter paradigm. The expense of designing and building a robust, high-performance single transmitter can be significantly greater than that associated with building several low-cost, lower-performance transmitters. In addition, a single transmitter is limited by its fault-intolerance and lack of spatial diversity.

In the DTB concept, two or more platforms transmit a common information signal on a carrier in such a way that their signals constructively interfere with each other at a desired location. DTB can potentially achieve an N^2 gain in power for an N-channel array, but its distributed nature requires overhead communication among transmitters for information synchronization, carrier alignment, and oscillator syntonization. In general, most DTB efforts presume that the locations of the transmitters are unknown; nonetheless, they use feedback from the receiver to adjust the transmitters' phases to reach the target coherent gain.

In this work, we demonstrate DTB using a high-accuracy microwave wireless positioning radar to measure the distance between platforms. The inter-platform distance measurements from the high-accuracy ranging system are used to adjust the phase of a transmitter to maintain phase coherence when the distributed transmitter platforms are moved, enabling geometric DTB. Measurements from laboratory and outdoor tests of DTB using continuous-wave tones for ranging estimation, which we believe to be the first of its kind, are provided.

9829-37, Session 9

Synthetic aperture radar speckle reduction for circle mode SAR images

Cameron Musgrove, Sandia National Labs. (United States)

Speckle is a consequence of coherent synthetic aperture radar (SAR) imaging. For very fine resolution SAR images speckle can reduce visual appeal. Typical speckle reduction methods combine neighboring pixels and result in a loss of image resolution which also can reduce visual appeal.

Another approach is to register and combine multiple, squinted images from a straight-line collection. In this case the registration process can be straightforward because the layover direction is the same for all images. However, for a circular SAR data collection the layover angle changes for every data sample and a more robust image registration is required.

This paper details a SAR image registration process for combining multiple circular SAR images to reduce speckle. The registration first uses SURF for coarse alignment, and then uses a multi-level fine-registration and warp.

9829-38, Session 9

Analysis of a novel photonic beam-space receiver for multi-function radar

Joseph C. Deroba, U.S. Army CERDEC Intelligence and Information Warfare Directorate (United States)

A novel imaging receiver architecture has been developed and is well documented. This work extends the original research on passive imaging to cover beam-forming techniques relevant to EW and radar applications. Of particular interest are the inherent properties of the optical up-conversion process and its particular effect on intermodulation distortion performance, system accessible bandwidth and sensitivity and down-stream processing requirements.

A full theoretical model and time-domain simulation has been created that allows for the study of the performance of the photonic beam-space receiver in great detail. Specific results of the model and their impacts to the design of a prototype beam-forming system will be discussed.

9829-39, Session 9

Matched Filter based Iterative Adaptive Approach

Ramesh Nepal, Yan R. Zhang, Zhengzheng Li, The Univ. of Oklahoma (United States); William Blake, Garmin International Inc (United States)

Matched Filter sidelobes from diversified LPI waveform design and sensor resolution are two important considerations in radars and active sensors in general. Matched Filter sidelobes can potentially mask weaker targets, and low sensor resolution not only causes a high margin of error but also limits sensing in target-rich environment/sector. The improvement in those factors, in part, concern with the transmitted waveform and consequently pulse compression techniques. An adaptive pulse compression algorithm is hence desired that can mitigate the aforementioned limitations. A new Matched Filter based Iterative Adaptive Approach, MF-IAA, as an extension to traditional Iterative Adaptive Approach, IAA, has been developed. MF-IAA takes its input as the Matched Filter output. The motivation here is to facilitate implementation of Iterative Adaptive Approach without disrupting the processing chain of traditional Matched Filter while also potentially reducing the computational load as MF-IAA can take advantage of variable processing window. As with IAA, MF-IAA is a user parameter free, iterative, weighted least square based spectral identification algorithm. This work focuses on the implementation of MF-IAA. The feasibility of MF-IAA and its variable processing window is studied using a realistic airborne radar simulator as well as actual measured airborne radar data. The performance of MF-IAA is measured with different test waveforms. In addition, cross-range super-resolution using MF-IAA as well as IAA is investigated. Sidelobe reduction as well as super-resolution enhancement with reduced computational load is also validated. The robustness of MF-IAA with respect to different LPI waveforms is also demonstrated.

9829-40, Session 9

An Implementation of Real-Time Phased Array Radar Fundamental Functions on DSP-Focused, High Performance Embedded Computing Platform

Xining Yu, The Univ. of Oklahoma (United States); Ankit Patel, Advanced Radar Research Ctr. (United States) and The Univ. of Oklahoma (United States); Yan R. Zhang, The Univ. of Oklahoma (United States); Allen Zahari, Mark Weber, NOAA-National Severe Storms Laboratory (United States)

A growing interest in the radar signal processor development is using multi-core DSPs for distributed and parallel functionalities. DSPs (Digital Signal Processors) are low-power processors optimized for SIMD (Single Instruction Multiple Data) operations. In order to better utilize the multiple cores and reduce workload on software development, TI implemented OpenCL (Open Compute Language) and OpenMP (Open Multi-Processing) frameworks. OpenCL uses a master-slave hierarchy where master CPUs dispatch kernels to be executed on slave CPUs. In our study, a TI Keystone II SoC was used. This platform integrates 4 ARM A15 and 8 C66 DSP cores in a package. OpenCL allows the ARM cores to dispatch kernels to the DSP cluster. Within the kernel, OpenMP is used to distribute computation across the 8 cores. Parallelizing code is trivial with OpenMP as it only requires the programmer to add a few lines to their sequential code. This makes for shorter development cycles and more flexible code compared to low-level multi-core programming. Thread allocation is handled in software which consumes clock cycles. Overhead is also introduced by OpenCL. The framework does not allow shared memory between host and slave. As a consequence, the host must send kernels to the slave, and must send and read back processed data. This study will analyze the benefits and drawbacks of using these frameworks as opposed to low-level high-performance code. The feasibility of these approaches are investigated for use in real-time processing of a generic large-scale phased array radar and pulsed-Doppler processing chain in the array channels.

9829-41, Session 9

Real-time radar signal processing using GPGPU (General-Purpose Graphic Processing Unit)

Fanxing Kong, Advanced Radar Research Ctr. (United States) and The Univ. of Oklahoma (United States); Yan R. Zhang, The Univ. of Oklahoma (United States); Jingxiao Cai, Advanced Radar Research Ctr. (United States) and The Univ. of Oklahoma (United States); Robert Palmer, University of Oklahoma (United States)

GPGPU (General-Purpose Graphic Processing Unit) refers to the approach of applying GPU (Graphic Processing Unit) in computations traditionally handled by CPU (Central Processing Unit). Because of its unique many-core architecture, GPU is extremely efficient in parallel computation, where each thread is independent from others, as in the case for many radar signal processing algorithms. In this study, we consider baseband radar IQ data cube obtained from generic and scalable phased array radar as the input to the GPU, and the application of basic pulsed-Doppler processing chain is assumed. The data cube is usually far larger than the number of cores available on GPUs, which indicates that each step of the radar signal processing algorithm may fully utilize all of the computational capability of the GPU, potentially maximizing the computational efficiency. In addition, the PCIe 3.0 x16 (Peripheral Component Interconnect Express) bus used in most current GPUs offers data rate of approximately 16 GB/s, which provides minimal latency of data transfer among the GPU, CPU and third-party devices like the data acquisition unit. It is therefore, practically

beneficial to explore the feasibility of using GPUs for real-time processing, as an alternative to CPU, FPGA (Field Programmable Gate Array), and DSP (Digital Signal Processor). In this study, we developed a general parallel signal processing chain, which includes beamforming, pulse compression and Doppler spectrum estimation. The overall processing time was benchmarked on multiple GPUs with different inputs. The experiment implied that scalable real-time radar signal processing can be achieved using commercial Desktop GPUs with relatively short development time.

9829-42, Session 9

Salisbury screens made from unidirectional carbon fiber laminates

Elliot J. Riley, Erik H. Lenzing, Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Carbon fiber composite materials have many useful material properties. The electromagnetic performance of these materials is of great interest for future applications. The work presented in this paper deals with the construction of Salisbury screen microwave absorbers made from carbon fiber composites. The lossy dielectric properties of unidirectional carbon fiber laminates are exploited to make radar absorbers that are wider band than traditional Salisbury screens made from resistive sheets. The theory, simulation, prototypes, and measurements of these absorbers are discussed.

9829-43, Session 10

Some applications of the characteristics non-uniform Doppler to radar

John E. Gray, Nancy A Breaux, Jeremiah J Hansen, Naval Surface Warfare Ctr. Dahlgren Div. (United States)

Since the inception of coherent waveforms, it has been realized that the effect of the motion of a non-point like object can induce structure in the return spectrum of the waveform, see for example in the electromagnetic literature (Van Bladel 1984). Discussion in the radar literature began in the nineties (see for example Gray 1990) and then in the academic literature with (Chen 2003,2006) and (Gray 2003). The explosion of interest since Chen's seminal papers has been centered on micro-Doppler, which is based on periodic motion about the central Doppler line, which have proven to have enormous applications (see Chen's recent books). While not as extensive in terms of potential applications, the non-uniform Doppler has applications to automobile radars, astrophysics, and moving sources, as well as other applications. In our contribution, we review the non-uniform Doppler and demonstrate some useful information that can be found in the spreading of the Doppler spectrum for the motion models: acceleration, jerk, quadric, and exponential slowdown as examples well as a characteristic of periodic motion. We illustrate this with an examples relevant to automotive radar, tracking meteors with ambient sources, characterizing moving sources and other interesting examples.

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9829-44, Session 10

Classification of human activity on water through micro-Dopplers using deep convolutional neural networks

Youngwook Kim, California State Univ., Fresno (United States); Taesup Moon, Daegu Gyeongbuk Institute of Science & Technology (Korea, Republic of)

Detection of humans and classification of their activity on the water has significant applications in surveillances, border patrols and rescue operations. Humans produce micro-Doppler signatures that are generated from moving limbs when illuminated by radar. There have been several research for recognizing humans on land by their unique micro-Doppler signatures, but humans on the water has not been intensively studied yet. In this study, we investigate the micro-Doppler signatures of humans on water including a swimming person, a swimming person pulling a floating object, and a rowing person in a small boat. The measured swimming styles are free stroke, backstroke, and breaststroke. It is observed that each activity has unique micro-Doppler signatures. Based on their micro-Doppler signatures, human activities are classified. For the classification, we propose to apply deep convolutional neural networks (DCNN) that is one of powerful deep learning technique. Whereas previous proposed schemes for micro-Doppler recognition mainly used the conventional supervised learning that relies on handcrafted features, we present an alternative deep learning approach. We apply the DCNN, one of the most successful deep learning algorithms for image recognition, directly to a raw micro-Doppler spectrogram of humans on the water. Without extracting any explicit features on the micro-Dopplers, the DCNN can learn the necessary features and build classification boundaries using the training data. We show that the DCNN can achieve accuracy of more than 87.8% for activity classification using the 5-fold validation.

9829-45, Session 10

Performance analysis and comparison of fall detectors

Baris Erol, Moeness G. Amin, Fauzia Ahmad, Villanova Univ. (United States); Boualem Boashash, Qatar Univ. (Qatar)

Falls are the major cause of accidents in elderly people. Even simple falls can lead to severe injuries, and sometimes death. Therefore, elderly care has drawn great attention in recent years. Radars offer many advantages compared to other modalities for fall detection due to their non-invasive nature, insensitivity to lighting conditions, etc. Micro-Doppler signatures have been commonly used to identify and discriminate humans from animals, as well as classifying different types of human activities. In the literature, it has been shown that use of micro-Doppler signatures for fall detection yields high classification rates. As such, a plethora of micro-Doppler features have been proposed over the past years, primarily those extracted from the linear and quadratic time-frequency signal representations and those which find a home in speech recognition. The micro-Doppler features are used by different classifiers, such as k-Nearest Neighbors (kNN) and Support Vector Machines (SVM). Although radar systems employed for collecting Doppler data may differ in waveform, frequency and aperture, system smartness and fall detection capabilities are typically guided by the detection and classification algorithm housed on the radar platform.

9829-46, Session 10

Person-oriented fall detection using radar systems

Branka Jokanovic, Moeness G. Amin, Fauzia Ahmad, Villanova Univ. (United States); Boualem Boashash, Qatar

Univ. (Qatar)

In the past, radar has been successfully used for monitoring and classification of different human motions in applications mainly related to defense and security. More recently, there has been a focus on using radar and other modalities for assisted living technologies to enable elderly to live independently while still providing them with effective health care. One of the major concerns in elderly care is the detection of falls. Majority of radar techniques proposed for fall detection aim at the general population and generic person. That is, very little or no knowledge about the observed person is used. In this paper, we observe micro-Doppler signatures of different persons and demonstrate that the prominent features of the same daily activity can vary from person to person. This suggests that, when developing an algorithm for human motion analysis, person-specific information about daily activities should be utilized. We propose a two-stage approach for personalized fall detection. The first stage involves a pre-screening operation to isolate important events, such as falls, from other normal daily activities. The pre-screener helps alleviate burden on the second stage, which employs a classification process to determine whether the pre-screened event is indeed a fall. We employ pseudo-personalized operators at the pre-screening level and personalized fall models for template matching based classification. Results show performance improvement over conventional non-personalized methods. (For special session on Radar Micro-Doppler)

9829-47, Session 10

Using RGBD data to simulate human activity recognition using micro-Doppler

David Tahmouh, U.S. Army Research Lab. (United States)

3D imaging modalities like RGBD video have the capability of simulating micro-Doppler to analyze the micro-motions of human subjects. An additional capability to the recognition of micro-motion is the recognition of the moving part, such as the hand or arm. RGBD video can be used to ground-truth the more sensitive radar micro-Doppler measurements and associate the moving part of the subject with the measured Doppler and RCS from the radar system. Combining the measured motions from the RGBD video with RCS values of the body into a simulation can create synthetic radar micro-Doppler. The simulated signatures can be used to classify activities and actions on their own, and can be compared to RGBD video which achieves an 86% accuracy using Doppler-based features.

9829-48, Session 10

Radar micro-Doppler based human activity classification for indoor and outdoor environments

Matthew Zenaldin, Ram M. Narayanan, The Pennsylvania State Univ. (United States)

The motivation of the work is to gather micro-Doppler signature data for many different human activities in multiple environments for military purposes. We want to understand how the signature is affected by both environment and aspect angle in order to determine what effects this has for classification. Micro-Doppler data are highly desirable for military uses such as covert missions, surveillance, and search-and-rescue missions.

We investigate how different environments impact the feature values and classification rate of micro-Doppler signatures (MDS) for human activity classification. MDSs were recorded in four environments: free space, through wall, through needle tree foliage, and through leaf tree foliage. We also perform a similar comparative analysis regarding how feature values and classification rates degrade as a function of aspect angle. The degradation as a function of aspect angle is only measured in a free space environment. Multiple human test subjects perform the following motions: walking, limping, jogging, walking with corner reflector, crawling, swinging arms, boxing, and waving. We use a coherent monostatic Doppler radar

operating in the C-band at 6.5 GHz. Various features are extracted from the MDS spectrograms which are then put into a Support Vector Machine for classification. The classification results are then compared.

SUBMITTED TO SPECIAL JOINT SESSION ON RADAR MICRO-DOPPLER

9829-49, Session 11

The generalized ambiguity function: a bridgework between classical and quantum radar

John E. Gray, Allen D Parks, Naval Surface Warfare Ctr. Dahlgren Div. (United States)

Woodward introduced the ambiguity function in the seminal book on radar as the means to solve the radar measurement problem. The radar measurement problem is to design a radar waveform to be broadcast by a radar or sonar, so as to maximize the receiver response to the signal which has interacted with an object. With a new interpretation of Woodward's ambiguity function as the expected value of an operator it is possible to cast measurement with active sensors in the same framework. The operator represents the physics of the interaction of the waveform with the object. This provides a new approach to understanding the return signal at the receiver as a measurement problem; thus the goal of the receiver designer is to obtain the expected value of an operator. With this formulation, we are able to provide a derivation of the design of a matched filter for operators that represent measurements. This language reveals more detailed understanding of the underlying interactions within the return signal that are not usually brought out by standard signal processing design techniques. It also provides a means to "post-select" the return signal so the receiver design for quantum radars to optimize detector characteristics for specific interaction operators. Thus, we provide a common framework for solving the measurement problem for radar, sonar, and quantum mechanics by casting them in the common language of quantum mechanics as a Rigged Hilbert Space. Thus, we provide a solution to receiver design for operators.

9829-50, Session 11

Quantum radar data fusion

Marco O. Lanzagorta, U.S. Naval Research Lab. (United States); Jeffrey K. Uhlmann, Univ. of Missouri (United States); Salvador E. Venegas-Andraca, Instituto Tecnológico y de Estudios Superiores de Monterrey (Mexico)

Recent theoretical and experimental research programs have generated promising results suggesting that quantum radar is a feasible technology that could outperform traditional sensor devices. Arguably, the fast and efficient generation of entangled microwave photons is the main challenge for the physical realization of a quantum radar system. A perfect microwave quantum illumination device, for instance, would be able to generate M independent mode pairs (equal to the product of the time length of the signal pulse and the bandwidth). However, for practical applications of X-band quantum radar, the bandwidth is of about 4 GHz with 1 ms length pulses. Consequently, M is a few orders of magnitude smaller than the required size for optimal quantum sensing. To overcome this limitation, we propose a parallel architecture of quantum sensors. However, while this architecture provides a larger number of modes, it also injects more noise into the detectors. Therefore, quantum radar data fusion algorithms are needed to maximize the efficiency of the overall system. In this paper we discuss the theoretical performance of the proposed parallel quantum radar system under the effects of noise and atmospheric attenuation.

9829-51, Session 11

Doppler effect in quantum radar

Marco O. Lanzagorta, U.S. Naval Research Lab. (United States); Oliverio Jitrik, The Ranken Institute (Mexico)

In traditional radar, the Doppler effect is crucial to detect moving targets. In the quantum radar context, however, most theoretical performance analyses have assumed static targets. In this paper we discuss the Doppler effect at the single photon level. As expected, the Doppler shift has equivalent equations for the classical and quantum settings. We also describe a variant of Young's double slit experiment, where the slits are replaced by moving scattering atoms. Subsequently, we describe how the Doppler effect produced by a moving target modifies the interferometric patterns observed by quantum radar. Finally, we analyze the theoretical performance of quantum radar to measure the radial velocity of an incoming target.

9829-52, Session 11

A quantum radar detection protocol for fringe visibility enhancement

Benjamin Koltenbah, Claudio G. Parazzoli, Barbara A. Capron, The Boeing Co. (United States)

We present analysis of a radar detection technique using a Photon Addition Homodyne Receiver (PAHR) that improves SNR of the interferometer fringes and reduces uncertainty of the phase measurement. Coherent light illuminates a target and the return signal interferes with the local oscillator reference photons to create the desired fringes. The PAHR alters the probability distribution of the returned light via interaction between the return photons and atoms in a cavity. This is modeled using standard Quantum Cavity Electro-Dynamics (QCED) analysis. The injected atoms are prepared in the desired quantum state. During the operator selected interaction time, the initial quantum state evolves in such a way that the photon distribution function changes resulting in lower photon count and phase noise and an increase in fringe SNR. The result is a 3-5X increase of fringe SNR. This method is best suited for low light intensity (low photon number, 1-5) applications. The detection protocol could extend the range of existing systems without loss of accuracy, or conversely enhance a system's accuracy for given range. We present quantum mathematical analysis of the method to illustrate how both range and angular resolution improve in comparison with standard measurement techniques. We also present an experimental path to validate the method and lead toward deployment in the field.

9829-53, Session 11

Quantum seismography

Marco O. Lanzagorta, U.S. Naval Research Lab. (United States); Oliverio Jitrik, The Ranken Institute (Mexico)

A major scientific thrust from recent years has been to try to harness quantum phenomena to increase the performance of a wide variety of information processing devices. In particular, quantum radar has emerged as an intriguing theoretical concept that could revolutionize electromagnetic standoff sensing. In this paper we will discuss how the techniques developed for quantum radar could also be used towards the design of novel seismographs able to detect small ground vibrations. We propose the design of an interferometric seismograph based on quantum radar principles. The theoretical performance of our quantum seismograph is analyzed using classical and non-classical photon sources. Finally, we use a hypothetical earthquake warning system in order to compare quantum seismography with traditional seismographic techniques.

9829-54, Session 11

Comparison between classical and quantum radar cross sections

Matthew J. Brandsema, Ram M. Narayanan, The Pennsylvania State Univ. (United States); Marco O. Lanzagorta, U.S. Naval Research Lab. (United States)

The radar cross section is a very useful concept in characterizing and detecting targets of interest. It represents an effective area of a particular target based upon the returns sent back to the radar. Every object has a unique cross section that changes as a function of observation angle. Recently, the idea of a quantum radar has been introduced and it shows much promise in providing many advantages over classical radar. The concept of the quantum radar cross section has been introduced in literature and analyzed.

This paper provides a direct comparison between the classical radar cross section and the quantum radar cross section for various geometries. This work expands upon previous work in the sense that many more atoms of the objects are taken into account. It is shown that a very small percentage of the objects atoms are needed to obtain an accurate quantum radar cross section simulation. The scripts written are also robust enough to simulate both 2D and 3D geometries as well as provide bistatic cross sections.

9829-55, Session 11

Calculating radar cross sections using quantum algorithms

Salvador E. Venegas-Andraca, Tecnológico de Monterrey (Mexico); Marco O. Lanzagorta, U.S. Naval Research Lab. (United States)

The Radar Cross Section of simple bodies can be computed exactly and those solutions are of great interest in radar theory as they can be used as guidelines for estimating more complicated scattered fields. Quantum computation is an established field of science and engineering devoted to build computers and information processing systems that use the quantum mechanical properties of Nature. In this paper we introduce some new quantum algorithms to compute the Radar Cross Section of three geometrical bodies: sphere, rectangle and cylinder. We shall provide a detailed description of the quantum circuits that constitute our algorithms, and we will present a concise comparison on the performance of our quantum algorithms with respect to classical algorithms developed for the same purpose.

9829-56, Session 12

Compressive sensing (CS) ISAR imaging through Maxwell's equations

Ligang Sun, Mengqi Hu, Shuxia Li, John Montalbo, Zhijun G. Qiao, The Univ. of Texas Rio Grande Valley (United States)

A new general echo model is created for high inverse synthetic aperture radar (ISAR) based on Maxwell's equations and a given SAR echo model. After considering the Doppler shifts which presenting different aspects to the radar and therefore causing artifacts in ISAR images, a compressive sensing (CS) matrix is constructed from the random partial Fourier matrices for processing the range CS ISAR imaging. The model also tries to figure out the track of the moving target and form three-dimensional images simultaneously. Based on the general model, several simulations which build CS ISAR imaging and the track of the moving target are showed in the end.

Conference 9830: Passive and Active Millimeter-Wave Imaging XIX

Thursday 21–21 April 2016

Part of Proceedings of SPIE Vol. 9830 Passive and Active Millimeter-Wave Imaging XIX

9830-1, Session 1

W-band active imaging by photonics-based synthesizer

Atsushi Kanno, Norihiko Sekine, Iwao Hosako, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan)

Millimeter-wave (mm-wave) imaging is promising for precision nondestructive testing (NDT) technique because of its transparent characteristics to materials. The NDT is quite useful for inspection of concealed materials in a box and a baggage in airports and logistic centers to enhance the security and safety. Nowadays, an mm-wave imaging system is being developed for whole human-body inspection, and is already installed at airport security checkpoints. The frequency of the used mm-wave signal is approximately 30 GHz; the wavelength of 10 mm limits the image resolution. In this scenario, the frequency of the signal should be increased for improvement of the resolution. However, the signal at this frequency such as 100 GHz has extremely high loss in electrical transmission line, and thus, the signal cannot be fed over a long-distance line. Photonics technology has an advantage on low-loss transmission line of 0.2 dB/km by an optical fiber, and can generate mm-wave-capable optical signals by advanced high-speed optical modulation and detection technologies.

In the study, photonics-based synthesizer configured with an optical modulation technique realizes a high-speed frequency sweeping feature with high stability and long-distance feeding by the optical fiber. The W-band signal generated by a high-power amplifier based on traveling-wave tube technology with a resultant output power up to 5 W can be irradiated to the target, and then, a focal-plane detector array produces two-dimensional images with a frame rate faster than 10 frames/s. Materials such as scissors, ceramic knives, cutter blades, and so on, set behind a 3-mm-thick conventional cardboard was clearly observed by the system. The frequency tunability by an optical modulation technique has at least 75–110 GHz typically, which is limited by the bandwidth of an optical-to-electrical converter. The signal generation at a frequency of 300 GHz is also demonstrated by this technique. For proof-of-concept demonstration of the NDT, transmission imaging as well as reflection is also discussed.

9830-2, Session 1

Progress on the development of the NIST 350 GHz RES video imager

Orlando Quaranta, Joel N. Ullom, Daniel T. Becker, Johannes Hubmayr, Nicholas G. Paulter Jr., National Institute of Standards and Technology (United States)

Millimeter wavelength radiation holds promise for detection of security threats at a distance, including suicide bomb belts and maritime threats in poor weather. The high sensitivity of superconducting Transition Edge Sensor (TES) detectors makes them ideal for passive imaging of thermal signals at these wavelengths. We have built a 350 GHz video-rate imaging system using a large-format array of feedhorn-coupled TES bolometers. The system currently consist of 251-detectors and operates at a standoff distance of 16 to 28 m, with an optimal resolution of 1.4 cm at 17 m. At 6 frames per second, the Noise Equivalent Temperature Difference (NETD) is 100 mK; higher frame rates can be achieved at the cost of higher noise (i.e. noise at 12 frames per second would be 1.4 times higher). We present the system description and results that demonstrate identification of concealed weapons in an indoor setting. We also present a description of the ongoing effort to expand the system capabilities, such as increasing the number of detectors. We also describe efforts toward validation of a computational model for mm-wave imaging.

9830-3, Session 1

Millimeter wave imaging at up to 40 frames per second using an optoelectronic photo-injected Fresnel zone plate lens antenna

Duncan A. Robertson, Univ. of St. Andrews (United Kingdom); Thomas F. Gallacher, Aalto Univ. (Finland)

Optoelectronic methods offer a promising approach for realizing rapid and highly reconfigurable beam steering for a wide range of applications, covering frequencies from microwave through to terahertz. In particular, the photo-injected Fresnel zone plate antenna (piFZPA), wherein a dynamic binary lens is created by the optical excitation of a plasma in the form of a Fresnel zone pattern within a semiconductor substrate, offers high speed, wide angle, precise beam steering with good beam quality. The piFZPA thus has the potential to enable video rate millimeter wave imagery using no moving parts.

We will present the latest results obtained using an advanced piFZPA demonstrator which exploits a commercial digital light projection (DLP) spatial light modulator for rapid mask reconfiguration and a high power laser illumination source to achieve high beam steering speeds. The piFZPA antenna pattern was characterized at both 94 and 188 GHz and achieved beam steering speeds of up to 17,500 beams per second. The piFZPA was combined with a 94 GHz FMCW radar transceiver to demonstrate non-mechanically scanned radar imaging at frame rates of up to 40 Hz for 2D PPI images and up to 7 Hz for 3D volumetric imagery. These results demonstrate a 3-order-of-magnitude increase in beam steering rate over our original projector-based experiments, whilst also extending the operating frequency beyond 100 GHz.

9830-4, Session 2

Imaging, doppler, and spectroscopic radars from 95 to 700 GHz

Ken B. Cooper, Jet Propulsion Lab. (United States)

We will present JPL's efforts to develop radar systems operating from 95 to 700 GHz for both defense and scientific applications. For security screening, a 340 GHz imaging radar with a compact four-element Schottky diode transceiver array was demonstrated with real-time frame rates exceeding 8 Hz. This radar also readily accommodates new industry-supplied InP-based 340 GHz multiplier modules, opening a clear path toward higher commercial readiness with superior performance and lower cost. Outfitted with a 680 GHz transceiver, the radar was also used to map spatiotemporal dynamics of wind-driven sand in the Mojave desert, with simultaneous velocity and range detection capability that far exceeds a lidar-based approach. For space science applications, this range-Doppler sensitivity to small particles is being leveraged in a 95 GHz prototype instrument for investigating jet phenomena in comets. In the realm of earth science, we are also developing a 183 GHz radar transceiver with wide tunability for humidity sounding inside upper-tropospheric clouds. This system utilizes a new power-combining architecture for Schottky diode frequency-doublers, with up to 1 Watt transmit power anticipated. Tuned slightly higher to the 220 GHz atmospheric transmission window, this transceiver system may enable lower altitude remote sensing measurements such as through-cloud, high-resolution altimetry.

**Conference 9830:
Passive and Active Millimeter-Wave Imaging XIX**

9830-5, Session 2

MIMO-based 3D imaging system at 360 GHz

Reinhold Herschel, Sandra Nowok, Rüdiger Zimmermann, Stefan A. Lang, Nils Pohl, Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik (Germany)

A mobile society raises needs for providing secure ways of travelling for millions of passengers. Due to numerous threats such as drug smuggling or even terrorist actions an effective screening of passengers gets crucial. Especially at airports this is a challenging task. Passenger scanning looks back on a long history of technological development. Many different approaches including passive and active radars at different frequency bands, synthetic aperture scanners and MIMO arrays have been developed for various security applications. Current approaches based on SAR imaging suffer from the long time required for each scan, which makes them unsuitable for high throughput. In contrast, a MIMO approach can reduce the scanning time by parallel measurement with an entire array of transmitters and receivers. However, all concepts have pros and cons depending on the kind of detected object. The aim of the FP7 project "TeraSCREEN" is to develop an imaging system which combines active and passive radar modules at different frequencies. All gained information from the different modules is combined in a common image processing unit to automatically look for potential threats in the detected images.

A crucial part of this comprehensive system is an active MIMO system at 360 GHz, which will be the main focus of the presentation. The MIMO system consists of 16 transmitter and 16 receiver antennas within one single array. Using a bandwidth of 30 GHz, a range resolution of 5 mm is obtained. With the 16x16 MIMO system 256 different azimuth bins can be distinguished, leading to an azimuth resolution of 0.078°. Mechanical beam steering is used to measure 130 different elevation angles. To obtain a resolution in elevation of 0.15°, a focusing elliptical mirror is used. With this system a high resolution 3D image can be generated with a frame rate of 4 frames per second.

The general concept of 360 GHz imaging will be presented. In the second part the beam steering in azimuth and elevation will be described in detail. This is followed by a discussion of preliminary results, generated by a 1x4 system operating at 90 GHz: the millimeter wave system built to verify the system approach in general. For the submillimeter wave system simulated results are shown. Finally, a suitable calibration method is presented, which allows to deal with disturbances arising from the frequency response of the used components and the differential phase drift among the individual transmitter and receiver circuits. The development is verified, based on the simulation at 360 GHz and the measurement at 90 GHz.

9830-6, Session 2

Combining MMW radar and radiometer images for enhanced characterization of scenes

Markus Peichl, Stephan Dill, Daniel Wallner, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Since several years the use of active (radar) and passive (radiometer) MMW remote sensing is considered as an appropriate tool for a lot of security related applications. Those are personnel screening for concealed object detection under clothing, or enhanced vision for vehicles or aircraft, just to mention few examples. Radars, having a transmitter for scene illumination and a receiver for echo recording, are basically range measuring devices which deliver in addition information about a target's reflectivity behavior. Radiometers, having only a receiver to record natural thermal radiation power, provide typically emission and reflection properties of a scene using the environment and the cosmic background radiation as a natural illumination source. Consequently, the appearance of a scene and its objects is quite different depending on the target and its scattering characteristics, and the actual illumination properties.

Typically technology providers are working either purely on radar or purely on radiometers for gathering information about a scene of interest. Rather rarely both information sources are really combined for enhanced information extraction, and then the sensor's imaging geometries usually do not fit adequately so that the benefit of doing that cannot be fully exploited. Consequently, investigations on adequate combinations of MMW radar and radiometer data have been performed. A mechanical scanner used from earlier experiments on personnel screening was modified to provide similar imaging geometry for Ka-band radiometer and K-band radar. First experimental results are shown and discussed.

9830-7, Session 2

High-sensitivity broadband 360GHz passive receiver for TeraSCREEN

Hui Wang, Matthew Oldfield, STFC Rutherford Appleton Lab. (United Kingdom); Itziar Maestrojuán, Anteral S.L. (Spain); Duncan Platt, Acreo AB (Sweden); Carl N. Brewster, STFC Rutherford Appleton Lab. (United Kingdom); Colin Viegas, Teratech Components Ltd. (United Kingdom); Bryon Alderman, STFC Rutherford Appleton Lab. (United Kingdom); Brian N. Ellison, STFC - RAL Space (United Kingdom)

No Abstract Available

9830-8, Session 3

220GHz wideband 3D imaging radar for concealed object detection technology development and phenomenology studies

Duncan A. Robertson, David G. Macfarlane, Univ. of St. Andrews (United Kingdom); Tomas Bryllert, Wasa Millimeter Wave AB (Sweden)

Submillimeter-wave 3D imaging radar with ultra-high volumetric resolution (~1cm³) is a promising technology for the detection of concealed objects on people but one which challenges radar system design in terms of wideband operation.

We present a 220GHz 3D imaging "Pathfinder" radar developed within the EU FP7 project CONSORTIS (Concealed Object Stand-Off Real-Time Imaging for Security). Pathfinder has been built to address two project objectives: (i) to de-risk the radar hardware technology development and (ii) to enable the collection of phenomenology data on representative targets and materials.

The radar uses wideband FMCW modulation and x24 frequency multiplication using a mixture of MMIC and Schottky diode components. A single transceiver channel, based on a self-mixing multiplier, is coupled to a lens antenna which is mechanically rastered to form 3D volumetric images of static test targets (mannequins etc.).

The transmitted chirp bandwidth is 30GHz which represents a very wide fractional bandwidth of 14%. The combination of DDS-based chirp generator and self-mixing multiplier-based transceiver yields a raw range point response which is close to ideal and only requires very minor nonlinearity compensation. Additionally, the phase noise of the transmitted signal is low maintaining a wide dynamic range (>60dB). The 30cm HDPE lens focusses the beam to a <1cm spot at a range of -1.5m and can clearly resolve small point targets separated by 10mm.

Pathfinder has proven the chirp generator and transceiver technology and is providing valuable phenomenology data. This information is being used within the CONSORTIS to develop automatic anomaly detection algorithms.

**Conference 9830:
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9830-9, Session 3

Optical and imaging performance testing for an improved real time 94GHz passive millimetre-wave imager

Colin D. Cameron, Rupert N. Anderton, Gordon N. Sinclair, James G. Burnett, QinetiQ Ltd. (United Kingdom)

This paper discusses the optical testing and imaging performance of the improved passive mm-wave imager design for use in degraded visual environments for base security and helicopter navigation reported in the 2014 conference.

The testing regime starts with optical component testing, to show whether each optical component conforms to its specification, and predict what effect each component will have on system performance. The testing described includes metrology of surface profiles, measurements of loss for each component, measurements of point spread functions and encircled energy of each component with optical power, and measurements of polarising efficiency on the polarising material and quarter-wave plate used in the system. The performance of the receivers is also measured in terms of noise equivalent temperature difference, frequency response and receiver feed horn beam pattern. Also described is the design of two corrector test lenses which allow either imager component with optical power to form a sharp image without the presence of the other component, and thus be tested individually.

Testing of the full optics is described, both using a single scanned receiver and later the full receiver array. The former gives better sampled point spread functions; the latter better represents the full system. The loss, effective aperture, field of view, depth of field, narcissus, thermal and fixed-pattern noise are also measured. Iterative methods to set the tolerance compensation and optimise the scan conversion look up tables are described.

Finally testing of the system imaging performance on bar targets and simple scenes is described.

9830-10, Session 3

Phenomenology of passive multi-band submillimeter wave imagery

Sissi Enestam, Perttu Kajatkari, Olli Kivimäki, Mikko M. Leivo, Anssi Rautiainen, Alekski A. Tamminen, Arttu R. Luukanen, Asqella Oy (Finland)

In 2015, Asqella Oy commercialized a passive multi-band submillimeter-wave camera system intended for use in walk-by personnel security screening applications.

In this paper we study the imagery acquired with the prototype of the ARGON passive multi-band submm-wave video camera. To challenge the system and test its limits, imagery has been obtained in various environments with varying background surface temperatures, with people of different body types, with different clothing materials and numbers of layers of clothing and with objects of different materials.

In addition to the phenomenological study, we discuss the detection statistics of the system, evaluated by running blind trials with human operators.

While significant improvements have been made particularly in the software side since the beginning of the testing, the obtained imagery enables a comprehensive evaluation of the capabilities and challenges of the multi-band submillimeter wave imaging system.

9830-12, Session 3

Module integration and amplifier design optimization for optically enabled passive millimeter-wave imaging

Andrew A. Wright, Richard D. Martin, Christopher A. Schuetz, Dennis W. Prather, Phase Sensitive Innovations, Inc. (United States)

Millimeter-wave (mm-wave) technology has given the ability to peer through degraded visual environments (DVE), but extensive research continues to improve passive sparse array imaging system for improved resolution and performance. Passive mm-wave receiver modules have been fervently pursued over the past several years for sparse array imaging systems that enables the capability of capturing video rate images in DVE. This paper discusses the efforts in improving the receiver module technology to improve video rate image resolution while improving the size, weight, power, and cost (SWaP-C) of the system. Major improvement of the receiver module is the push from 77 GHz to 95 GHz, the next considered low attenuation region in the atmospheric window. Pushing to higher frequencies will improve the resolution of the captured mm-wave images. Using Northrop Grumman InP low noise amplifiers (LNA), custom designed SiGe LNAs and liquid crystal polymer (LCP) technology, a higher frequency, narrowband and reduced SWaP-C can be achieved. Previous generation of millimeter-wave (mm-wave) receiver module technology involved ceramic substrates for the RF path, multi-layer FR-4 PCB for bias control, and mm-wave LNAs integrated into a high precision aluminum housing made the modules difficult to manufacture and expensive, hence the use of LCP technology. LCP simplifies the packaging effort by having both the DC circuit and RF components on a single substrate, while reducing the complexity of the receiver module. This reduces size, weight, and cost. With advanced SiGe:BiCMOS fabrication foundries, a 95 GHz narrowband low noise amplifiers was developed. Considering SiGe technology can be extensively cheaper than InP, GaAs, or GaN technology, hence, reduced cost of the receiver module considering only one InP LNA would be required for the front to minimize noise, while the SiGe LNAs for higher gain. The SiGe LNA also have low power consumptions compared to other narrow band 95 GHz amplifiers currently on the market. With the noted improvements the receiver module can be pushed to higher frequencies while improving the SWaP-C.

9830-13, Session 3

Concealed object detection using the passive THz image without its viewing

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

We analyze the images captured by commercially available passive THz camera and propose a real-time algorithm, based on the correlation function using, for concealed object detection without the passive THz image viewing. This algorithm allows us to do a conclusion about presence of forbidden objects on the human body.

To increase the quality of THz images we propose one more algorithm in comparison with algorithms, which have developed by us early.

We discuss new method, which allows to increase a resolution of the image that is captured by the passive THz camera for long distance between a person and the THz camera. It means that we develop a method allowing the THz camera zooming due to computer processing of the image.

9830-14, Session 3

Code modulated interferometric imaging system using phased arrays

Vikas Chauhan, Kevin B Greene, Brian A Floyd, North Carolina State University (United States)

Millimeter-wave (mm-wave) imaging provides compelling capabilities for security screening, navigation, and even biomedical applications. Traditional scanned or focal-plane mm-wave imagers are bulky due to their use of external optics and costly due to their reliance on custom hardware. In contrast, phased-array hardware developed for mass-market 60-GHz wireless communications and 77-GHz automotive radar promise to be extremely low cost. In this work, we present techniques which can allow low-cost phased-array receivers to be reconfigured or repurposed as interferometric imagers, removing the need for custom hardware and thereby reducing cost. Since traditional phased arrays power combine incoming signals prior to digitization, orthogonal code-modulation is applied to each incoming signal using phase shifters within each front-end and four-level (or two-bit) codes. These code-modulated signals can then be combined and processed coherently through a shared hardware path. Once digitized, visibility functions can be recovered through squaring and code-demultiplexing operations. The squaring operation results in a summation of complex code-multiplexed visibilities. Provided that codes are selected such that the product of two orthogonal codes is a third unique and orthogonal code, it is possible to demultiplex complex visibility functions directly. As such, the proposed system modulates incoming signals but demodulates desired correlations. In this work, we present the operation of the system, a validation of its operation using behavioral models of a traditional phased array, and a benchmarking of the code-modulated interferometer against traditional interferometer and focal-plane arrays.

Conference 9831: Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR VII

Monday - Wednesday 18-20 April 2016

Part of Proceedings of SPIE Vol. 9831 Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR VII

9831-1, Session 1

NATO Joint ISR (JISR) and Unified Vision 3026 (UV16) (Invited Paper)

Matthew F. Kauffmann, U.S. Air Force (United States)

No Abstract Available

9831-2, Session 1

SET-218 RTG in interoperability and networking of disparate sensors and platforms for ISR applications (Invited Paper)

Tien Pham, Michael A. Kolodny, Susan Toth, U.S. Army Research Lab. (United States)

No Abstract Available

9831-3, Session 1

Commonality-based interoperability

Christine L. Moulton, Alan T. Krzywicki, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

No Abstract Available

9831-4, Session 1

OSUS sensor integration in Army experiments

Robert Ganger, Mark Nowicki, CUBRC (United States); Jesse Kovach, U.S. Army Research Lab. (United States)

Live sensor data was obtained and fed into the AI-TECD (Actionable Intelligence Technology Enabled Capabilities Demonstration) "Micro Cloud" during the E15 Ft. Dix event of July 2015. This was provided by the Open Standard for Unattended Ground Sensors (OSUS, formerly Terra Harvest) Army Research Lab (ARL) system. This data was an enabler for other technologies, such as Sensor Assignment to Mission (SAM), Sensor Data Server (SDS), and the AI-TECD Sensor Dashboard, providing rich sensor data (including images) for use by the COIST analyst. This paper describes how the OSUS data was integrated and used in the E15 event to support COIST operations.

9831-5, Session 1

Application of standardized sensor systems for industrial control

Kevin Klawon, Chris Weisenborn, Doug Estep, Univ. of Dayton Research Institute (United States)

The DIA, in conjunction with the Army Research Lab (ARL), wanted to create an Unmanned Ground Sensor (UGS) controller that is (a) interoperable across all controller platforms, (b) capable of easily adding new sensors, radios, and processes and (c) backward compatible with existing UGS systems. To achieve this, the Open Standard for Unattended Sensors (OSUS) was created using Java and an Open Services Gateway (OSGi) platform. OSUS-R is a reference implementation of this standard. OSUS-R is an extensible framework that provides a modularized environment for deploying functionality in "bundles". These bundles can publish, discover, and share services available from other external bundles or bundles provided by the OSUS core.

This paper provides a brief overview of the OSUS standard/system and its components. It further describes how one could use OSUS to produce new products by using OSUS as its core. This paper will describe how OSUS was used to create a product for the Airforce Civil Engineering Center (AFCEC) called the Industrial Civil Engineering Environment (ICEE). ICEE provides the ability to view Civil Engineering assets across multiple vendors and domains including HVAC, Building Automation Systems, Electrical / Power, Fire / Emergency Response, Airfield Lighting, Video, etc. Using OSUS, ICEE can collect EMCS data from multiple manufacturers, integrate data from disparate systems for decision makers, provide real-time energy efficiency data at the device level, provide real-time machine performance readings to see if maintenance is needed, provide cyber security improvement options, and provide capability to create dashboards at the technician, base, and directorate level.

9831-6, Session 1

ARL PED efforts at Enterprise Challenge 2016 (EC16)

Susan Toth, U.S. Army Research Lab. (United States); William Hughes, Radiance Technologies, Inc. (United States) and U.S. Army Research Lab. (United States); Tien Pham, U.S. Army Research Lab. (United States)

In 2011 ARL developed a framework for sensor integration and asset discovery. Because this framework continues to be relevant and necessary, ARL will again participate in Enterprise Challenge in 2016. Incorporating an expeditionary PED model, ARL will demonstrate the utility of tactical wide-area and persistent sensing in a bandwidth constrained environment, with the inclusion of an effective Sensor 3D Common Operating Picture to enable appropriate sensor management. To support this evolution, ARL developed an expeditionary deployable PED system designed to support multiple streams of information, to include Wide Area Airborne Surveillance data. This system, coupled with new Full Motion Video processing techniques and a self contained datastore, moves full processing, discovery and asset management to the tactical edge.

9831-7, Session 1

Toward sensor modular autonomy for persistent land ISR

Paul A. Thomas, Defence Science and Technology Lab. (United Kingdom); Gillian F Marshall, David Faulkner, Philip Kent, QinetiQ Malvern Technology Centre (United Kingdom); Scott Page, Simon Islip, James Oldfield, Cubica Technology (United Kingdom); Toby P Breckon, Mikolaj E

Conference 9831: Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR VII

Kundegorski, Durham University (United Kingdom); David J Clark, Create Technologies (United Kingdom); Tim Styles, AptCore Ltd (United Kingdom)

No Abstract Available

9831-8, Session 2

The missions and means framework (MMF) as an ontology *(Invited Paper)*

Paul H. Deitz, U.S. Army Materiel Systems Analysis Activity (United States)

The analysis of warfare frequently suffers from an absence of logical structure for a] specifying explicitly the military mission and b] quantitatively evaluating the mission utility of alternative products and services. In 2003, the Missions & Means Framework (MMF) was developed to redress these short comings. The MMF supports multiple combatants, levels of war and, in fact, is a formal embodiment of the Military Decision-Making Process (MDMP).

A major effect of incomplete analytic discipline in military systems analyses is that they frequently fall into the category of ill-posed problems in which they are under-specified, under-determined, or under-constrained. Critical context is often missing. This is frequently the result of incomplete materiel requirements analyses which have unclear linkages to higher levels of warfare, system-of-systems linkages, tactics, techniques and procedures, and the effect of opposition forces. In many instances the capabilities of materiel are assumed to be immutable. This is a result of not assessing how platform components morph over time due to damage, logistics, or repair.

Though ill-posed issues can be found many places in military analysis, probably the greatest challenge comes in the disciplines of C4ISR supported by ontologies in which formal naming and definition of the types, properties, and interrelationships of the entities are fundamental to characterizing mission success. Though the MMF was not originally conceived as an ontology, over the past decade other workers, particularly in the field of communication, have labelled the MMF as such. This connection will be described and discussed.

9831-9, Session 2

Ontology-aided feature correlation for multi-modal urban sensing

Archan Misra, Kasthuri Jayarajah, Ee-Peng Lim, Singapore Management Univ. (Singapore)

In this work, we continue our ongoing explorations on the combined use of multi-modal sensing (including user-generated social media content, mobile device-based location tracking and camera-based video monitoring) for understanding of transient and localized urban events. Our investigations will utilize three distinct data sources: (a) metadata and images captured from Instagram; (b) video feeds captured from selected cameras on the SMU campus and (c) group-based user movement captured from mobile devices of LiveLabs participants at SMU. A common theme will be to explore the use of multi-dimensional features (from video, mobile and textual metadata) to aid such situational understanding.

We shall first show how video-based capture of anonymized location/movement traces on the SMU campus can be combined with inferences on group transitions (obtained from LiveLabs mobility traces) to improve the accuracy of tracking group movements on campus. In particular, we show that novel correlation measures employed on such intrinsically noisy, multi-modal data streams can provide robust and reliable inference of the movement of individuals in groups.

Subsequently, we shall focus on the problem of using both the image content-related features, and metadata-related features, obtained from Instagram feeds. The goal will be to show how the use of relatively simple

ontology-based reasoning on the combined set of metadata and content-specific features can improve the fidelity and accuracy of Instagram-based inferring.

We shall show these two contributions may be viewed as specialized instances of a generic information extraction and fusion pipeline for urban situational understanding, and shall point out the role of problem-specific ontologies in aiding such intelligent information extraction and fusion.

9831-10, Session 2

Agile development of ontologies through conversation

Dave Braines, Amardeep Bhattal, IBM United Kingdom Ltd. (United Kingdom); Geeth R. de Mel, IBM Thomas J. Watson Research Ctr. (United States); Alun D. Preece, Cardiff Univ. (United Kingdom)

Ontologies and semantic systems are necessarily complex but offer great potential in terms of their ability to fuse information from multiple sources in support of situation awareness. Current approaches do not place the ontologies directly into the hands of the business user but instead hide them away behind traditional applications. We have been experimenting with human-friendly ontologies and conversational interactions to enable non-technical business users to interact with and extend these dynamically. In this paper we outline our approach via a worked example, covering: OWL ontologies, ITA Controlled English, Sensor/mission matching and conversational interactions between human and machine agents.

9831-11, Session 2

MINI-DASS: an information-centric approach to discovering relevant information

Michael A. Kolodny, U.S. Army Research Lab. (United States)

No Abstract Available

9831-12, Session 2

Toward unified query processing for ISR information needs and collection management

Anne-Claire Boury-Brisset, Defence R&D Canada (Canada)

No Abstract Available

9831-13, Session 2

Sensor Assignment to Mission (SAM) in AI-TECD (Actionable Intelligence Technology Enabled Capabilities Demonstration)

Robert Ganger, Ronald Rudnicki, Yonatan Schreiber, CUBRC (United States); Geeth R. de Mel, IBM Thomas J. Watson Research Ctr. (United States)

Sensor-mission assignment involves the allocation of sensors and other information-providing resources to missions in order to cover the information needs of the individual tasks in each mission. Sensor-mission assignment is a general concept for which many solutions have been

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developed. In particular, IBM Laboratories put forth a solution known as Sensor Assignment to Mission (SAM) that has taken several forms during its development, including SAM-CE (SAM-Controlled English) and SAM/OWL (ISTAR ontology-based). Recently, CUBRC, Inc. was tasked with enhancing the SAM/OWL version using a Sensor Ontology that extends the I2WD Common Core Ontologies. This version uses a triple store and SPARQL to provide the data storage and analytics for sensor assignment. It integrates with the CERDEC-sponsored AI-TECD (Actionable Intelligence Technology Enabled Capabilities Demonstration), and was demonstrated at the CERDEC E15 demonstration event at Ft. Dix, NJ during July 2015. This paper describes the enhancements to the SAM/OWL version, and how it was demonstrated.

9831-14, Session 2

Variations of context-aware resource selection in disadvantage networks

Geeth R. de Mel, IBM Thomas J. Watson Research Ctr. (United States); Alun D. Preece, Cardiff Univ. (United Kingdom); Dave Braines, IBM United Kingdom Ltd. (United Kingdom); Tien Pham, U.S. Army Research Lab. (United States)

Effective resource selection for user requirements is a complex task especially in dynamic and heterogeneous environments; the complexity is further exacerbated due to the varying contexts one find in such environments—be they user context or the context of the environment. Motivated by these observations, in the past few years we have conducted research into implementing mechanisms to introduce context of operation into the resource selection process by means of knowledge base heuristics. In this paper we present our findings and their impact, especially with respect to the coalition operations.

9831-15, Session 3

The quest for multisensory big data ISR situation understanding (*Invited Paper*)

Steven K. Rogers, Air Force Research Lab. (United States)

No Abstract Available

9831-16, Session 3

Experiments using a multi-modal fusion plugin for source selection in tactical networks

Kevin Chan, U.S. Naval Research Lab. (United States); Rommie Hardy, Kelvin M. Marcus, Lisa M. Scott, U.S. Army Research Lab. (United States)

In highly contested and constrained networked environments, the need to collaboratively gather and share intelligence grows in complexity as the number of available sources of information increases. As these information sources continually evolve and increase, developing a practical strategy to reliably query this growing number of sources becomes important as it relates to assisting decision makers on which sources to use. We consider the performance of such a strategy based on metrics relating to the quality of information (QoI): accuracy, timeliness, completeness, and reliability. Previous work has shown that the formulation of such a strategy can be used to share and process information using the analytic hierarchy process (AHP) while considering network metrics such as effective data rate, link integrity and the utility of information. Using the AHP strategy we will develop a plugin that serves as a method for gathering and processing the

collaborative set of hard/soft network measurements from each source. The plugin will be tested in an emulated network environment to show how this method works in dynamic environments representative of tactical networked environments. Using an example scenario, we will analyze and measure the effectiveness of AHP for source selection given multiple information sources. The experiment outlined in this paper will show how collaborative information can be processed and shared using the AHP formulation to assist a decision maker using elements from communications, information, and social networks.

9831-17, Session 3

Enabling human-automation collaborative target tracking using an array of sensors

Terry Stanard, Jason Roll, Tony Ayala, Air Force Research Lab. (United States); Michael Bowman, Infoscitex Corp. (United States)

Intelligence, surveillance, and reconnaissance (ISR) operations in urban environments can be particularly challenging due in part to the physical proximity and height of the buildings which can cause occlusions of sensors. Operational and laboratory settings have shown it is very difficult for a single operator to manually track a moving target using a set of grounded, steerable cameras within an urban environment. Although computer vision technologies are available for auto-tracking, they are unreliable over all of the real-world variations in lighting, visibility, and visual clutter.

Our laboratory is developing an interface for investigating innovative automation technologies that flexibly collaborate with human operators to track one or more targets using multiple sensors. The interface features a top-down map showing a monitored area with streets and buildings depicted, as well as the location, position, and current field of view of camera sensors. The operator can select sensors to view using the map. Individual sensor views show the current real-time feed of a camera, which the operator can steer and zoom.

We will present the results of an initial human performance study evaluating several kinds of automated aiding for tracking a fast-walking pedestrian: (1) operator selects sensors and manually turns them towards anticipated target area (2) Nearby sensors automatically turn towards the target area to facilitate acquisition; (3) Capabilities of #2 plus automation ranks and displays sensor videos providing the best view of the target.

9831-18, Session 3

Next-generation neurosynaptic tactical ISR systems

Flavio Bergamaschi, David Conway-Jones, IBM United Kingdom Ltd. (United Kingdom)

The widespread use of multimode ISR assets and persistent surveillance in tactical networks pose new challenges for communications bandwidth, power, centralized vs distributed processing, sensor site accessibility, etc, across a broad range of critical missions. There is a need to shift the current paradigm of centrally integrating all sources of intelligence to a more distributed paradigm where relevant feature extraction, classification and fusion can be distributed to the edge of the network where the sensory data has been produced. In this paper we will present the current advances in Spiking Neural Networks and low power hardware platforms for brain-like computing that can be particularly suitable for implementing sensor data processing and actuator control algorithms. We will elaborate on how the spiking neural network information flow model of short and high parallel algorithms contrasts with the traditional symbolic information flows (e.g. text, high precision numeric values and formulas) usually manipulated in conventional von Neumann computing architectures. We will also present recent experimental results and discuss how this technology has been used to perform tasks like feature extraction and classification of sensor data, and semi-autonomous control of unmanned assets.

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9831-19, Session 3

Software architecture of biomimetic underwater vehicle

Tomasz Praczyk, Piotr Szymak, Polish Naval Academy (Poland)

The presentation outlines software architecture of autonomous biomimetic underwater vehicle built within the project "Autonomous Underwater Vehicle with silent undulating propulsion for reconnaissance purposes" financed by Polish National Center of Research and Development. Moreover, it also gives some results of research on vehicle autonomy, especially collision avoidance. A pure algorithmic and a neuro-algorithmic collision avoidance approaches are shortly explained. The algorithmic system makes decisions determined by a "hand-made" algorithm, whereas, neuro-algorithmic one is a hybrid of the algorithm and a neural network.

9831-20, Session 3

Combining Cognitive Engineering and Information Fusion Architectures to Build Effective Joint Systems

Amy L. Sliva, Joe Gorman, Martin Voshell, Charles River Analytics, Inc. (United States); James Tittle, Charles River Analytics Inc (United States); Christopher L. Bowman, Data Fusion Corp. (United States)

For effective decision making, military Command and Control (C2) requires robust situational understanding produced by translating multi-INT intelligence, surveillance, and reconnaissance (ISR) into actionable intelligence. These information products must be delivered according to the evolving decision needs of dynamic mission contexts. However, traditional ISR pipelines rely upon highly distributed analysis and processing, exploitation, and dissemination that reduce coordination between operators, analysts, and Commanders. The Dual Node Decision Wheels (DNDW) architecture was previously described as a novel approach toward integrating analytic and decision-making processes. In this paper, we extend DNDW with a technical description of components in this framework, combining structures of the Dual Node Network (DNN) for Information Fusion and Resource Management with a variation on Rasmussen's Decision Ladder to provide guidance on constructing information systems that better serve decision-making requirements.

The DNN takes a component-centered approach to system design, decomposing each asset in terms of data inputs and outputs according to their intended roles and interactions in a fusion network. However, to ensure relevancy to C2 processes, principles from cognitive systems engineering dictate that system design should also take a human-centered view, with information needs driving the architecture and capabilities of network assets. We present a new node structure for DNDW that uses a unique hybrid DNN top down system design and human-centered process design, combining DNN node decomposition with artifacts from cognitive analysis (i.e., system abstraction decomposition models, decision ladders) to provide ISR work domain and task-level insights at different levels of the system. This structure will ensure not only that the information fusion technologies and processes are structured effectively, but that the resulting information products will align with the requirements of human decision makers.

9831-21, Session 3

Dragon pulse information management system: A unique model-based approach to implementing domain agnostic system of systems and behaviors

Thomas S. Anderson, U.S. Army Corps of Engineers

(United States) and U.S. Army Engineer Research and Development Ctr. (United States)

The Global Information Network Architecture is an information technology based on Vector Relational Data Modeling, a unique computational paradigm that was developed under CRADA at the Naval Postgraduate School and DoD network certified by USARMY as the Dragon Pulse Information Management System. This is a network available modeling environment for modeling models, where models are configured using domain relevant semantics and use network available systems, sensors, databases and services as loosely coupled component objects. The configured models are executable applications. All component system information syntax is embraced at the model boundary as object components that relate to the homogenized semantic domain application model. Domain solutions are based on mission tactics, techniques, and procedures and subject matter input. Three recent ARMY use cases a) ISR and Force Protection domain where we designed and implemented an information model that aggregates legacy and new network available video and cameras from Ft Bragg Simmons Army Air Field (SAAF) and open source change detect software as components in an automated over watch capability with pan-tilt-zoom, change detect and notification. b) TRADOC Analysis Center network managed modeling and simulation behavior validation library integrated with Combat XXI models c) TRADOC Analysis Center Digital Library with behaviors.

9831-25, Session 3

Research on biomimetic underwater vehicles for underwater ISR

Piotr Szymak, Tomasz Praczyk, Polish Naval Academy (Poland)

In the recent years, a dynamical development of underwater robotics has been noticed. Autonomous biomimetic underwater vehicles (BUVs) with undulating propulsion are a new branch in this area. They imitate both the construction and kinematics of motion of underwater living organisms, e.g. fishes. Such vehicles have the following features crucial from the point of view of military applications: their propulsion is more energy efficient and more silent than classical propulsion based on screw propellers (based on initial research carried out in Polish Naval Academy), they are very difficult to differentiate from the real inhabitants of underwater environment (larger secrecy and potential range of operation).

The presentation includes results of the research on BUVs carried out within two projects. The first project is carried out in Poland. The main objective of the proposed project is to build heterogeneous torpedo-shaped BUVs with undulating propulsion for selected scenarios of underwater ISR. New constructions of BUVs are based on experiences from building 5th version of BUV CyberFish, which was built in Cracow University of Technology in cooperation with Polish Naval Academy. The second project was started within Unmanned Maritime Systems Programme in European Defense Agency. The project is carried out by Poland in cooperation with Germany. The main objective of the project is to build BUVs similar to real inhabitants of underwater environment, prepared for their swarm operation. The project was entitled "Swarm of Biomimetic Underwater Vehicles for Underwater ISR". The presentation is general report of the research on BUVs and it is mainly focused on hardware development of the BUV construction.

9831-22, Session 4

Investigating performance variability of processing, exploitation, and dissemination using a sociotechnical system analysis approach

Jennifer Danczyk, Arthur Wollocko, Michael Farry, Charles River Analytics, Inc. (United States)

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Data collection processes supporting Intelligence, Surveillance, and Reconnaissance (ISR) missions have recently undergone a technological transition accomplished by investment in sensor platforms. Various agencies have made these investments to increase the resolution, duration, and quality of data collection, to provide more relevant and recent data to warfighters. However, while sensor improvements have increased the volume of high-resolution data, they often fail to improve situational awareness and actionable intelligence for the warfighter because it lacks efficient Processing, Exploitation, and Dissemination and filtering methods for mission-relevant information needs. The volume of collected ISR data often overwhelms manual and automated processes in modern analysis enterprises, resulting in underexploited data, insufficient, or lack of answers to information requests. The outcome is a significant breakdown in the analytical workflow. To cope with this data overload, many intelligence organizations have sought to re-organize their general staffing requirements and workflows to enhance team communication and coordination, with hopes of exploiting as much high-value data as possible and understanding the value of actionable intelligence well before its relevance has passed.

Through this effort we have taken a scholarly approach to this problem by studying the evolution of Processing, Exploitation, and Dissemination, with a specific focus on the Army's most recent evolutions using the Functional Resonance Analysis Method. This method investigates socio-technical processes by analyzing their intended functions and aspects to determine performance variabilities. Gaps are identified and recommendations about force structure and future R&D priorities to increase the throughput of the intelligence enterprise are discussed.

9831-23, Session 4

Modular analytics management architecture for interoperability and decision support

Stephen Marotta, Max Metzger, Joe Gorman, Charles River Analytics, Inc. (United States); Amy Sliva, Charles River Analytics (United States)

The Dual Node Decision Wheels (DNDW) architecture has been presented as a new approach to information fusion and decision making, integrating PED, analysis, and C2 processes into a fluid, coordinated workflow. By combining cognitive systems engineering processes, such as decision wheels, with the formal Dual Node Network (DNN) technical architecture for information fusion, DNDW provides a mean for aligning relevant data and information products with C2 requirements and organizational decision-making processes. In this paper, we present the Modular Analytics Management Architecture (MAMA) as a prototype system that implements the principles of the DNDW architecture, providing a flexible environment for the interoperability of heterogeneous sensors, data sources, and analytic technologies that can be queried to support specific information needs for more robust situation understanding and decision making.

MAMA is a scalable, modular architecture that facilitates the flow of data between multiple analytics engines. Instead of a large, monolithic system, it supports the creation of a distributed solution comprised of smaller, more specialized analytics. The flexible nature of the architecture means that users can retask or repurpose individual analytics to address evolving C2 decision-making requirements or adapt to new mission contexts. MAMA provides a specialized API that enables two-way communication between analytics engines using a variety of messaging frameworks and handles heterogeneous data input formats. The modular design of AMA allows the user to create an adapter to interface the analytics engines with the operating environment of the host system to maximize portability. To facilitate dissemination of the most relevant information products, the architecture includes customizable data aggregation and feature extraction capabilities that can be tailored to higher-level analytic requirements. The highly configurable system design enables developers to build analytical systems that directly align with organizational structures and processes and can support their specific information needs.

9831-24, Session 5

Applying traditional signal processing techniques for social media exploitation for situational understanding

Tarek Abdelzaher, Univ. of Illinois at Urbana-Champaign (United States); Heather Roy, U.S. Army Research Lab. (United States); Shiguang Wang, Prasanna Giridhar, Md. Tanvir Al Amin, Univ. of Illinois at Urbana-Champaign (United States); Elizabeth K. Bowman, Michael A. Kolodny, U.S. Army Research Lab. (United States)

Signal processing techniques such as filtering, detection, estimation and frequency domain analysis have long been applied to extract information from noisy sensor data. This paper describes the exploitation of these signal processing techniques to extract information from social networks, such as Twitter and Instagram. Specifically, we view social networks as noisy sensors that report events in the physical world. We then present a data processing stack for detection, localization, tracking, and veracity analysis of reported events using social network data. We show, using a controlled experiment, that the behavior of social sources as information relays varies dramatically depending on context. In benign contexts, there is general agreement on events, whereas in conflict scenarios, a significant amount of collective filtering is introduced by conflicted groups, creating a large data distortion. We describe signal processing techniques that mitigate such distortion, resulting in meaningful approximations of actual ground truth, given noisy reported observations. Finally, we briefly present an implementation of the aforementioned social network data processing stack in a sensor network analysis toolkit, called Apollo. Experiences with Apollo show that our techniques are successful at identifying and tracking credible events in the physical world

9831-26, Session 5

Feature evaluation for determining moving target indicator (MTI) data quality

Ryan A. Elwell, U.S. Army Communications-Electronics Research Development and Engineering Command (United States)

There is a long-standing initiative in the radar community to create an interpretability scale to describe the quality of MTI. Recent work has yielded a qualitative scale that evaluates quality based on desired task, object, speed, and environment/confusion. To improve the effectiveness of the scale and the understanding of MTI utility in the community, it is desired to map these qualitative categories to quantitative measures which can be mapped appropriately to the scale. In this paper, we propose a set of quantitative features, supported by analysis of feature separation. Features are derived from detection and track level data. Feature separability is evaluated with a variety of statistical, classification-based, and heuristic methods. This understanding of the feature space leads to a better understanding of the scale itself, and allows data to be mapped qualitatively to parameters of interest to the radar research and development community.

9831-27, Session 5

Advanced air drop sensor system for early warning, area denial, wide-area surveillance, and target recognition

Ron Knobler, Robert Fish, Matthew J. Rohrer, Richard D. Porter, Peter Scheffel, Jonathan Williams, John H. McQuiddy, McQ, Inc. (United States)

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McQ is currently developing the Air Delivered Unattended Ground Sensor (ADUGS) system for the DoD, which consists of a network of sensors to be used in anything from a hand emplaced to airdropped deep battlespace applications. Each sensor contains one or more sensing modules (customized for a given mission) to perform the appropriate target detection, classification, and feature extraction. An onboard open standards for unattended sensors (OSUS) controller provides a plug and play and standard interface for the sensing modules, as well a local communications mesh radio, long haul radio, sensor fusion algorithms, information assurance, and mission rules. Both multimodal fusion and multi sensor fusion are performed on the sensor node through passing detection features between neighboring sensors over the common sensor radio (CSR). Multi sensor fusion establish tracks, speed/direction of travel, number of targets, and time/location information – all based on target features extracted from separate algorithms. Image processing also provides a best image of the target. As a result of this advanced processing, Long haul transmission and required user interaction responding to detected targets is minimized. The open architecture and opens standards being developed allows for future enhancements (including new detection modules and new algorithms) by a variety of organizations. A system overview and state of the research for this project will be presented.

9831-28, Session 5

Multi-gigabit free-space optical data communication and network system

Jony Jiang Liu, John E. McElhenny, Leonid A. Beresnev, U.S. Army Research Lab. (United States); Richard D. Vaughn, U.S. Army Research, Development and Engineering Command (United States); David Schneider, Technical Research Institute (United States)

Advanced compact, lightweight, and networked high-bandwidth optical communication system will present significant capability for ISR data and information transfer in the battlefield. Such new systems have the features of intelligent mobile networking (precision pointing and tracking), anti-jam, jitter compensation, and high data rate. Our design of the compact optical network and communication system comprised of several pairs of gimbaled adaptive laser transceiver nodes (LTNs). Each LTN represents an intelligent fiber collimator with integratable capabilities for pointing, tracking, and mitigation of atmospheric turbulence and jitter. For tactical to long-range applications, the system will be able to receive and transmit data signals at 2.5 to 10 Gbit/s with the potential of 40 Gbit/s in multiple channels. The agile and tracking capabilities of the system will be scalable and deployable for networked ground-to-ground, ground-to-air/space, and air-to-ground platforms. We will report our development in building such high bandwidth free-space optical data communication system and enabling the technologies for next generation battlefield ISR data transportation and real-time information processing.

9831-29, Session 5

A VRDM approach to an interoperable and integrated solution to identifying obfuscated network traffic

Ryan Kelly, Naval Postgraduate School (United States); Thomas S. Anderson, U.S. Army Engineer Research and Development Ctr. (United States)

The cyber attribution problem has considerably reduced deterrence effectiveness against malicious online actors. Without attribution, these actors can launch anonymous cyber attacks with impunity and may redirect reprisal. The ineffectiveness of attribution would be less of a concern if anonymous traffic was blocked before a concerning event. We use a Vector Relational Data Modeling (VRDM) approach in the Global Information Network Architecture (GINA) to determine if online identities originate from

anonymous relays by examining integrated sensor input and round trip timing analysis. We were able to use statistically significant network traffic characteristics to discern and terminate anonymous relay traffic.

9831-30, Session 5

A Vector Relational Data Modeling approach to Insider Threat intelligence

Ryan Kelly, Thomas S Anderson, Naval Postgraduate School (United States)

Evolving cyber crime and persistent threat of network intrusions have shown to outpace Federal cyber defenses due to limitations of funding, technology, and available human intellectual capital. The current approach to network security is fragmented and human dependent, and is only as effective as the skill of the human analyst. Rule and anomaly based protection are subverted by obfuscation techniques and an active response can result in a self-induced denial of service. Building on Vector Relational Data Modeling (VRDM), we extend a semantically based executable information model for an automated cyber threat analysis and response using IP geo-location as a threat indicator within a common cyber threat operating picture. The VRDM information model executes a correlation between multiple cyber security systems as a means of process definition and automation within the Global Information Network Architecture (GINA). Intrusion detection systems (IDS) create alerts that generally require human analysis to verify. The configured capability enables the semi-sentient behavior necessary to emulate the investigative procedure of an expert cyber security analyst and then executes an appropriate response based on the results of the automated investigation. This approach is a configured decentralized cyber-security integration that combines the effectiveness of multiple network defense systems, makes near real time threat determinations, and establishes command links to network hardware without any programming of code.

9831-31, Session 5

Information technology and social stability (Invited Paper)

Abbe Mowshowitz, The City College of New York (United States)

Social instability results from unemployment and the weakening of family/community ties. This is a critical issue in national security in as much as instability leads to open conflict, war and terrorism.

Information technology is inherently job destructive and thus contributes to weakening the nuclear family. Given the role of IT in the modern world, there are no easy solutions to this challenge. Job training for high technology activities is only a stopgap measure. In the long term new ways are needed for engaging people in and rewarding them for participation in Oeconomic activities.

Conference 9832: Laser Radar Technology and Applications XXI

Tuesday - Wednesday 19-20 April 2016

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9832-1, Session 1

Progress in advanced lidar components and systems (*Invited Paper*)

Paul McManamon, Exciting Technology, LLC (United States)

No Abstract Available

9832-2, Session 2

Design of the processing chain for a high-altitude, airborne, single-photon lidar mapping instrument

Joshua M. Gluckman, Woolpert, Inc. (United States)

Processing data from high-altitude, airborne lidar instruments which employ single-photon sensitive, arrayed detectors poses several challenges. Arrayed detectors produce large volumes of data; single-photon sensitive detectors produce high levels of noise; and high-altitude operation makes accurate geolocation difficult to achieve. To address these challenges a unique and highly automated processing chain for high-altitude, airborne single-photon lidar mapping instruments has been developed. The processing chain includes algorithms for coincidence processing, noise reduction, self-calibration, data registration, and geolocation accuracy enhancement. Common to all single-photon sensitive systems is a high level of background photon noise. A key step in the processing chain is a fast and accurate algorithm for density estimation that is used to separate the lidar signal from the background photon noise permitting the use of a wide-range gate and daytime operation. Additional filtering algorithms are used to remove or reduce other sources of system and detector noise. An optimization algorithm that leverages the conical scan pattern of the instrument is used to improve geolocation, and to self-calibrate the system.

9832-3, Session 2

Linear lidar versus Geiger-mode lidar: impact on data properties and data quality

Andreas Ullrich, Martin Pfennigbauer, RIEGL Laser Measurement Systems GmbH (Austria)

LIDAR technology has matured over the last two decades and is used in numerous fields of applications over short and long ranges, stationary from tripods but also mounted on moving platforms on almost any kind of vehicle, cars, ships, aircrafts and UAVs. LIDAR provides highly accurate point clouds with a significant number of additional valuable attributes per point. LIDAR has become the inevitable technology to provide accurate 3D data fast and reliably even in adverse measurement situations and harsh environments. It provides highly accurate point clouds with a significant number of additional valuable attributes per point. LIDAR systems based on Geiger-mode avalanche photo diode arrays, also called single photon avalanche photo diode arrays, earlier employed for military applications, now seek to enter the commercial market of 3D data acquisition, advertising higher point acquisition speeds from longer ranges compared to conventional techniques. Publications pointing out the advantages of these new systems refer to the other category of LIDAR as „linear LIDAR“, as the prime receiver element for detecting the laser echo pulses - avalanche photo diodes - are used in a linear mode of operation. We analyze the differences between the two LIDAR technologies and the fundamental

differences in the data they provide. The limitations imposed by physics on both approaches to LIDAR are also addressed and advantages of linear LIDAR over the photon counting approach are discussed. To this end we analyze the respective system's key parameters like area coverage, range noise, spatial frequency of ground sampling based on specification sheets, simulations, and field data.

9832-4, Session 2

Comparison of simulated and experimental 3D laser images using a GmAPD array: application to long-range detection

Antoine Coyac, Nicolas Rivière, Laurent Hespel, Xavier Briottet, ONERA (France)

We previously highlighted interests and potential of 3D focal plane arrays for laser imaging, at long range and/or weak signal conditions, by presenting our own 3D laser imaging end-to-end simulator, titled MATLIS 4D + LANGDOC, based on the Geiger detection mode. Modeling of 3D scenes is a way to generate various scenarios, in terms of observation conditions, geometry and composition of the scene. We can mention long range detection of electrical cables, recognition of airport runways or disaster areas, and Digital Surface Models reconstruction. Some of those cases have been realized on test bench for experiments using our 3D laser imaging platform named POMEROL, operating with a Geiger mode 3D camera and a very high pulse repetition frequency laser. Experimental 3D images have been compared to simulated ones obtained with MATLIS 4D on equivalent scenarios, thanks to sensitivity tests, in order to validate the LANGDOC module, providing an error estimation. Improvements have been added to the simulator, in order to simulate the image acquisition with a higher accuracy, considering several system and environmental parameters, including noise models (dark count rate, crosstalk), timing jitter, atmospheric turbulence and aerosols effects on laser illumination and radiometric balance. Thanks to the high PRF, dynamic acquisition will be available soon, to simulate the trajectory of airborne platforms (planes, UAVs) over a scene of interest. The simulator is then a useful tool for accurate performance assessments of such a system, for several civilian, military and environmental applications. Field campaigns will be conducted soon to demonstrate all the POMEROL potential for operational missions.

9832-5, Session 2

Compact Geiger-mode obstacle avoidance lidar test results

Ian Humphrey, James B. Johnson, UTC Aerospace Systems (United States); Gary Kamerman, FastMetrix, Inc. (United States); Jonathan C. Jarok, Scott W. Ramsey, UTC Aerospace Systems (United States)

No Abstract Available

9832-39, Session 2

Laser pulse production for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar

D. Barry Coyle, Paul R. Stysley, NASA Goddard Space

**Conference 9832:
Laser Radar Technology and Applications XXI**

Flight Ctr. (United States); Demetrios Poullos, Gregory B. Clarke, American Univ. (United States); Gordon Blalock, Genesis Engineering Solutions, Inc. (United States)

NASA is building the Global Ecosystems Dynamics Investigation (GEDI) Lidar, to be installed aboard the International Space Station. GEDI will use 3 NASA-developed laser transmitters to produce 12 parallel tracks of 25 m footprints on the Earth's surface, via an active optical system, necessary for accurate global biomass assessment. The Lasers and Electro-Optics Branch at Goddard Space Flight Center has been tasked with building these units as well as a dedicated unit for life testing, and taking them all through environmental qualification. We will report on the laser delivery process as well as plans and status for integration & testing with the instrument.

9832-6, Session 3

Simulation of a Doppler lidar system for autonomous navigation and hazard avoidance during planetary landing

Scott E. Budge, David B. Chester, Utah State Univ. (United States)

The latest mission proposals for exploration of solar system bodies require accurate position and velocity data during their descent phase in order to ensure safe, soft landing at the pre-designated sites. During landing maneuvers, the accuracy of the on-board inertial measurement unit (IMU) may not be reliable due to drift over extended travel times to destinations. NASA has proposed an advanced Doppler lidar system with multiple beams that can be used to accurately determine attitude and position of the landing vehicle during descent, and to detect hazards that might exist in the landing area.

In order to assess the effectiveness of such a Doppler lidar landing system, it is valuable to simulate the system with different beam numbers and configurations. In addition, the effectiveness of the system to detect and map potential landing hazards must be understood. This paper reports the simulated system performance for a proposed multi-beam Doppler lidar using the LadarSIM system simulation software. Details of the simulation methods are given, as well as lidar performance parameters such as range and velocity accuracy, detection and false alarm rates, and examples of the Doppler lidar's ability to detect and characterize simulated hazards in the landing site. The simulation includes modulated pulse generation and coherent detection methods, beam footprint simulation, beam scanning, and interaction with terrain.

9832-7, Session 3

3D flash lidar performance in flight testing on the Morpheus autonomous, rocket-propelled lander to a lunar-like hazard field

Vincent E. Roback, Farzin Amzajerjian, NASA Langley Research Ctr. (United States); Alexander E. Bulyshev, Analytical Mechanics Associates, Inc. (United States); Paul Brewster, Bruce W. Barnes, NASA Langley Research Ctr. (United States)

For the first time, a 3-D imaging Flash Lidar instrument has been used in flight to scan a lunar-like hazard field, build a 3-D Digital Elevation Map (DEM), identify a safe landing site, and, in concert with an experimental Guidance, Navigation, and Control (GN&C) system, help to guide the Morpheus autonomous, rocket-propelled, free-flying lander to that safe site on the hazard field. The flight tests served as the TRL 6 demo of the Autonomous Precision Landing and Hazard Detection and Avoidance Technology (ALHAT) system and included launch from NASA-Kennedy, a lunar-like descent trajectory from an altitude of 250m, and landing on a

lunar-like hazard field of rocks, craters, hazardous slopes, and safe sites 400m down-range. The ALHAT project developed a system capable of enabling safe, precise crewed or robotic landings in challenging terrain on planetary bodies under any ambient lighting conditions. The Flash Lidar is a second generation, compact, real-time, air-cooled instrument. Based upon extensive on-ground characterization at flight ranges, the Flash Lidar was shown to be capable of imaging hazards from a slant range of 1 km with an 8 cm range precision and a range accuracy better than 35 cm, both at 1- σ . The Flash Lidar identified landing hazards as small as 30 cm from the maximum slant range which Morpheus could achieve (450 m); however, it was occasionally susceptible to scintillation arising from air heated by the rocket engine and to pre-triggering on a dust cloud created during launch and transported down-range by wind.

9832-8, Session 3

3D lidar for hazard detection and autonomous deep space operations

Miguel San Martin, Anup B. Katake, Jet Propulsion Lab. (United States); Gary Kamerman, FastMetrix, Inc. (United States)

No Abstract Available

9832-9, Session 3

Laser-induced satellite communication relay system for GPS navigation and data transfer for space communication like in Mars

Mohammad M. Anwar, Asiatic Society of Bangladesh (Bangladesh)

Laser beam source will be very efficient for doing such work for communication relay or for even direct transmitting data from earth to mars or even mars to earth by using a satellite based laser induced data relay system by placing any satellite between mars and earth or even direct data transmission to mars. The Data relay system will contain transmitter and receiver both in mars and earth surface land station where laser beam data transmitter will send data to the mars using two planets geostationary orbiting satellites one in the orbit around the earth and another in the orbit around the mars and the signal will be down linked to the mars surface based station and also will be transmitted data from the mars to the earth surface for gps navigation for space shuttle and also for other survey in the mars surface for weather forecasting and for other reason.

9832-10, Session 4

Remote sensing-based detection and quantification of roadway debris following natural disasters

Colin Axel, Jan A. N. van Aardt, Rochester Institute of Technology (United States); Felipe Aros-Vera, Ohio University, Department of Industrial and Systems Engineering (United States); Jose Holguin-Veras, Rensselaer Polytechnic Institute, Department of Civil and Environmental Engineering (United States)

Timely knowledge of road network conditions is vital to formulate an efficient emergency response plan following any major disaster. Fallen buildings, immobile vehicles, and other forms of debris often render roads impassable to responders and evacuees.

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The status of roadways is generally determined through time- and resource-heavy methods, such as field surveys and manual interpretation of remotely sensed imagery. However, airborne lidar systems provide an alternative, cost-effective option for performing network assessments. The 3D data can be collected quickly over a wide area and provide valuable insight about the geometry and structure of the scene.

This paper presents a method for automatically detecting and characterizing debris in roadways using airborne lidar data. Lidar returns, falling within the road extent, are extracted from the point cloud and clustered into individual objects using region growing. Objects are classified as debris or non-debris using surface properties and contextual cues. Debris piles are reconstructed as surfaces using alpha shapes, from which an estimate of debris volume can be computed. The penetration depth of debris and the maximum passable width along the roadway are derived. Validation of the technique is demonstrated through an experiment conducted using artificial debris piles. Finally, results using lidar data, collected after a natural disaster, also are presented.

Initial results indicate that accurate debris maps can be automatically generated using the proposed method. These debris maps would be an invaluable asset to disaster management and emergency response teams attempting to reach survivors despite a crippled transportation network.

9832-11, Session 4

An automated method for registering lidar data in restrictive, tunnel-like environments

Walter Zacherl, The Univ. of Arizona (United States) and U.S. Army (United States); Eustace L. Dereniak, Lars R. Furenlid, Eric W. Clarkson, The Univ. of Arizona (United States)

Algorithms for object recognition such as the Scale Invariant Feature Transform (SIFT) and its derivatives can facilitate automated registration of lidar datasets. For SIFT to function in this role, the change in perspective between datasets is limited to about 30 degrees. Additionally, datasets must be arranged as range images or 2D matrices of sampled distances from a reference plane to the object in a Cartesian basis. To apply SIFT-based registration methods to tunnel-like environments, geometries with high length-to-width ratios, many closely-spaced datasets must be collected to keep the change in perspective between neighboring datasets small and the coverage complete. Example environments include corridors in robotic navigation, caves in archeology, and esophagi in medical imaging. The new automated registration method, similar in principle to SIFT, relaxes the change in perspective requirement and can be applied to datasets in a curvilinear coordinate representation. The form of the datasets is assumed to be a 2D matrix of range data referenced from a fixed point and sampled on a regular 2D-grid in polar and azimuthal coordinates. Initially, the data is filtered with a series of discrete Gaussian and derivative of Gaussian filters. The outputs of the filters form a second-order Taylor series approximation to the surface about each sampled point. Next, the principal curvatures with respect to the surface normal are calculated and compared across neighboring datasets to determine homologies. Finally, the best fit transfer matrix is determined. The new method permits greater separation between datasets reducing raw data volume requirements and processing time.

9832-12, Session 4

Laser range profiling for small target recognition

Ove Steinvall, Michael Tulldahl, FOI-Swedish Defence Research Agency (Sweden)

The detection and classification of small surface targets at long ranges is a growing need for naval security. Long range ID or ID at closer range of very small targets has its limitations in imaging due to the demand on very

high transverse sensor resolution. It is therefore motivated also to look for 1D laser techniques for target ID. These include vibrometry, and laser range profiling. Vibrometry can give good results but is also sensitive to certain vibrating parts on the target being in the field of view.

Laser range profiling is attractive because the maximum range can be substantial, especially for a small beam width. A range profiler can also be used in a scanning mode to detect targets within a certain sector. The same laser can also be used for active imaging when the target comes closer and is angular resolved.

The present paper will show both experimental and simulated results for laser range profiling of small boats out to 6-7 km range. We obtained good results with the profiling system both for target detection and recognition. Comparison of experimental and simulated range waveforms based on CAD models of the target support the idea of having a profiling system as a first recognition sensor and thus narrowing the search space for the automatic target recognition based on imaging at close ranges.

The experiments took place in the Baltic Sea with many other active and passive EO sensors beside the profiling system. Discussion of data fusion between laser profiling and imaging systems will be given.

9832-13, Session 4

Automated feature extraction for 3-dimensional point clouds

Lori A. Magruder, Holly Leigh, Alexander A. Soderlund, Bradley Clymer, Jessica Baer, Amy L. Neuenschwander, Applied Research Lab. (United States)

Light detection and ranging (LIDAR) technology offers the capability to rapidly capture high-resolution, 3-dimensional surface data with centimeter-level accuracy for a large variety of applications. Due to the foliage-penetrating properties of LIDAR systems, these geospatial data sets can detect ground surfaces beneath trees, enabling the production of high-fidelity bare earth elevation models in both urban and rural environments. Precise characterization of the ground surface allows for identification of terrain and non-terrain points within the point cloud, and facilitates further discernment between natural and man-made objects based solely on structural aspects and relative neighboring parameterizations. A framework is presented here for automated extraction of natural and man-made features that does not rely on coincident ortho-imagery or point RGB attributes. The TEXAS (Terrain EXtraction And Segmentation) algorithm is used first to generate a bare earth surface from a lidar survey, which is then used to classify points as terrain or non-terrain. Further classifications are assigned at the point level by leveraging local spatial information. Similarly classed points are then clustered together into regions to identify individual features. Descriptions of the spatial attributes of each region are generated, resulting in the identification of individual tree locations, forest extents, building footprints, and 3-dimensional building shapes, among others. Results of the fully-automated feature extraction algorithm are then compared to ground truth to assess completeness and accuracy of the methodology.

9832-14, Session 5

Generating passive NIR images from active LIDAR

Shea Hagstrom, Joshua B. Broadwater, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

Many modern LIDAR platforms contain an integrated RGB camera for capturing contextual imagery. However, these RGB cameras do not collect a near-infrared (NIR) color channel, omitting information useful for many analytical purposes. This raises the question of whether LIDAR data, collected in the NIR, can be used as a substitute for an actual NIR image in this situation. Generating a LIDAR-based NIR image is potentially useful in situations where another source of NIR, such as satellite imagery, is not available. LIDAR is an active sensing system that operates very differently

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from a passive system, and thus requires additional processing and calibration to approximate the output of a passive instrument. We examine methods of approximating passive NIR images from LIDAR for real-world datasets, and assess differences with true NIR images.

9832-15, Session 5

Real-time, mixed-mode computing architecture for waveform-resolved lidar systems with total propagated uncertainty

Robert L. Ortman, Domenic Carr, Ryan James, Daniel Long, Matthew O'Shaughnessy, Christopher R. Valenta, Grady H. Tuell, Georgia Tech Research Institute (United States)

GTRI has developed novel lidar-processing algorithms capable of producing real-time point clouds and total propagated uncertainty (TPU) and realized them in hardware and software to support waveform-resolved bathymetric lidar. The system employs a "mixed-mode" computing architecture, including an FPGA, CPU, and GPU, to produce lidar point clouds colored by depth or TPU. Noise reduction and ranging are performed in the digitizer's user-programmable FPGA; coordinates and TPU are calculated on the GPU. The system is capable of computing coordinates and TPU at over 20 million points per second.

A Keysight M9703A digitizer with user-programmable Xilinx Virtex 6 FPGAs digitizes up to eight channels of lidar data, performs ranging, and delivers the data to the CPU via PCIe. For each laser pulse, 1024 samples of raw data are recorded along with ranging results. The floating-point-intensive coordinate and TPU calculations are performed on an NVIDIA Tesla K20 GPU. Raw data and computed products are written to an SSD RAID.

Our lidar processing architecture provides a significant improvement over existing systems in its ability to not only compute and display bathymetric lidar point clouds in real-time but also provide National Geospatial Intelligence Agency (NGA)-compliant accuracy assessments (TPU). The system has been successfully tested using bathymetric lidar data collected at a seven-meter-deep water tank in Georgia Tech Mechanical Engineering Building as well as simulated waveforms for depths up to 20 m. The stored waveforms have been played back through the system using a Keysight M8190A arbitrary waveform generator at a 40 kHz trigger rate.

9832-16, Session 5

A developed calibration method for LDV in SINS/LDV integrated navigation systems

Guo Wei, Chunfeng Gao, Qi Wang, Qun Wang, Xingwu Long, National Univ. of Defense Technology (China)

The basic function of the vehicle position and azimuth determining system (PADS) is to provide the user with accurate geographical coordinate, azimuth, attitude and other navigation data on an automatic and continuous basis, which are the reference standards for the missile launch. As a new velocity sensor, laser Doppler velocimeter (LDV) is gradually applied in vehicle navigation field. It has many advantages such as high accuracy, rapid dynamic response and large measuring range. Similar to odometer, LDV cannot be used alone for navigation without orientation information, while SINS/LDV integration can achieve. Before navigation, calibration of LDV is needed and the calibration accuracy determines the navigation accuracy. The accuracy of the conventional calibration method depends on the known starting point and terminal point position accuracy and on the initial azimuth misalignment, so this analytic calibration method cannot meet the requirements in some applications. This paper describes a developed calibration method. A unique Kalman filter, the core of this development, is designed to calibrate the parameter of LDV in real time. To validate the availability of the developed method, simulation and test is reported. The results show that the IMU-vehicle azimuth installation angle and the LDV installation angle can be automatically calibrated by the developed calibration method with satisfying accuracy.

9832-17, Session 5

Research on the method of extracting DEM based on GBInSAR

Jianping Yue, Shun Yue, Hohai Univ. (China); Zhiwei Qiu, HoHai Univ (China); Xueqin Wang, Hohai Univ. (China); Leping Guo, HoHai Univ (China)

Precise topographical information has a very important role in geology, hydrology, natural resources survey and deformation monitoring. The extracting DEM technology based on synthetic aperture radar interferometry(InSAR) obtains the three-dimensional elevation of the target area through the phase information of the radar image data. The technology has large-scale, high-precision, all-weather features. Ground synthetic aperture radar interferometry (GBInSAR) merges three important technologies effectively including interferometric survey, stepped frequency continuous wave and synthetic aperture radar. By changing track in the location of the ground radar system up and down, it can form spatial baseline. Then we can achieve the DEM of the target area by acquiring image data from different angles. Three-dimensional laser scanning technology can quickly, efficiently and accurately obtain DEM of target area, which can verify the accuracy of DEM extracted by GBInSAR. But research on GBInSAR in extracting DEM of the target area is a little. For lack of theory and lower accuracy problems in extracting DEM based on GBInSAR now, this article conducted research and analysis on its principle deeply. The article extracted the DEM of the target area, combined with GBInSAR data. Then it compared the DEM obtained by GBInSAR with the DEM obtained by three-dimensional laser scan data and made statistical analysis and normal distribution test. The results showed the DEM obtained by GBInSAR was broadly consistent with the DEM obtained by three-dimensional laser scanning. And its accuracy is high. The difference of both DEM approximately obeys normal distribution. It indicated that extracting the DEM of target area based on GBInSAR is feasible and provided the foundation for the promotion and application of GBInSAR.

9832-18, Session 6

A lightweight and rugged laser radar system enabled by non-mechanical electro-optic beam steerers

Scott R. Davis, Scott D. Rommel, Benjamin Luey, Joseph D. Gamble, Derek Gann, Michael Ziemkiewicz, Michael H. Anderson, Vescent Photonics Inc. (United States)

There is currently a good deal of interest in developing laser radar (ladar) for autonomous navigation and collision avoidance in a wide variety of vehicles. In many of these applications, minimizing size, weight and power (SWaP) is of critical importance, particularly onboard aircraft and spacecraft where advanced imaging systems are also needed for location, alignment, and docking. In this paper, we describe the miniaturization of a powerful ladar system based on an electro-optic (EO) beamsteering device in which liquid crystal birefringence is exploited to achieve a 20° x 5° field of view (FOV) with no moving parts. In addition to scanning, the device is capable of operating in a "point and hold" mode where it locks onto a single moving object. The non-mechanical design leads to exceptionally favorable size and weight values: 1 L and < 1 kg respectively. Furthermore, these EO scanners operate without mechanical resonances or inertial effects. A demonstration was performed with a 50 kHz, 1 microjoule laser with a 2 mm beam diameter to image at a range of 100 m yielding a 2 fps frame rate limited by the pulse laser repetition rate. The fine control provided by the EO steerer results in an angle precision of 6x10⁻⁴ degrees. In this paper, we will present the results of a series of imaging demonstrations performed in the field under a variety of different conditions which show the significant performance characteristics of this new technology.

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9832-19, Session 6

Progress on MEMS-scanned lidar

Barry L. Stann, John F. Dammann Jr., Mark M. Giza, U.S. Army Research Lab. (United States)

The Army Research Laboratory (ARL) has continued to research a short-range lidar imager for use on small unmanned ground vehicles (UGV) and recently small unmanned air vehicles (UAV). The current lidar brassboard is based on a micro-electro-mechanical system (MEMS) mirror coupled to a low-cost pulsed erbium fiber laser. It has a 5-6 Hz frame rate, an image size of 256 (h) x 128 (v) pixels, a $42^\circ \times 21^\circ$ field of regard, 35 m range, eyesafe operation, and 40 cm range resolution with provisions for super-resolution. Experience with driving experiments on small ground robots and efforts to extend the use of the lidar to UAV applications has encouraged work to improve the lidar's performance. In the area of signal processing, we will discuss capability to recover up to 3 returns per pixel, an improved pulse correlation routine, and an improved range interpolation scheme. The data acquisition system can now capture range data from the three return pulses, and information such as time, operating parameters, and data from an inertial navigation system. We will mention the addition and performance of subsystems to obtain eye-safety certification and to automatically correct a left-to-right scan error that arises during changes in ambient temperature. To meet the enhanced range requirement for the UAV application, we discuss a new receiver circuit that improves the signal-to-noise (SNR) several-fold over the existing design. Complementing this work, we discuss research to build a low-capacitance large area detector that may enable even further improvement in receiver SNR.

9832-20, Session 6

UAV-borne lidar with MEMS mirror-based scanning capability

Veljko Milanovic, Abhishek Kasturi, James Yang, Mirrorcle Technologies, Inc. (United States)

A "point-and-range" LiDAR module was developed for UAV applications based on low SWaP (Size, Weight and Power) gimbal-less MEMS mirror beam-steering technology. The demonstrator includes a Raspberry Pi embedded system with a camera module relaying images over a Wi-Fi connection to a ground operator. An Android application streams the images from the UAV, and upon the operator's selection of a target object or area within an image, the MEMS mirror directs the module's transmitted beam toward the intended object based on the calibration between the camera and the MEMS scan module. The camera and the scan module are calibrated over their common field of regard (FoR) allowing simple and accurate open loop beam steering operation. For demonstration purposes, we used a simple off-the-shelf OEM laser range finder (LRF) with a 100m range, +/-1.5mm accuracy, and 10Hz ranging capability. The LRFs receiver optics were modified to accept 20° of angle, matching the transmitter's FoR. A relatively large (4.2mm) diameter MEMS mirror with +/- 10° optical scanning angle was utilized in the demonstration to maintain the small beam divergence of the module. The MEMS mirror PCB and its digital-input driver PCB are approximately 20mm x 20mm x 15mm in volume and weigh only 10g. The complete LiDAR prototype can fit into a small volume of <90mm x 60mm x 40mm, and weigh <50g when powered by the UAV's battery. The MEMS mirror based LiDAR system allows for on-demand ranging of points or areas within the FoR without altering the UAV's position. Increasing the LRF ranging frequency and stabilizing the pointing of the laser beam by utilizing the onboard inertial sensors and the camera are additional goals of the next design.

9832-21, Session 6

Design and performance of a multi-channel readout circuit for APD array in laser radar system

Yuxing Ding, Genghua Huang, Haiwei Wang, Weiming Xu, Rong Shu, Shanghai Institute of Technical Physics (China)

Laser Radar is a 3D laser imaging technology which can be used in the Earth remote sensing with airborne, space borne or other platforms. The imaging density of a laser radar system is partly decided by the number of elements of the detector which is used in the laser radar system. By replacing the single element APD in the 128-pixel scanning laser radar system we built in 2013 with an 8*8 array APD, the imaging density of the system will increase significantly. However, it is too complicated to readout all the 64 outputs of the 8*8 APD simultaneously by board level circuit while maintaining measure accuracy of laser radar system because of the circuit bandwidth limitation, signal delay and noise caused by PCB tracks.

In this case, a CMOS readout circuit is designed for the 8*8 APD (first sensor). By integrating multi-channel high bandwidth preamplifiers and high speed comparators in one integrated circuit we can process 64 channel APD signals in very limited space and increase the bandwidth of the circuit. Meanwhile, it is possible for us to combine the APD array and readout circuit into one small package to reduce the tracks between APD array and readout circuits which can always induce noise and affect the measure accuracy. Moreover, the small package can reduce the volume of the radar system which is extremely limited in space borne platforms. Thus, high bandwidth, high accuracy, low noise, compact package can be achieved in one 8*8 APD array with readout circuit. These advantageous characteristics make the readout circuit suitable for various APD array readout applications with high accuracy.

9832-22, Session 6

Accelerating space-charge gratings in photorefractive crystals: novel approach for laser Doppler velocimetry

Igor A. Sokolov, Mikhail A. Bryushinin, Ioffe Physical-Technical Institute (Russian Federation)

The interferometric techniques for detection of phase- and frequency-modulated optical signals are very sensitive but often suffer from the slow drift of the light phase, which is caused by a thermal expansion of the interferometer's components, air flows and low-frequency vibrations. The two-wave mixing (TWM) in photorefractive crystals as well as the non-steady-state photoelectromotive force (photo-EMF) provide an elegant solution of this problem. The dynamic space-charge gratings responsible for these effects automatically adjust the optimal operating point of the interferometer and correspondingly keep the stability of the detected signal. The interference pattern is usually created by two coherent light beams, which can be shifted by frequency or phase modulated by a sinusoidal signal. Constant frequency shift can arise because of the Doppler effect and sinusoidal phase modulation appears in the beam reflected from a vibrating object.

In this study we try to extend the variety of the effects observed in photoconductive media introducing linear frequency modulation (LFM) in the light beams forming interference pattern. We investigate theoretically and experimentally the manifestation of such illumination in the non-steady-state photo-EMF and two-wave mixing effects. We also discuss the possible application of the discovered pulsed response in laser Doppler velocimeters.

In this work we used frequency shifts and sweep rates in ranges $|df|=0-10$ MHz and $|A|=0.0005-1000$ MHz/s. They would correspond to the following ranges of velocity and acceleration of the light reflecting object: $|V|=0-3$ m/s and $|a|=0.0003-600$ m/s².

The devices realized on the considered effects will inherit the advantages of the devices using conventional non-steady-state photo-EMF and two-

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wave mixing effects. They include the rather high sensitivity and adaptivity, i.e. the possibility of operation in the presence of a slow phase drift in the interferometric setup. The devices will also be able to detect light signals with complicated wave fronts, even with speckle patterns produced by reflection from the real diffusely scattering objects.

Linear frequency modulation of optical beams provides another way to excite time-dependent two-wave mixing and photo-EMF signals. The effects reveal themselves as optical and electrical pulses arising in photoconductive and photorefractive media at the moments, when the interference pattern slows-down and stops, or at the moments, when resonant excitation of space-charge waves occurs. Duration, amplitude and shape of the pulses are determined by the sweep rate of linear frequency modulation and by the material parameters. This may allow development of new techniques for material characterization and detection of frequency modulated optical signals.

9832-23, Session 6

Pulse laser imaging amplifier for advanced Ladar systems

Vladimir B. Markov, Anatoliy Khizhnyak, Ivan V. Tomov, Advanced Systems & Technologies, Inc. (United States); David Murrell, Air Force Research Lab. (United States)

Security measures require a round the clock surveillance of government and military areas such as borders, bridges, industrial facilities, ports, military bases, reservoirs, and others. Likewise large public facilities, including sport arenas, airports, and malls are placing ever-increasing demands for active security systems. Performance of existing camera systems is sufficient to perform the job, except night time when powerful illumination of the surveillance scene is required to contest the impact of light pollution on neighboring areas. A new class of high-power infrared (IR) laser illuminators is now available that extends the use of low-cost visible cameras into nighttime and low-light operation. However the high-power laser illumination is often undesired, for example, when the goal is a covert surveillance missions and the reduced illumination power reduces the detection probability. Other scenarios of a coherent imaging include operation against live species and microorganisms that do not withstand high illumination intensity. These and many others operational conditions require qualitative coherent imaging at low-intensity illumination arriving at conditions, when the intensity of the object-scattered light can be lower than the sensitivity of the Ladar receiver image detector. This will require signal amplification with the gain in the range of a few dozens of dB's. Such gain level can be achieved by using the technique that involves multiple passes of the object-returned light wave through the coherent (laser) amplifier – the technique that requires assembling of a complex amplifying system.

This presentation discusses the novel in a high-gain intra-cavity amplification of cohere imaging signals. The important advantage of the approach with its ability to synchronize the incoming signal wave and the amplifying wave with the precision ≤ 1 ns, and the spectrum of the incoming signal not directly matched to the cavity mode but to the spectral band of the amplifier. The laboratory system with the gain > 40 dB and an angle of view 20 mrad has been practically demonstrated.

9832-38, Session 6

Large-aperture, wide-angle non-mechanical beam steering using polarization gratings

Steve Serati, Lance Hosting, Jay E. Stockley, Hugh J. Masterson, Christopher L. Hoy, Kelly Kluttz, RoyInn A. Serati, Boulder Nonlinear Systems (United States)

Several years ago, Boulder Nonlinear Systems (BNS) and North Carolina State University (NCSU) developed a novel non-mechanical beam steering

technique that uses a stack of thin liquid crystal polarization gratings (LCPGs) to efficiently steer a beam over a large field-of-regard (FOR) in discrete steps. The technology has been evolving over time and now BNS is developing the capability to fabricate LCPGs with clear apertures that exceed 10 cm and using these large LCPGs in new beam steering configurations for active and passive sensor systems for both defense and commercial applications. This paper describes the large-aperture LCPG steering configurations being developed and the performance being achieved.

9832-24, Session 7

Novel ultra-compact high-performance eye-safe laser range-finder with burst mode and wide-temperature range operation

Mark Silver, Thales Optronics Ltd. (United Kingdom); Ashleigh Barron, Thales UK Ltd. (United Kingdom); Stephen T. Lee, Andrew G. Borthwick, Graham Morton, Craig McNeill, David McSporrn, Ian McRae, Gordon McKinlay, David Jackson, William Alexander, Thales Optronics Ltd. (United Kingdom)

Compact eye-safe laser rangefinders are a key technology for future sensors. In addition to reduced size, weight and power (SWaP), compact LRFs are increasingly being required to deliver a higher repetition rate, burst mode capability. Burst mode allows acquisition of telemetry data from fast moving targets or while sensing-on-the-move. We will describe a new, ultra-compact, long-range, eye-safe laser rangefinder that incorporates a novel transmitter that can deliver a burst capability. The transmitter is a diode-pumped, erbium:glass, passively Q-switched, solid-state laser which uses design and packaging techniques adopted from the telecom components sector. The key advantage of this approach is that the transmitter can be engineered to match the physical dimensions of the active laser components and the sub-millimetre sized laser spot. This makes the transmitter significantly smaller than existing designs, leading to big improvements in thermal management, and allowing higher repetition rates. In addition, the design approach leads to devices that have higher reliability, lower cost, and smaller form-factor, than previously possible. We present results from the laser rangefinder that incorporates the new transmitter. The LRF has dimensions (L x W x H) of 100 x 55 x 34 mm and achieve ranges of up to 15km from a single shot, and over a temperature range of -32°C to +60°C. Due to the transmitter's superior thermal performance, the unit is capable of repetition rates of 1Hz continuous operation and short bursts of up to 4Hz. Short bursts of 10Hz have also been demonstrated from the transmitter in the laboratory.

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9832-25, Session 7

Three-dimensional image reconstruction using bundle adjustment applied to multiple texel images

Bikalpa Khatiwada, Scott E. Budge, Utah State Univ. (United States)

The importance of creating 3D imagery is increasing and has many applications in the field of disaster response, digital elevation models, object recognition, and cultural heritage. Several methods have been proposed to register texel images, which consist of fused ladar and digital imagery. The previous methods were limited to registering up to two texel images or multiple texel swaths having only one strip of ladar data per swath. One area of focus still remains to register multiple texel images to create a 3D model.

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The process of creating true 3D images using multiple texel images is described. The texel camera fuses the 2D digital image and calibrated 3D lidar data to form a texel image. The images are then taken from several perspectives and registered. The advantage of using multiple full frame texel images over 3D- or 2D-only methods is that there will be better registration between images because of the overlapping 3D points as well as 2D texture used in the joint registration process. The individual position and rotation mapping to a common world coordinate frame is calculated for each image and optimized. The proposed methods incorporate bundle adjustment for jointly optimizing the registration of multiple images. Sparsity is exploited as there is a lack of interaction between parameters of different cameras. Examples of the 3D model are shown and analyzed for numerical accuracy.

9832-26, Session 7

Simulated full-waveform lidar compared to Riegl VZ-400 terrestrial laser scans

Angela M. Kim, Richard C. Olsen, Naval Postgraduate School (United States); Martin Béland, Univ. Laval (Canada)

A 3-D Monte Carlo ray-tracing simulation of LiDAR propagation models the reflection, transmission and absorption interactions of laser energy with materials in a scene. Parameters defining the LiDAR sensor and collection geometry can be modified as needed. In this presentation, a model scene consisting of a single Coast Live Oak (*Quercus agrifolia*) is generated by the high-fidelity tree voxel model VoxLAD. The VoxLAD model uses terrestrial LiDAR scanner data to determine Leaf Area Density (LAD) measurements for small volume voxels (~20 cm³) of a single tree canopy. Information from the VoxLAD model is used within the LiDAR propagation simulation to determine the probability of LiDAR energy interacting with materials at a given voxel location, and the directional scattering should an interaction occur. Simulated full-waveform LiDAR signals compare favorably to those obtained with a Riegl VZ-400 terrestrial laser scanner.

9832-27, Session 7

Direct detection lidar imaging through turbulence: computational grid size optimizations

Douglas G. Youmans, Parsons Corp. (United States)

Atmospheric turbulence affects laser radar imaging through the atmosphere, both on the outward path and on the return path. Typically a laser mode is numerically propagated outward to the target to model beam-spread and hot-spot formation. This often requires large matrices to sample the beam source region and the large, aberrated beam spot on target, as well as proper sampling of the turbulence spectrum. Likewise, a return path plane-wave may be generated to compute a point spread function due to turbulence and to aperture diffraction and aberrations. This matrix only needs to be larger than the size of the receiving aperture, but must also adequately sample the turbulence spectrum.

The storage of these matrices for Monte Carlo image realizations, followed by numerical image processing, feature extraction, and testing image processing algorithms, can require large amounts of memory. We examine the storage of these matrices at the full matrix sizes versus vastly downsized one point per detector pixel, Nyquist sampling per pixel, 2x Nyquist, 3x Nyquist, etc. sampling per pixel matrix storage. The reduction in image quality and degradation in turbulence modeling accuracy will be discussed.

9832-28, Session 7

Application and capabilities of lidar from small UAV

Michael Tullidahl, Fredrik Bissmarck, Håkan Larsson, Christina Grönwall, Gustav Tolt, Jonas Nordlöf, FOI-Swedish Defence Research Agency (Sweden)

The purpose of this study is to present and evaluate the benefit and capabilities of high resolution 3D data from unmanned aircraft, especially in conditions where existing methods (passive imaging, 3D photogrammetry) have limited capability. Some examples of applications are detection of obscured objects under vegetation, change detection, detection in dark or shadowed environments, and an immediate geometric documentation of an area of interest. Applications are exemplified with experimental data from our small UAV test platform 3DUAV with an integrated rotating laser scanner and with test data collected with a terrestrial laser scanner. Our airborne experimental system consists of the Velodyne HDL-32E lidar on a six-rotor aircraft with a total weight of 7 kg. We process lidar data combined with inertial navigation system (INS) data for generation of a highly accurate point cloud. The combination of INS and lidar data is achieved in a dynamic calibration process that minimizes the navigation errors from a low-cost and light-weight MEMS based (microelectromechanical systems) INS. This system allows for studies of the whole data collection-processing-application development chain and also serves as a platform for evaluation of other platform/sensor concepts in similar or related applications. We discuss applications and capabilities in relation to system aspects such as integration, accuracy, and laser sensor performance (range, multiple echo detection capability).

9832-29, Session 8

Integrated analysis of light detection and ranging (LiDAR) and hyperspectral imagery (HSI) data

Angela M. Kim, Fred A. Kruse, Richard C. Olsen, Naval Postgraduate School (United States)

LiDAR and hyperspectral data provide rich and complementary information about the content of a scene. In this work, we examine methods of data fusion, with the goal of minimizing information loss due to point-cloud rasterization, and spatial-spectral resampling. Two approaches are investigated and compared: 1) Spectral indices such as Normalized Difference Vegetation Index (NDVI), hyperspectral similarity measures (for example Mixture Tuned Matched Filtering (MTMF)), and spatial "texture" features are calculated and appended as attributes to each LiDAR point falling within the spatial extent of the pixel. Cluster analysis or supervised machine learning approaches are used to classify the resulting fused point cloud. 2) LiDAR raster products (DEMs, DSMs, slope, height, aspect, etc) are created and appended to the hyperspectral image cube. Traditional spectral classification techniques are then used to classify the fused image cube. The methods are compared in terms of classification accuracy. LiDAR data and associated orthophotos of the NPS campus collected during 2012 - 2014 and hyperspectral Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data collected during 2011 are used for this work.

9832-30, Session 8

Application of image classification techniques to multispectral lidar point cloud data

Chad Miller, Judson Thomas, Angela M. Kim, Jeremy P. Metcalf, Richard C. Olsen, Naval Postgraduate School (United States)

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Data from Optech Titan are analyzed here for purposes of terrain classification, adding the spectral data component to the LiDAR data point cloud analysis. The approach used here combines the three-spectral sensors into one point cloud, combining the intensity information from the 3 sensors. Nearest-neighbor sorting techniques are used to create the merged point cloud. The merged point cloud is analyzed using spectral analysis techniques that allow for the exploitation of color, derived spectral products (pseudo-NDVI), as well as lidar features such as Above Ground Level (AGL) values, and return number. Standard spectral image classification techniques are used to train a classifier, and analysis was done with a maximum likelihood classification. Classification results are compared for 3 cases: sole use of spectral information, sole use of point cloud (x,y,z) information, and combined use of spectral and lidar terms.

9832-31, Session 8

Field-widened Michelson interferometer system as the spectroscopic filter of high-spectral-resolution lidar

Zhongtao Cheng, Dong Liu, Yongying Yang, Jian Bai, Yibing Shen, Yudi Zhou, Yupeng Zhang, Jing Luo, Zhejiang Univ. (China); Chong Liu, Zhejiang University (China)

We propose and develop a field-widened Michelson interferometer (FWMI) system to act as a new type of spectroscopic filter in HSRL application. Due to the field widening characteristic, the FWMI can allow relatively large off-axis incident angle, and can be designed to any desirable wavelength. The theoretical foundations of the FWMI are introduced in this paper, and the developed prototype interferometer is described. It consists of a solid arm made of the glass H-ZF52 with the dimension of 37.876mm, and an air gap with the length of 20.382mm. These two interference arms are connected to a cube beam splitter to constitute a Michelson interferometer. Due to the matched dimensions and refractive indices of the two arms, the experimental testing results show that the OPD variation of the developed FWMI is about 1/10 lambda and the RMS is less than 1/40 lambda when the incident angle is as much as 3.5 degree (half angle). To lock the filtering frequency of the FWMI to the laser transmitter, a frequency locking system, which is actually an electro-optic feedback loop, is established. The setup and principle of this frequency locking system are also described in detail. Good locking accuracy of the FWMI within several MHz is demonstrated through the frequency locking technique. All these results validate the feasibility of this developed FWMI system as a spectroscopic filter of an HSRL.

9832-32, Session 8

Polarized high-spectral-resolution lidar based on field-widened Michelson interferometer

Zhongtao Cheng, Dong Liu, Yongying Yang, Jian Bai, Yibing Shen, Jing Luo, Yupeng Zhang, Yudi Zhou, Zhejiang Univ. (China); Chong Liu, Zhejiang Univ (China)

A polarized high-spectral-resolution lidar (HSRL) based on a field-widened Michelson interferometer (FWMI) is developed in Zhejiang University, China, which is intended to profile various atmospheric aerosol optical properties simultaneously, such as the backscatter coefficient, the extinction coefficient, depolarization ratio, lidar ratio, etc. Due to the enlarged field-of-view (FOV) of the FWMI spectroscopic filter compared with the conventional Fabry-Perot interferometer (FPI) filter, we can expand the angular acceptable angle of the HSRL system to about 1 degree yet without any degradation of the spectral discrimination, enhancing the photon efficiency considerably. In this paper, we describe the developed FWMI-based polarized HSRL system comprehensively. The instrument configuration parameters and overall systematic structure are first presented. Then the FWMI subsystem, as the core apparatus of this HSRL,

is particularly focused on. Instrumental calibration approach and the data retrieval are also discussed in detail. With the current development status, preliminary measurements for the atmospheric condition in Hang Zhou of China is carried out which verifies the feasibility of the HSRL instrument. To our knowledge, this HSRL system is the first new generation of lidar which employs the FWMI spectroscopic filter in China, and great potential will be shown with the gradually improved engineering design in near future.

9832-33, Session 9

Atmospheric absorption versus deep ultraviolet (pre-)resonance in Raman lidar

Hans D. Hallen, North Carolina State Univ. (United States); Adam H. Willitsford, Johns Hopkins Univ. Applied Physics Lab., LLC (United States); Ryan R. Neely III, C. Todd Chadwick, C. Russell Philbrick, North Carolina State Univ. (United States)

The resonant and pre-resonant Raman scattering of several liquids and solid materials has been investigated near their deep ultraviolet absorption features. A frequency-doubled optical parametric oscillator (OPO) generated a tunable excitation beam in the 215-600 nm range. We previously investigated and reported the resonance Raman scattering of several hydrocarbon species, and demonstrated that major enhancements in the Raman scatter in hydrocarbon liquids are observed at the wavelengths corresponding to the narrow, phonon-allowed, vapor absorption peaks. These resonances exhibit no pre-resonance, but lie on the pre-resonance features of higher energy, symmetry-allowed, absorptions. We have also investigated pre-resonance and resonance Raman spectroscopy near an absorption band of ice for 2.9 eV to 5.6 eV excitation energies. The A-term of the Raman scattering tensor describes the pre-resonant enhancement of these spectra due to the strong ice absorption at 150 nm. A wide resonance structure near the final-state-effect related absorption in ice is also found, contrasting the hydrocarbon results noted above. The results suggest that use of pre-resonant or resonant Raman LIDAR could increase the sensitivity to improve spatial and temporal resolution of atmospheric water vapor measurements. However, these shorter wavelengths also exhibit higher ozone absorption. These opposing effects are modeled using MODTRAN for several configurations relevant for studies of boundary layer water and in the vicinity of clouds. Such data could be used in studies of the measurement of energy flow at the water-air and cloud-air interface, and may help with understanding some of the major uncertainties in current global climate models.

9832-34, Session 9

Broadband on-chip mid-IR supercontinuum generation

Xiang Zhang, Wenbo Li, Hongyu Hu, Niloy K. Dutta, Univ. of Connecticut (United States)

We numerically demonstrate mid-IR supercontinuum generation in a non-uniformly tapered chalcogenide planar waveguide. This planar rib waveguide of As₂S₃ glass on silica is 2 cm long with increasing etch depth longitudinally to tailor the total dispersion. This waveguide has zero dispersion at two wavelengths. The dispersion profile is varying along the propagation distance, leading to continuous modification of the phase-matching condition for dispersive wave emission and enhancement of energy transfer efficiency between solitons and dispersive waves. Numerical simulations are conducted for secant input pulses at a wavelength of 1.55 μm with a width of 50 fs and peak power of 2 kW. Results show this proposed scheme significantly broadens the generated continuum, extending from -1 μm to -7 μm, which manifests the potential for mid-IR laser sources.

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9832-35, Session 9

Lidar for monitoring oil and gas field

Alexsandr S. Grishkanich, Sergey V. Kascheev, Alexsandr P. Zhevlakov, Julia Ruzankina, Leonid Smirnov, ITMO Univ. (Russian Federation); Igor S. Sidorov, Univ. of Eastern Finland (Finland)

The role of laser sensor designed for remote sensing of the earth's surface to use the lidar working on the method of Raman scattering. You can also use the method and fluorescent radiation to find oil and gas deposits, but this method has one significant drawback, is the effect of fluorescence quenching in the atmosphere.

Oil and gas inside earth's crust. To ensure that we are able to find them, as they would help us diffuse to the surface, and we can only detect their presence. Lidar mounted on a vehicle, at equal intervals of time let the probing beams, which in turn a few are scattered in the collision with the ground, after which heading back carrying information about the probed surface.

Substances indicators decided to take the ethane (C₂H₆) and hydrogen Sulfide (H₂S), because they are direct constituents of oil and gas. Given the spectral characteristics of the detected substances and the maximum transmittance of the atmosphere, lying in the ultraviolet region of the spectrum, it's safe to say that the research will be conducted in the ultraviolet region.

The radiation source is a YAG-Nd laser, because the research will be conducted in the ultraviolet region of the spectrum, you should use the 4 harmonic of the laser, i.e. 266 nm.

Using the scheme of monostatic lidar, was developed by the structural scheme. The basis of the optical scheme is the receiving scheme Cassegrain. Calculating overall performance of the lens was developed by its design.

This lidar search of oil and gas fields becomes possible..

9832-36, Session 9

Comprehensive view of high-spectral-resolution lidar technique from the perspective of spectral discrimination

Zhongtao Cheng, Dong Liu, Yongying Yang, Jian Bai, Yibing Shen, Jing Luo, Yudi Zhou, Yupeng Zhang, Zhejiang Univ. (China); Chong Liu, Zhejiang Univ (China)

As already known commonly, high-spectral-resolution lidar technique (HSRL) employs a narrowband spectroscopic filter to separate the elastic backscattered aerosol signal from the thermal Doppler broadened molecular backscattered contribution. This paper presents a new and comprehensive view of HSRL technique from the perspective of spectral discrimination, without concretizing the analysis into a specific spectral discrimination filter. We first introduce a theoretical model for retrieval error evaluation of an HSRL instrument with general three-channel configuration. The model only takes the error sources related to the spectral discrimination parameters into account, while other error sources not associated with these focused parameters are excluded on purpose. Monte Carlo (MC) simulations are performed to validate the correctness of the theoretical model. Results from both the model and MC simulations agree very well, and they illustrate one important, although not well realized fact: a large molecular transmittance and a large spectral discrimination ratio (SDR, i.e., ratio of the molecular transmittance to the aerosol transmittance) are beneficial to promote the retrieval accuracy. Since the signal-to-noise ratio (SNR) and SDR of the lidar system are often trade-offs, we suggest considering a suitable SDR for higher molecular transmittance (thus higher SNR) instead of using unnecessarily high SDR when designing the spectral discrimination filter. This view interprets the function of the narrowband spectroscopic filter in HSRL system essentially, and will provide some general guidelines for the reasonable design of the spectral discrimination filter for HSRL community.

9832-37, Session 9

High-spectral-resolution lidar for ocean ecosystem studies

Zhongtao Cheng, Yongying Yang, Yibing Shen, Jian Bai, Kaiwei Wang, Yudi Zhou, Jing Luo, Yupeng Zhang, Dong Liu, Zhejiang Univ. (China); Chong Liu, Zhejiang Univ (China)

Over 70% of the earth's surface is covered by the ocean that contains rich resources. However, the development and utilization of ocean resources are greatly limited as a result of human's limited knowledge of the ocean. Remote sensing methods have played important roles in understanding and exploring the ocean, and lidar is one of the most outstanding representatives for its high spatial and temporal resolution. High-spectral-resolution lidar (HSRL) employs an ultra-narrow spectral filter to separate scattering signals from particles and water molecules, and obtain the optical properties of the ocean water with high accuracy. By now, the most popular HSRLs in atmospheric remote sensing are those based on iodine filter at 532nm. And they have already been applied in oceanographic profiling and produced lots of useful information for ocean studies. Nevertheless, the spectral absorption of seawater varies with its temperature, salinity and other characteristics. Since the strong absorption of seawater greatly limits the detection depth of lidar ocean sensing, an optimal working wavelength with smaller absorption but larger scattering will improve the detection depth significantly. Field-widened Michelson interferometer (FWMI), whose central transmittance can be tuned to any wavelength, can be employed as the HSRL spectral filter and solve the problem above. The valley transmittance can be located at the central frequency of the lidar transmitting laser while the peak transmittance at the two Brillouin scattering sidebands. Moreover, the FWMI has a very large field of view (FOV) which gives its superiority over Fabry-Perot interferometer (FPI), which is another popular HSRL filter. The principle of the FWMI and its application in HSRL for ocean remote sensing will be given in detail. Preliminary experiments showed that the HSRL instrument basing on FWMI could be employed in ocean studies.

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9833-15, Session PSWed

Sounding using ground-based and cluster-satellite plasmaspheric EM wave propagation techniques

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Measurements of the electron density distribution of the plasmasphere assist in determining Space Weather events and their effects on Space equipment. Electron density variations have full control over electromagnetic wave propagation through the vast three-dimensional area of the plasmasphere. Sounding of the lower-plasmasphere is typically performed using ionosondes. Ionosondes operate on active radar principles to provide sounding and directly measure plasma electron density variations with respect to geographic location, time and altitude. Numerous ground-based ionosondes are currently in use worldwide. In-situ plasmaspheric measurements are obtained using sounding rockets and various space missions. Numerous cluster-satellite missions provide measurements of the field and plasma gradients. Subsequently, the electron current density is determined. A comparison between long-term data obtained from various European ionosondes and the 4-point CLUSTER mission are presented. The results exhibit an expected systematic trend between them. The various discrepancies are analyzed, explained and future research work is proposed.

9833-1, Session 1

Atmospheric propagation of high-power laser radiation at different weather conditions

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Applications based on the propagation of high power laser radiation through the atmosphere are limited in range and effect, due to weather dependent beam wandering, beam deterioration, and scattering processes. Security and defense related application examples are countermeasures against hostile projectiles and the powering of satellites and aircrafts. For an examination of the correlations between weather condition and laser beam characteristics DLR operates at Lampoldshausen a 130 m long free transmission laser test range. Sensors around this test range continuously monitor turbulence strength, visibility, precipitation, temperature, and wind speed. High power laser radiation is obtained by a TruDisk 6001 disk laser (Trumpf company) yielding a maximum output power of 6 kW at a wavelength of 1030 nm. The laser beam is expanded to 180 mm and focused along the beam path. Power and intensity distribution are measured before and after propagation, providing information about the atmospheric transmission and alterations of diameter and position of the laser beam. Backscattered laser light is acquired by a photo receiver. As a result, measurements performed at different weather conditions show a couple of correlations to the characteristics of the laser beam. The experimental results are compared to a numerical analysis. The calculations are based on the Maxwell wave equation in Fresnel approximation. The turbulence is considered by the introduction of phase screens and the “von Karman” spectrum.

9833-2, Session 1

Estimation of atmospheric parameters from time-lapse imagery

Jack E. McCrae Jr., Santasri Basu, Steven T. Fiorino, Air Force Institute of Technology (United States)

A time-lapse imaging experiment was conducted to estimate various atmospheric parameters for the imaging path. Atmospheric turbulence caused frame-to-frame shifts of the entire image as well as parts of the image. The statistics of these shifts encode information about the turbulence strength (Cn^2) along the optical path. The shift variance observed is simply proportional to the variance of the tilt of the optical field averaged over the area being tracked. By presuming this turbulence follows the Kolmogorov spectrum, weighting functions can be derived which relate the turbulence strength along the path to the shifts measured. These weighting functions all peak at the camera and fall to zero at the object. The larger the area observed, the more quickly the weighting function decays. One parameter we would like to estimate is r_0 (the Fried parameter, or atmospheric coherence diameter.) The weighting functions derived for pixel sized or larger parts of the image all fall faster than the weighting function appropriate for estimating the spherical wave r_0 . If we presume Cn^2 is constant along the path, then an estimate for r_0 can be obtained for each area tracked, but since the weighting function for r_0 differs substantially from that for every realizable tracked area, it can be expected this approach would yield a poor estimator. Instead, the weighting functions for a number of different patch sizes can be combined through the Moore-Penrose pseudo-inverse to create a new weighting function which yields the least-squares optimal linear combination of measurements for estimation of r_0 . This approach is carried out, and it is observed that this approach is somewhat noisy because the pseudo-inverse assigns weights much greater than one to many of the observations.

9833-3, Session 1

Beaconless adaptive-optics technique for HEL beam control

Vladimir B. Markov, Anatoliy Khizhnyak, Advanced Systems & Technologies, Inc. (United States)

Effective performance of forthcoming laser systems capable of power delivery on a distant target requires an adaptive optics system to correct atmospheric perturbations on the laser beam. The turbulence-induced effects are responsible for beam wobbling, wandering, and intensity scintillation, resulting in degradation of the beam quality and power density on the target. Adaptive optics methods are used to compensate for these negative effects. In its turn, operation of the AOS system requires a reference wave that can be generated by the beacon on the target. This report discusses a beaconless approach for wavefront correction with its performance based on the detection of the target-scattered light. Post-processing of the beacon-generated light field enables retrieval and detailed characterization of the turbulence-perturbed wavefront -data that is essential to control the adaptive optics module of a high-power laser system.

9833-4, Session 1

A fast calculating two-stream-like multiple scattering algorithm that captures azimuthal and elevation variations

Steven T. Fiorino, Air Force Institute of Technology (United States); Brannon J. Elmore, Air Force Institute of Technology (United States) and Oak Ridge Institute for Science and Education (United States); Jaclyn Schmidt, Air Force Institute of Technology (United States) and Applied Research Solutions (United States); Elizabeth Matchefts, Air Force Institute of Technology (United States) and Southwestern Ohio Council for Higher Education (United States); Jarred Burley, Air Force Institute of Technology (United States)

Properly accounting for multiple scattering effects can have important implications for remote sensing and possibly directed energy applications. For example, increasing path radiance can affect signal noise. This study describes the implementation of a fast-calculating two-stream-like multiple scattering algorithm that captures azimuthal and elevation variations into the Laser Environmental Effects Definition and Reference (LEEDR) atmospheric characterization and radiative transfer code. The unique aspect of this multiple scattering algorithm is that it fully solves for molecular, aerosol, cloud, and precipitation scattering single-scatter layer effects with a Mie algorithm at every calculation point/layer rather than an interpolated value from a pre-calculated look-up-table. This top-down cumulative diffusivity method first considers the incident solar radiance contribution to a given layer accounting for solid angle and elevation, and it then measures the contribution of diffused energy from previous layers based on the transmission of the current level to produce a cumulative radiance that is reflected from a surface and measured at the aperture at the observer. The aforesaid leads to a unique set of asymmetry and backscattering phase function parameter calculations which account for the radiance loss due to the molecular and aerosol constituent reflectivity within a level and allows for a more accurate characterization of diffuse layers that contribute to multiple scattered radiances in an inhomogeneous atmosphere. Special consideration is made for cloud layers where the primary contribution to the observed diffuse radiance is due to the reflectivity of the clouds itself. The code logic is valid for various spectral bands between 350 nm and microwave wavelengths, and the accuracy of this algorithm is demonstrated by comparing the results from LEEDR to other radiative transfer models, as well as observed sky radiance data.

9833-5, Session 2

Ground station diversity requirements for cloud free LOS links

Christopher I. Moore, Jake Griffiths, Taylor Page, Lindsey Willstatter, Linda M. Thomas, U.S. Naval Research Lab. (United States)

No Abstract Available

9833-6, Session 2

Bi-directional free space laser communication of gigabit Ethernet (GBE) telemetry data using dual atmospheric effect mitigation approach

Eric Y. Chan, Jonathan M. Saint Clair, The Boeing Co. (United States)

This paper presents experimental demonstration of optical components applicable in free space laser communication systems for bi-directional transmission of Gigabit Ethernet telemetry data and control messages using a dual atmospheric effect mitigation approach. Free space laser communication is a viable solution for long distance (>1 km) telemetry link between aircraft and ground station. There are major challenges for optical transmission of telemetry data: (1) Free space laser communication signals propagating over long distances through the Earth's lower atmosphere from transmitter to receiver experience turbulence effects which cause optical beam scintillation, wander and breakup, all of which cause signal fading at the receiver. (2) An optical signal in free space has a fading effect which is caused by communications terminal equipment's in-ability to maintain perfect pointing along a line of sight due to vibrations/motions of the mobile platform. (3) A number of existing telemetry systems have already been adapted to the global grid using Gigabit Ethernet (GBE) for high speed telemetry data. We have found an incompatibility problem with existing laser communication equipment which are designed for very high speed Synchronous Optical Network (SONET). The first two problems are addressed by using an Optical Combining Receiver Array (OCRA) approach to mitigate the atmospheric turbulence effect and a Framer/Forward Error Correction/Interleaver (FFI) to mitigate severe fading due to motions of the mobile platform. The third problem is addressed by using a commercially available intelligent small form factor (SFF) transceiver to convert the GBE data into SONET OC3 optical data stream to be processed by the FFI.

9833-7, Session 2

Enhanced link availability for FSO time-frequency transfer using adaptive optic terminals

Keith Petrillo, Johns Hopkins Univ. (United States); Michael L. Dennis, Juan C. Juarez, Johns Hopkins Univ. Applied Physics Lab., LLC (United States); Esther Baumann, National Institute of Standards and Technology (United States); Hugo Bergeron, Ctr. d'Optique, Photonique et Laser (Canada); Ian Coddington, National Institute of Standards and Technology (United States); Jean-Daniel Deschenes, Polyrix, Inc. (Canada); Fabrizio R. Giorgetta, Nathan R. Newbury, William C. Swann, National Institute of Standards and Technology (United States)

No Abstract Available

9833-8, Session 2

Free-space and underwater GHz data transmission using AlGaInN laser diode technology

Stephen P. Najda, Piotr Perlin, Tadek Suski, Lucja Marona, Mike Boćkowski, Mike Leszczyński, Przemek Wisniewski, Robert Czernecki, TopGaN Ltd. (Poland); Robert Kucharski, Ammono S.A. (Poland); Gregorz Targowski, TopGaN Ltd. (Poland); Scott Watson, Anthony Kelly, Univ. of Glasgow (United Kingdom)

Laser diodes fabricated from the AlGaInN material system is an emerging technology for defence and security applications, in particular for free space laser communication. Conventional underwater communication is done acoustically with very slow data rates, short reach, and vulnerable for interception. AlGaInN blue-green laser diode technology allows the possibility of both airborne links and underwater telecom that operate at very fast data rates (GHz), long reach (100's of metres underwater) and can be quantum encrypted.

The latest developments in AlGaInN laser diode technology are reviewed for defence and security applications. The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., ~380nm, to the visible ~530nm, by tuning the indium content of the laser GaInN quantum well. Ridge waveguide laser diode structures are fabricated to achieve single mode operation with optical powers of >100mW. Visible light communications at high frequency (up to 2.5 Gbit/s) using a directly modulated 422nm Gallium-nitride (GaN) blue laser diode is reported in free-space and underwater.

High power operation of AlGaInN laser diodes is also reviewed. Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. Laser bars of up to 5mm with 20 emitters have shown optical powers up to 4W cw at 422nm with a common contact configuration. An alternative package configuration for AlGaInN laser arrays allows for each individual laser to be individually addressable allowing complex free-space and/or fibre optic system integration within a very small form-factor.

9833-9, Session 2

Lasercomm system development for high-bandwidth terrestrial communications

Juan C. Juarez, Katherine T. Souza, Andrea M. Brown, Ryan P. DiNello-Fass, Hala Tomey, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

No Abstract Available

9833-10, Session 3

Passive adaptive imaging through turbulence

David H. Tofsted, U.S. Army Research Lab. (United States)

Standard methods for improved imaging system performance under degrading optical turbulence conditions typically involve active adaptive techniques where a guide star supplies a known collimated light source in the object field that can be analyzed to determine the incident phase front perturbation pattern. Alternatively, numerous image correction algorithms have been studied. Here, an adaptive aperture is considered as a key component of a passive adaptive system where no active sources are available in the object field. Theoretical analyses of short-exposure turbulence impacts indicate that varying aperture sizes experience turbulence impacts differently. Smaller apertures may often outperform larger aperture systems as turbulence strength increases, and corresponding coherence length decreases. This suggests a controllable aperture is advantageous. A controllable aperture can also be used to perform sub-aperture image acquisition and cross-correlation to determine the phase pattern. A four sub-aperture pattern produces 5 operating modes (beyond tip and tilt) that correct for aberrations over an annular pattern. Progress to date will be discussed regarding development and field trials of the prototype system.

9833-11, Session 3

Controlled simulation of optical turbulence in a temperature gradient air chamber

Italo Toselli, Univ. of Miami (United States); Fei Wang, Soochow Univ. (China) and Univ. of Miami (United States); Olga Korotkova, Univ. of Miami (United States)

An atmospheric turbulence simulator is built and characterized for in-lab optical wave propagation with controlled strength of the refractive-index fluctuations. The temperature gradients are generated by a sequence of

heat guns placed with controlled individual strengths and orientations. The temperature structure functions are measured in several directions transverse to propagation path with the help of a two-dimensional thermocouple array and used for evaluation of the corresponding refractive-index structure functions of optical turbulence. The effect of the turbulence on the propagating laser beam statistics is illustrated for various turbulence regimes.

9833-12, Session 3

Atmospheric refraction: applied image analysis and experimental examples

Daniel Short, Jose L. Barraza, Ivan V. Dragulin, David G. Voelz, New Mexico State Univ. (United States)

The effects of the clear atmosphere on imaging and other optical applications include short time scale turbulent spreading, usually considered stochastically, and effects of refraction, which are more deterministic with longer time scales. Refraction can produce spectacular effects, such as mirages; however, more subtle effects occur daily that can significantly impact the perceived image such as the position of an object or its apparent proportions. Expressions describing various aspects of the phenomena date back to publications more than a half century ago, but with the pervasiveness of optical technologies today for imaging, location and communication there is a need for straightforward descriptions relating observed image shifting and stretching/compression to the index profiles. In this paper, simple analytical expressions are derived to describe ray behavior along horizontal paths. Time-lapse imaging experiments over a 15 km path were conducted to measure refractive effects and the images were analyzed to determine the characteristics of the atmospheric refractive index profile. This analysis, in conjunction with the time-lapse imagery, will be used in the future to study the statistics of refractive effects over long time periods.

9833-13, Session 3

Capturing atmospheric effects on 3D millimeter-wave radar propagation patterns

Richard D. Cook, Steven T. Fiorino, Air Force Institute of Technology (United States); Kevin J. Keefer, Air Force Institute of Technology (United States) and Applied Research Solutions (United States); Jeremy Stringer, Air Force Institute of Technology (United States)

The need to model millimeter wave (MMW) radar propagation is imperative to proper design of aeronautical, civil, and military systems. Traditional radar propagation modeling is done using a path transmittance with little to no input for weather and atmospheric conditions. As radar advances into the MMW regime, atmospheric effects such as attenuation and refraction become more pronounced than at traditional radar wavelengths. The DoD High Energy Laser Joint Technology Office's High Energy Laser End-to-End Operational Simulation (HELEEOS) in combination with the Laser Environmental Effects Definition and Reference (LEEDR) code have shown great promise simulating atmospheric effects on laser propagation. Indeed, the LEEDR radiative transfer code provides results for the UV through RF domain. Our research attempts to apply these models to characterize the far field radar pattern in three dimensions as a signal propagates from an antenna towards a point in space. Furthermore, we do so using realistic three dimensional atmospheric profiles derived from NOAA numerical weather models or a climatological database. The results from these simulations are compared to those from traditional radar propagation software packages. In summary, a fast running method has been investigated which can be incorporated into computational models to enhance understanding and prediction of MMW propagation through various atmospheric and weather conditions.

9833-14, Session 3

Diffraction propagation and recovery of modulated (including chaotic) electromagnetic waves through uniform atmosphere and modified von Karman phase turbulence

Monish R. Chatterjee, Fathi H. A. Mohamed, Univ. of Dayton (United States)

In recent work, electromagnetic (EM) propagation through modified von Karman-type atmospheric phase turbulence has been examined using several strategies. The (typically narrow) phase turbulence has been modeled as a thin random phase screen transverse to the propagation. Diffraction propagation of a profiled (or uniform) plane EM wave through such a screen has been carried out, and the complex received field amplitudes and phases computed numerically. Subsequently, time statistics of the turbulence have been obtained using pre-selected repetition times for the phase screen insertion. Thereafter, the generation and propagation of chaos waves via an acousto-optic Bragg cell under first-order feedback was carried out, from where the corresponding time statistics of the chaos was also numerically derived. Using the two statistical time models, in recent work, a transfer function formalism involving cross-spectral densities between turbulence and chaos was developed. With the goal of transmitting information-carrying chaos waves through the turbulence, the transfer function formalism was used to eventually obtain the joint temporal cross-correlation of the modulated chaos wave and the turbulence. A method to extract the information from the cross-correlation is currently under investigation. In a parallel approach, the diffraction of a time-modulated plane EM wave through both a uniform and a phase-turbulent atmosphere is currently under study, and results from this approach are presented in this paper. Specifically, an input EM wave is treated as having a modulated optical carrier, which is then represented by use of a sinusoidal phasor with a slowly time-varying envelope. Using a combination of phasors and spatial Fourier transforms, the resulting complex phasor wave is then transmitted across the propagation path (with or without turbulence) through the dual use of the Kirchhoff-Fresnel integral and the random phase screen. The objective is to ascertain if the presence of turbulence imparts any amplitude and/or phase distortion of the embedded message carried by the EM carrier. Additionally, in the follow-up work, the transmitted EM wave is assumed to be an encrypted chaotic carrier, for which a similar phasor-Fourier transform approach may be applied to determine the recovery via demodulation of the information encrypted on the chaos as it propagates through the turbulence. Some preliminary results are presented via comparisons between non-chaotic and chaotic information transmission through atmospheric turbulence, outlining thereby any possible improvement in system performance by utilizing the robust features of chaos.

9833-17, Session 3

Development and characterization of FPGA modems using forward error correction for FSOC

Kerry A. Mudge, Kenneth J. Grant, Bradley A. Clare, Defence Science and Technology Group (Australia); Colin L Biggs, William G. Cowley, Univ. of South Australia (Australia); Sean Manning, Defence Science and Technology Group (Australia); Gottfried Lechner, Univ. of South Australia (Australia)

No Abstract Available

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9834-1, Session 1

Full spatially resolved laser modeling and design using GLOSS

Jared Hudock, Mark Decker, John E. Koroshetz, L-3 Communications Advanced Laser Systems Technology, Inc. (United States)

The development of new, high performance laser designs is often a very time consuming and expensive proposition. Design iterations can involve multiple procurement cycles of expensive, long lead components such as laser pump diodes, optical crystals, custom lenses, and complex prisms. These iterations can be minimized by taking advantage of the power of today's PCs to create accurate, spatially resolved models of such laser designs. L-3 Advanced Laser Systems Technology (ALST) is developing a Generalized Laser and Optics Simulation Suite (GLOSS) to quickly and reliably design high performance, military grade laser transmitters. GLOSS uses state of the art wave propagation based algorithms to rigorously simulate the dynamics of laser oscillation. Laser pulse energy, pulse width, beam size, beam shape, and divergence are among the many key performances parameters GLOSS models have the capability to predict. Detailed intra-cavity mode maps can be generated to aide in the appropriate sizing of optics inside the laser resonator. In this presentation, the GLOSS modeling methodology will be discussed and examples of its powerful capability will be demonstrated. Results of the GLOSS model of a production laser designator transmitter found in a current ALST ground laser target designator system will be presented. The model predictions are within 10-15% of actual laser performance when compared to production data from multiple lasers. This level of accuracy from a theoretical model can greatly reduce the development cost and time to market of L-3 ALST products by minimizing the need for costly design iterations.

9834-2, Session 1

Measurement of basic spectroscopic parameters of Er-doped Y₂O₃ ceramic

Zackery D. Fleischman, Tigran Sanamyan, U.S. Army Research Lab. (United States)

In our ongoing effort to improve mid-IR power scaling and efficiency, we have recently demonstrated high power CW laser operation in Er doped Y₂O₃ at cryogenic temperature. The laser can deliver over 20W of mid-IR power at ~ 2.7 μm, and over 10 W simultaneously at 2.7 and 1.6 μm at dual wavelength, cascade operation mode. Further increases in laser performance require in-depth study and analysis of basic spectroscopic properties of the 4I11/2 to 4I13/2 laser transition. In this work, we report the results of experimental measurements of quantum efficiency and branching ratio of the erbium initial laser state of 4I11/2 in Y₂O₃ ceramic at the temperature range of 10 - 300 K. A series of Er:Y₂O₃ samples with dopant concentration between 0.2-10 at.% were used for fluorescence and absorption measurements. The low concentration samples were used for accurate fluorescence measurements while the high concentration samples allowed for studying the effects of reabsorption.

9834-3, Session 1

Er-doped YVO₄ amplifier diode pumped at 976 nm

Alex A. Newburgh, Mark Dubinskii, U.S. Army Research

Lab. (United States)

Lasers and amplifiers in the ~1.55-1.65 μm wavelength range are of great interest for eye-safe laser range finding, fiber-optic communications and ladar applications. With the advent of resonant pumping of Er³⁺ (4I15/2 4I13/2) there has been major paradigm shift toward this excitation scheme for major power scaling. In the meantime for moderate power applications listed above, where heat deposition is not as critical as in high power systems, pumping by better developed, more efficient and less expensive laser diodes near 980 nm (4I15/2 4I11/2) may still hold promise for its practicality. Also, usually 980-nm excitation in Er³⁺-doped laser materials is achieved via Yb³⁺-co-doping, which involves Yb³⁺ → Er³⁺ nonradiative energy transfer. Though often simplifying laser design, this transfer presents an additional energy conversion step, thus increasing heat deposition and reducing overall laser efficiency. We present the investigation results of the 976-nm diode pumped Yb-free Er-doped YVO₄ slab for the amplification of 1.6 μm laser radiation, including performance data and beam quality analysis. To the best of our knowledge, this represents the first use of non-resonant pumping of Er:YVO₄ as an amplifier with a single pass gain rivaling the current state-of-the-art Er:YAG gain of 45%.

9834-4, Session 1

Wide-bandwidth ceramic Tm:Lu₂O₃ amplifier

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States)

We report on investigation of novel ceramic Tm:Lu₂O₃ amplifier lasing at around 2-μm and offering efficient generation of high-energy pulses with high-peak power at high repetition rate, high efficiency, and with near-diffraction-limited beam quality (BQ). The amplifier has a bandwidth of over 300 nm, which offers broad tunability. The bandwidth also supports generation of ultrashort pulses down to about 30 fs. The "2-for-1" pump architecture of Tm ion enables >20% wall-plug efficiency. High thermal conductivity of the Lu₂O₃ host supports operation at high-average power. Ceramic nature of the Lu₂O₃ host overcomes the scalability limits of single crystal sesquioxides. This work also presents the relative performance of Tm:Lu₂O₃, Tm:YAG, and Tm:YLF. Measurements of spectral properties, gain uniformity, and thermo-optical distortions are presented.

9834-34, Session 1

Spectroscopy and laser performance

Nikolay E. Ter-Gabrielyan, U.S. Army Research Lab. (United States)

An efficient, Er³⁺/Yb³⁺-co-doped GdVO₄ laser pumped at 980 nm laser and emitting at 1.6 μm (π-polarization) has been demonstrated in both CW and Q-switched modes. Its performance is compared to the operation of similar, but Yb³⁺-free, Er³⁺:GdVO₄ laser, resonantly pumped at 1530 nm. The limitation of two pumping approaches will be discussed.

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9834-35, Session 1

Advanced materials for power scaling of ER-doped fiber lasers

Mark Dubinskii, U.S. Army Research Lab. (United States); E. Joseph Friebele, U.S. Naval Research Lab. (United States); Shubin Jiang, AdValue Photonics, Inc. (United States); John Ballato, Clemson Univ. (United States); Peter D. Dragic, Univ. of Illinois at Urbana-Champaign (United States)

No Abstract Available

9834-5, Session 2

Myths, legends, and facts from SDI to tactical battlefield lasers: Reflections of a ‘Star Warrior’ (Invited Paper)

James A. Horkovich, Directed Energy Professional Society (United States)

This talk presents a history of missile defense and the “Star Wars” program and its’ evolution to today’s tactical battlefield laser systems, marking the 30th anniversary of President Ronald Reagan’s “Star Wars” speech. Since Archimedes’ “Burning Glass” at the siege of Syracuse 212 B.C. through the development of the LASER man has been fascinated with the idea of using directed energy weapons. But nothing did more to focus this effort than the threat posed by Mutually Assured Destruction. Under Reagan’s “Star Wars” plan years and billions of dollars were invested in making high energy laser systems a reality. This presentation discusses the fundamentals of laser physics and traces the development of these systems in the USA and USSR from the Gas Dynamic LASER laboratory in the 1960s and the USAF Airborne Laser Laboratory of 1981 through the SDI era and up to today. In reflecting on the effort invested in developing this technology, this interdisciplinary talk addresses the role that this technology played in changing the geopolitical state of the cold war and continues to play in international defense efforts today. Note: This talk takes 45 – 50 minutes in its complete form. It is most suited as a plenary or historical talk,

9834-6, Session 2

Advanced laser architecture for two-step laser tandem mass spectrometer

Anthony W. Yu, Molly E. Fahey, Steven X. Li, NASA Goddard Space Flight Ctr. (United States)

Future astrobiology missions will focus on planets with significant astrochemical or potential astrobiological features, such as small, primitive bodies and the icy moons of the outer planets that may host diverse organic compounds. These missions require advanced instrument techniques to fully and unambiguously characterize the composition of surface and dust materials. Laser desorption/ionization mass spectrometry (LDMS) is an emerging instrument technology for in situ mass analysis of non-volatile sample composition. A recent Goddard LDMS advancement is the two-step laser tandem mass spectrometer (L2MS) instrument to address the need for future flight instrumentation to deconvolve complex organic signatures. The L2MS prototype uses a resonance-enhanced multi-photon laser ionization mechanism to selectively detect aromatic species from a more complex sample. By neglecting the aliphatic and inorganic mineral signatures in the two-step mass spectrum, the L2MS approach can provide both mass assignments and clues to structural information for an in situ investigation of non-volatile sample composition. In this paper we will describe our development effort on a new laser architecture that is based on the previously flown Lunar Orbiter Laser Altimeter (LOLA) laser transmitter for the L2MS instrument. The laser provides two discrete mid-infrared wavelengths (2.8 μm and 3.4 μm) using monolithic optical parametric

oscillators and ultraviolet (UV) wavelength (266 nm) on a single laser bench with a straightforward development path toward flight readiness.

9834-7, Session 2

Three year aging of prototype flight laser at 10 kHz and 1 ns pulses with external frequency doubler for ICESat-2 Mission

Oleg A. Konoplev, Consultant (United States); Furqan L. Chiragh, Aleksey A. Vasilyev, Sigma Space Corp. (United States); Ryan E. Edwards, Fibertek, Inc. (United States); Mark A. Stephen, Elisavet Troupaki, Michael A. Krainak, NASA Goddard Space Flight Ctr. (United States); Nicholas W. Sawruk, Floyd E. Hovis, Jack Pepper, Fibertek, Inc. (United States); Kathy Strickler, ASRC Federal Space and Defense (United States)

We present the results of three year life-aging of a specially designed prototype flight source laser operating at 1064 nm, 10 kHz, 1ns, 15W average power and external frequency doubler. The Fibertek-designed, slightly pressurized air, enclosed-container source laser operated at 1064 nm in active Q-switching mode. The external frequency doubler was set in a clean room at a normal air pressure. The goal of the experiment was to measure degradation modes at 1064 and 532 nm discreetly. The external frequency doubler consisted of a Lithium triborate, LiB3O5, crystal operated at non-critical phase-matching. Due to 1064 nm diagnostic needs, the amount of fundamental frequency power available for doubling was 13.7W. The power generated at 532 nm was between 8.5W and 10W, depending on the level of stress and degradation. The life-aging consisted of double stress-step operation for doubler crystal, at 0.35 J/cm2 for almost 1 year, corresponding to normal conditions, and then at 0.93 J/cm2 for the rest of the experiment, corresponding to accelerated testing. We observed no degradation at the first step and linear degradation at the second step. The linear degradation at the second stress-step was related to doubler crystal output surface changes and linked to laser-assisted contamination. We discuss degradation model and estimate the expected lifetime for the flight laser at 532 nm. This work was done within the laser testing for NASA’s Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) LIDAR at Goddard Space Flight Center in Greenbelt, MD with the goal of 1 trillion shots lifetime.

9834-8, Session 2

Beam shaping to provide round and square-shaped beams in optical systems of high-power lasers

Alexander V. Laskin, Vadim V. Laskin, AdIOptica Optical Systems GmbH (Germany)

Optical systems of modern high-power lasers require control of irradiance distribution: round or square-shaped flat-top or super-Gaussian irradiance profiles are optimum for amplification in MOPA lasers and for thermal load management while pumping of crystals of solid-state ultra-short pulse lasers to control heat and minimize its impact on the laser power and beam quality while maximizing overall laser efficiency, variable profiles are also important in irradiating of photocathode of Free Electron lasers (FEL). It is suggested to solve the task of irradiance re-distribution using field mapping refractive beam shapers like piShaper. The operational principle of these devices presumes transformation of laser beam intensity from Gaussian to flattop one with high flatness of output wavefront, saving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field, negligible residual wave aberration, and achromatic design provides capability to work with ultra-short pulse lasers having broad spectrum. Using the same piShaper device it is possible to realize beams with flat-top, inverse Gauss or super Gauss irradiance distribution by simple variation of input beam diameter, and the beam shape

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can be round or square with smooth edges.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in optical systems of high-power lasers. Examples of real implementations and experimental results will be presented as well.

9834-10, Session 3

High-gain multi-passed Yb:YAG amplifier for ultra-short pulse laser

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States); Detao Du, General Atomics Aeronautical Systems, Inc. (United States) and General Atomics Technologies (United States)

We report on a Yb:YAG laser amplifier for ultrashort pulse applications at kW-class average power. The laser uses two large aperture, disk-type gain elements fabricated from composite ceramic YAG material, and a multi-passing architecture to obtain high gain in a chirped-pulse amplification system. The disks are edge-pumped [1, 2, 3], thus allowing for reduced doping of crystals with laser ions, which translates to lower lasing threshold and lower heat dissipation in the Yb:YAG material. The latter makes it possible to amplify a near diffraction-limited seed without significant thermo-optical distortions.

This work presents results of testing the laser amplifier with relay optics configured for energy extraction with up to 40 passes through the disks. This work was in-part supported by the US Army ARDEC Contract Number W15QKN09C0156. Applications for the ultrashort pulse laser amplifier include laser induced plasma channel, laser material ablation, and laser acceleration of atomic particles.

1. J. Vetrovec et al., "Ytterbium-based disk amplifier for an ultra-short pulse laser," SPIE vol. 7578 (2010)
2. J. Vetrovec et al., "Initial Testing of Edge-Pumped Yb:YAG Disk Laser with Multi-Passed Extraction," SPIE vol. 8235 (2012)
3. J. Vetrovec et al., "Erbium-Based Edge-Pumped Disk Laser," SPIE vol. 8599 (2013)

9834-11, Session 3

Laser study of the diode pumped LHPG-grown Yb:YAG single-crystalline fiber

Jun Zhang, Youming Chen, U.S. Army Research Lab. (United States); Gisele Maxwell, Shasta Crystals (United States); Mark Dubinskii, U.S. Army Research Lab. (United States)

Single-crystalline fibers (SCF) fabricated from rare-earth (RE) doped yttrium-aluminum garnet (YAG) by laser heated pedestal growth (LHPG) or micro-pulling-down (uPD) techniques have captured significant attention of the high power laser community, and currently are considered to be a proper vehicle for major fiber laser power scaling. This is based on two major benefits of crystalline materials, in particular YAG, versus glass from which conventional fibers are made: (i) ten times higher thermal conductivity and (ii) at least 100 times lower SBS gain than that of glass. As most often found in the literature today, in the SCF lasers with air cladding the pump power is guided inside the fiber, thus flood-illuminating the gain medium, while the signal is in a propagation mode inside the fiber, with the mode size and shape defined by external cavity configuration. The SCF diameters reported so far were from 500 μm to 1000 μm . We report the laser study results of air-clad, 50-100 μm diameter, Yb:YAG SCFs grown by LHPG. To the best of our knowledge, laser performance of air-clad SCF as thin as 50-100 μm diameter is reported for the first time. SCF with the lengths of 50-100 mm and Yb concentrations of 1-10% were studied. In laser experiments SCFs were pumped by laser diode modules in the spectral range of 970-980 nm. SCF laser performance was studied in several laser

configurations with varying output coupler reflectivities. Maximum achieved slope efficiency was measured to be over 55%.

9834-12, Session 3

Tm/Ho co-doped ultrashort fiber laser with low noise

Ahmet E. Akosman, Michelle Y. Sander, Boston Univ. (United States)

A Tm/Ho co-doped mode-locked soliton fiber laser design is presented with stable and low noise single-pulsing operation at a repetition rate of 135 MHz and a transform limited pulse durations of 375 fs. The fiber laser is directly core-pumped at a wavelength of 790 nm. For single-pulsing operation, the fiber laser is operated at a center wavelength of 1983 nm and can be tuned over an 8 nm bandwidth via the pump power. The fiber laser consists of a linear cavity which allows scaling of the repetition rate by reducing the cavity length and utilizing the high absorption at 790 nm and efficient absorption/emission dynamics without photodarkening. Co-doping with Tm/Ho increases the efficiency of the lasing with enhanced cross-relaxation and suppressed energy upconversion rates. Stable mode-locked operation with reduced ripples in the optical spectrum and high signal-to-background ratios in the RF spectrum are obtained. Low relative intensity noise with an rms fluctuation level of 0.013% (from 10 Hz to 15 MHz), and low phase noise with a timing jitter of 20 fs (from 10 Hz to 1 MHz) are demonstrated. The proposed laser design can be adjusted to be operated in three main different regimes which are q-switching, single-pulsing and multi-pulsing cw mode-locking. Due to the efficient absorption/emission dynamics with 790 nm core-pumping, q-switching can be induced at relatively high repetition rates (around hundreds of kHz with energetic short pulses). The mW output power levels of the laser can be scaled in consecutive amplifier stages.

9834-13, Session 3

Supercontinuum generation in dispersion-varying microstructured optical fibers

Xiang Zhang, Hongyu Hu, Wenbo Li, Niloy K. Dutta, Univ. of Connecticut (United States)

We numerically study the broadband mid-infrared supercontinuum generation in a 3 cm non-uniform SF57 microstructured fiber. The total dispersion of the fiber is tailored by linearly varying the air hole diameters along the propagation distance. The fiber has zero dispersion at two wavelengths. The varying of air holes allows a continuous shift of the higher zero dispersion wavelength (ZDW) to a longer wavelength. The input pulse undergoes soliton fission, soliton self-frequency shift and transfer energy to dispersive waves in the vicinity of second ZDW at frequencies determined by the phase matching condition. With this axially non-uniform structure, the dispersive waves can be generated towards longer wavelengths due to the progressive modification of phase matching condition as the pulse propagates through the fiber. Our results show this scheme can significantly broaden the output spectra compared to fibers with fixed ZDWs. By launching hyperbolic secant pulses at 1.55 μm with a width of 100 fs and peak power of 6 kW, the generated continuum spans from -1 μm to -4.7 μm limited by the material transmission window. If the transmission window of the material is wider, the spectra can even extend to over 5 μm .

9834-14, Session 3

Intra-cavity mode formation employing diffractive phase structures

Yakov G. Soskind, DHPC Technologies (United States); Igor Anisimov, Air Force Research Lab. (United States)

Size reduction of a laser cavity is highly desirable during the process of a

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laser system's design, as it allows reducing the weight and size of the laser system as a whole, as well as increasing the robustness of the system's operation under severe environmental conditions. This cavity length reduction should be achieved without sacrificing the output laser beam quality, especially in the far field region.

One approach to reducing the laser cavity length is based on the selection of single higher order transverse modes. We show that a single transverse mode operation is essential for producing the high far field beam quality. In the past, the selection of a single high order transverse mode was performed by employing amplitude masks or localized pumping of the gain medium. Both approaches resulted in extra cavity losses, and the associated increase in the laser oscillation threshold. In this work, we provide details of a "lossless" intracavity mode formation technique employing diffractive phase structures. The size and shape of the diffractive structures can be tailored for selection of the specific transverse higher order mode. Our results illustrate field evolution within laser cavities, and show how diffraction of laser radiation on the phase structures influences the intracavity mode formation. Several key characteristics of the output modes are provided, including round-trip losses, as well as their modal amplitude and phase distributions. Results of this work can be applied to resonator optimization of various laser systems and reduction in their length.

9834-15, Session 4

Wavelength stabilized and multiplexed diode lasers for highly efficient resonant pumping of Er:YAG lasers

Haro Fritsche, DirectPhotonics Industries GmbH (Germany); Oliver Lux, Martin Gaertner, Casey Schuett, Technische Univ. Berlin (Germany); Sebastian Fetissow, Andreas Grohe, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany); Hans Joachim Eichler, Technische Univ. Berlin (Germany)

Resonant pumping of Er:YAG is rapidly emerging as an effective approach to realize high power lasers with emission wavelengths around 1.6 μm . The resonant pumping process of Er:YAG can be realized with several pump wavelengths between 1450 nm and 1570 nm with increasing quantum efficiency at longer wavelengths. Commonly used pump lasers for this scheme are fiber lasers operating at 1532 nm. Alternatively, the development of high power diode lasers offers the possibility to exploit the multiplicity of pumping bands. However, due to the narrow linewidth of the Er:YAG absorption lines, wavelength stabilization and spectral narrowing of the diode laser radiation is required in order to ensure high absorption efficiency.

In our approach, implementation of a volume Bragg grating into the diode laser system allowed for reduction of the pump laser linewidth to 170 pm as well as for wavelength stability of 230 MHz over an hour. Furthermore, through the simple adjustment of the pump laser wavelength of the diode modules, dual-wavelength pumping of Er:YAG at 1470 nm and 1532 nm was enabled. As a result, the slope efficiency of a resonantly pumped Er:YAG laser emitting at 1645 nm was as high as 65% both in cw and Q-switched operation. Due to the high wavelength stability of the pump lasers we obtained a frequency stability of about 50 MHz at 1645.55 nm. Moreover, we successfully demonstrated the feasibility of the Q-switched Er:YAG laser for methane detection in the mbar range by means of absorption measurements under laboratory conditions.

9834-16, Session 4

A fiber-coupled module producing >900W from a 225 micron fiber, with >50% efficiency and 0.7 kg/kW

Christopher Ebert, Dave A. Irwin, Tina Guiney, Tobias P.

Koenning, Dean Stapleton, Steven G. Patterson, DILAS Diode Laser, Inc. (United States)

Specifically optimized for both high efficiency and low SWaP, DILAS Diode Laser, Inc. continues to improve and optimize high-brightness fiber-laser pump modules. Starting with a 330W module in full production, power-scaled versions capable of 650 W and 900 W with >50% efficiency will be covered. Utilizing a 225 μm /0.22 NA fiber output, these pumps enable single-mode kW-class fiber amplifiers ranging from 1 kW to 3kW. Designed for low SWaP, these modules are produced using mounted diode laser bars from a standard manufacturing line and commercial, off-the-shelf optics. Cooling is accomplished through macro channel coolers that eliminate the need for micro-channels and the associated coolant issues while permitting 2-phase operation without modification of the module. This innovative macro channel cooler is specifically designed to reduce both weight and thermal resistance, and also provides an ideal substrate for power-scaling the diode module while maintaining efficiency. Utilizing AuSn hard solder on CTE matched substrates eliminates the problems associated with Indium-based diode solder joints and permits hard pulsing of the laser diodes with any pulse width/duty cycle parameter set. Optional VBG stabilization is available on all versions for applications requiring wavelength stability over a wide temperature range.

9834-17, Session 4

New advancements in 793 nm fiber-coupled modules for Tm fiber laser pumping, including packages optimized for low SWaP applications

Christopher Ebert, Steven G. Patterson, David A. Irwin, Tina Guiney, Tobias P. Koenning, DILAS Diode Laser, Inc. (United States); Heiko Kissel, Wilhelm Faßbender, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

Targeted at the 793nm absorption band, DILAS Diode Laser, Inc. offers a range of products specifically designed for Thulium fiber laser pumping, spanning from 12 W to >300W of pump power and coupled into fiber sizes starting at 105 μm and upwards. A variety of different diode architectures are utilized, ranging from single-emitters, conduction-cooled bars, and DILAS's T-bar structure extended to the 793nm range, resulting in a wide variety of power levels and packaging options to support different applications. As IRCM for airborne platforms is a major application for Th fiber lasers, packages optimized for low SWaP will be presented, which utilize a combination of the T-bar structure and macrochannel coolers specifically designed for compact, lightweight applications. Examples and results of Th fiber lasers pumped using DILAS diodes will also be presented and discussed.

9834-18, Session 4

Advances in AlGaInN laser diode technology for defence and sensing applications

Stephen P. Najda, Piotr Perlin, Tadek Suski, Lucja Marona, Mike Boćkowski, Mike Leszczyński, Piotr Wisniewski, Robert Czernecki, TopGaN Ltd. (Poland); Robert Kucharski, Ammono S.A. (Poland); Gregorz Targowski, TopGaN Ltd. (Poland)

Laser diodes fabricated from the AlGaInN material system is an emerging technology for defence and security applications. The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., -380nm, to the visible -530nm, by tuning the indium content of the laser GaInN quantum well, giving rise to new and novel applications including displays and imaging systems, atomic clock and

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quantum information, free-space and underwater telecom and lidar.

Ridge waveguide AlGaInN laser diode structures are fabricated to achieve single mode operation with high optical powers of >100mW and high reliability suitable for telecom applications.

Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. We demonstrate the operation of monolithic AlGaInN laser bars with up to 20 emitters giving optical powers up to 4W cw at ~395nm with a common contact configuration. These bars are suitable for optical pumps and novel extended cavity systems. An alternative package configuration for AlGaInN laser arrays allows for each individual laser to be individually addressable allowing complex free-space and/or fibre optic system integration within a very small form-factor.

9834-19, Session 5

Final-stage diamond Raman elements for beam combination and mode conversion with ultra-high brightness (*Invited Paper*)

Aaron M. McKay, Robert J. Williams, Hadiya Jasbeer, Soumya Sarang, David W. Coutts, David J. Spence, Richard P. Mildren, Macquarie Univ. (Australia)

Ever since the laser's invention there has been an ongoing drive to increase laser power and explore ever more extreme possibilities for their application. Progress in high power laser technology has seen development of gas and chemical lasers above a megawatt of average power, to more practical solid-state systems producing single beam powers at tens of kilowatts. The unique properties of photons, beamed at the speed of light and able to interact highly selectively within specific material or agents in a target, ensures their exciting future use to enhance the present applications and explore new ones such as clean energy generation, removal of space debris, advanced biomedical technology and artificial "guide-stars" for astronomy and advanced guidance systems.

In this paper, progress in diamond Raman lasers configured for high power generation will be reviewed. Major achievements include pulsed power systems that enable simultaneous brightness and wavelength conversion, and cw wavelength converters with output powers of several hundred watts and polarization converters. We discuss design principles and factors crucial to attaining efficient performance. Experiments to date have not revealed substantial thermal effects in the diamond crystal – we discuss the likely saturation mechanisms and strategies for generating output beyond the kilowatt level.

9834-20, Session 5

High-power, highly-efficient Raman fiber laser pumped by laser diodes

Yaakov Glick, Viktor Fromzel, Jun Zhang, U.S. Army Research Lab. (United States); Asaf Dahan, Soreq Nuclear Research Ctr. (Israel); Mark Dubinskii, U.S. Army Research Lab. (United States)

We demonstrate a high power (few 10's of Watts) highly efficient (over 50% optical-to-optical) Raman fiber laser, pumped directly by laser diodes at 976nm. We have taken advantage of high Ge-doping level, hence high Raman gain, of a commercial graded-index core fiber, which is used as the Raman gain medium. An oscillator configuration is used which includes spectral filtering, to prevent the generation of the 2nd Stokes. To the best of our knowledge this is the highest power Raman fiber laser directly pumped by laser diodes. In addition it is the highest power Raman fiber laser demonstrated based on a graded-index fiber.

9834-21, Session 5

Power scaling of a self-Raman Nd:YVO₄ laser transmitter for space-based sodium lidar instrument

Anthony W. Yu, Michael A. Krainak, Diego Janches, NASA Goddard Space Flight Ctr. (United States)

We are currently developing a laser transmitter to remotely measure Sodium (Na) by adapting existing lidar technology with space flight heritage. The developed instrumentation will serve as the core for the planning of a Heliophysics mission targeted to study the composition and dynamics of Earth's mesosphere based on a spaceborne lidar that will measure the mesospheric Na layer. We present modeling and performance results from our power scaling effort on a diode-pumped Q-switched self-Raman c-cut Nd:YVO₄ laser with intra-cavity frequency doubling that produces multi-watt 589 nm wavelength output. We will review technologies that provide strong leverage for the sodium lidar laser system with strong heritage from the Ice Cloud and Land Elevation Satellite-2 (ICESat-2) Advanced Topographic Laser Altimeter System (ATLAS).

9834-22, Session 5

Traverse-modal-instability (TMI)-free Yb-doped 35um core and 250-um clad chirally coupled core (3C) fiber MOPA with 475W output power

Manoj Kanskar, Jim Zhang, Timothy S. McComb, nLIGHT Corp. (United States); Joona J. Koponen, Changgeng Ye, Ossi Kimmelma, Ville Aallos, nLIGHT Corp., Lohja (Finland); I-Ning Hu, Almantas Galvanauskas, Univ. of Michigan (United States)

Typically, core size of fiber lasers and amplifiers is increased to mitigate nonlinear effects to achieve high average and peak powers. However, it has recently been experimentally discovered that increasing power to even a few hundred watts in Large Mode Area (LMA) fiber leads to sudden degradation in modal quality due to threshold-like onset of coupling of power from fundamental to higher order mode leading to time-dependent periodic and chaotic oscillation over millisecond time-scale. The onset of this modal instability depends on core, cladding and numerical aperture, seed/pump power and operating thermal properties. More importantly, degree of suppression of higher order mode plays a pivotal role in defining the modal instability threshold. 3C fiber has demonstrated effectiveness in suppressing higher order mode especially at high peak power in short pulses. Here, under CW operation, we experimentally demonstrate onset of modal instability at 475 W in counter-pumped Yb-doped 35-μm core & 250-μm clad 3C fiber which is two-times higher compared to 229 W calculated for an LMA fiber with the same geometry and thermal loading conditions. The measured value of 475 W closely matches theoretically predicted value of 467 W for this particular 3C fiber with approximately 50 dB/m higher-order mode suppression. This result highlights the importance of increasing the degree of HOM suppression. Further increase in TMI threshold should be achievable by further optimization of 3C fiber to reach with higher degrees of HOM suppression.

9834-23, Session 6

A compact diode pumped opto-mechanically Q-switched erbium glass laser with 10ns pulse

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**Conference 9834:
 Laser Technology for Defense and Security XII**

Present work is focused on the use of opto-mechanically Q-switching technique in combination with diode pumped erbium glass scheme for generating shorter laser pulse duration of ~10ns with good output energy stability. Idea is also to explore the possibility of use this simple, low cost, rugged and robust Q-switching technique for laser building to the maximum extent. In order to shorten laser pulse width higher gain in active media, shorter cavity length, higher rotational speed (faster switching time) and/or combination of these can be used. Recent advent of new and higher concentration erbium ytterbium glass materials is enhancing the possibility of achieving high laser gain in small volume. This small laser volume also increases the opportunity of reducing laser cavity length of laser systems. Increasing motor speed may not always be possible due to space and other parameter limitations. Hence, it is proposed to use higher gain laser material in combination with fast axis collimated linear laser diodes and small cavity length for short pulse generation.

In this study, design simulations are performed for visualization of pump uniformity and prediction of laser gain locations in active media. Simulation results are used for placement and orientation of other laser components in laser cavity. Next, experimentation has been performed in long pulse mode and a compact design prototype has been made and functionally tested in Q-switching mode. Laser output with stable energy of ~5mJ and pulse width of ~10ns is achieved at 1Hz repetition rate and far-field divergence is measured 4mrad (~90% energy).

9834-24, Session 6

A compact laser target designator

Stephen T. Lee, Mark Silver, Ashleigh Barron, Andrew G. Borthwick, Graham Morton, Ian McRae, Megan Coghill, Craig Smith, Colin Scouler, George Gardiner, Norman Imlach, Craig McNeill, David McSporran, Dale Rodgers, Duncan Kerr, William Alexander, Thales UK Ltd. (United Kingdom)

Lasers intended for application to man-portable and hand-held laser target designators are subject to significant constraints on size, weight, power consumption and cost. These constraints must be met while maintaining adequate performance across a challenging environmental specification. One of the challenges of operating a Nd³⁺:YAG laser over a broad ambient temperature range is that of diode-pump-tuning. This system is specified to operate over an ambient temperature range of -46°C to +71°C, and the system electrical power consumption requirements preclude active temperature control. As a result the laser must tolerate a 32.8nm pump wavelength range. The optical absorption of Nd³⁺:YAG varies dramatically over this wavelength range. This paper presents a laser that minimises the effect of this change on laser output. A folded U-shaped geometry laser resonator is presented, made up of a corner cube at one end and a plane mirror substrate at the other. The action of the corner cube coupled with this configuration of end mirrors results in a resonator that is significantly less sensitive to misalignment of the end mirror and/or the corner cube. This U-shaped resonator is then further folded to fit the laser into a smaller volume. Insensitivity of this compact folded resonator to mirror misalignments was analysed in Zemax via a Monte-Carlo analysis and the results of this analysis are presented. The resulting laser output energy, pulse duration and beam quality of this athermally pumped, misalignment insensitive folded laser resonator are presented over an ambient temperature range of -46°C to +71°C.

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9834-25, Session 6

Short-pulse broadband tunable laser source

Christopher G. Brown, Univ. Research Foundation (United States); Steven R. Bowman, U.S. Naval Research Lab. (United States)

This paper will review the design and performance of a broadband tunable source emitting from the ultraviolet through the mid-infrared region. The system architecture includes short-pulse diode seeds, ytterbium, erbium, and thulium fiber amplifiers, and multiple nonlinear crystals. The amplifiers are injected at 1 μm, 1.5 μm, and 1.9 μm by distributed feedback laser diodes to ensure precise wavelengths and pulse durations. All three single-mode outputs are free-space combined before being focused into the nonlinear crystals. Frequency conversion is generated via phase matching in beta-barium borate and silver gallium selenide crystals, and quasi-phase matching in lithium niobate, gallium nitride, and gallium arsenide crystals. Sum and difference frequency combinations of the three fiber lasers allow for numerous wavelengths ranging from 266 nm to 11 μm to be generated.

9834-26, Session 6

Investigating the influence of spectrum and temperature on nanosecond pulse amplification in Thulium fiber

Stefan Gausmann, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Fraunhofer-Institut für Lasertechnik (Germany); Ali Q. Abdulfattah, Alex M. Sincore, Joshua D. Bradford, Nathan Bodnar, Lawrence Shah, Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

2 μm pulsed fiber lasers are attractive sources for nonlinear frequency conversion to mid-IR. For three-level laser systems like thulium-doped silica fiber, the design of the amplifier, in particular the fiber length, must be optimized relative to the desired output wavelength and energy. In this work we investigate energy storage and extraction in an amplifier based on a large mode area (LMA), step index thulium fiber. Of specific interest are the impacts of the temperature and seed wavelength for 793 nm diode pumping. A Q-switched thulium-fiber oscillator, producing 50 μJ, 60 nanosecond pulses at 20 kHz repetition rate, seeds a 90-cm long section of LMA polarization maintaining (PM) Tm: fiber with 25 μm core and 400 μm cladding diameter. The fiber is free-space pumped in counter-propagating geometry. The temperature of the Tm: fiber amplifier mount is varied from 15°C to 28°C, and the seed wavelength is varied from 1817 nm - 1948 nm. We applied a simple two-level model to simulate the energy extracted from the amplifier, which agrees well with the experimental results despite neglecting effects such as cross-relaxation and excited state absorption. The maximum measured output energy of 300 μJ, corresponding to a gain of ~7.8 dB, is achieved at 15°C at 1947 nm, 16 W absorb pump power.

9834-27, Session 6

Er-doped semi-guiding high-aspect-ratio core (SHARC) fiber amplifier generation 150 μJ, 0.5-nsec pulses at 15 kHz

Friedrich P. Strohkendl, Sean W. Moore, Fabio Di Teodoro, Vladimir V. Shkunov, David A. Rockwell, Raytheon Space and Airborne Systems (United States); John R. Marcianite, Univ. of Rochester (United States)

We present recent experimental results on a pulsed Er-doped semi-guiding high-aspect-ratio core (SHARC) fiber amplifier having core dimensions of 8x240 μm². The 5-m fiber was coiled with a bend diameter of ~15 cm and core-pumped by a 1470 nm Raman fiber laser; the signal wavelength was 1560 nm. We have produced pulse energies > 150 μJ and peak powers > 350 kW at a pulse rate of 15 kHz. We have achieved nearly diffraction-limited beam quality in both transverse dimensions. Spectral measurements indicate that significant spectral broadening does not occur until the peak power exceeds ~ 120 kW.

**Conference 9834:
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9834-28, Session 6

Development of high-power and high-energy 2 μm bulk solid-state lasers and amplifiers (*Invited Paper*)

Wayne S Koen, Cobus Jacobs, Lorinda Wu, Hencharl Strauss, CSIR National Laser Ctr. (South Africa)

An overview of 2 μm lasers and amplifiers developed at the CSIR National Laser Centre in South Africa is presented. A diverse range of near diffraction-limited 2 μm lasers and amplifiers were developed which varied from high-energy, single-frequency oscillators and amplifiers, to compact and efficient MOPA systems delivering high average powers. This was made possible by exploiting various advantageous properties of holmium-doped YLF while mitigating its detrimental properties through the use of novel pump and laser design approaches.

9834-31, Session PSWed

Research on the optimal structure configuration of dither RLG used in skewed redundant INS

Chunfeng Gao, Qi Wang, Guo Wei, Chunfeng Gao, National Univ. of Defense Technology (China)

The actual combat effectiveness of weapon equipment is restricted by the performance of Inertial Navigation System (INS), especially in those high reliability requirements situations such as fighter, satellite and submarine. Through the use of skewed sensor geometries, redundant technique has been applied to reduce the cost and to improve the reliability of the INS. In this paper the structure configuration and the inertial sensor characteristics of Skewed Redundant Strapdown Inertial Navigation System (SRSINS) using dithered Ring Laser Gyro (RLG) are analyzed. For the dither coupling effects of the dither gyro, the system measurement errors can be amplified if the individual gyro dither frequency is near one another or the structure of the SRSINS is unreasonable. Based on the characteristics of RLG, the research on coupled vibration of dithered RLG in SRSINS is carried out. On the principle of optimal navigation performance, optimal reliability and optimal cost-effectiveness, the comprehensive evaluation scheme of the inertial sensor configuration of SRINS is given.

9834-32, Session PSWed

Highly-efficient high-energy 1.5 μm pulsed fiber laser with precise line width and wavelength control of individual pulses

Doruk Engin, Ibraheem Darab, Chuck Culpeper, John Burton, Wei Lu, Jean-Luc Fournon, Lew Holt, Shantanu Gupta, Fibertek, Inc. (United States)

High average power (>20 W), high energy, polarization maintaining (PM) pulsed fiber laser with precise control of individual pulse width, linewidth and wavelength, is an enabler for long range geometric and 3-D imaging technologies, which aim at characterizing targets beyond the physical-aperture diffraction-limit of the receiver system. Furthermore, highly reliable and efficient transmitters are desirable for implementation of the technology on flight and space platforms. The 1.5 μm optical band is well-suited for the application due to higher eye safe power and availability of mature, versatile detector technologies. Er and ErYb doped fiber amplifiers are mature, monolithic laser technologies that have demonstrated a long heritage of reliability as part of the telecom industry. A cladding pumped ErYb LMA fiber amplifier is the most reliable and mature approach for achieving large average powers (10-200 W), and high pulse energies. Here a turn-key, 1550 nm PM fiber amplifier system based on COTS

cladding pumped ErYb LMA fiber, generating >22 μJ pulse energy with near transform limited linewidth (200-800 MHz) is presented. Wavelength separation between individual pulses (20-100 pm) and pulse widths (2-10 nsec) are controlled with high accuracy. The 22 W laser is optimized for high peak power (>4 kW) operation at low duty cycles (~0.1%) while maintaining diffraction limited beam quality ($M2 < 1.2$). High wall plug efficiency (~10%) for the FPGA controlled system is maintained by temporal and spectral ASE suppression. Stimulated Brillouin Scattering and Four Wave Mixing limit the maximum achievable pulse energy. Dependence of the fiber nonlinearities on line-width, pulse width, and wavelength separation between individual pulses is characterized. Further scaling of the power up to 40 W average, >8 kW peak, using cladding pumped PM ErYb LMA fiber amplifiers will be discussed.

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9834-33, Session PSWed

Applications of signal multiplexing in fiber optic-based acoustic and seismic sensors

William R. Folks, Richard D. Costley, U.S. Army Engineer Research and Development Ctr. (United States); Clay K. Kirkendall, Optical Sciences Division, Naval Research Laboratory (United States); Gustavo Galan-Comas, Eric W Smith, Michael W Parker, Kent K Hathaway, US Army Engineer Research and Development Ctr (United States)

Fiber optic systems are deployed in a variety of settings as strain sensors to locate small disturbances along the length of an optical fiber cable, often tens of kilometers long, attached to an interrogator unit. This technology has the advantages of low cost and design simplicity, as the sensor is its own source of telemetry and may be easily repaired or replaced. The interrogator unit incorporates an interferometer that detects small changes in optical signal phase. One of the limitations of current technology is noise from optical backscatter events in the fiber, resulting in a degraded signal in individual spatial zones and leading to signal fading. Detection within these zones along the length of the fiber is then obscured. Signal multiplexing may be used to increase sensitivity and signal-to-noise ratio and reduce signal fading. In such an architecture, multiple channels of differing wavelengths are multiplexed together and transmitted along the fiber to provide increased signal diversity. In this paper, we report on results from two different systems that were tested using such techniques. The signal from the sensor is analyzed to assess repeatability under varying test conditions. The correlation between an acoustic reference source and the signature detected with a fiber optic sensor and interrogator for multiplexed and single channel systems are compared. It may be shown that the interrogator system with diversity results in a more repeatable measurement. Applications include perimeter surveillance, border security, security perimeters, and the monitoring of fixed structures such as dams, bridges, and oil pipelines.

Conference 9835: Ultrafast Bandgap Photonics

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9835-1, Session 1

Nonequilibrium materials: using ultrafast laser pulses to change band structures (Invited Paper)

Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Soon after it was discovered that intense laser pulses of nanosecond duration from a ruby laser could anneal the lattice of silicon, it was established that this so-called laser annealing is a thermal process. The past two decades have shown that ultrashort laser pulses in the femtosecond regime can induce athermal, nonequilibrium processes that lead to either transient phase changes in semiconductors through ultrafast ionization or permanent phase changes through nonequilibrium doping. In this talk we will review work in both of these regimes and show how ultrafast lasers can be used to collapse the bandgap of a semiconductor or to hyperdope a semiconductor far above the solubility limit, leading to the formation of an intermediate band. This work not only reveals important information on the electron dynamics but also permits creating materials with novel properties.

9835-2, Session 1

Quantum molecular dynamics and finite element frequency domain modeling of ultrafast laser-driven self-assembled surface structures in semiconductors (Invited Paper)

Ben R. Torralva, Michael J. Abere, Steven M. Yalisove, Univ. of Michigan (United States)

The ability of ultrashort laser pulses to significantly, yet in many cases temporarily, alter the band structure of semiconductors in less than a picosecond following laser exposure is one of the key and most fascinating discoveries to emerge from ultrafast laser-materials interaction research. A fundamental property of light-matter interaction is the ability of light to couple to a plasma to form surface-plasmon-polaritons (SPP). In this talk, results of nonadiabatic quantum molecular dynamics simulations will be presented that detail the impact on the band structure and atomic motion of GaAs with ~10% of the valence electrons excited to the conduction band by ultrashort-pulsed laser excitation. A primary result is the ultrafast formation of vacancy/interstitial pairs due to the impulsively softened bonds. These point defects ultimately lead to the formation of high-spatial-frequency-laser-induced-periodic-surface-structures (HSFLIPSS) after 100s of laser exposures. The structures form due to the formation of grating-coupled SPP. A fundamental requirement for the formation of an SPP is that the real part of the dielectric function be negative. Since GaAs does not have a negative real dielectric function, the laser pulse must be of sufficient intensity to drive the real part negative while the laser pulse is on. The significant alteration of the dielectric function allows for different types of SPP coupling to the surface depending on the existing surface morphology. Finite element frequency domain simulations using modeled dielectric functions will be shown for various stages of the HSFLIPSS development that evolves from coupling to shallow gratings to gratings with a photonic band gap.

9835-3, Session 1

First-principles simulation for strong and ultra-short laser pulse propagation in dielectrics (Invited Paper)

Kazuhiro Yabana, Univ. of Tsukuba (Japan)

First-principles density functional theory has been successful for ground state properties of various matters. Time-dependent density functional theory (TDDFT) is an extension of the density functional theory so as to describe electron dynamics. We have been developing a computational method to describe electron dynamics in a unit cell of crystalline solid under a spatially-uniform, time-dependent electric field, solving the time-dependent Kohn-Sham equation in real time. The method can be used to describe various phenomena relevant to light-matter interactions without any empirical parameters. Applications include dielectric function, nonlinear susceptibilities, coherent phonon generation, high harmonic generation, and optical breakdown. In the method, the basic input is the optical electric field $E(t)$ and one of the outputs is the averaged density of electron current in a unit cell of solid, $J(t)$. Therefore, this calculation can be regarded as a numerical constitutive relation that is useful even for very strong electric field. Under this recognition, we combine the microscopic electron dynamics calculation by TDDFT with the macroscopic Maxwell equations for laser pulse propagation in a multiscale prescription, which we call the Maxwell + TDDFT multiscale simulation. We apply the multiscale method for phenomena at laser intensities around the damage threshold. Close to the threshold, we expect appearances of extremely nonlinear polarization in the medium. We calculate a modulation of a few-cycle laser pulse passing through a thin film of SiO₂, and compare the result with measurements by attosecond streaking technique. We have found very nice agreements between theory and measurement. We estimate the damage threshold from calculated energy transfer from the laser pulse to electrons in the medium. We also estimate the depth of ablation from the energy transfer. It was found that characteristic features of damages are reasonably understood from the energy transfer by our multiscale calculation.

9835-4, Session 1

Why bandgap collapse drives the self-organization of high frequency LIPSS in semiconductors (Invited Paper)

Steven M. Yalisove, Univ. of Michigan (United States)

GaAs single crystals were irradiated in air using a kHz repetition rate 150fs, 780nm laser. SEM, TEM, STEM, and x-ray spectroscopy (XEDS) results support a model where the initial generation of Frenkel Pairs are possible as long as the fluence is above the band gap collapse threshold. These defects dissociate as a result of the bond softening in the first 10 ps. Interstitials diffuse to the surface and islands nucleate. Subsequent exposures grow these randomly arranged small islands wider and taller (less than 2nm at this stage). Once tall enough to permit a surface plasmon polariton (SPP) to be generated the absorption of light then generates more Frenkel pairs at the crests of the SPPs in coherence with the laser. These regions eventually get pinned because of vacancy coalescence into pits at the surface where the islands can now only grow in amplitude. As the islands get taller, a higher energy SPP can form and quickly alter its wavelength toward the grating coupled SPP. This occurs by random nucleation and competitive growth. Once the surface is completely covered with LIPSS at this wavelength, continued irradiation results in a strain driven bifurcation of the ripples. STEM images show that these are epitaxial to the substrate, have a corrugation that is more than 100 nm above and below the original surface, and have a wavelength that is 180 nm. Furthermore, XEDS of the thin cross section samples in the TEM show 50-50 GaAs stoichiometry with no evidence of oxygen in the film.

9835-5, Session 1

Femtosecond x-ray and electron scattering studies of light-driven dynamics in materials (*Invited Paper*)

Aaron M. Lindenberg, SLAC National Accelerator Lab. (United States) and Stanford Univ. (United States)

Novel characterization techniques developed over the past decade or so have revolutionized our ability to visualize the microscopic processes that determine the functional properties of materials. The overarching challenge here is that the relevant time-scales and length-scales for these processes are typically 10-13 seconds (100 femtoseconds) and 10-10 m (1 Å) such that our view of how a material functions is often blurred out in time or in space. In this talk I will describe recent experiments using femtosecond x-ray, electron, and optical pulses as a means of probing and directing the dynamics of materials as they transform in-situ. I will focus on two broad examples: (1) I will describe experiments probing electric field-driven structural changes in which all-optical biases at terahertz frequencies enable us to elucidate fundamental time-scales for switching in both ferroelectric and phase-change materials. These results show, surprisingly, that one can drive large-scale reorientations of the polarization of a ferroelectric thin film on femtosecond time-scales. With respect to phase-change materials, I will show, contrary to established ideas in the field, that sub-picosecond duration electric field pulses can initiate threshold switching processes and amorphous-to-crystalline transitions, associated with novel possibilities for data storage devices operating at terahertz frequencies. (2) Finally, I will discuss experiments (and coupled first principles molecular dynamics simulations) probing dynamic rippling and deformations of monolayer transition metal dichalcogenide MoS₂ films on femtosecond time-scales, as well as studies probing the interlayer coupling in multilayer TMDC MoSe₂ and ReS₂ films that gives rise to many of their unique functional properties.

9835-6, Session 1

Dynamically measuring of the band structure using attosecond methods and high harmonic generation in solids (*Invited Paper*)

Giulio Vampa, Thomas Hammond, Univ. of Ottawa (Canada); Nicolas Thire, Bruno E. Schmidt, François Légaré, Institut National de la Recherche Scientifique (Canada); Chris McDonald, Thomas Brabec, Univ. of Ottawa (Canada); Dennis Klug, National Research Council Canada (Canada); Paul B. Corkum, Univ. of Ottawa (Canada) and National Research Council of Canada (Canada)

When intense femtosecond midinfrared laser pulses interact with a crystal, high harmonics of the fundamental frequency are generated by the recollision of accelerated electrons with their holes and their recombination. The pairs travel a significant portion of the Brillouin zone before recolliding, storing information about the underlying bands in the process. This information is naturally transferred to the high harmonic photons.

In our experiment we extract this information by perturbing the trajectories of electron-hole pairs with a weak second harmonic field. First, a numerical experiment proves the validity and the robustness of the method to reconstruct the band gap over the whole Brillouin Zone. Second, a preliminary experiment in ZnO is able to determine which valence band mostly contributes to high harmonic generation.

9835-7, Session 1

Ultra-short pulse lasers and nanostructures: focus on simulations (*Invited Paper*)

Traian Dumitrica, Univ. of Minnesota, Twin Cities (United States)

Many recent theoretical and experimental works have demonstrated that femtosecond laser pulses can induce irreversible ultrafast material modifications, in the form of solid-liquid or solid-solid transitions.

Particularly interesting are ultrafast structural changes caused by the large amplitude of the coherent phonons induced by laser excitation, such as in Peierls-distorted Bi or ferroelectric GeTe materials. We show here for the first time the ability of coherent phonons to forcibly drive precise transformations in carbon nanotubes

The response of carbon nano-structures to femtosecond laser pulses is studied with nonadiabatic simulation techniques, which accounts for the evolution of electronic and ionic degrees of freedom, and for the coupling with the external electromagnetic field. As a direct result of electronic excitation, three coherent breathing phonon modes are excited in carbon nanotubes: two radial vibrations localized in the caps and cylindrical body, and one longitudinal vibration coupled to the nanotube length. Under high absorbed energies (but below 2.9eV/atom, the graphite's ultrafast fragmentation threshold), the resulting oscillatory motion leads to the opening of nanotube caps. Following the cap photofragmentation the nanotube body remains intact for the rest of the 2ps simulation time.

9835-8, Session 2

High-harmonic generation in atoms, molecules and wide-bandgap semiconductors (*Keynote Presentation*)

Paul Corkum, Univ. of Ottawa (Canada) and National Research Council of Canada (Canada); Giulio Vampa, Thomas Hammond, Univ. of Ottawa (Canada)

Extreme nonlinear optics, a theory describing the conversion of many infrared photons into a single, shorter-wavelength photon, was developed about 20 years ago for atoms and molecules. It is based on an electron tunnelling from the atom or molecule, moving in the continuum under the influence of the infrared light field and then re-colliding and recombining to the initial state. Extreme nonlinear optics has led to attosecond pulses, a laser-based source of coherent soft X-ray, a means to image molecular orbitals or to following chemical dynamics and even a method to measure the time dependent field of a light pulse.

Recently high harmonics have been produced from solids and in the case of wide bandgap semiconductors irradiated with mid-infrared light pulses experiment show that the re-collision mechanism applies. With re-collision demonstrated in solids, it seems possible that all transparent condensed media can be studied with high harmonic spectroscopy and the opportunity exists to adapt attosecond and imaging technology from gases to condensed media.

This talk will review high harmonic generation in gases with special emphasis on technology that might be important for condensed media. It will show how we confirm the mechanism and suggest where the technology might lead.

9835-9, Session 3

Nondegenerate two- and three-photon nonlinearities in semiconductors (*Keynote Presentation*)

Matthew C. Reichert, Peng Zhao, Himansu S. Pattanaik, David J. Hagan, Eric W. Van Stryland, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Nondegenerate two-photon absorption, ND 2PA, in semiconductors is enhanced by 2 orders of magnitude over the degenerate case due to intermediate-state resonance enhancement, ISRE. Associated with this enhancement in loss is enhancement of the nonlinear refractive index, n_2 . Even larger enhancement of 3PA is calculated and observed. These large nonlinearities have implications for applications including nondegenerate 2-photon gain and 2-photon semiconductor lasers. Calculations for enhancement of ND 2PA in quantum wells is also presented showing another order of magnitude increase in 2PA. Potential devices include room temperature gated infrared detectors for LIDAR and all-optical switches.

9835-10, Session 3

Numerical approaches for predicting two-photon absorption induced single-event effects in semiconductors (*Invited Paper*)

Joel M. Hales, Ani Khachatryan, Sotera Defense Solutions, Inc. (United States) and U.S. Naval Research Lab. (United States); Nicolas J. H. Roche, U.S. Naval Research Lab. (United States) and The George Washington Univ. (United States); Stephen Buchner, Jeffrey Warner, Dale P. McMorrow, U.S. Naval Research Lab. (United States)

Since the initial demonstration of nonlinear optical (NLO) approaches for simulating the effects of ionizing radiation on electronics systems in 2002, charge carrier generation via two-photon absorption (2PA) has developed into an essential tool for the development of radiation-hardened electronics for space-based applications. Specifically, free carriers are generated in silicon-based devices via 2PA using tightly focused, near-infrared femtosecond optical pulses with the expressed purpose of studying a class of radiation-induced phenomena referred to as single-event effects, or SEEs. As the experimental applications of 2PA SEE have continued to evolve, there has been an increasing need for a quantitative understanding of the carrier generation process. However, there are significant complexities associated with accurately modeling this physical process including the extraordinary non-paraxial focusing conditions encountered during beam propagation, a multiplicity of NLO phenomena that participate in the generation of carriers, and complicated changes in beam shape that can occur during propagation.

In this paper, two numerical approaches for determining the charge generated in semiconductors under conditions relevant for 2PA SEE experiments are presented. The first approach uses a simple analytical expression (considering only 2PA) to determine the maximum charge generated with knowledge of only a small number of experimental/material parameters. This approach can be quite valuable for estimating the generated charge when a more rigorous beam propagation approach is not available and, under certain experimental conditions, is shown to be quantitatively accurate. The second approach employs a comprehensive beam propagation method to determine the conditions under which the analytical approach is valid and to assess the impacts of more complex NLO interactions on the generated charge. Specifically, the role of laser beam depletion due to 2PA and free-carrier absorption can be significant particularly at elevated pulse energies. In order to calculate the value most relevant for 2PA SEE experiments, i.e. collected charge, a rectangular-parallel-piped integration approach is employed. This allows one to determine the impact of device geometry on the resulting collected charge. Interestingly, phase-based NLO effects, such as nonlinear refraction and

free-carrier refraction, can play a significant role when the lateral dimensions of the device under test are comparable in size to the focused beam. Finally, in addition to studying these phenomena in Si, two additional III-V semiconductors that are of topical interest, i.e. GaAs and GaN, are discussed. These three semiconductors possess very different NLO responses under similar experimental conditions and therefore represent a large cross-section of germane devices. These numerical approaches can provide value to the radiation-effects community by predicting the impacts that varying experimental parameters will have on 2PA SEE measurements.

9835-11, Session 3

Fiber laser comb sources for sensing and time/frequency standards (*Invited Paper*)

Khanh Q. Kieu, College of Optical Sciences, The Univ. of Arizona (United States)

Optical frequency combs (OFCs) are useful tool for many applications including optical clocks, precision frequency/time transfer, low phase noise microwave generation, astronomical spectrograph calibration, molecular spectroscopy, coherent LIDAR, and arbitrary optical/RF waveform generation. The main advantage of OFCs arises from the fact that thousands of highly coherent optical frequencies are precisely defined with only two degrees of freedom namely the carrier-envelop-offset frequency (fceo) and the repetition rate of the femtosecond laser pulse train. OFCs will probably find more widespread use in practical applications if they are less expensive, easier to build, and more robust such that they can work outside of controlled laboratory environment. We will present our research effort in developing compact and low cost fiber-based OFCs for gas sensing and time/frequency standards. We will discuss the performance of a low noise all-fiber erbium femtosecond (fs) frequency comb based on a simple and robust tapered-fiber carbon nanotube (tf-CNT) saturable absorber design. A free-running fceo linewidth of ~ 20 kHz is demonstrated which is comparable to the best reported performance to date for fiber-based frequency combs. We have also been able to demonstrate real-time absorption spectroscopy measurements using dual-comb technique without the need for complex servo locking or post-signal processing with accurate frequency referencing and relatively high signal to noise ratio. The results show that the relatively simple tf-CNT fiber laser design can provide a compact, robust and high-performance fs frequency comb.

9835-12, Session 3

Anomalous velocity enhancing of soliton, propagating in nonlinear PhC, due to its reflection from nonlinear ambient medium (*Invited Paper*)

Vyacheslav A. Trofimov, Tatiana M. Lysak, Lomonosov Moscow State Univ. (Russian Federation)

We demonstrate new possibility of soliton velocity control at its propagation in nonlinear layered structure (1D photonic crystal), which is placed in the nonlinear ambient medium. Nonlinear response of an ambient medium as well as PhC layers is cubic one. Some PhC layers can possess linear response.

At initial time moment, a soliton spread a few layers of PhC. Then, soliton propagates across the layered structure because of initial wave-vector direction presence for laser beam. A laser beam reaches PhC faces and reflects from them. As a nonlinear medium surrounds the PhC then a laser pulse obtains additional impulse after interaction with this medium and accelerates (or slows down or stops of light near the PhC phases). Nonlinear response of a? ambient can be additionally created by another laser beam which shines near the PhC faces.

9835-13, Session 3

Exciton dynamics in two-dimensional semiconductors and organic/inorganic thin films *(Invited Paper)*

Vinod M. Menon, The City College of New York (United States)

I will discuss the use of ultrafast spectroscopy to understand exciton dynamics in ordered and disordered nanomaterial systems. First, I will address exciton lifetimes in two-dimensional semiconductors of transition metal dichalcogenides. Following this I will discuss ultrafast exciton dynamics observed in ZnO nanoparticles and the appearance of random lasing in these systems. Finally I will present an approach to directly visualize exciton diffusion in ordered and disordered organic thin films.

9835-14, Session 3

Spectroscopic diagnostics of defect and interface effects on carrier dynamics in semiconductor optoelectronics *(Invited Paper)*

Adam C Scofield, Andrew I. Hudson, The Aerospace Corp. (United States); Baolai L. Liang, Univ. of California, Los Angeles (United States); Nathan P. Wells, The Aerospace Corp. (United States); Diana L. Huffaker, Univ. of California, Los Angeles (United States); William T. Lotshaw, The Aerospace Corp. (United States)

Steady-state and time-resolved spectroscopy is capable of providing detailed information about carrier generation, transport, and relaxation in semiconductor materials and device test structures. In conjunction with analyses of experimental data that are based on response functions derived from physical models, spectroscopic diagnostics represent an important and often underutilized tool for quantitative determinations of material optoelectronic properties and root-cause analyses of property or performance anomalies. We have applied time-resolved and steady-state absorption and luminescence techniques to a variety of III-V materials and reference heterostructures in order to investigate the mechanisms limiting carrier lifetime and develop a capability to provide actionable feedback to R&D efforts for improvement and optimization of material/device performance. Our work has focused on some specific photovoltaic materials and test structures, and THz optoelectronics.

To exemplify our work we will present the results of photoluminescence experiments and model-based analyses designed to assess the carrier dynamics impacts of defects and interface quality in double heterostructure test vehicles grown by MOCVD and MBE. Low temperature experiments will be shown to be critical to the identification and analysis of these effects. The results of a corresponding study of ultrafast carrier relaxation in LT-GaAs will also be presented.

9835-15, Session 3

THz photoconductive materials and devices: is there a good figure-of-merit? *(Invited Paper)*

Elliott R. Brown, Weidong Zhang, Wright State Univ. (United States)

Ultrafast photoconductive (PC) devices are arguably the most important breakthrough in the THz field during the past 25 years. PC switches are the building block of time-domain systems such as spectrometers, and photomixers are the same for frequency-domain components such as local

oscillators. A longstanding issue is the choice of PC material and laser-drive wavelength, the most popular combination still being low-temperature-grown (LTG) GaAs driven by lasers in the range ~780-to-850 nm. Because of the cost and difficulty of ~800-nm optics and photonics, THz researchers have gravitated to the fiber-optic telecom bands, especially around 1550 nm where erbium-doped fiber lasers lay the foundation. Unfortunately, none of the PC materials there have yet been as effective as LTG GaAs around 800 nm for a variety of reasons including low breakdown voltage, low photocarrier mobility, or low 1550-nm absorption coefficient. This paper reviews the state-of-the art in 1550-nm PC materials including ion-implanted InGaAs, InGaAs/InAlAs heterostructures, Er-doped InGaAs, and Er-doped GaAs. The latter has been our focus recently because it displays extrinsic photoconductivity whereby the photocarriers are unipolar (usually electrons) but are excited with absorption coefficient (~10⁴ cm⁻¹) and lifetime (< 1 ps) akin to intrinsic ultrafast photoconductors like LTG-GaAs. And it begs for a different figure-of-merit (FoM) than the photoconductive gain-bandwidth product (GB) appropriate to small-signal behavior. It will be argued that the device-specific quantity FoM = $\eta_{sub 0} \times C \times GB \times V_{sub B}$ or some variant makes sense, where $\eta_{sub 0}$ is the external optical quantum efficiency, $\eta_{sub C}$ is the circuit impedance matching efficiency, and $V_{sub B}$ is the breakdown voltage. It is similar to the Johnson FoM for power transistors and the speed index of analog switches, and all three have the same dimensions: V/s.

9835-16, Session 3

Carrier excitation and recombination in Fe:GaN: application to high-speed photoconductive switching *(Invited Paper)*

Jacob H. Leach, Keith R. Evans, Kevin Udworthy, Kyma Technologies, Inc. (United States); David Look, Wright State Univ. (United States)

Wide bandgap solid-state photoconductive switches (PCSSs) are poised to serve as nearly ideal switches for a number of high speed pulsed power applications. Depending on geometry and triggering scheme, GaN-based devices are suitable for switching in sub-ns time regimes with sub-Ohm on-resistances. This work will outline some of the physics of carrier excitation and recombination for semi-insulating GaN, as a function of growth methods and intentional and unintentional impurity concentrations. The mechanisms of carrier excitation and recombination are deduced from Photo-Hall effect measurements, steady-state and time-resolved photoluminescence, optical absorption, and photoconductive switch performance. As the materials properties have ramifications on the photoconductive switch performance we will discuss methods for 'tuning' the switch performance for higher speeds, higher current handling capability, or reduced optical excitation requirements. The latest results from Kyma's program focused on developing high rep rate pulsed power supplies based on GaN-PCSS devices using commercial off-the-shelf laser diodes will be discussed as well.

9835-17, Session 3

Direct look at charge, spin, and lattice dynamics in solids with ultrafast terahertz spectroscopy *(Invited Paper)*

Dmitry Turchinovich, Max-Planck-Institut für Polymerforschung (Germany)

Ultrafast terahertz spectroscopy allows one to directly resolve the ultrafast dynamics of charge, lattice and spins in the unique regime $\omega \tau \approx 1$, where ω is the electromagnetic wave oscillation frequency, and τ is the characteristic timescale at which the fundamental phenomena in the three subsystems comprising the solid occur. In this talk, after a brief introduction into the technique, two recent case studies will be discussed. (i) Ultrafast electron conduction in graphene. It will be shown that the free-carrier conductivity of graphene in arbitrary

ultrafast, (sub-)picosecond electric fields is defined by the thermodynamic balance maintained within the electronic structure of graphene acting as thermalized electron gas. Within this simple thermodynamic picture, and without the resort to microscopic electron kinetics, one can perfectly well describe the ultrafast electronic response in graphene, in particular its inherent resistivity at strong fields and high frequencies [1]. This thermodynamic picture, in particular, explains the apparent speed barrier to ultra-high speed graphene transistor operation, and paves the way to breaking this barrier. (ii) The fundamental observation of spin-controlled electron conduction of Fermi-level electrons in ferromagnetic metals will be also discussed. It will be shown that using ultrafast THz spectroscopy it is possible to directly quantify the Mott picture of conduction in ferromagnetic transition metals - the effect directly employed in modern magnetic sensor technologies such as giant magnetoresistance [2].

[1] Z. Mics et al., "Thermodynamic picture of ultrafast charge transport in graphene," Nature Communications 6, 7655 (2015).

[2] Z. Jin et al., "Accessing the fundamentals of magnetotransport in metals with terahertz probes," Nature Physics 11, 761 (2015)

9835-20, Session 4

Linear and nonlinear optical properties of nano-crystal quantum dots *(Invited Paper)*

Alexander L. Efros, U.S. Naval Research Lab. (United States)

The linear optical properties of semiconductor nanocrystals (NCs), which are also called NC quantum dots are determined by optical transitions between electron and hole quantum confined levels and the absorption band edge and the photoluminescence of the semiconductor NCs can be shifted up to 1 eV to the blue from the bulk energy gap of the semiconductor by decreasing the NC size only.

The energy spectra of biexcitons, i.e., two electron hole pairs, determine almost all the nonlinear optical properties of nanocrystals (NCs), including stimulated emission. This is a unique property of strongly confined quantum dots. The electron ground state is a 1S level, two fold degenerate with respect to the spin projection. It is separated from the next highest, 1P, level by typically 300-500 meV. Since the Pauli principle allows only two electrons in this ground state quantum size level, to excite a 3rd e-h pair demands an extra 300-500 meV.

Turn out that nonradiative Auger recombination which occurs in charged NCs or in NC where more than one electron-hole pair were created is the central non-radiative relaxation process, which negatively affect the performance of all NC based devices. I am going to discuss why the nonradiative Auger recombination is enhanced in NCs and how we can suppress them.

9835-21, Session 4

Ultrafast dynamics of charge transfer in semiconductor quantum dots relevant to solar hydrogen production *(Invited Paper)*

Todd D. Krauss, Sanela Lampa-Pastirk, Cunming Liu, Fen Qiu, Univ. of Rochester (United States)

Artificial conversion of sunlight to chemical fuels has attracted attention for several decades as a potential source of clean, renewable energy. For example, in light-driven proton reduction to molecular hydrogen, a light-absorbing molecule (the photosensitizer) rapidly transfers a photoexcited electron to a catalyst for reducing protons. Generally speaking, the most efficient and active catalytic systems for proton reduction in solution have photosensitizers and catalysts that contain extremely rare metals, such as ruthenium and/or platinum. As such, these systems are not considered viable for large-scale energy production.

We recently found that CdSe quantum dots (QDs) and simple aqueous Ni²⁺

salts in the presence of a sacrificial electron donor form a highly efficient, active, and robust system for photochemical reduction of protons to molecular hydrogen. To understand why this system has such extraordinary catalytic behavior, ultrafast transient absorption (TA) spectroscopy studies of electron transfer (ET) processes from the QDs to the Ni catalysts were performed. Ultrafast TA measurements were performed in a typical pump-probe setup using a Ti:sapphire regenerative amplifier light source. CdSe QDs transfer photoexcited electrons to a Ni-dihydrolypoic acid (Ni-DHLA) catalyst complex extremely fast and with high efficiency: the amplitude-weighted average ET lifetime is 69 ± 2 ps, and ~90% of ultrafast TA signal is assigned to ET processes. Interestingly, under high fluence, sufficient to create on average almost 2 excitons per QD, the relative fraction of TA signal due to ET remains well over 80%, and depopulation from exciton-exciton annihilation is minimal (6%). We also found that increasing QD size and/or shelling the core CdSe QDs with a shell of CdS slowed the ET rate, in agreement with the relative efficiency of photochemical H₂ generation. The extremely fast ET provides a fundamental explanation for the exceptional photocatalytic H₂ activity of the CdSe QD/Ni-DHLA system and guides new directions for further improvements.

9835-22, Session 4

Charge carrier photogeneration and recombination dynamics in quantum-dot solids probed by ultrafast photocurrent spectroscopy *(Invited Paper)*

Victor I. Klimov, Los Alamos National Lab. (United States)

This presentation provides an overview of photophysical studies of quantum dots conducted in the context of solar energy conversion. A specific focus is on early time carrier dynamics investigated using a combination of optical and transient photocurrent (TPC) spectroscopies. In TPC measurements, we incorporate quantum dots into a fast electro-optical switch triggered by femtosecond laser pulses and monitor photocurrent transients using a broadband sampling oscilloscope with the 10-to-40 ps time resolution. Applying this approach, we can resolve early time processes observed prior to charge extraction from the quantum dots as well as later-time dynamics due to carrier relaxation within the spectrum of band-edge states and non-geminate recombination. We are also able to probe directly in the photocurrent the process of carrier multiplication wherein multiple excitons are generated by single photons. In addition, this method allows us to study the competition between charge extraction and Auger recombination as well as the effect of sample temperature and applied electric field on multiexciton yields.

9835-23, Session 4

Coherently controlled solid state emitters for photonic quantum entanglement generation *(Invited Paper)*

Sophia Economou, Virginia Polytechnic Institute and State Univ. (United States)

Entanglement is recognized as the cornerstone of many novel quantum-based technologies and future quantum devices that will enable radically new capabilities in computing, secure communications and metrology. Photonics is a very promising avenue for quantum computing, quantum communications and quantum-enhanced sensing. For these technologies to materialize, a key challenge is the deterministic creation of a large-scale entangled photonic state. Currently, the generation of entangled states of photons in the lab is inefficient and probabilistic, as it relies on probabilistic processes. We have developed deterministic approaches to generate large scale entangled chains and ladders of photons emitted from solid state emitters, driven periodically by ultrafast lasers.

The basis of our approach was proposed in 2009 by Rudolph et al, who proposed a periodically pumped quantum dot (QD) containing a single

electron. The efficient spontaneous emission of the QD and the fact that the emitted photon is entangled with the spin in the QD allows for a large chain of entangled photons when the system is pulsed periodically with appropriate ultrafast lasers. This approach provided a huge improvement over purely probabilistic approaches, but still required further (probabilistic) manipulation in order to achieve two-dimensional entanglement, as required for quantum computing.

In follow-up work, we showed that a pair of coupled quantum dots that is coherently controlled such that the resident spins become entangled can form the basis for a two-dimensional 'ladder' of entangled photons. Each QD is pulsed as in the 1D approach, but with the additional advantage that the entanglement between the spins is transferred to the emitted photons. Our approach is the first time a two-dimensional entangled photonic state was proposed. The challenge however remained that pulse-induced entanglement between the QD spins is challenging experimentally. In very recent work, we have shown that in fact the free evolution based on exchange interaction between the spins can be used along with single spin coherent control in order to generate the required entangling operation between the spins, greatly simplifying the protocol.

More recently, we have also shown that the structure of certain defect color centers in solids, in particular the NV center in diamond and the silicon vacancy in silicon carbide provide an attractive level structure and selection rules for the generation of entangled photons. These systems may offer additional capabilities, such as high temperature operation and long coherence times, increasing the size of the entangled system.

9835-24, Session 4

Entanglement of light in crystals and photonic chips *(Invited Paper)*

Paulo A. Nussenzveig, Univ. de São Paulo (Brazil)

Entanglement of bright beams of light is a useful resource for applications in information protocols.

By using continuous variables, much in the spirit of the original analysis by Einstein, Podolsky, and Rosen, it is possible to perform deterministic tasks and also to use detection tools available to classical communications systems. We have concentrated our efforts on nonlinear optical processes using bulk crystals inside optical cavities. The cavity bandwidth sets a maximum repetition rate for information processing and communications. An interesting pathway consists in investigating similar effects in miniaturized cavities on photonic chips, with the additional benefit of compatibility with micro-electronics.

In this talk, I will present an overview of our research on the generation of continuous-variable entanglement in bulk nonlinear crystals, as well as nonclassical light generated in silicon chips.

9835-25, Session 4

On-chip photonic-phononic processing *(Invited Paper)*

Birgit Stiller, Moritz Merklein, Benjamin J. Eggleton, The Univ. of Sydney (Australia)

Research in the field of integrated photonics brings several applications forward, ranging from optical communication, computing, sensing to all-optical data processing. Recently, we have shown photon-phonon interaction in these integrated photonic circuits which led to progress on narrow linewidth lasers or tunable microwave filters. In the context of optical signal processing, one interesting question to solve concerns on-chip all-optical storage methods to delay and synchronize optical data pulses. One technique to store light pulses for several nanoseconds is based on stimulated Brillouin scattering (SBS) where information from optical pulses is encoded in acoustic phonons. We demonstrated for the first time the storage of nanosecond pulses in a fully integrated chip-scale platform. This allows us amongst others to reduce the necessary optical power and the

size of the storage medium. Based on the high nonlinear gain which this new generation of Chalcogenide waveguides provide, we are now able to push this light storage technique further to even more complex data processing.

9835-26, Session 5

The bulk photovoltaic effect as a novel mechanism for sensing devices and applications *(Invited Paper)*

Steve Young, U.S. Naval Research Lab. (United States)

The bulk photovoltaic effect describes the generation of photocurrents and photovoltages in bulk materials lacking a center of symmetry. Its principal mechanism is "shift current," a nonlinear-optical, inherently quantum mechanical process. Recently, great strides have been made experimentally and theoretically in understanding the fundamental physics of shift current and identifying new classes of materials exhibiting improved performance. However, while most attention has been devoted to its prospects as means of solar energy capture, shift current bulk photovoltaic effect possesses a number of distinguishing features that make it well-suited to sensing and switching applications: photovoltages substantially exceeding the material's band gap, response amplitudes and directions that can depend on both photon energy and polarization, and response that occurs on ultrafast timescales.

These properties arise from the fundamentally quantum nature of the phenomenon: light not only generates carriers but drives them as well. The carriers are in unthermalized, coherent states, and due to the breaking of inversion symmetry, possess net momentum and produce current, which persists only for the duration of illumination. Unlike photoresponse that occurs due to thermalized carriers in an external field, photovoltages can be arbitrarily high, and the response profile depends strongly on the illumination frequency, changing not only amplitude but even sign across the spectrum. The process is second-order, and thus also strongly depends on the polarization of the illumination; in many cases symmetry requires orthogonal polarizations to produce equal but opposite response. Additionally, since carriers are excited directly into current-carrying states, the response proceeds much more rapidly than field driven current. This has been observed PTO subjected to 5mJ/cm^2 40fs FWHM laser pulses as opposing structural responses occurring at distinct timescales, the first as a consequence of shift current photovoltage generated during the pulse, and the second by the backflow of thermalized carriers. Recent research has focused on identifying materials with increased response and more accessible band gaps, and understanding the role of device structure on overall efficiency. It has become clear that optimal materials, oxide or otherwise, are characterized by strongly broken symmetry and covalent electronic states, and the key to efficiency is minimizing conventional conductivity. These and other advances are rapidly increasing the viability of bulk photovoltaic effect for application and devices in a wide range of contexts.

9835-27, Session 5

Advances in ultrafast optics and imaging applications *(Invited Paper)*

Guy Satat, Barmak Heshmat, Nikhil Naik, Albert R. Sanchez, Ramesh Raskar, MIT Media Lab. (United States)

The use of ultrafast imaging has been a fundamental piece to many advances in various imaging applications, including looking behind corners and imaging behind scattering layers. Critical components to these advances are emerging sensors with picosecond (ps) time resolution, which enable accurate temporal information acquisition without the need for conventional interferometric geometries. Typical computational imaging techniques in traditional scene analysis exploit sensor parameters such as spatial resolution, wavelength, and polarization. However, these parameters alone are limited in their ability to capture the complex dynamics of light

propagation. Ultrafast time-resolved sensors overcome this limitation and enable complicated analysis of light-in-flight in various imaging geometries.

One of the most notable applications of ultrafast imaging is imaging beyond the conventional field of view of the camera. We have already demonstrated full 3D reconstruction of complex objects hidden around corners. The sensor measures the time-of-flight of indirect reflections from the hidden object and a reconstruction algorithm is used to invert the measurements to recover the object.

To use ultrafast measurements for sensing beyond line-of-sight or conventional field of view, we usually need to solve a complex inverse problem. A key insight in solving the inverse problem is to treat light propagation between the scene and sensors in a five dimensional space comprising of space (2D), angle (2D), and time (1D). Thus, by combining forward models of light propagation and advanced signal processing and optimization techniques, we are able to invert the measurement and recover the hidden scene.

Ultrafast imaging has also been shown to enable simultaneous localization and identification of objects with temporal signatures hidden behind scattering layers. For instance, recovery of different material properties, such as albedo and fluorescence lifetime, have been demonstrated. The latter is extremely challenging since the time-resolved measurement couples spatial information as well as the fluorescence profile.

Along with a discussion on existing results, we will explore promising future directions, including (1) using spectral (THz) and temporal signatures to recover hidden objects, (2) exploiting complete light profile to overcome volumetric scattering, and (3) performing temporal coding of the space domain.

9835-28, Session 5

Non-line-of-sight imaging from scattered light (*Invited Paper*)

Jessica A. Zeman, Talha Sultan, Kevin W. Eliceiri, Andreas Velten, Univ. of Wisconsin-Madison (United States)

Non-line-of-sight imaging systems illuminate a visible relay surface in the scene with a short pulse or rapidly varying light source. The returned light from this relay surface is detected with high time resolution so that the path length of photons from the source via the relay surface to the detector can be established through the time of flight. Using this information we can computationally backproject detected light to reconstruct an image of the scene as seen from the position of the relay surface including objects that are occluded from the position of the light source and detector.

I will be presenting recent progress on reconstruction algorithms. Our current backprojection methods provide reconstructions of the scene in a fast linear reconstruction method without the use of prior scene information. They are however intrinsically flawed exhibit method related reconstruction artifacts even if presented with perfect noiseless data of the scene. We are developing an iterative backprojection method to improve reconstructions. This iterative method uses the results of a first backprojection to create a improved higher iteration reconstructions.

Further I present studies of the resolution of non line of sight imaging systems and link the point spread function and resolution of our method to established theoretical models of direct imaging methods.

I will also summarize some applications we are currently working on, such as a method to explore the entrances of caves on the moon from a low lunar orbit. Lunar caves provide access to the sub-surface geology, potential shelter for human exploration, and could harbor volatile materials. In our current work we are developing mission concepts for scouting of caves to enable further exploration using rovers.

9835-29, Session 5

Multiphoton optical imaging with compact fiber laser (*Invited Paper*)

Khanh Q. Kieu, College of Optical Sciences, The Univ. of Arizona (United States)

I will discuss the ultrafast fiber laser systems that we have recently developed using carbon nanotubes (CNT) saturable absorber. The emphasis will be put not only on the excellent performance of the developed lasers but also on their commercialization path where long term operation and stability are crucial. A newly developed laser is only useful when it is successfully used in a real application. For that reason, I will also discuss the latest results that we have been able to achieve through the use of these laser systems. In particular, I will discuss the application of these lasers in multiphoton microscopy of 2-dimensional layered materials (graphene, GaSe, MoS₂), photonic devices and biological tissues.

9835-18, Session 6

Coherent x-rays driven by ultrashort-pulse lasers: generation, application, and prospects (*Keynote Presentation*)

Henry C. Kapteyn, Kapteyn-Murnane Labs., Inc. (United States)

Ultrafast laser pulses represent an ideal starting point for frequency conversion of light to almost any wavelength from the THz to x-rays. High-harmonic upconversion is a unique process enabled by the combination of very high peak field-strength, and few-cycle pulse duration, created by USP lasers. HHG makes it possible to generate coherent light in the spectral region from the Vacuum-UV all the way to the x-ray region of the spectrum. HHG sources are now finding increasingly diverse application for both science and technology, ranging from basic studies of atomic processes, materials dynamics revealed through time and angle-resolved photoemission (TR-ARPES), and nanoscale imaging with resolution limited only by the (very short) wavelength of the light, to imminent industrial applications in semiconductor manufacturing metrology. Furthermore, our recent work has demonstrated that the coherent nature of the HHG process makes possible unprecedented control over light in a new region of the spectrum, allowing us to, for example, control the polarization state and spectral bandwidth, creating the most complex time-domain waveforms ever measured and characterized. In this talk, I will review our recent work demonstrating the extension of useful HHG sources into the soft x-ray region of the spectrum using two distinct approaches, as well as our efforts at commercial implementation of HHG sources, and finally the prospects for extending HHG techniques to the generation of fully coherent hard x-rays, with the prospect for revolutionizing x-ray technology for medicine and security.

9835-19, Session 6

Perturbative wave-mixing and amplification in the extreme ultraviolet region (*Invited Paper*)

Lap Van Dao, Peter Hannaford, Swinburne Univ. of Technology (Australia)

In non-perturbative nonlinear optics the light interaction with the medium can be approximated by a classical or quantum treatment through the time-dependent Schrödinger equation. The non-perturbative approach has been successfully applied to high-harmonic generation of extreme ultraviolet (XUV) radiation. In perturbative nonlinear optics the response of the medium is expanded in many orders, expressed as linear and nonlinear terms in which high orders of response are taken into account.

Depending on the strength of the field the highest orders of response need to be considered. The detailed response of a single atom or molecule to an intense electromagnetic field is quite complex, but the fundamental underlying physics can be unexpectedly simple in many cases.

We report the investigation of the wave-mixing and application process with two multiple-cycle (40 fs) pulses with incommensurate frequencies (at 1400 nm and 800 nm). Different extreme ultraviolet mixing fields can be separated spatially by using of a non-collinear scheme of the two beams [1]. When a very high intensity pulse ($> 7.1014 \text{ Wcm}^{-2}$) at 800 nm is applied in addition to a high intensity pulse at 1400 nm we are able to amplify the coherent extreme ultraviolet radiation in the photon energy range around 80 eV by more than an order of magnitude compared to the generation with a single-wavelength pulse [2]. This opens the way to extend the powerful techniques of perturbative nonlinear optics to the case of a high intensity driving field in multiple-photon processes.

References:

1. L. V. Dao, K. B. Dinh, H. V. Le, N. Gaffney, P. Hannaford, Wave-mixing with high-order harmonics in extreme ultraviolet region, *Appl. Phys. Lett.* 106, 021118 (2015)
2. L. V. Dao, Kh. B. Dinh, P. Hannaford, "Perturbative Optical Parametric Amplification in the Extreme Ultraviolet", *Nature Communications* 6, 7175 (2015)

9835-30, Session 7

Supercontinuum fiber lasers: new developments and applications (*Invited Paper*)

Adam L. Devine, Lucy E. Hooper, John R. Clowes, Fianium Ltd. (United Kingdom)

The invention of photonic crystal fibers (PCF) twenty years ago opened up an entirely new area in photonics, and the subsequent development of supercontinuum fiber lasers has demonstrated a remarkable example of synergy between laser physics and photonics. From the very first laboratory demonstration of supercontinuum generation using PCF, it was evident that it was only a matter of time before compact and reliable supercontinuum fiber lasers would find numerous applications in everyday life.

Recent advances in the development of high power supercontinuum fiber lasers with powers exceeding 50W and spectral brightness of tens of mW/nm coupled with mature fiber technology and componentry, have attracted the attention of serious players within both medical and industrial markets.

In this talk we give an overview of the latest developments of high power supercontinuum fiber lasers, discuss the fundamental limitations of power scaling and spectral broadening and review the existing and emerging applications of this unique light source which combines the broadband properties of a light bulb with the spatial properties of a laser.

9835-31, Session 7

Mid-IR Kerr-lens mode-locked polycrystalline Cr²⁺:ZnS lasers (*Invited Paper*)

Sergey B. Mirov, The Univ. of Alabama at Birmingham (United States) and IPG Photonics - Mid-Infrared Lasers (United States); Sergey Vasilyev, Igor S. Moskalev, Mikhail S. Mirov, IPG Photonics - Mid-Infrared Lasers (United States); Valentin P. Gapontsev, IPG Photonics Corp. (United States)

This talk summarizes recent improvements of output characteristics of polycrystalline Cr:ZnS/Se master oscillators in Kerr-Lens-Mode-Locked regime: 1.9 W average power at 41 fs pulse duration, 24 nJ pulse energy and

550 kW peak power with efficiency of 19% with regards to 1567 nm pump power from linearly polarized Er-fiber laser. A simple design of mid-IR fs Cr:ZnS MOPA enabled power scaling to 71 W at 79 MHz repetition rate. This was accompanied by a 2 fold spectral broadening to 600 nm at -10 dB level, pulse compression from 44 to 33 fs, and overall 25 % optical to optical efficiency.

Dispersion management of the resonator within 500 nm bandwidth (1/3 of an octave) enabled pulse duration of Cr:ZnS master oscillator approaching 3 optical cycles and 950 nm spectral span (3/5 of an octave). Further improvements of the optical coatings will result in octave-spanning polycrystalline Cr²⁺:ZnS/ZnSe lasers. This will bring ultrafast mid-IR lasers in line with state-of-the-art Ti:sapphire oscillators.

High nonlinearity of II-IV semiconductors and random quasi-phase-matching in polycrystalline material in combination with MW-level optical power in the gain element of fs laser, offer a number of unique possibilities. The effects of efficient up-conversion of mid-IR fs pulses in the laser medium are observed in current experiments. Synchronous pumping of polycrystalline Cr²⁺:ZnS/ZnSe by 1.5 μm pico- and femtosecond fiber lasers may increase the yield of sum- and difference-frequency mixing by several orders of magnitude. Implementation of synchronously pumped OPO based on random quasi-phase-matching in polycrystalline Cr²⁺:ZnS/ZnSe represents another interesting opportunity, which may lead to ultrafast oscillators with exceptionally broad spectral coverage spanning 2 to 6 μm .

9835-32, Session 7

Trends in high-power ultrafast lasers (*Keynote Presentation*)

Clara J. Saraceno, Florian M. Emaury, Andreas Diebold, Michael Kopp, Ivan Graumann, Matthias Golling, Ursula Keller, ETH Zürich (Switzerland)

Ultrafast laser sources are one of the main scientific achievements of the past decades. Finding new avenues to obtain higher average powers from these sources is currently a topic of important research efforts. Such high peak power and high repetition rate sources have a strong impact on a wide range of applications both in industry for high precision and high-speed micro-machining and in scientific research for example in the emerging fields of high harmonic generation and attosecond science.

Among different ultrafast technologies, Semiconductor saturable absorber mirror (SESAM) modelocked thin-disk lasers currently enable the highest average powers and pulse energies of any ultrafast oscillator, making them excellent table-top sources for these applications. To-date, an average power of 275 W with 583 fs pulses has been achieved directly from an oscillator based on the gain material Yb:YAG. In addition, a pulse energy of 80 μJ was recently demonstrated at an average power of 240 W in 1.1 ps pulses. These results set the performance frontiers of ultrafast oscillators in terms of average power and pulse energy of femtosecond oscillators.

In this presentation, we will review the current state-of-the art of this technology. We will present key elements for average power and pulse energy scaling in this laser geometry. We will discuss pulse duration scaling using different promising novel gain materials to extend the state-of-the-art performance of such oscillators to the sub-100 fs regime, as well as perspectives and future steps towards further scaling to kW average powers and several hundreds of μJ .

9835-33, Session 7

High-power mid-infrared femtosecond laser sources (*Invited Paper*)

Andreas Schmitt-Sody, Air Force Research Lab. (United States); Adrian P. Lucero, Boeing-SVS, Inc. (United States); Jennifer Elle, Air Force Research Lab. (United States); Evan Lang, The Ohio State Univ. (United States); Matthew Dmonkos, Air Force Research Lab. (United States)

Present on high energy femtosecond laser sources using ZnSe as host crystal. That allows us to access wavelength only available to optical parametric sources with a direct laser source. We will present current status of our systems.

9835-34, Session 7

Advanced concepts for high-power short-pulse CO₂ laser development *(Invited Paper)*

Daniel F. Gordon, Yu-hsin Chen, U.S. Naval Research Lab. (United States); Victor H. Hasson, Univ. of Arizona (United States); Luke A. Johnson, Michael H. Helle, U.S. Naval Research Lab. (United States); Andreas Schmitt-Sody, Air Force Research Lab. (United States); John P. Palastro, Joseph R. Penano, U.S. Naval Research Lab. (United States)

Ultra-short pulse lasers are dominated by solid-state technology, which typically operates in the near-infrared. Efforts to extend this technology to longer wavelengths are meeting with some success, but the trend remains that longer wavelengths correlate with greatly reduced power. The carbon dioxide (CO₂) laser is capable of delivering high energy, 10 micron wavelength pulses, but the gain structure makes operating in the ultra-short pulse regime difficult. The Naval Research Laboratory and Air Force Research Laboratory are developing a novel CO₂ laser designed to deliver -1 Joule, -1 picosecond pulses, from a compact gain volume (-2x2x80 cm). The design is based on injection seeding an unstable resonator, in order to achieve high energy extraction efficiency, and to take advantage of power broadening. The unstable resonator is seeded by a solid state front end, pumped by a custom built titanium sapphire laser matched to the CO₂ laser bandwidth. In order to access a broader range of mid infrared wavelengths using CO₂ lasers, one must consider nonlinear frequency multiplication, which is non-trivial due to the bandwidth of the 10 micron radiation. Finally, it may be possible to overcome the bandwidth limitation of the CO₂ gain medium via Raman amplification in a plasma.

9835-35, Session 8

Modeling of ultrafast laser pulse propagation *(Keynote Presentation)*

Miroslav Kolesik, College of Optical Sciences, The Univ. of Arizona (United States); Jeffrey Brown, The Univ. of Arizona (United States); Anand Bahl, Christopher Shannor, College of Optical Sciences, The Univ. of Arizona (United States)

Simulations in modern nonlinear optics dealing with ultrafast, high-intensity pulses face multiple challenges. The first stems from the fact that the dynamics of ultrashort optical pulses can not be efficiently modeled at the level of Maxwell equations. Instead, pulse propagation models are necessary that can be simulated efficiently across disparate spatial and time scales. The second issue is the description of light-matter interactions. As the nonlinear optics pushes into new regimes, e.g. studying light-matter interactions in strong multicolor fields and the nonlinear propagation dynamics in mid-infrared wavelength range, the need to respect the first principles is ever greater for simulations of gaseous and condensed media alike. This talk will discuss both the current state of the art and promising directions in the field of ultrashort pulse modeling.

In the first part of this contribution, various ways will be discussed to approach the transformation of the Maxwell equation system into models suitable for numerical simulation of pulses in practically relevant situations. With the emphasis on modern methods, state of the art simulation engines will be described in broad strokes, together with illustrative examples of envelope-pushing simulation studies.

The second portion of the talk will be devoted to the light-matter interaction modeling.

We will briefly describe several problems in this field that recently receive a great deal of attention, and will offer our thoughts on promising directions, ranging from the numerically intensive Maxwell-Schrodinger integration to computationally less demanding effective models.

The discussion will touch upon commonalities and differences in the new approaches that have to be developed for gases and condensed media. We will conclude with illustrative examples showcasing our recent progress toward self-consistent quantum-physics based modeling of nonlinear interactions in strong optical fields.

9835-36, Session 8

Breakdown of reciprocity for high peak power laser pulses *(Invited Paper)*

John P. Palastro, Joseph R. Peñano, Bahman Hafizi, Michael H. Helle, Gregory DiComo, U.S. Naval Research Lab. (United States); William Nelson, Univ. of Maryland, College Park (United States)

Monostatic atmospheric turbulent channels exhibit the property of reciprocity, or symmetry with respect to interchange of point sources and receivers. It is precisely this property that allows for correction of turbulent phase distortions and coherent illumination of a beacons target. Typical beacons emit low power light that propagates linearly through the turbulent channel. By measuring the phase of the received beacon light, and applying the conjugate phase to an outgoing pulse, the source can be reproduced at the target. If, however, the outgoing pulse is also amplified to high peak powers, it will experience nonlinear modifications to its refractive index, breaking the reciprocity of the channel. This breakdown of reciprocity limits the effectiveness of phase correction for high peak power lasers. We will present simulations and theory demonstrating the conditions for reciprocity breakdown. We will show that at high powers, phase correction can reproduce the source intensity, but not the phase. Finally we show that at high peak powers, phase correction is more effective in stronger turbulence due to spatial incoherence weakening the nonlinearity.

9835-37, Session 8

Absolute measurement of the ultrafast nonlinear electronic and rovibrational response in hydrogen and deuterium *(Invited Paper)*

Jared Wahlstrand, Univ. of Maryland, College Park (United States); Sina Zahedpour, Univ. of Maryland (United States); Yu-Hsiang Cheng, Univ. of Maryland (United States) and National Institute for Standards and Technology (United States); John P. Palastro, Univ. of Maryland, College Park (United States) and U.S. Naval Research Lab. (United States); Howard M. Milchberg, Univ. of Maryland, College Park (United States)

The electronic, rotational, and vibrational components of the ultrafast optical nonlinearity in gaseous hydrogen and deuterium are measured directly and absolutely at intensities up to the ionization threshold of $\sim 10^{14}$ W/cm². We overlap in a gas target a 40 fs pump pulse centered at 800 nm and a chirped supercontinuum pulse spanning the wavelength range 450 to 700 nm. Using spectral interferometry, we measure the spectral phase and amplitude of the probe pulse. Using the known chirp of the supercontinuum, we extract the time-dependent refractive index, which allows separation of the instantaneous from the delayed rotational response. In hydrogen and deuterium, only a few rotational states are populated at room temperature, resulting in an oscillating refractive index change that

we analyze to find the rotational component of the optical nonlinearity. To distinguish the rovibrational component from the electronic component, both of which appear effectively instantaneous with a 40 fs pump pulse, we measure the phase shift as a function of the probe wavelength with which the pump pulse overlaps. This can be tuned by changing the pump-probe time delay. The vibrational nonlinearity is resonant when the pump and probe frequencies differ by the vibrational mode frequency. This novel technique, which relies on vibrational two-beam coupling, allows us to measure the vibrational component of the nonlinearity even though our pump pulse is far too long to directly excite the vibrational mode, which in hydrogen has a frequency greater than 100 THz. As the most basic nonlinear interactions of the simplest molecules exposed to high fields, these results constitute a benchmark for high field laser-matter theory and simulation.

9835-38, Session 8

Remote optical magnetometry (*Invited Paper*)

Luke A. Johnson, Phillip A. Sprangle, U.S. Naval Research Lab. (United States)

A remote magnetometry concept using intense laser pulses and atmospheric oxygen will be discussed. This mechanism has applications in the remote detection of underwater and underground objects. In our concept, Kerr self-focusing is used to bring a polarized, high-intensity, laser pulse to focus at a remote detection site where the laser pulse induces a ringing in the oxygen magnetization current. This current creates a co-propagating electromagnetic field behind the laser pulse, i.e., the wakefield, which has a rotated polarization that depends on the background magnetic field. The detection signature for underwater and underground objects is the change in the wakefield polarization between different measurement locations. The coupled Maxwell-density matrix equations are used to describe the oxygen magnetization in the presence of an intense laser pulse and ambient magnetic field. The magnetic dipole transition line that is considered is the b-X transition band of oxygen near 762nm. The major challenges are the collisional dephasing of the atmospheric oxygen transitions and the strength of the effective magnetic dipole interaction. In addition, we will review other remote magnetometry concepts and their challenges.

9835-39, Session 8

Nonlinear guiding of high-peak power laser pulses in atmospheric turbulence (*Invited Paper*)

Joseph R. Penano, Michael H. Helle, U.S. Naval Research Lab. (United States); Gregory DiComo, Univ. of Maryland, College Park (United States); John P. Palastro, U.S. Naval Research Lab. (United States)

The utility of ultrashort laser pulses for applications, such as remote detection or atmospheric beacon beam generation, among others, depends on the ability to deliver high intensity at long ranges. Previous studies have shown that this can be difficult in the presence of strong atmospheric turbulence. When the peak-power of the laser pulse is much greater than the self-focusing power of air, and the laser spot size is large compared with the field coherence length, turbulence can seed filamentation and disrupt laser propagation. Here, we discuss a way for a high-power pulse to nonlinearly self-guide over potentially long distances through atmospheric turbulence. The concept relies on propagating a Gaussian pulse with a power slightly less than the critical self-focusing power of air to stall diffraction, and with a spot size less than the inner scale of turbulence in order to prevent turbulence-induced spreading. Under these conditions, we show that the pulse can propagate many vacuum Rayleigh lengths undergoing wander, but without appreciable spreading. The balancing of diffraction and nonlinear self-focusing is an unstable equilibrium that

determines the distance over which the pulse is guided. In situations where atmospheric extinction depletes energy from the pulse, a negative chirp can be applied to temporally compress the pulse as it propagates to maintain peak power. We analyze the problem theoretically and with 3D, time-dependent simulations of pulse propagation in turbulence. We derive expressions for the beam wander and effective transverse coherence length in the nonlinear guiding regime and compare with laboratory results in which we propagate a high-power laser pulse through artificially generated, strong turbulence and demonstrate guiding for ~ 10 Rayleigh lengths.

9835-40, Session 8

Mid-IR USPL concepts and development at NRL (*Invited Paper*)

Michael H. Helle, Joseph R. Penano, U.S. Naval Research Lab. (United States); Gregory DiComo, Research Support Instruments, Inc. (United States); John P. Palastro, Daniel F. Gordon, U.S. Naval Research Lab. (United States); Yu-hsin Chen, Research Support Instruments, Inc. (United States); Antonio Ting, U.S. Naval Research Lab. (United States)

Numerous existing and potential applications of intense ultrashort pulses require propagation through atmosphere. Air's relatively small n_2 , compared to condensed matter, means that GW's of laser power can be transmitted before the onset of nonlinear self-focusing and filamentation. While the basic science of filamentation is of great interest, the use of filaments has been limited due to maximum propagation distances of 10's meters. One possible route to increasing transmitted power is to take advantage of the wavelength scaling, λ^2 , of nonlinear self-focusing. We will discuss recent and ongoing investigations of NIR and MWIR ultrashort pulse propagation in turbulent atmosphere

At NRL, we have constructed a continuously tunable, indoor turbulence range for studying the propagation of ultrashort pulse lasers (USPL) through distributed atmospheric turbulence. We used a Laser Inner Scale and Scintillation Diagnostic (LISSD) and a commercial scintillometer to characterize this range. Experimentally we were able to reliably generate conditions of distributed turbulence with characteristic Cn_2 values ranging from 10^{-16} - 10^{-12} m^{-2/3}. Results were obtained that show ultrashort pulses are able to self-guide through turbulent atmosphere. These results were obtained using our kHz Ti:Sapphire laser system (5mJ, 35fs, 800nm). Propagation results characterizing nonlinear guiding at 800nm will be discussed. Additionally, initial experiments on wavelength scaling will also be presented using our newly upgraded 20mJ kHz system. This new system has an OPA extension that is capable of tunably producing ultrashort pulses ranging from 1.14-2.6 μ m with a maximum energy of 5mJ at 1.6 μ m.

9835-41, Session 9

Nonlinear optical phenomena in semiconductors induced by strong terahertz waves (*Keynote Presentation*)

Koichiro Tanaka, Kyoto Univ. (Japan)

The coherent nonlinear interaction of intense electric fields with electronic transitions in semiconductors exhibits intriguing nonperturbative phenomena. Exciton in semiconductors, which is a hydrogen-like bound state of the electron-hole pair, has a binding energy of 1 - 10 THz and serves us a fascinating playground for studying extreme nonlinear optical phenomena in terahertz (THz) frequency region. It is easy to realize the highly nonperturbative regime at comparably moderate fields (~ 10 kV/cm) in THz region, where the Rabi energy and the ponderomotive energy approach the same order of magnitude as the transition energy. Here, we focus on the strong THz-field effect on electron-hole system including excitons in GaAs. Intense THz pulses were generated by optical rectification in LiNbO₃ using the tilted-pulse-intensity-front scheme. Pulse shaping enables us to prepare tunable THz light with narrow bandwidth (50 GHz - 200 GHz). THz-pump

and NIR-probe experiment elucidates the dynamical change of absorption spectrum of semiconductors under illumination of THz electric field as high as 100 kV/cm. Below 10 kV/cm, the Rabi splitting of excitonic systems in GaAs quantum wells (QW) has been clearly observed with the resonant excitation of the 1s-2p transition. The characteristic broadened spectra cannot be explained by a simple model of two-level systems under rotating wave approximation. In the higher field region as high as 50 kV/cm, strong modulation of the absorption spectrum appears even in the band-to-band transition region, such as Franz-Keldysh type spectral modulation. We will discuss the physical mechanism of the spectral modulation in time-domain.

9835-42, Session 10

Optical Stark effect in 2D semiconductors
(Invited Paper)

Edbert J. Sie, Massachusetts Institute of Technology (United States); James W. Mclver, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany); Yi-Hsien Lee, National Tsing Hua Univ. (Taiwan); Liang Fu, Jing Kong, Nuh Gedik, Massachusetts Institute of Technology (United States)

Semiconductors that are atomically thin can exhibit novel optical properties beyond those encountered in the bulk compounds. Monolayer transition metal dichalcogenides (TMDs) are leading examples of such semiconductors that possess remarkable optical properties. They obey unique selection rules where light with different circular polarization can be used for selective photoexcitation at two different valleys in the momentum space. These valleys constitute bandgaps that are normally locked in the same energy. Selectively varying their energies is of great interest for applications because it unlocks the potential to control valley degree of freedom, and offers a new promising way to carry information in next-generation valleytronics. In this proceedings paper, we demonstrate that the energy gaps at the two valleys can be shifted relative to each other by means of the optical Stark effect in a controllable valley-selective manner. We briefly discuss the physics of the optical Stark effect, and we describe the mechanism that leads to its valley-selectivity in monolayer TMD tungsten disulfide (WS₂). Finally, we review the prospects and the challenges of using this effect for applications.

9835-43, Session 10

Ultra-fast bandgap photonics in mid-IR wavelengths
(Invited Paper)

Enam Chowdhury, Kyle R. P. Kafka, Drake R. Austin, Kevin Werner, Noah Talisa, The Ohio State Univ. (United States); Boquin Ma, Communication Univ. of China (China); Cosmin I. Bлага, Louis F. DiMauro, Hui Li, Allen Yi, The Ohio State Univ. (United States)

There has been a tremendous interest in studying femtosecond laser matter interaction in mid IR wavelength ranges, because of existence of many molecular resonances in 2-10 μm wavelength range, enhancement of electron ponderomotive energy at longer wavelengths due to λ² scale [1], efficient generation of XUV attosecond pulses, imaging and detection of cancer and many other applications. Mid IR femtosecond interaction with solids are interesting in their own right for several reasons. For traditional insulators, the reduced individual photon energies at mid IR wavelengths should exhibit a transition from multiphoton to tunneling ionization, when compared to similar interactions with UV-VIS-near IR femtosecond pulses. Semiconductors like Si and Ge become transparent 'high band gap' semiconductor at mid IR wavelengths. With fluence near damage threshold, when sufficient electron population transfer into conduction band occurs and all insulators become metal-like, mid IR frequencies present an interesting paradigm, i.e. much larger ponderomotive energies of electrons (compared with near IR wavelengths) which may be very

sensitive to alignment of laser polarization direction along different lattice axes of symmetry. Interaction of such excited electrons with lattice under strong mid IR fields also led to high harmonic generation in solids, which will be discussed. As a multiple pulse laser matter interaction phenomenon, laser induced Periodic Surface Structures (LIPSS) formation from near IR to mid IR wavelengths generation will be discussed, as LIPSS carry great importance in laser micro/nano machining, surface modification applications such as solar cells, wave guides, super hydrophobic surfaces, integrated optoelectronic and optoplasmonic devices and many others [2,3]. The exact process of LIPSS generation is not completely understood [4,5]. Dynamics of the process is studied by us from femtosecond to nanosecond regime to properly understand how short lived surface field ripples can guide material movements at much longer timescale.

Along with fundamental strong field laser solid interactions in mid IR regime, novel ultrafast sources of mid IR light will also be discussed.

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9835-44, Session 10

Formation and all-optical control of optical patterns in semiconductor microcavities
(Invited Paper)

Rudolf Binder, College of Optical Sciences, The Univ. of Arizona (United States); Ming Ho Luk, The Univ. of Arizona (United States); Nai-Hang Kwong, College of Optical Sciences, The Univ. of Arizona (United States); Przemyslaw Lewandowski, Stefan Schumacher, Univ. Paderborn (Germany); Yuen Chi Tse, Ka Pang Chan, Pui Tang Leung, The Chinese Univ. of Hong Kong (Hong Kong, China); Jacqueline I. Bloch, Aristide Lemaitre, Lab. de Photonique et de Nanostructures (France); Omblin Lafont, Ctr. National de la Recherche Scientifique (France); Philippe Roussignol, Ecole Normale Supérieure (France) and Univ. Pierre et Marie Curie (France) and Univ. Paris 7-Denis Diderot (France); Emmanuel Baudin, Jérôme Tignon, Ecole Normale Supérieure (France)

Semiconductor microcavities offer a unique way to combine transient all-optical manipulation of GaAs quantum wells with the benefits of structural advantages of microcavities. In these systems, exciton-polaritons have dispersion relations with very small effective masses. This has enabled prominent effects, for example polaritonic Bose condensation, but it can also be exploited for the design of all-optical communication devices. The latter involves non-equilibrium phase transitions in the spatial arrangement of exciton polaritons.

We consider the case of optical pumping with normal-incidence, yielding a spatially homogeneous distribution of exciton-polaritons in the semiconductor quantum wells. Exciton-exciton interactions allows for four-wave mixing processes, which can exhibit instabilities if certain threshold

behavior requirements are met. Such instabilities can lead, for example, to the spontaneous formation of hexagonal polariton lattices (corresponding to six-spot patterns in the far field), or to rolls (corresponding to two-spot far field patterns). The orientation of the roles can be manipulated for example through small built-in anisotropies, or through (weak) optical control fields that act as seeds. We discuss our recent efforts to model these systems using a microscopic many-body theory as well as simplified population-competition models. We also present initial experimental results.

The concept of all-optical switching at low power levels involves two different two-spot far field patterns that can be regarded as two states of the switch: one state that emerges as a consequence of a small built-in anisotropy, and the other that is obtained through a weak seed pulse. The switching between the two states is reversible.

9835-60, Session 10

Effect of high-optical excitation on the ultrafast electron dynamics in stacked-monolayer graphene samples (*Invited Paper*)

Juan A. Castañeda, Bernardo B. C. Kyotoku, Univ. Estadual de Campinas (Brazil); Henrique Guimarães Rosa, UPM (Brazil); Carlos Henrique Brito-Cruz, Univ. Estadual de Campinas (Brazil); Jose C. V. Gomes, National Univ. of Singapore (Singapore); Eunezio Antonio Thoroh de Souza, UPM (Brazil); Hugo L. Fragnito, UNICAMP (Brazil); Lazaro A. Padilha, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

No Abstract Available

9835-45, Session 11

A new look at an old problem: How fast can an insulator turn into a metal? (*Keynote Presentation*)

Hermann A. Dürr, SLAC National Accelerator Lab. (United States)

One of the great drivers for understanding the spectacular, yet complex properties of strongly correlated electron materials is the desire to ultimately transcend the use of semiconductor electronics. The need to establish speed limits for electronic switching is clearly important for technology. However, it also serves fundamental science: it enables us to disentangle competing interactions in the time domain. In this talk I will focus on the insulator-to-metal transitions in magnetite (Fe₃O₄) and vanadium dioxide (VO₂), materials where these phenomena were first discovered. A combination of femtosecond optical spectroscopy and x-ray diffraction at the Linac Coherent Light Source can be used to unravel their mechanism by separating electron and lattice dynamics. I will also show how intense THz pulses will ultimately allow us to address the feasibility of future oxide based electronics devices.

9835-46, Session 11

Ultrafast bandgap dynamics and insulator-to-metal transitions probed by time-resolved ARPES (*Invited Paper*)

Martin Wolf, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany)

Photoexcitation of insulating or semiconducting materials above the band gap leads to non-equilibrium processes on ultrafast timescales. Depending on the excitation density their dynamics are governed by exciton formation, hot carrier scattering or laser induced band gap renormalization and phase transitions. We use time- and angle-resolved photoemission spectroscopy (trARPES) to probe ultrafast insulator-to-metal transitions induced by femtosecond laser excitation of band gap materials where many-body correlation effects or strong electron-phonon coupling lead to the formation of broken symmetry ground states, e.g. charge-density waves (CDW) states with periodic lattice distortion.

For the correlated electron material VO₂, strong photoexcitation leads to a quasi-instantaneous band gap collapse upon photo-excitation, followed by hot carrier relaxation within 200 fs. In conjunction with many body theory, these results show that the photoinduced phase transition is caused by doping of the valence band with photoholes, leading to an significantly enhanced screening of the Coulomb interaction and a drastic band gap renormalization [1]. Furthermore, we have studied the ultrafast dynamics of the electronic structure during photo-induced phase transition in the charge-density wave compounds TbTe₃, DyTe₃ and TiSe₂. Using trARPES we can directly map the transient changes of the Fermi surface and the dynamics of opening and closing of the CDW gap [2]. For TiSe₂ we find an unusual binding energy dependence of the relaxation rate back to the CDW phase and scaling like the imaginary part of a model self-energy. This is identified as a signature of strong electron-hole scattering driving the electronic instability in phase transition in TiSe₂ [3].

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9835-47, Session 11

Ultrafast currents in insulators (*Invited Paper*)

Joachim Burgdörfer, Technische Univ. Wien (Austria)

We theoretically investigate the generation of ultrafast currents in insulators induced by strong few-cycle laser pulses.

Ab initio simulations based on time-dependent density functional theory give insight into the atomic-scale properties of the induced current signifying a femtosecond-scale insulator-metal transition. We observe the transition from nonlinear polarization currents during the laser pulse at low intensities to tunnellinglike excitation into the conduction band at higher laser intensities. At high intensities, the current persist after the conclusion of the laser pulse considered to be the precursor of the dielectric breakdown on the femtosecond scale. We find evidence that the broken inversion symmetry in a transparent dielectric (SiO₂) gives rise to a nonlinear generalization of the photogalvanic effect. Most surprisingly, the direction of the current undergoes a sudden reversal above a critical threshold value of laser intensity $I_c \sim 3 \times 10^{13} \text{ W/cm}^2$. We trace this switching to the transition from nonlinear polarization currents to the tunnelling excitation regime. The latter is found to be sensitive to the relative orientation between laser polarization and chemical bonds. We demonstrate control of the ultrafast currents by the time delay between two laser pulses. The current control by the nonlinear photogalvanic effect is found to be remarkably robust and insensitive to laser-pulse shape and carrier-envelope phase.

Work in collaboration with I. Floss, G. Wachter, C. Lemell, S. Sato, X. Tong, K. Yabana

9835-48, Session 11

Ultrafast nano-infrared study of the ultrafast insulator-to-metal transition in vanadium dioxide *(Invited Paper)*

Aaron Sternbach, Univ. of California, San Diego (United States); Mengkun Liu, Stony Brook Univ. (United States); James Hinton, Univ. of California, San Diego (United States); Tetiana Slusar, Electronics and Telecommunications Research Institute (Korea, Republic of); Alexander S. McLeod, Martin Wagner, Univ. of California, San Diego (United States); Elsa Abreu, ETH Zürich Institute of Quantum Electronics (Switzerland); Ruben Iraheta, Univ. of California, San Diego (United States); Fritz Keilmann, Ludwig-Maximilians-Univ. München (Germany); Alfred Leitenstorfer, Univ. Konstanz (Germany); Michael M. Fogler, Univ. of California, San Diego (United States); Hyun Tak Kim, Electronics and Telecommunications Research Institute (Korea, Republic of); Richard D. Averitt, Dmitri N. Basov, Univ. of California, San Diego (United States)

We have devised and implemented the technique of time resolved scanning near-field optical microscopy to study the inhomogeneous development of a phase transition in the time domain with 20 nanometer spatial resolution and 100 femtosecond temporal resolution. The subject of our study is Vanadium Dioxide, which is a canonical correlated electron system that exhibits an insulator to metal transition. We observe an abrupt rise in the photoconductivity at several hundred femtoseconds followed by a slow rise, which takes place on the order of several hundred picoseconds. Our measurement resolves the rise time of the IMT in individual sites; we further observe inhomogeneous dynamics that are dependent on local strain. Our results pave the way for studying a plethora of systems where phase transitions involve inhomogeneities and phase separation.

9835-49, Session 11

Theoretical description of pump/probe experiments in nesting induced charge density wave insulators *(Invited Paper)*

James Freericks, Oleh Matveev, Georgetown Univ. (United States); Andrij M Shvaika, Institute for Condensed Matter Physics of NAS of Ukraine (Ukraine); Thomas P. Devereaux, Stanford Institute for Materials & Energy Sciences (United States) and SLAC National Accelerator Lab. (United States)

In this work we examine the solutions for two models of charge density wave ordering. The first is a simple band insulator with a checkerboard pattern for the site energy, which is a noninteracting system that can be solved exactly. The second is the spinless Falicov-Kimball model in the ordered phase, which is the simplest model of a strongly correlated electron-driven charge density wave insulator. This system is particularly interesting because it has a quantum tricritical point where weakly correlated ordered phases, metallic phases, and strongly correlated phases all coexist. The time resolved photoemission is solved by examining the nonequilibrium dynamical mean-field theory solution, which provides an exact solution for both cases, subject to only the numerical accuracies of the associated algorithms used to solve them. We will study how the gap closes and how the order parameter behaves in these systems as a function of the pump fluence and the pulse duration. Contact will be made to relevant experiments wherever it is feasible. In particular, these calculations show how the gap can be suppressed, and only recover over some moderate

time-frame, even if the order parameter remains nonzero. Calculations are performed on parallel high performance computers with efficient algorithms that scale to thousands of processors.

9835-50, Session 12

Higgs mode excitation in superconductors by intense terahertz pulse *(Invited Paper)*

Ryusuke Matsunaga, Ryo Shimano, The Univ. of Tokyo (Japan)

Recent development of intense terahertz (THz) pulse generation technique has offered novel opportunities to reveal ultrafast phenomena in a variety of materials on tabletop experiments and provided a new pathway toward the ultrafast control of quantum matter. Here we present our recent study of nonequilibrium dynamics in metallic superconductors NbTiN excited by intense THz wave. The superconducting gap energy, which can be viewed as an order parameter, is located in the THz frequency range. So the strong THz pulse excitation makes it possible to instantaneously excite high-density quasiparticles at the gap edge without injecting excess energies. Further, it has become possible to coherently drive the superconducting ground state without exciting incoherent quasiparticles by tuning the photon energy below the gap. The ultrafast dynamics of the order parameter induced by such an intense low energy excitation is directly probed by weaker THz pulse, and the nature of a collective excitation, namely the Higgs amplitude mode is revealed. Efficient THz higher-harmonic generation from a superconductor is discovered, manifesting the nonlinear coupling between the THz wave and the Higgs mode. We will also report the experimental results for plural collective modes in a multi-gap superconductor MgB₂.

9835-51, Session 12

Femtosecond terahertz dynamics of cooperative transitions: from charge density waves to polariton condensates *(Invited Paper)*

Michael Porer, Paul Scherrer Institut (Switzerland) and Univ. of Regensburg (Germany); Jean-Michel Menard, Christoph Poellmann, Univ. Regensburg (Germany); Hatem Dachraoui, Univ. Bielefeld (Germany); Leonidas Mouchliadis, Ilias E. Perakis, Univ. of Crete (Greece); Ulrich Heinzmann, Univ. Bielefeld (Germany); Jure Demsar, Johannes Gutenberg Univ. Mainz (Germany); Kai Rosnagel, Christian-Albrechts-Univ. zu Kiel (Germany); Elisabeth Galopin, Aristide Lemaître, Alberto Amo, Jacqueline I. Bloch, Lab. de Photonique et de Nanostructures (France); Rupert Huber, Univ. Regensburg (Germany)

In complex solids, spontaneously broken symmetries often result in coupled order parameters that coexist [1]. Thus the driving mechanisms of some of the most fascinating phase transitions, such as stripe formation, unconventional superconductivity or colossal magnetoresistance have remained elusive. Ultrafast light pulses can now prepare non-equilibrium states whose dynamics provide insight into the interplay between electronic, spin, and lattice orders. In the first experiment reported here, we demonstrate a qualitatively new non-thermal phase transition for an intriguing example of a charge density wave (CDW) – a static modulation of the conduction electron density accompanied by a periodic lattice distortion (PLD). With 12-femtosecond optical pulses, we perturb the CDW in the transition metal dichalcogenide 1T-TiSe₂. The subsequent non-adiabatic dynamics is probed with ultrafast terahertz spectroscopy tracing PLD-induced phonons, optical conductivity of free charge carriers and spectral fingerprints of the CDW-induced correlation gap. We observe a transient

non-thermal state of the system in which the PLD persists in a coherently excited state while the exciton-like electronic order is quenched [2]. This proves that excitons are not the sole driving force of the CDW transition in 1T-TiSe₂, thus resolving a long-standing mystery.

Spectacular phenomena such as superfluidity or superconductivity are caused by Bose-Einstein condensation. The internal structure of such quantum fluids formed by elementary excitations has remained largely elusive, though important information on the nature and dynamics of the condensing quasiparticles may be encoded therein. For the prominent example of exciton-polaritons, photons hybridized with hydrogen-like bound electron-hole pairs, only the photon component of the condensate has been resolved [3], while the exact role of the excitons remains unclear. In the second experiment discussed here, we demonstrate that ultrafast terahertz spectroscopy can trace the matter component of condensing polaritons. By monitoring intra-excitonic terahertz transitions, we study how a reservoir of optically dark excitons forms and feeds the degenerate condensed phase. Unlike in atomic gases, the atom-like transition in excitons is dramatically renormalized upon macroscopic ground state population. Our results prove the macroscopic population of the ground state and establish differences between polariton condensation and photon lasing [4], opening a new access to macroscopic wavefunctions.

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9835-52, Session 12

Phase coherence and pairing amplitude in photo-excited superconductors (*Invited Paper*)

Luca Perfetti, Ecole Polytechnique (France); Christian Piovera, Laboratoire des solides Irradiés, Ecole Polytechnique (France); Zailan Zhang, Institut de Minéralogie et de Physique des Milieux Condensés, Sorbonne University (France)

I will present time resolved photoelectron spectroscopy data of La₂V₂S₃ and of high temperature superconductor Bi₂Sr₂CaCu₂O_{8-x}. The misfit compound La₂V₂S₃ is insulating up to high temperatures although band structure calculations predict a finite density of the electronic states at the chemical potential. The breakdown of the Fermi liquid theory is monitored in the reciprocal space by angle resolved photoelectron spectroscopy. It follows that La₂V₂S₃ holds a pseudogap which scales as the incommensurate V-V distortion of the VS₂ layers. Upon photoexcitation, the electronic states relax energy in to phonon modes and the pseudogap is partially filled. In contrast to charge density wave compounds, the observed dynamics is faster than 80 fs. We ascribe the sudden melting of the pseudogap to the strong electron-phonon coupling of the aperiodic V-V potential.

New data on Bi₂Sr₂CaCu₂O_{8-x} reveal interesting aspects of photoexcited superconductors. The electrons dynamics show that inelastic scattering by nodal quasiparticles decreases when the temperature is lowered below the critical value of the superconducting phase transition. This drop of electronic dissipation is astonishingly robust and survives to photoexcitation densities much larger than the value sustained by long-range superconductivity. The unconventional behavior of quasiparticle scattering is ascribed to superconducting correlations extending on a length scale comparable to the inelastic mean-free path. Our measurements indicate that strongly driven superconductors enter in a regime without phase coherence but finite pairing amplitude. The latter vanishes near to the critical temperature and has no evident link with the pseudogap observed by Angle Resolved Photoelectron Spectroscopy.

9835-53, Session 13

Electronic and structural response of materials to fast intense laser pulses, including light-induced superconductivity (*Keynote Presentation*)

Roland E. Allen, Texas A&M Univ. (United States)

This talk will review experimental and theoretical studies of materials responding to fast intense laser pulses, with heavy emphasis on those cases where the electronic response and structural response are both potentially important (and ordinarily coupled). Examples are nonthermal insulator-to-metal transitions and light-induced superconductivity in cuprates, fullerenes, and an organic Mott insulator.

9835-54, Session 14

Controlling superconductivity with light (*Invited Paper*)

Michael Först, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany)

Solids with strongly correlated electrons are those, in which the Coulomb interactions between charge carriers dominate the energy landscape, rather than being perturbations to the kinetic energies. Hence, the familiar concepts of band theory and classical magnetism fail to describe their macroscopic properties. One remarkable consequence is that even if the number of electrons per unit cell is fractional, these solids can be insulating. Furthermore, strongly correlated electron systems can exhibit very surprising properties, such as high-temperature superconductivity in copper-oxide ceramics or colossal magneto-resistance in the manganites.

Our group aims to use coherent low-energy light fields to manipulate the crystal lattice in these materials in order to control the macroscopic properties dynamically. The overarching goal is to induce new phenomena and functionalities. How can light control electrical and optical properties in these compounds? Can it be used to control magnetic order without delivering helicity? Most exotically, can light be used to induce superconductivity above equilibrium critical temperatures?

By using light and by watching the evolving properties using ultrafast optical and x-ray probes, we seek to understand the important aspects of the underlying physics of this dynamic phase control.

9835-55, Session 14

Stimulation and engineering of quantum phases by time-dependent optical perturbations (*Invited Paper*)

Victor Galitski, Univ. of Maryland, College Park (United States)

I will review our theory work and related experimental developments on dynamic stimulation of various quantum states by optical perturbations. A key idea here is that the thermal distribution (“non-negotiable” in equilibrium) is rarely optimal for the occurrence of a given quantum state and dynamic perturbations can be used to change the distribution and enhance the underlying state. I will show how both Cooper pairing and phase coherence can be dynamically enhanced in conventional and high-temperature superconductors, as well as cold atom superfluids. In the second part of my talk, I will discuss periodic-in-time (Floquet) perturbations induced by light that can be used to engineer electronic band structure at will in solid-state materials, enabling exotic quantum states to exist.

9835-56, Session 14

Excitation of coherent oscillations in underdoped cuprate superconductors *(Invited Paper)*

Matthias C. Hoffmann, SLAC National Accelerator Lab. (United States); Wei-Sheng Lee, SLAC National Accelerator Lab. (United States) and Stanford Univ. (United States); Georgi L. Dakovski, Joshua J. Turner, SLAC National Accelerator Lab. (United States); Simon M. Gerber, Paul Scherrer Institut (Switzerland); Doug Bonn, Department of Physics and Astronomy, University of British Columbia (Canada); Walter N Hardy, Department of Physics and Astronomy, University of British Columbia (Canada) and SLAC National Accelerator Lab (United States); Marco Salluzzo, CNR-INFM and Dipartimento di Scienze Fisiche, Università di Napoli (Italy); Ruixing Liang, Department of Physics and Astronomy, University of British Columbia (Canada)

Low-energy single-particle and collective excitations play a crucial role in understanding the properties of matter, especially in the formation of exotic ground states such as superconductivity (SC) and spatially-modulated e.g. charge density waves (CDW). Recent advances in the generation of strong field THz pulses permit to directly and selectively drive low-energy modes in solid-state systems out of equilibrium. This is in stark contrast to relying on photoexcitation using femtosecond laser pulses with photon energies >1 eV, well above the band gap, obscuring the subtle effects in the low energy (meV) regime. Here we explore this selectivity by exciting underdoped YBa₂Cu₃O_{6.5} (YBCO) and NBCO with strong single-cycle broadband THz pulses, while monitoring the response on the femtosecond time scale via the change in reflectivity in the near-infrared range. YBCO, part of the 123 family of high-temperature cuprate superconductors, has recently received a great deal of attention primarily due to the observation of a quasi-two-dimensional CDW forming at about 150K in underdoped samples, and appearing to compete with SC below T_c. The microscopic mechanism of how this CDW form still remains elusive. More importantly, whether this CDW state is simply competing or intertwined with SC in a more complex way require further investigation. Revelation of its collective excitations could shed some lights on these issues.

9835-57, Session 14

THz field control of orbital order in manganites *(Invited Paper)*

Simon Wall, Timothy Miller, ICFO - Institut de Ciències Fotòniques (Spain); Ravindra W. Chhajlany, ICFO - Institut de Ciències Fotòniques (Spain) and Adam Mickiewicz Univ. (Poland); Maciej Lewenstein, ICFO - Institut de Ciències Fotòniques (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain); Michael Gensch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

We study how domains of orbital order in the prototypical layered manganite La_{0.5}Sr_{1.5}MnO₄ can be controlled by the polarization of THz light pulses. We measure orbital order through the optical anisotropy the domains generate. THz fields are generated by a Free Electron Laser with a pulse duration of 10s ps and at 13 MHz repetition rate. The field passes through a THz waveplate, which is used to rotate the polarization of the light. When the field polarization is aligned to one of the domain directions, an increase in the optical anisotropy is observed, and when the field is rotated to lie along the opposite domain the direction of the anisotropy is also rotated.

We measure the full temperature dependence of the effect and find that the

domain control is absent above the ordering temperature (i.e. there are no domains to control) but increases rapidly once orbital order forms. However, once magnetic correlations occur the ability to control domains is reduced.

We can explain this effect by considering the response of a quantum material to an applied electric field. The THz field pushes localized charges towards neighbouring occupied sites. Due to the strong onsite Coulomb interaction, this generates an energy penalty, which can be reduced if the orbital domain rotates. This picture is confirmed by 4-th order perturbation theory of a simple Hamiltonian that can capture the basic physics of the manganites.

9835-58, Session 14

Ultrafast magnetism of ferrimagnetic oxides driven by electronic and phononic excitations *(Invited Paper)*

Ilie E. Radu, Technische Univ. Berlin (Germany) and Helmholtz-Zentrum Berlin (Germany); Sebastian Mährlein, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Radu Abrudan, Ruhr-Univ. Bochum (Germany); Torsten Kachel, Helmholtz-Zentrum Berlin (Germany); Clemens von Korff Schmising, Technische Univ. Berlin (Germany); Alexander Paarmann, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Michael Gensch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Pablo Maldonado, Uppsala Univ. (Sweden); Roman V. Pisarev, Ioffe Physical-Technical Institute (Russian Federation); Stefan Eisebitt, Technische Univ. Berlin (Germany); Martin Wolf, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Peter M. Oppeneer, Uppsala Univ. (Sweden); Tobias Kampfrath, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany)

Using light to control the magnetic order parameter on ultimate time and length scales is a core research activity of modern magnetism [1]. Of particular interest for both fundamental and applied science is the use of femtosecond (fs) laser pulses to fully switch the magnetization orientation of a spin ensemble on ultrashort time scales [2,3].

Recent time-resolved XMCD investigations of ferrimagnetic GdFeCo alloys revealed the existence of a transient ferromagnetic state mediating the ultrafast magnetization switching of antiferromagnetically coupled Fe and Gd spins [2]. In a following study, the transient state was shown to drive a novel magnetization reversal mechanism where spin switching is purely thermal, i.e. without using any magnetic field [3]. Although groundbreaking, these experiments leave open several intriguing questions on the microscopic mechanism of the ultrafast magnetization reversal in the ferrimagnetic compounds. For instance, how does the symmetry and strength of the exchange interaction affect the magnetization switching process? What is the role of the electronic structure of the host material, i.e. going for instance from a metallic to an insulating host? Can we employ different quasiparticles (other than electronic excitations) to efficiently photo-drive the spin switching process?

Here, we present two novel research approaches that address these topics by studying insulating ferrimagnetic garnets (as e.g. Ho₃Fe₅O₁₂ and Y₃Fe₅O₁₂) upon:

1. a strong, delocalized photo-excitation of the electronic and spin sub-systems and fs X-ray probing of the constituent magnetic elements
2. a direct and resonant excitation of the phonon subsystem by using mid-IR laser radiation and magneto-optical probing in visible spectral range

In these garnets the ferrimagnetic coupling between the Fe species (i.e. Fe³⁺ ions with tetrahedral and octahedral coordination) and between Fe and the rare earth (Ho) sublattices is mediated by super-exchange interaction over the oxygen anions. Thus, by monitoring the laser-driven spin and electron dynamics in an element- and site-specific manner we obtained,

for the very first time, a direct view on the dynamics of the exchange interaction itself during the magnetization-switching event. Possible implications for the magnetic switching phenomena in ferrimagnetic alloys and heterostructures will be discussed.

In the second study, we reveal a novel pathway for ultrafast demagnetization of spin-ordered solids by resonant excitation of their crystal lattice, which leaves the electronic sub-system unaffected. In particular, by exciting the Fe-O asymmetric stretch vibration in Y3Fe5O12 using intense mid-IR pulses, we are able to demagnetize the sample within 21 ps. Given the long spin-lattice relaxation times in Y3Fe5O12 (hundreds of ns up to microseconds), such a phonon-driven demagnetization process is surprisingly fast, indicating a highly efficient non-equilibrium energy transfer between the optical phonons and spins.

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9835-59, Session 14

Controlling magnetism by ultrashort laser pulses: from fundamentals to nanoscale engineering (*Invited Paper*)

Theo Rasing, Radboud Univ. Nijmegen (Netherlands)

From the discovery of sub-picosecond demagnetization over a decade ago to the recent demonstration of magnetization reversal by a single 40 femtosecond laser pulse, the manipulation of spins by ultra short laser pulses has become a fundamentally challenging topic with a potentially high impact for future spintronics, data storage and manipulation and quantum computation [1]. The realization that femtosecond laser induced all-optical switching (AOS) as observed in ferrimagnets exploits the laser induced strongly non-equilibrium dynamics and the antiferromagnetic exchange interaction between their sublattices [2-4], opens the way to engineer new magnetic materials for AOS [5,6], though for real applications nanoscale control of inhomogeneities appears to be relevant [7]. We have recently demonstrated that in dielectric materials, the exchange interaction can directly be manipulated by a fs laser pulse, opening up a new and more energy efficient way of manipulating magnetic order [8]. We have also discovered a conceptually new approach for ultrafast modulation of the magneto-optical response of a magnetic dielectric, based on the interaction between pump and probe in the medium. Another challenge is how to bring the optical manipulation of magnetic media to the required nanoscale, which may be possible using plasmonic or wave-shaping techniques [9]. Recent results with engineered hybrid magnetic materials and nanofocusing [10] will be discussed, showing the practical potential of AOS.

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9835-61, Session 14

Contributions from coherent and incoherent lattice excitation to ultrafast optical control of magnetic anisotropy of metallic films (*Invited Paper*)

Vladimir N. Kats, Ioffe Physical-Technical Institute (Russian Federation); Tatiana N. Linnik, V.E. Lashkaryov Institute of Semiconductor Physics (Ukraine); A. S. Salasyuk, Ioffe Physical-Technical Institute (Russian Federation); Andrew W. Rushforth, The Univ. of Nottingham (United Kingdom); Mu Wang, Univ. College London (United Kingdom); Peter Wadely, The Univ. of Nottingham (United Kingdom); Andrey V. Akimov, The Univ. of Nottingham (United Kingdom); Stuart Cavill, The Univ. of York (United Kingdom); V. Holy, Charles Univ. in Prague (Czech Republic); Alexandra M. Kalashnikova, Alexey V. Scherbakov, Ioffe Physical-Technical Institute (Russian Federation)

Changing magnetic anisotropy, which originates from spin-lattice coupling, by femtosecond laser pulses is a very efficient way to control magnetic state of matter on a (sub)picosecond time scale. Clearly, optically-induced generation of collective excitations of lattice, or phonons, paves a way towards such a control. Here we examine experimentally and phenomenological, how coherent and incoherent phonons contribute to control of the magnetic anisotropy in the optically excited [1].

By monitoring optically triggered magnetization precession in 100 nm thick film of magnetostrictive metallic alloy Galfenol Fe81Ga19 grown on a low symmetry 311-GaAs substrate we distinguish two competing contributions to ultrafast changes of magnetic anisotropy. Absorption of laser pulse energy results in an increase of lattice temperature on a picoseconds time scale, also seen as incoherent phonons generation. They give rise to changes of the magnetic anisotropy parameters, as has been extensively explored earlier. However, we show that dynamical strain, i.e. coherent acoustic phonons, accompanying ultrafast lattice heating, may also effectively contribute to the anisotropy change at direct optical excitation. Furthermore, we demonstrate the regime when the coherent acoustic phonons govern the excitation of magnetization precession in optically excited magnetic metallic film. Importantly, an unambiguous distinction between coherent and incoherent phonon contributions to the optically induced magnetic anisotropy changes becomes possible due to the low symmetry of the Galfenol film under study.

Conference 9836: Micro- and Nanotechnology Sensors, Systems, and Applications VIII

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9836-1, Session 1

Current best estimates of planet populations (*Invited Paper*)

Leslie A. Rogers, Univ. of California, Berkeley (United States) and The Univ. of Chicago (United States)

Exoplanets are revolutionizing planetary science by enabling statistical studies of a large number of planets. Empirical measurements of planet occurrence rates inform our understanding of the ubiquity and efficiency of planet formation, while the identification of sub-populations and trends in the distribution of observed exoplanet properties provides insights into the formation and evolution processes that are sculpting distant Solar Systems. In this talk, I will review the current best estimates of planet populations. I will focus in particular on *eta*_Earth, the occurrence rate of habitable zone rocky planets, since this factor strongly influences the design of future space based exoplanet direct detection missions.

9836-2, Session 1

Optical interferometric observations of GEO satellites: an update (*Invited Paper*)

Sergio R. Restaino, J. Thomas Armstrong, Ellyn K. Baines, Henrique R. Schmitt, James H. Clark, U.S. Naval Research Lab. (United States)

We describe multi-baseline observations of a geostationary satellite using the Navy Precision Optical Interferometer (NPOI) during the glint season of March 2015. We succeeded in detecting DirecTV-7S with an interferometer baseline length of 8.8 m on two nights, with a brief simultaneous detection at 9.8 m baseline length on the second night. These baseline lengths correspond to a resolution of ~ 4 m at geostationary altitude.

This is the first multiple-baseline interferometric detection of a satellite.

9836-3, Session 1

Application-driven computational imaging (*Invited Paper*)

Scott McCloskey, Honeywell Automation & Control Solutions (United States)

Computational imaging has become increasingly pervasive in recent years, delivering new functionality to mobile cameras with traditional optical designs and increasing re-thinking the entire opto-mechanical concept of a camera. Several computational cameras (Lytro, light, etc.) have recently been marketed to various segments of the consumer photography market, where the objective is to capture an aesthetically pleasing image in order to engage photographers. Compared to traditional cameras, computational cameras require significantly more image processing, and are thus hard to incorporate in embedded industrial devices with slower – and fewer – processing cores. However, the goal of aesthetic perfection is often beyond the needs of industrial imaging. In many such systems, the image is only ever ‘seen’ by a downstream recognition algorithm which has some level of robustness to defocus, noise, color imperfections, etc. Once the corresponding image quality thresholds are satisfied, any processing which further improves the image quality is, in the industrial imaging domain, wasted effort. So, for industrial imaging applications, there exists a novel optimization problem: how do we produce, using the least amount of

computation possible, a processed image that is just above the relevant thresholds for recognition?

In addition to motivating and explaining these tradeoffs, this talk considers the specific case of light field imaging (using the Lytro camera hardware), which uses a microlens array to capture the photon count associated with a large aperture while preserving the wide depth of field associated with a small one. We show that, by quantifying the recognition algorithm’s robustness to defocus and exposure, we can reduce the computational complexity of the refocusing operation by more than 90%.

9836-4, Session 1

Applications of high-temperature and multispectral imaging for improving industrial efficiency (*Invited Paper*)

Sharath Venkatesha, Wing Kwong Au, Honeywell Automation & Control Solutions (United States)

High temperature imaging systems enable continuous monitoring of industrial furnaces. Fast and accurate estimation of 3D radiance field within an enclosure allows real time control to improve or maintain process efficiency. Traditional flame field reconstruction methods use a three-color imaging with the assumption that the cameras can capture the full spectrum. However, a poor dynamic range results in inaccurate intensity-temperature transformation. We perform an extended temperature range mapping using a color HDR camera with multiple imager parameter settings and/or multi spectral imaging device. We also account for the dynamic nature of the flame by effectively combining multiple frames. Our system also extends the state-of-art methods by using multi-resolution radiance field estimation to improve system performance.

Multi-spectral imagers are also used to estimate the combustion efficiency of flue gases emitted from an industrial flare stack. Monitoring a flare stack is essential to detect the boundary of a flame and estimate the amount of unburnt hydrocarbons (UHCs). Infrared thermal imaging cameras obviously provide better reliability over color cameras, but it is essential to capture the flare data using narrow bands of LWIR/MWIR to perform species detection. Our system uses a filter wheel in combination with a LWIR camera. A HDR camera also adds information from visible domain and helps in detection of black smoke. The system is designed to work in harsh environmental conditions and work from extended distances from the flare stack, up to 500 feet.

9836-5, Session 2

Technological challenges on the path to discovery in astrophysics (*Keynote Presentation*)

Mario R. Perez, NASA Headquarters (United States)

Over the next decade, NASA’s Astrophysics Division expects to undertake space flight missions that will explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions; missions that will study how galaxies and stars formed and evolved to shape the universe we see today; and missions that will search out and characterize the planets and planetary systems orbiting other stars. Nevertheless, as compelling as these future missions will be, implementing them presents many daunting technological challenges. To overcome these challenges and pave the way to ever more ambitious missions, NASA’s Astrophysics Division established the Strategic Astrophysics Technology (SAT) program to support the

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maturation of key technologies to the point at which they are feasible for implementation in space flight missions. In this talk, the SAT program will be presented describing the process to establish priorities, the technology management components and the efforts to move these technologies into mission concepts and flight missions.

9836-6, Session 2

Extreme metamaterials (*Invited Paper*)

Nader Engheta, Univ. of Pennsylvania (United States)

The fields of condensed matter physics and nanoscience have seen fascinating development in recent years. As a result, construction and synthesis of composite materials with unusual parameter values have now become a reality, providing exciting platforms for unconventional light-matter interaction. In my group, we are exploring some of these extreme scenarios, such as structures with effective near-zero permittivity, near-zero permeability, and near-zero refractive index offering extreme features such as very high phase velocity, very low energy velocity, extremely thin (one-atom-thick) metasurfaces, nanoscale computation in optical nanocircuits, extreme anisotropy, subwavelength nonreciprocal vortexes, giant nonlinearity in phase-change dynamics, “static optics”, and more. These “extreme metamaterials” platforms provide us with unprecedented features and functionalities in wave interaction in devices and components. In this talk, I will give an overview of some of these features, and discuss some of the opportunities and challenges in this area.

9836-7, Session 2

Gallium nitride electro-acoustic devices and acoustic metamaterials (*Invited Paper*)

Mina Rais-Zadeh, Univ. of Michigan (United States)

In recent years, we have witnessed rapid advancement of electromagnetic metamaterials. Inspired by the same concept, acoustic metamaterials are a class of acoustic devices that are engineered such that they exhibit properties not yet found in nature. Gallium nitride, being one of a few piezoelectric semiconductors with low acoustic loss is a perfect material for implementing acoustic metamaterials and for use in electro-acoustic applications. Interactions of electrons and phonons are facilitated by the piezoelectric effect in addition to the deformation coupling (normally occurring in non-piezoelectric semiconductors) in gallium nitride, a property that can be used to implement a variety of very interesting devices and metamaterials, such as resonant transistors and oscillators, acoustic amplifiers, circulators, couplers, and even phonon diodes. Successful implementation of this new class of devices requires materials that can be engineered to deliver sound waves in a uni-direction. Non-reciprocity and uni-directional sound transmission can be achieved using acoustoelectric effect, which is most dominantly seen in gallium nitride, a piezoelectric semiconductor. One-way transmission of sound is otherwise not possible through non-engineered materials, surfaces, or structures. This talk covers theoretical basis of such devices and overviews recent advances in gallium nitride-based electro-acoustics and acoustic metamaterial technology. When combined with other gallium nitride based electronics, the complete system can be a power tool used for communication, detection, and sensing applications.

9836-8, Session 2

Flat optics with dielectric metasurfaces (*Invited Paper*)

Andrei Faraon, Amir Arbabi, Yu Horie, Seyedeh Mahsa Kamali, Ehsan Arbabi, California Institute of Technology (United States)

Flat optical devices based on sub-wavelength high index dielectric structures promise to revolutionize the field of free-space optics. I discuss our work on high contrast transmitarrays and reflectarrays that enable precise control of both polarization and phase with large transmission and high spatial resolution. These structures are composed of arrays of silicon nano-posts located on top of a low index substrate like silica glass or transparent polymers. Complete control of both the phase and polarization of light is achieved at the level of single silicon nano-post, which enables sampling of the optical wavefront with sub-wavelength spatial resolution. We demonstrate high numerical aperture lenses, high performance waveplates and polarizers. Devices operating simultaneously at different wavelengths are demonstrated. Ultra-thin optical elements integrated on flexible substrates are fabricated and characterized. Multiple flat optical elements are integrated in optical systems such as planar retro-reflectors and Fourier lens systems. New functionalities enabled by flat optical components and the prospects for tunable devices are discussed.

9836-9, Session 2

Materials by design: using architecture and nanomaterial size effects to attain unexplored material property spaces (*Invited Paper*)

Julia R. Greer, Lucas R. Meza, Arturo Mateos, Victoria Chernow, Xiaoxing Xia, Rachel Lionats, California Institute of Technology (United States)

Creation of extremely strong yet ultra-light materials can be achieved by capitalizing on the hierarchical design of 3-dimensional nano-architectures. Such structural meta-materials exhibit superior thermo-mechanical properties at extremely low mass densities (lighter than aerogels), making these solid foams ideal for many scientific and technological applications. The dominant deformation mechanisms in such “meta-materials”, where individual constituent size (nanometers to microns) is comparable to the characteristic microstructural length scale of the constituent solid, are essentially un-known. To harness the lucrative properties of 3-dimensional hierarchical nanostructures, it is critical to assess mechanical properties at each relevant scale while capturing the overall structural complexity.

We present the fabrication of 3-dimensional nano-lattices whose constituents vary in size from several nanometers to tens of microns to millimeters. We discuss the deformation and mechanical properties of a range of nano-sized solids with different microstructures deformed in an in-situ nanomechanical instrument. Attention is focused on the interplay between the internal critical microstructural length scale of materials and their external limitations in revealing the physical mechanisms which govern the mechanical deformation, where competing material- and structure-induced size effects drive overall properties.

We focus on the deformation and failure in metallic, ceramic, and glassy nano structures and discuss size effects in nanomaterials in the framework of mechanics and physics of defects. Specific discussion topics include: fabrication and characterization of hierarchical 3-dimensional architected meta-materials for applications in biomedical devices, ultra lightweight batteries, and damage-tolerant cellular solids, nano-mechanical experiments, flaw sensitivity in fracture of nano structures.

9836-10, Session 3

Integrated photonics for electronic warfare (*Keynote Presentation*)

Nicole DiLello Heidel, Josh Conway, Defense Advanced Research Projects Agency (United States)

The last decade has seen a steady decline in DARPA investment in photonics microsystems for defense. This talk will explore the source of decline and how advanced integration is enabling new capabilities and renewed investment. (Approved for Public Release, Distribution Unlimited.)

9836-11, Session 3

Using narrow-linewidth lasers for rapidly tunable microwave signal generators
(Invited Paper)

John E. Bowers, Tin Komljenovic, Jared C. Hulme, Univ. of California, Santa Barbara (United States)

Narrow-linewidth lasers are a key component of photonic microwave signal generators, as the width of the generated RF signal is equal to the beat note of used lasers. Heterogeneous silicon photonics platform opens up a possibility of improving the coherence of fully integrated photonic microwave generators by providing means to separate the photon resonator and absorbing active medium; improving the total Q factor of the laser cavity and providing the control of the spontaneous emission into the lasing mode. Further improvement in the laser linewidth is possible by using ring resonators inside the laser cavity. Using the rings inside the cavity benefits the linewidth in two ways: (1) resonance cavity length enhancement and (2) negative optical feedback. The combined effect allows for record linewidth performance as was recently demonstrated: widely-tunable fully monolithically-integrated semiconductor lasers with 50 kHz integrated linewidths. We further theoretically predict that at least an order of magnitude better performance is achievable and that sub-kHz linewidths should be obtainable using low-loss silicon waveguide platform with -0.5 dB/cm of loss. Heterogeneous platform further complements the microwave signal generator with demonstrated high-speed modulators with 74 GHz bandwidth and detectors with 12 dBm output power at 40 GHz. The InP-based modified uni-traveling carrier photodiodes on SOI waveguides have the highest reported output power levels at multi-GHz frequencies for any waveguide photodiode technology including native InP, Ge/Si, and heterogeneously integrated photodiodes.

9836-12, Session 3

Optical components and integrated circuits for RF photonics *(Invited Paper)*

Leif A. Johansson, Steven Estrella, Jeremy Thomas, Daniel S. Renner, Milan L. Masanovic, Freedom Photonics, LLC (United States)

RF photonic systems place extremely high demands on optical component performance. To achieve this, a low noise, high power optical source, a high power, linear and low V_{π} optical modulator, sharp and uniform optical filters and high saturation power photodetectors are required. While some of these individual components exist, they have not, to date, been integrated in any currently existing monolithic or hybrid photonic integration platform. In this paper, recent advances in discrete component performance will be presented, including optical sources, modulators and detectors. In addition, options for the integration of these components onto an integrated photonic platform will be reviewed.

Freedom Photonics is currently developing high power, high wall-plug efficiency optical sources, Sub-volt V_{π} modulators and high power MUTC photodetectors. Recent results for these components will be presented. Further options and preliminary results for integrating these components on a single photonic platform will be reviewed. Approaches that will be considered are monolithic (single material system) versus hybrid integration approaches, including performance trade-offs in these approaches. Further, a brief discussion of optimal operating wavelength will be included.

9836-13, Session 4

Advanced sensors research and development for fossil energy-based electric power generation *(Keynote Presentation)*

Sydni Credle, National Energy Technology Lab. (United States)

The Crosscutting Technology Research Program (CTRP) within the U.S. Department of Energy's (DOE) National Technology Research Laboratory (NETL) is developing advanced technologies needed to achieve fossil energy-based power generation with high efficiency and lower environmental impact. Advanced components used for coal-fired power generation include industrial gas turbines, advanced combustion, gasification systems, solid oxide fuel cells, as well as carbon capture and carbon storage technologies. To support the development of these components, CTRP has an active R&D portfolio across five (5) research programs – Sensors & Controls, High-Performance Materials, Simulation-Based Engineering, Water Management R&D, and Innovative Energy Concepts. An overview of the CTRP Sensors & Controls (S&C) program will be provided. The S&C program is devoted to developing novel technologies in two research areas of Advanced Sensors and Distributed Intelligent Controls. Special emphasis will be devoted to advanced sensor development efforts for energy applications that require high-temperature (greater than 1000°C) and high-pressure (up to 1000 psi) operation as well as the ability to withstand harsh corrosive/erosive environments. The breadth of innovation supported by NETL S&C program will be presented in the form of project highlights across different sensor technologies including fiber optics, advanced materials for sensor application, embedded sensing, wireless technologies, and microsensors. Lastly, new sensors R&D initiatives for FY16 will be summarized along with perspective as to how these current efforts align with other projects in the CTRP Sensors & Controls research portfolio and also greater DOE mission goals.

9836-14, Session 4

Multi-functional fiber sensors for radiation environments *(Invited Paper)*

Kevin P. Chen, Mohamed A. S. Zaghoul, Aidong Yan, Sheng Huang, Rongzhang Chen, Univ. of Pittsburgh (United States); Ming-Jun Li, Corning Incorporated (United States)

The safe and efficient operations of nuclear reactors and various fuel cycle processes demand gathering multitude information with high spatial resolution. Fiber sensors, well known for their resilience in radiation environments have been explored for radiation environments. One of the unique traits of optical fiber sensors are their capabilities of performing high spatial resolution measurements using various distributed sensing schemes such Rayleigh, Brillouin, and Raman scattering processes. However, the reliability of distributed measurements are often undermined by permanent modification of fiber properties under radiation.

In this paper, we present a new multi-core fiber with rectangular geometry designed for distributed measurements in radiation environments. A radiation sensitive fiber core is integrated in fiber to serve as distributed calibration and measurements of radiations with high spatial resolution. Multiple fiber cores with distinct Brillouin scattering characteristics were also integrated in fiber to differentiate temperature and strain responses of the fibers in radiation environments. Using Brillouin scattering optical time-domain reflectometry, this paper report simultaneous measurements of temperature, strain, and radiation dosage with spatial resolution better than 10-cm and gamma radiations dosages up to 1 MGy. The implementation of multi-functional distributed fibers will have potential to significantly improve the safety of nuclear systems in both short and long terms.

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9836-15, Session 4

Graphene-based composite sensors for energy applications *(Invited Paper)*

Charter D. Stinespring, Saurabh Chadhari, Andrew R. Graves, Megan V. Cain, West Virginia Univ. (United States)

The objectives of this research are to develop and demonstrate the use of graphene-nanoparticle composites as a high sensitivity, rapid response electronic nose for sensing gas species in energy applications. Graphene based device structures suitable for the temperature range of 500 oC - 1000 oC are targeted. The scope of work includes: a) development of procedures for controllable nucleation and growth of nanoparticles on graphene surfaces, b) fabrication graphene-nanoparticle composite sensors, c) measurement of electrical properties of graphene-nanoparticle composites, and d) determination of sensor characteristics (selectivity and sensitivity) in simple mixtures. The graphene films are synthesized on 6H-SiC (0001) surfaces using a halogen based plasma etching process followed by rapid thermal annealing at atmospheric pressure in Ar. Using lithography free methods, simple sensor structures consisting of interdigitated fingers are then deposited on these films. This is followed by the nucleation of either Ag, Au, Pt, or Ir nanoparticles on the graphene surfaces using solution based techniques. The graphene and graphene-nanoparticle composites are characterized by x-ray photoelectron spectroscopy and Raman spectroscopy to establish film quality and characterize defect structures which play a key role in determining the electrical and sensor characteristics of the films. Atomic force microscopy is used to characterize the particle size distribution of the nucleated nanoparticles. Electrical properties of the graphene and graphene-nanoparticle composites are characterized using two and four point current-voltage measurements. Gas sensor response as a function of temperature is characterized for H₂ and CO in Ar gas mixtures. This presentation will provide an overview of the research performed to date.

9836-16, Session 4

Microwave photonic distributed sensing in harsh environments *(Invited Paper)*

Hai Xiao, Liwei Hua, Lei Yuan, Yanjun Li, Yang Song, Clemson Univ. (United States)

Harsh environment sensing and monitoring capabilities are required in advanced energy systems for reliability assurance, efficiency improvement, and emission minimization. Distributed temperature and strain monitoring are critical to operate gasifiers, combustors and boilers for process optimization, efficiency enhancement, fuel flexibility, and emission reduction. Unfortunately, there is a serious lack of available techniques for in situ long-term monitoring because of the extremely harsh environments involved. Given the fact that clean energy production will be necessary for a sustainable economy for many years to come, research and development are needed to address the technological challenges and bridge the capability gaps.

In this paper, we report a new distributed fiber optic sensing technique using optical carrier based microwave interferometry. By reading the fiber optic interferometers in microwave domain, the microwave-photonics system offers many unique features including high signal quality, relieved requirement on fabrication, low dependence on the types of optical waveguide, and insensitivity to the variations of polarization. The microwave-photonics sensing technique has been demonstrated using different types of optical fibers including singlemode fiber, multimode fiber, single crystal sapphire fiber and polymer fiber. Using the joint time-frequency domain signal processing method, many optical fiber interferometers with the same or different optical path differences were interrogated in the microwave domain and their locations could be unambiguously determined. The distributed sensing capability was demonstrated using cascaded weak optical reflectors along a single optical fiber, where any two arbitrary reflectors could be paired to define a low-finesse Fabry-Perot interferometer. Spatially continuous, fully

distributed temperature and strain measurements were used as examples to demonstrate the capability of the proposed concept. With a microwave bandwidth of 6 GHz, the spatial resolution was about 3 cm. In addition to strain and temperature measurements, the new sensing technology can also be flexibly designed to measure other physical, chemical and biological quantities by encoding the parameters to be measured into the OPDs of the interferometers.

9836-17, Session 4

Functionalized optical fiber sensor R&D for energy-related harsh environment sensing applications at the National Energy Technology Laboratory *(Invited Paper)*

Paul R. Ohodnicki Jr., National Energy Technology Lab. (United States)

A research program has been established at the National Energy Technology Laboratory to develop enabling technologies for energy-related harsh environment sensing applications with a particular focus on fossil-based power generation and subsurface applications such as CO₂ sequestration and oil & gas resource recovery. This presentation will overview recent advances in materials and associated device integration including new oxide based functional sensor layers for high temperature applications as well as harsh environment solution phase sensing. Opportunities, needs, and future plans for continued research in enabling technologies and materials for harsh environment sensing applications will also be motivated.

9836-18, Session 5

Electronics for harsh environment sensing: possibilities with GaN and diamond *(Invited Paper)*

Srabanti Chowdhury, Univ. of California, Davis (United States) and Arizona State Univ. (United States)

Recent progress made in Gallium Nitride electronics establishes GaN as superior semiconductor technology compared to the state-of-the-art in both high power and high frequency applications. GaN has successfully pushed the limits of performance beyond other III-Vs and Si in switching and RF power amplification applications, due to its unique material properties, which enable it to withstand high breakdown field and high current density. Powered by the growth of GaN on Si and availability of bulk GaN substrates (with defect densities lower than 10⁻⁴cm⁻²), lateral and vertical geometry devices are perfectly positioned to address a large spectrum of power electronic application with increased power density. The wide bandgap property of the material allows it to operate at very high temperature, a field currently being explored for application pertaining to hybrid solar cells and collocated sensors at high temperature environment. SiC a leader and a competitor of GaN in many such high-power and high-temperature applications has advanced the research of the electrical contacts and packaging technologies, which are being applied to evaluate GaN.

Beyond GaN in terms of energy bandgap is Diamond with a bandgap of 5.47eV that presents tremendous opportunity, again due to its rich material properties, to advance the performance space beyond what can be achieved with SiC and Diamond. In this presentation we will focus on the recent innovations in power electronics and RF electronics made possible by GaN, discuss its temperature tolerance and project it as a material for electronics for collocated sensors in extreme environment. The presentation will also give an account of the current status of Diamond based devices and evaluate its role in building collocated electronics for sensors for extremes. In summary, both GaN and Diamond present great potential to serve at high temperatures and harsh environments and currently demand research attention at material, device, packaging, and circuit level.

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9836-19, Session 5

**Wireless fully passive bio-potential
 recording/stimulation devices (*Invited
 Paper*)**

Junseok Chae, Arizona State Univ. (United States); Helen Schwerdt, Massachusetts Institute of Technology (United States); Félix A. Miranda, NASA Glenn Research Ctr. (United States); Shiyi Liu, Arizona State Univ. (United States)

Existing recording / stimulating system all comprise active components such as amplifier and microcontroller. One of the main concerns of using active components is the heat generation from the electronics could lead to heat trauma. Our work overcome this disadvantage via fully-passive wireless biotelemetry. This unique wireless telemetry utilizes EM backscattering methods to record / stimulate biosignal. Their small size and ability to operate without any battery or energy harvester make them attractive and feasible for chronic recording / stimulation inside or on the body. We, for the first time, demonstrate wireless recorder having sensitivity of less than 40 μ Vpp and stimulator having capability of more than 1 mA, all operating in a fully-passive manner.

9836-20, Session 5

**Extreme temperature packaging:
 challenges and opportunities (*Invited
 Paper*)**

R. Wayne Johnson, Tennessee Technological Univ. (United States)

Consumer electronics account for the majority of electronics manufactured today. Given the temperature limits of humans, consumer electronics are typically rated for operation from -40 $^{\circ}$ C to +85 $^{\circ}$ C. Military applications extend the range to -65 $^{\circ}$ C to +125 $^{\circ}$ C while underhood automotive electronics may see +150 $^{\circ}$ C. With the proliferation of the Internet of Things (IoT), the goal of instrumenting (sensing, computation, transmission) to improve safety and performance in high temperature environments such as geothermal wells, nuclear reactors, combustion chambers, industrial processes, etc. requires sensors, electronics and packaging compatible with these environments. Advances in wide bandgap semiconductors (SiC and GaN) allow the fabrication of high temperature compatible sensors and electronics. Integration and packaging of these devices is required for implementation into actual applications. The basic elements of packaging are die attach, electrical interconnection and the package or housing. Consumer electronics typically use conductive adhesives or low melting point solders for die attach, wire bonds or low melting solder for electrical interconnection and epoxy for the package. These materials melt or decompose in high temperature environments. This paper examines materials and processes for high temperature packaging including liquid transient phase and sintered nanoparticle die attach, high melting point wires for wire bonding and metal and ceramic packages. The limitations of currently available solutions will also be discussed.

9836-21, Session 5

**Charged particles enabled sensors for
 extreme conditions (*Invited Paper*)**

M. Saif Islam, Univ. of California, Davis (United States)

Accurate sensing of physical state variables such as temperature, pressure, radiation, vibration, flow as well as analytes such as gases, chemicals and hydrocarbon ratio in extreme conditions are very important. Such extremes include high temperature (>350 $^{\circ}$ C), high pressure, high shock

(>50,000 g), high radiation (>100 Mrads), erosive flow, corrosive media, and electrostatic discharge and electromagnetic interference are crucial for automotive and aviation engines, energy exploration and production, industrial processing and space exploration. Field ionization devices with ultra-sharp nanostructures exhibit interesting functionalities including gas ionization sensing, efficient field emission and accurate finger-printing of biological, chemical and agricultural analytes. This presentation will offer examples of engineered one-dimensional semiconductor nanostructures as ultra-selective sensors and discuss their importance in sensing temperature, pressure and other physical states chemicals under extreme conditions. We will also show how such charged particle based devices can be functional multicomponent orthogonal sensors for a number of physical state variables in extreme environments.

9836-22, Session 5

**Experimental durability testing of 4H SiC
 JFET integrated circuit technology at 727
 C (*Invited Paper*)**

David Spry, Philip G. Neudeck, NASA Glenn Research Ctr. (United States); Liangyu Chen, Optical Associates, Inc. (United States) and NASA Glenn Research Ctr. (United States); Carl Chang, Vantage Partners, LLC (United States); Dorothy Lukco, Glenn Beheim, NASA Glenn Research Ctr. (United States)

Recently, we have reported SiC integrated circuits (IC's) with two-levels of metal interconnect that have started demonstrating prolonged operation for thousands of hours at their intended peak ambient operational temperature of 500 $^{\circ}$ C [1]. However, it is recognized that testing of semiconductor microelectronics at temperatures above their designed operating envelope is vital to qualification and lifetime prediction of chips prior to deployment. Towards this end, we previously reported 4H-SiC JFET IC ring oscillator operation on an initial fast thermal ramp test through 727 $^{\circ}$ C [2]. However, this thermal ramp was not ended until a peak temperature of 880 $^{\circ}$ C (well beyond the electrical failure temperature) was attained. While we hypothesize that extensive physical degradation noted in post-test inspection (including loss of backside contact due to loss of platinum in the die attach paste) was the result of excessive $T > 800^{\circ}$ C, further experiments are necessary to better understand failure mechanisms and upper temperature limit of this durable extreme-temperature 4H-SiC IC technology.

Towards this end, we report on additional experimental testing of custom-packaged 4H-SiC JFET IC devices at temperatures above 500 $^{\circ}$ C. In one test the temperature was ramped and then held at 727 $^{\circ}$ C and all devices periodically measured until electrical failure was observed. A 4H-SiC JFET and epilayer resistor test devices on this chip electrically functioned with little change for around 28 hours at 727 $^{\circ}$ C before rapid increases in device resistance caused failure. A 0.5 mm² area metal-insulator-metal capacitor exhibited gradual leakage current increase from -1-2 μ A to 10-20 μ A over the same 28 hours. Post-test analysis performed on this sample involves field emission scanning electron microscopy (FESEM) of focus ion beam (FIB) prepared cross-sectional images, X-ray photoelectron spectroscopy (XPS), Auger electron spectroscopy (AES), and energy-dispersive X-ray spectroscopy (EDS). Insights into the extreme temperature durability-limiting physical mechanisms for this 4H-SiC IC technology will be presented.

9836-23, Session 6

**Neurotechnology for monitoring and
 regulating sensory, motor, and autonomic
 functions (*Keynote Presentation*)**

Douglas Weber, Pae Wu, Defense Advanced Research

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Projects Agency (United States); Gretchen Knaack,
Quantitative Scientific Solutions (United States)

The rapid and exponential advances in micro- and nanotechnologies over the last decade have enabled technologies that communicate directly with the nervous system to measure and effect neural activity. The earliest implementations focused on restoration of sensory and motor function, but as knowledge of physiology improves and technology continues to scale in resolution, precision, and even invasiveness, new modes such as engaging with the autonomic system herald an era of health restoration that may replace many pharmaceuticals. DARPA's Biological Technologies Office is continuing to push the boundaries of neurotechnology through programs investing in neural interfaces that are effective, reliable, and safe enough for long-term use in humans. DARPA's Hand Proprioception and Touch Interfaces (HAPTIX) program is working to create a fully implantable system that interfaces with peripheral nerves in amputees to enable natural control and sensation for prosthetic limbs. Advancing the neural interface technologies beyond standard electrode implementations, the Electrical Prescriptions (ElectRx) program is investing in innovative approaches to engaging with the peripheral nervous system in minimally-to-noninvasive ways such as through the advent of novel magnetic, optogenetic, and ultrasound-based technologies. In each instance, these new mechanisms of interrogating and stimulating the peripheral nervous system are driving towards unparalleled spatiotemporal resolution, specificity and targeting, and noninvasiveness with the expectation of moving towards chronic, human-use applications in closed-loop neuromodulation for the treatment of disease.

9836-24, Session 6

Wireless communication links for brain-machine interface applications *(Invited Paper)*

Larry Larson, Brown Univ. (United States)

Recent experiments have demonstrated the ability of neuroscientists to gain direct access to neural signals in real time, and decode the resulting information to control various prosthetic devices. This - along with deep brain stimulation for Parkinson's disease and a variety of other conditions - leads to the conclusion that widespread "brain interface" technology is a real (if long term) possibility. This paper will summarize the various approaches that have been developed to wirelessly communicate with the brain, including technology constraints, dc power limits, compression and data rate issues.

9836-25, Session 6

Organic electronics for human interface sensors *(Invited Paper)*

George G. Malliaras, Ecole Nationale Supérieure des Mines de Saint-Étienne (France)

The field of organic electronics has made available a range of materials with properties that are suitable for human interface devices. These include mechanical flexibility, mixed ionic/electronic conduction, facile biofunctionalization, and capability for drug delivery. I will present examples of organic-based devices for recording electrophysiological and metabolic signals, in both invasive and cutaneous formats. I will also discuss ways to establish a bi-directional interface through the use of electrical and chemical stimulation. Finally, I will describe a list of research priorities and future needs, as well as the technical challenges that face the transition to system-level applications.

9836-26, Session 6

Materials and nonconventional micro-fabrication techniques for ultra-compliant peripheral nerve interfaces *(Invited Paper)*

Christopher J. Bettinger, Carnegie Mellon Univ. (United States)

Peripheral neural interfaces (PNI) are devices that link the information flow within the nervous systems to synthetic systems. PNI are essential components that underpin many technologies for rehabilitation and neuromodulation. This presentation will describe recent progress in materials and microfabrication processes for ultracompliant conformal electrode arrays for reliable high-resolution peripheral neural interfaces to stimulate individual nerve fascicles. Two technologies will be described: (1) synthesis and processing of elastomeric conducting polymers; (2) transfer printing of microstructures to adhesive ultracompliant hydrogel-based substrates. Structure-processing-property relationships will be emphasized.

Elastomeric conducting polymers. Conducting polymers (CPs) have the potential for use in neural interface technologies through their ability to reduce electrode impedance and promote ion-electron exchange at the abiotic-biotic interface. CPs exhibit Young's moduli on the order of 1.5GPa, orders of magnitude higher than those observed in the peripheral nervous system. This discussion will highlight recent advances in templating of CPs to confer elastomeric properties to these prospective electrode materials.

Hydrogel transfer printing of microelectrode arrays. Ultracompliant microelectrode arrays have the potential to reduce the modulus mismatch at the tissue-device interface, which is a challenge for many microfabricated brain-machine interfaces. Here, we describe a novel processing strategy for integrating electronic materials with ultracompliant hydrogel substrates.

9836-27, Session 6

Smart contact lens and glasses for ubiquitous healthcare *(Invited Paper)*

Sei Kwang Hahn, Dohee Keum, Pohang Univ. of Science and Technology (Korea, Republic of)

Among various wearable medical devices, ocular lens is greatly advantageous for healthcare applications because it can be used as an efficient interface between the human body and electronic devices. Here, smart contact lens and glasses have been developed for the diagnosis and treatment of diabetes as a model system for ubiquitous healthcare. The smart contact lens was composed of a biosensor to measure a tear glucose level in real-time and a drug delivery system to deliver diabetic therapeutics. The smart eye glasses was composed of a Witricity power system and a wireless communication system. We could confirm the feasibility of smart contact lens and glasses for further theranostic applications.

9836-28, Session 6

Bio-electronic retinal prosthesis *(Invited Paper)*

James Weiland, The Univ. of Southern California (United States)

Retinal prosthesis have progressed from laboratory and early clinical experiments, to medical devices approved for sale by the FDA and European Union. This seminar will review the history of retinal prostheses for the blind, focusing in particular on the Argus II implant clinical trial and experiments on-going to improve the function of this device. The clinical trials have shown that individuals who have at best light perception vision, can use spatial information from the retinal prosthesis to detect motion, locate objects, and read letters. Improvements in navigation and mobility have been noted. The ability to perceive forms has been inconsistent in the

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implant patients. Form vision requires the ability to combine percepts from individual electrodes into shapes. A first step is limiting the size of each individual percept to an area near the electrode. Using mouse retina as a model, in vitro retinal responses to epiretinal stimulation were imaged using genetically encoded calcium indicators. Epiretinal implant patients drew the shape of percepts in response to single and multi-channel stimulation. Using calcium imaging to record cell activity allowed simultaneous visualization of multiple retinal ganglion cells. Biphasic pulses in the range typically used for retinal stimulation (0.5-2 ms) resulted in elongated areas of activation, suggesting activation of axons passing electrode. Stimulation with longer pulses, including 20 ms square waves, result in activity focused around electrode, suggesting that axonal stimulation is avoided with these types of stimuli. Patient reports are consistent with the in vitro results. Future research in retinal prosthesis will involve brain imaging of implant patients over time, to measure changes in brain structure and/or function related to use of the device and incorporation of sophisticated image processing algorithms to enhance the user's capabilities.

9836-29, Session 6

Graphene FETs on biocompatible and ultra-flexible membrane *(Invited Paper)*

Kyung-Ah Son, Baohua Yang, Hwa-Chang Seo, Danny Wong, Jeong-Sun Moon, HRL Labs., LLC (United States)

In this paper, we report the first graphene FETs fabricated on a biocompatible and ultra-flexible membrane for in vivo sensor and electronics applications. Microbial cellulose (MBC) membrane, a biopolymer, is used as the substrate for its unique benefits: biocompatibility, bio-integrativity (cell attachment and proliferation), high strength when wet, ultra-conformability, high purity, high crystallinity, and availability at a low cost in a large scale (e.g., sheets & rolls). For a monolayer CVD graphene transferred over a MBC membrane (< 10 μm thick), we measured carrier mobility of 1600 cm²/Vs and sheet resistance of 1100 ohm/square. Graphene FETs fabricated on MBC show G_m >200 mS/mm and I_{ds} ~380 mA/mm at V_{ds}=1V, which are very promising for high-sensitivity neuroelectric potential sensing. We will present our ongoing effort on graphene FETs on MBC for potential use in vivo as neuroelectric sensors and implantable electronics.

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9836-30, Session 7

Telemedicine and mHealth odyssey: a journey from the battlefield to academia *(Keynote Presentation)*

Ronald Poropatich, Univ. of Pittsburgh (United States) and Univ. of Pittsburgh Medical Ctr. (United States); Gary R Gilbert, Telemedicine and Advanced Technology Research Center, US Army Medical Research and Materiel Command (United States)

Since 1992, military medicine has considered the relevance, sustainability and promise of telemedicine in the context of its mission and obligations for service members at home, abroad and in war zones. More recently the advances in mobile computing and increased adoption of the Smartphone with evolving capabilities for imaging and body-worn sensor integration has emerged in the field called mobile health, or mHealth. This presentation highlights the first 20 years of the U.S. Army telemedicine and mHealth programs and how similar technologies have translated to wide scale civilian health care system implementation at the University of Pittsburgh Medical Center (UPMC).

The US Army telemedicine program includes both overseas and stateside locations that covers 22 time zones and generates over 5000 tele-consults per month for over 20 medical specialties. The successful US Army "mCare" program developed to augment soldier care management with

geographically located providers, utilizes secure mobile messaging and the soldier's own cell phone.

A DoD funded traumatic brain injury (TBI) research project developed at the University of Pittsburgh for Veterans includes a mobile health application that demonstrates the effectiveness and affordability of communicating with patients through their personal mobile devices with their care managers. Preliminary data are encouraging for adoption and utilization of a mobile telemedicine platform to meet the complex needs of those recovering from TBI, and the program adoption of this platform will be a focus of this presentation. Future research interests will describe the use of telemedicine on unmanned air platforms for casualty evacuation during war.

9836-31, Session 7

Smart ophthalmics: the future in tele-ophthalmology has arrived *(Invited Paper)*

Wolfgang Fink, Mark A. Tarbell, The Univ. of Arizona (United States)

Mobile Health (M-Health) is the intersection of mobile technology and healthcare. M-Health and Tele-Health are deeply intertwined and share the possibility of reshaping how and where healthcare is delivered. M-Health is an emerging field characterized by the use of portable, mobile devices capable of collecting, storing, retrieving, and transmitting data over wireless networks in real time for the purpose of improving safety and quality of care. Moreover, M-Health and Tele-Health harbor the potential of significant savings in healthcare costs to patients, health insurers, and economies at large. In particular, the Smart Ophthalmics project is designed to extend ophthalmic healthcare to people who operate/live in austere environments (e.g., military, third world, natural disaster), or are geographically dispersed (e.g., rural populations), where time, cost, and the possibility of travel/transportation make access to even adequate medical care difficult. Ocular trauma, glaucoma, and macular degeneration are all significant causes of preventable vision loss, if detected and treated early.

A series of optical devices are developed that act as medical (i.e., ophthalmic) examination extensions to a smartphone. A visiting healthcare practitioner attaches such a device to a smartphone and runs a custom app to perform a specialized examination of specific areas of the eye. Using a WiFi or cell signal, the smartphone app submits the collected examination data to a smart remote expert system, which provides in-depth medical analysis processing. The analysis results are sent back in near real-time and are displayed onscreen to the healthcare practitioner to facilitate, e.g., a triage process.

We have established a smart service platform in ophthalmology by creating a server-based teleradiologic analysis capability for current and future smartphone-based ophthalmic examination devices, including but not limited to an ophthalmoscope and a portable visual field test. Examination data gathered with these and future devices are sent wirelessly to a remote server for automated analysis, the results of which are sent back to the originating smartphone. Analyses performed currently comprise: early glaucoma detection and hill-of-vision assessment to determine the contrast sensitivity across the retina.

While image capture can be performed in isolation, e.g., on a smartphone, image interpretation and the development of an expert system for smart image classification mandate an active server back end having access to essential medical context, thereby delivering a rapid, "in-situ" informed analysis, e.g., to a forward operating base in a military setting. Moreover, Smart Ophthalmics will not only augment existing, clinic-centric ophthalmic examination infrastructure, but will add a fully automated pre-diagnostic capability in lieu of the absence of qualified medical personnel, e.g., in disaster-stricken areas or in the theatre. In this regard, teleradiologic offers the potential of both rapidity of evaluation and increased coverage. Telemedicine can also promote health care efficiency by improving screening and triage processes and helping to ensure that patients see an appropriate provider only when needed to avoid unnecessary visits. This will lead to the eventual integration of the smart service platform and its associated devices into established ophthalmic clinical practice.

9836-32, Session 7

Ceeable visual field analyzer (CVFA) for the portable, comprehensive, and tele-medical assessment of visual performance in warfighters, veterans, and civilians
(Invited Paper)

Chris Adams, John Cerwin, Ceeable, Inc. (United States);
Wolfgang Fink, The Univ. of Arizona (United States)

Vision is the primary sense used by warfighters, veterans, and civilians, and visual information is essential during all phases of military operations. Risks during military operations include possible corneal, lens and retinal damage from military combat, UV exposure, retinal thermal damage from excessive visible light and IR/laser exposure, intracranial and/or intraocular hypertension such as from head trauma (e.g., due to explosions), and toxic environmental poisoning.

Moreover, over 285 million people in the world are visually impaired, of whom 39 million are blind and 246 million have moderate to severe visual impairment. It is predicted that without extra interventions, these numbers will rise to 75 million blind and 200 million visually impaired by the year 2020. The main causes of blindness are cataract (47.8%), glaucoma (12.3%), age related macular degeneration (8.7%), and diabetic retinopathy (4.8%).

Age-related macular degeneration, the 3rd leading cause of blindness, affects 25-30 million people worldwide in some form. Similar to glaucoma, AMD is generally not curable. Worldwide, 2.5 million people experience vision loss due to diabetic retinopathy.

Therefore, the development and deployment of a portable, easy-to-use, integrated, worldwide accessible, and comprehensive test and diagnosis system for visual performance is warranted for: (1) Accurately and rapidly assessing visual performance; (2) characterizing and diagnosing visual performance and ocular conditions; and (3) detecting the onset of ocular conditions to allow for timely countermeasures as well as patient follow-up over time.

To that effect, Ceeable has developed a web-based, tele-medical screening system, employing an integrated and comprehensive visual field test system, called CVFA (Computerized Visual Field Analyzer). CVFA has been shown to be effective in multiple clinical studies. The technology is rapid (< 5 minutes per eye), easy (use of touchscreen), accurate (spatial resolution < 1 degree), non-invasive, and comprehensive. The technology automatically analyzes visual field data and objectively identifies and characterizes the occurring visual field defects (scotomas) to generate new diagnostic insight. Conditions such as glaucoma, age-related macular degeneration (AMD) with distinction between wet and dry AMD, and other eye disorders have been detected.

The Ceeable CVFA is readily adaptable to traditional clinical and non-clinical settings (e.g., in forward operating bases in the theatre). The enabling technologies are a low-cost tablet computer and internet connection. Ceeable is deploying the technology on a global basis to patients who will benefit from monitoring changes in visual function.

9836-33, Session 7

Prognostics and health management (PHM) for astronauts: a collaboration project on the International Space Station
(Invited Paper)

Alexandre Popov, Univ. of Ontario Institute of Technology (Canada) and AIAA Systems Engineering Technical Committee (United States); Wolfgang Fink, California Institute of Technology (United States) and The Univ. of Arizona (United States); Andrew Hess, The Hess PHM Group Inc. (United States)

Long-duration missions bring numerous risks that must be understood and mitigated in order to keep astronauts healthy, rather than treat a diagnosed health disorder. With limited medical ground support, personal health-tracking tools are required for any crew member to predict and assess health risks if no preventive measures are taken. This conceptual paper refines a concept employing technologies from Prognostics and Health Management (PHM), namely real-time health monitoring and condition-based health maintenance with predictive diagnostics capability. The conceptual paper focuses on particular PHM-based solutions to bring Human Health and Performance [HH&P] technologies to the required technology readiness level [TRL] in order to mitigate the HH&P risks of manned space exploration missions. Mapping the particular PHM-based solutions to some HH&P technology candidates, namely by NASA designation, the Autonomous Medical Decision technology and the Integrated Biomedical Informatics technology the conceptual paper emphasize key points that make the concept different from that of conventional medicine as well as telemedicine including space medicine. The proposed technology solutions are to bridge PHM, an engineering discipline, to HH&P domain in order to mitigate the risks by focusing on efforts to reduce countermeasure mass and volume and drive the risks down to an acceptable level. The Autonomous Medical Decision technology is based on wireless handheld devices and is a result of a paradigm shift from telemedicine to that of health support autonomy. The Integrated Biomedical Informatics technology is based on Crew Electronic Health Records [CEHR] system with predictive diagnostics capability developed for crew members rather than for healthcare professionals. The paper explores the proposed PHM-based solutions on crew health maintenance in terms of predictive diagnostics providing early and actionable real-time warnings of impending health problems that otherwise would have gone undetected.

To elevate the HH&P technologies the paper also discusses the PHM principles, such as Condition Based Maintenance [CBM], as well as techniques with data fusion and data mining capabilities to assess the value of CEHR augmented with real-time data monitoring for accurate predictive diagnostics on manned space exploration programs.

The primary benefit of the technologies development for the HH&P domain is the ability to successfully achieve affordable human space missions to Low Earth Orbit [LEO] and beyond. Space missions on the International Space Station Program [ISSP] directly contribute to the knowledge base and advancements in HH&P, thanks to continued operations on ISS, a unique human-tended test platform and the only test bed within the space environment. In-space test beds such as ISS are crucial to the development and validation of the technologies needed for the manned space exploration missions. The concept is to be validated on the International Space Station, the only "test bed" on which to prepare for future manned exploration missions. The paper authors believe that early self-diagnostic and autonomous identification of proper preventive responses on negative trends are critical in order to keep astronauts healthy.

9836-34, Session 7

M-health and affordable robotics: merging service systems for global robot assisted rehabilitation
(Invited Paper)

Michelle J. Johnson, Univ. of Pennsylvania (United States)

Stroke is the leading cause of disability, affecting more than 7 million in the USA and billions worldwide. Our goal is to improve the health and function to persons with persistent motor deficits due to a stroke in the USA and in developing countries where more than 80% of those living with a stroke reside. Over 6.8 million adults live in USA with disabilities due to a stroke and by 2030 an additional 4 million will. Unfortunately, only about 10% of the 75% who have an impairment in their upper-arm will achieve full recovery. The issues influencing rehabilitation outcomes are complex; these could be characterized as poverty, increase in health costs, short length of stays, insurance limitations, and physical constraints on therapist services (e.g., time). Evidence support rehabilitation robots role in improving rehabilitation outcomes and reducing barriers to rehabilitation services; they have the potential to narrow the gap between those who recover and those who do not. Unfortunately, these robots are often too costly for deployment

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in the home, in rural settings and in poorer and low-resources communities. In these communities there is less access to rehabilitation and associated medical and rehabilitation technologies. The development of affordable robot technologies combined with the utilization of cheaper and more accessible mobile technologies for M-health offer an enormous potential increasing access to effective rehabilitation for low-resource environments both in the US and worldwide. Very little is known about the effectiveness of a rehabilitation service delivery in developing countries where M-health mobile tools combined with robot technologies are used for tele-rehabilitation. We report our efforts to develop an affordable technology gym that uses robotics for stroke rehabilitation in Mexico. Results show that our application in Mexico of affordable robotics and rehabilitation technology gym used for stroke rehabilitation was just as effective in improving recovery of function in the upper and lower limb as standard of care. Leveraging these ideas we describe a novel and more cost-effective solution for Botswana, Africa that attempts to incorporate mhealth tools to provide permit use of the gym at a distance.

9836-35, Session 7
System perspectives for mobile platform design in M-Health (Invited Paper)

Janet Roveda, Wolfgang Fink, The Univ. of Arizona (United States)

This paper introduces a mobile platform design for a wearable sensor node in a stress management application. We use 1000Hz for ECG sensor sampling frequency with each sample represented as 10 bits for transmission and 12 bits binary for storage. This mobile platform integrates ECG sensor, accelerometer, and temperature sensor onto one board. The integration allows simplification of individual sensor design. Hence, by wearing one integrated wearable sensor node, we can measure heart rate, respiration rate, posture, bodily activity, and core temperature. Battery life and weight are additional important features for wearable sensors. Wearable sensors stream real time data to mobile platforms via low-power and reliable wireless interfaces (e.g., wireless Ethernet or Bluetooth). Different data transmitting modes can affect battery life by over 30%. Signals such as ECG, respiratory waveform, posture, temperature, etc. are stored as packets, which are transmitted by the integrated wearable sensor node to a mobile platform. To ensure data security, data packets are encrypted using Advanced Encryption Standard (AES) and compressed with compressive sensing approach right before transmission. Once transmitted, data will be stored on the smartphones, smartwatches, or tablets from which data may be further uploaded to the cloud. We apply the locality sensitive hash function with sublinear search complexity to establish search indices for data packet storage and retrieval in the cloud. We also introduce a new privacy-preserving data recovery mechanism for point of care to explore the cloud for its computing resources to avoid the expensive data reconstruction of the encrypted compressive sensing measurements. A Texas Instruments microprocessor (model no:MSP440) is integrated in the new mobile platform for the wearable sensor to perform data packet encryption and compressive sensing. To reduce power consumption, we use different sampling rates for various types of measurements. For example, by using a low sampling rate for slowly changing signals, such as body temperature, the data packet size may be reduced which in turn reduces packet transmission time and power consumption during data transmission. However, in the stress management application, heart rate variability (HRV) is a critical metric to provide stress level indication. A low sampling rate in ECG sensor design will lead to inaccurate HRV values. We demonstrate comparisons of HRV estimations with 128Hz, 256Hz, 512Hz, and 1000Hz sampling rate. Experimental results show that different sampling rates have little influence on -within-subject measurements while between-subject measurements are drastically affected by them. Therefore, for self-monitoring applications, relatively low sampling rates may help reduce power consumption without providing wrong trend indications of stress development. Spline and interpolation methods may be used during the data process on smartwatches, smartphones, or tablets to improve R-peak sampling accuracy without using high sampling rates. We use the Android Operating system to create an Application Program Interface between the new mobile platform for wearable sensor node and the smartphone. To

perform real time monitoring, we integrate basic data analysis and feature filtering into an App that can be executed directly on the mobile platforms for the wearable sensor and the smartphone.

9836-36, Session 8
Optoelectronics of 2D materials beyond graphene: physics and new devices (Invited Paper)

Farhan Rana, Cornell Univ. (United States)

Two dimensional materials beyond graphene, most notably transition metal dichalcogenides (TMDs), have generated tremendous interest among researchers. TMDs are direct bandgap semiconductors with bandgaps in the visible to near-IR wavelength range. The strong light absorption exhibited by these materials makes them attractive for opto-electronic applications most notable among which are light detection and emission. Despite the recent progress in material synthesis and growth, carrier lifetimes and nonradiative electron-hole recombination mechanisms in TMDs remain poorly understood. Developing a better understanding of the non-radiative electron-hole recombination mechanisms in TMDs is especially important because the reported quantum efficiencies in both TMD light emitters and detectors are extremely poor; in the .0001-.01 range. Similar quantum efficiencies for TMDs have been observed in photoluminescence experiments. In contrast, the best reported internal and external quantum efficiencies observed in photoluminescence in III-V semiconductors exceed 0.9 and 0.7, respectively. Therefore, most of the electrons and holes injected either electrically or optically in TMDs recombine non-radiatively. The mechanisms by which electrons and holes recombine non-radiatively, and the associated time scales, remain to be clarified. We will present our work in studying the dynamics of photoexcited electrons and phonons in 2D materials and devices using ultrafast optical/terahertz pump-probe and correlation spectroscopy. Our experimental work on metal dichalcogenide materials and devices (such as photodetectors and light emitters) as well as our theoretical results show that defect assisted recombination involving capture of excitons and carriers by Auger scattering is the fastest mechanism for the non-radiative recombination of photoexcited electrons and holes. In particular, the very Coulomb interaction that resulted in the strongly bound excitons in these materials, causes extremely fast capture of the excitons by defects resulting in extremely poor quantum efficiencies in optoelectronic devices. The large sensitivity of device performance to defects is thus fundamental to 2D TMD materials. Our optical pump-probe experiments show two distinct time scales associated with the capture and recombination of photoexcited carriers. The fast time scale is in the 2-4 ps range, and the slow time scale is in the 60-80 ps range. These two time constants are attributed to two different defect levels, one or perhaps both belonging to group VI atom vacancies that are extremely fast carrier capture sites. Our ultrafast two-pulse photovoltage correlation experiments show that the photoresponse of TMD photodetectors also exhibit the same two time scales. The temperature and optical fluence dependence of these time constants agree with carrier and exciton capture by defects via Auger scattering. The metal-TMD photodetectors exhibit intrinsic response speeds in the few picosecond range that are suitable for operation at frequencies approaching ~300 GHz. Carrier mobility in 2D TMDs is also critically important for electronic device applications. Our optical-pump THz-probe experiments have shown that carrier mobilities in multi-layer TMDs are phonon limited even at fairly low temperatures and can exceed several thousand sq-cm/V-s at temperatures below 50K. However, mobilities of monolayer samples are limited by defect/impurity scattering and do not exceed few hundred sq-cm/V-s even at low temperatures. Again, our works points to the importance of controlling defects and impurities in TMDs for device applications. Finally, our recent experimental work has shown that other than electronics and optoelectronics, 2D materials could be very promising for high frequency MEMs devices. Our work has shown that mechanical oscillations in these atomically thin membranes can reach terahertz frequencies and can enable MEMs resonator structures with record frequency-quality factor products at these high frequencies.

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9836-37, Session 8

Exciton dynamics engineering for high-luminescence efficiency of transition metal dichalcogenide monolayers *(Invited Paper)*

Linyou Cao, North Carolina State Univ. (United States)

Two-dimensional (2D) transition metal dichalcogenide (TMDC) materials such as monolayer MoS₂ and WS₂ promise the development of atomic-scale light emission devices, but their luminescence efficiencies are very low despite perfect surface passivation and strong exciton binding energy. Here we demonstrate that the luminescence efficiency is significantly limited by the substrate and can be improved by orders of magnitude through substrate engineering. The substrate effects mainly lie in doping the monolayers and affecting the monolayers' exciton dynamics, including facilitating the non-radiative recombination and slowing the radiative decay. Using proper substrates like mica and Teflon can minimize the adverse effect of doping, and by suspending the monolayer can mitigate both effects. Suspended monolayers generally show luminescence efficiency more than one order of magnitude higher than supported monolayers, which can be up to 40% at room temperatures. Additionally, we also demonstrate that, by removing the substrate, exciton-exciton annihilation emerges as an important factor to determine the luminescence efficiency. Our result provides useful guidance for the rational design of high-performance 2D TMDC light emission devices.

9836-38, Session 8

Black phosphorus infrared photodetector integrated on silicon photonics *(Invited Paper)*

Mo Li, Nathan Youngblood, Che Chen, Univ. of Minnesota, Twin Cities (United States)

Black phosphorus recently emerged as a new addition to the family of 2D materials. Few layer black phosphorus has a layer tunable direct bandgap in the range of 0.3-1.8 eV, nicely covers the infrared spectrum range. We demonstrate a gated multilayer black phosphorus photodetector integrated in a silicon photonic waveguide operating in the near-infrared telecom band. Using an interferometry methods, optical absorption in black phosphorus is precisely determined. In a significant advantage over graphene devices, black phosphorus photodetectors can operate under a bias with very low dark current and attain intrinsic responsivity up to 125 mA/W and 657 mA/W in 11.5nm and 100 nm thick devices, respectively. The photocurrent is dominated by the photovoltaic effect with a high response bandwidth exceeding 3 GHz. We also show preliminary results of photodetection in the mid-infrared range.

9836-39, Session 8

Control of exciton-photon interaction in 2D transition metal dichalcogenides *(Invited Paper)*

Vinod M. Menon, The City College of New York (United States)

Transition metal dichalcogenides (TMDs) have emerged as an attractive class of two-dimensional (2D) semiconductors that show unprecedented strength in its interaction with light. In this talk I will discuss approaches to enhance the strength of this interaction using microcavities, plasmonic antenna structures and metamaterials. Specifically I will discuss enhancement of spontaneous emission, formation of strongly coupled exciton-photon quasiparticles and enhanced nonlinear optical response from 2D TMDs embedded in microcavities. Potential applications of such structures with controlled exciton-photon interaction and the use of unique valley properties in these TMDs will also be addressed.

9836-40, Session 9

Soft electronics for the human body *(Keynote Presentation)*

John A. Rogers, Univ. of Illinois at Urbana-Champaign (United States)

Biology is soft, curvilinear and transient; silicon technology is rigid, planar and everlasting. Electronic systems that eliminate this profound mismatch in properties create opportunities for devices that can intimately integrate with the body, for diagnostic, therapeutic or surgical function with important, unique capabilities in biomedical research and clinical healthcare. Over the last decade, new concepts in materials science, mechanical engineering, manufacturing and device design has led to the emergence of diverse classes of 'biocompatible' electronic systems. This talk describes the key ideas, with examples ranging from wireless, skin-like electronic 'tattoos' for continuous monitoring of physiological health to bioresorbable electronics for nerve stimulation and intracranial monitoring, to electronically 'instrumented' balloon catheters for interventional cardiology.

9836-41, Session 9

Challenge and perspective of macro-scale, multi-functional high-performance flexible electronics *(Invited Paper)*

Kuniharu Takei, Osaka Prefecture Univ. (Japan)

High performance, flexible active device components play an important role to enable future flexible and wearable electronics applied to a variety of applications such as healthcare/medical devices, robotic prosthesis, and human interactive devices as examples. For the material formation on flexible substrates, organic and/or inorganic materials have been often proposed to fabricate and integrate flexible transistors, sensors, and some other devices. In this talk, printed inorganic nanomaterial-based flexible devices will be introduced as the one of possible techniques. Especially, I will talk about flexible printed strain and temperature sensors that can be applied to wearable healthcare devices. For those sensors, nanomaterial composition including carbon nanotubes and silver nanoparticles were used to realize high sensitive and selective flexible sensors formed by using a screen printer. Furthermore, low-power flexible digital complementary metal-oxide-semiconductor (CMOS) circuits will be introduced as the one of important components for the practical flexible electronics such as signal processing circuits and analog circuits on a flexible substrate. n-type and p-type thin film transistors were fabricated using carbon nanotube network film and InGaZnO thin film, respectively. For high integration of circuits and sensors without using expensive infrastructures used for Si-based devices, three-dimensional vertical integration of CMOS circuits and sensors are proposed in addition to conventional planar integration. This vertically integration of active devices were realized by applying printing techniques. Finally, the challenge and perspective for the flexible electronics will be discussed to move forward to realizing future flexible electronics.

9836-42, Session 9

CMOS technology: a critical enabler for free-form electronics-based killer applications *(Invited Paper)*

Muhammad M. Hussain, Aftab M. Hussain, Amir N. Hanna, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Complementary metal oxide semiconductor (CMOS) technology offers batch manufacturability by ultra-large-scale-integration (ULSI) of high performance electronics with a performance/cost advantage and profound reliability. However, as of today their focus has been on rigid and bulky thin

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film based materials. Their applications have been limited to computation, communication, display and vehicular electronics. With the upcoming surge of Internet of Everything, we have critical opportunity to expand the world of electronics by bridging between CMOS technology and free form electronics which can be used as wearable, implantable and embedded form. The asymmetry of shape and softness of surface (skins) in natural living objects including human, other species, plants make them incompatible with the presently available uniformly shaped and rigidly structured today's CMOS electronics. But if we can break this barrier then we can use the physically free form electronics for applications like plant monitoring for expansion of agricultural productivity and quality, we can find monitoring and treatment focused consumer healthcare electronics - and many more creative applications. In our view, the fundamental challenge is to engage the mass users to materialize their creative ideas. Present form of electronics are too complex to understand, to work with and to use. By deploying game changing additive manufacturing, low-cost raw materials, transfer printing along with CMOS technology, we can potentially stick high quality CMOS electronics on any existing objects and embed such electronics into any future objects that will be made. The end goal is to make them smart to augment the quality of our life.

9836-43, Session 9
**Emerging and potential opportunities for
 2D flexible nanoelectronics (Invited Paper)**

Deji Akinwande, Weinan Zhu, Saungeun Park, The Univ. of Texas at Austin (United States)

The last 10 years have seen the emergence of two-dimensional (2D) nanomaterials such as graphene, transition metal dichalcogenides (TMDs), and black phosphorus (BP) among the growing portfolio of layered van der Waals thin films. Graphene, the prototypical 2D material has advanced rapidly in device, circuit and system studies that has resulted in commercial large-area applications. In this work, we provide a review and perspective of the emerging and potential translational applications of 2D materials including semiconductors, semimetals, and insulators that comprise the basic material set for diverse nanosystems. Applications include RF transceivers, smart systems, the so-called internet of things, and neurotechnology. We will review the DC and RF electronic performance of graphene, MoS₂ and BP thin film transistors. 2D materials at sub-um channel length have so far enabled cutoff frequencies from baseband to 100GHz suitable for low-power RF and sub-THz concepts. Future applications will be discussed.

9836-44, Session 9
**Dual-use application of killer app FHE
 products for Mil/Aero (Invited Paper)**

Douglas Hackler, American Semiconductor, Inc. (United States)

The flexible electronics industry has adopted flexible hybrid electronic (FHE) systems as a go to market strategy. Promising high volume products are emerging for body worn bio patches, conformal structural electronic appliques and smart labels. These products which were principally developed for high volume consumer and industrial market solutions are directly applicable to advanced defense systems. This presentation will highlight the state of the art (SOTA) for bio patch, conformal and smart FHE products and identify opportunities for them to be used at dual use technology for defense systems. A discussion of the manufacturing base for the SOTA flexible products will be presented and current experimental results will be shared for performance of FHE prototypes. American Semiconductor (ASI) is a leading developer of flexible integrated circuits and hybrid integration technology. ASI's Flex™ ADC is the industry's first fully flexible ADC. These 2.5V 12-bit IC's support flexible applications with radius of curvature as low as 5mm. ASI's Flexform-ADC™ development kit is a commercial FHE product that includes a user printable FHE substrate

enabled with on-board circuitry and ADC capability for development of advanced flexible sensors. ASI is a member of the Nano-Bio-Manufacturing Consortium (NBMC) and is currently working to assist in forming a thin device technology node for FHE-MII.

9836-45, Session 9
**Flexible hybrid electronics: Defense
 Department perspective (Keynote
 Presentation)**

Eric Forsythe, U.S. Army Research Lab. (United States); Benjamin Leever, Michael F. Durstock, Richard Vaia, Air Force Research Lab. (United States); David C. Morton, U.S. Army Research Lab. (United States); Mark Gordon, Office of Assistant Secretary of Defense (United States) and National Ctr. For Advanced Technologies (United States)

The Defense Department has recently established the Flexible Hybrid Electronic (FHE) Manufacturing Institute that will serve as a public-private partnership between industry, government, and academia to address the manufacturing challenges associated with the materials, packaging, design, and testing of flexible hybrid electronics packaged systems. The Flexible Hybrid Electronics Manufacturing Institute is positioned to leverage the intersecting electronic packaging industry and the high-performance printing industry, both well-established US industrial and academic areas of strength. This manufacturing ecosystem offers an opportunity for the Defense Department programs, both industrial and laboratories, to realize applied research results in small-scale manufacturing. The FHE Institute will provide a partnership for integration of the ecosystem through the Institute hub where pilot-scale manufacturing can meet small-volume demonstrations for DoD programs. These processes will benefit from the commercial scale opportunities for cost-benefits. This invited talk will provide an overview of the FHE manufacturing platform and specific Defense applications that include; soldier performance monitoring, light weight rugged portable sensors for dismount warfighters, and ubiquitous sensing. FHE materials scale-up: Includes conductive and active inks and pastes, and novel substrates that flex and stretch, and of low-cost renewable sources such as textiles and cellulose. The Institute will focus on (5) technical manufacturing topic areas; Thinned device processing: Leading ultra-thin silicon integrated circuits and sensors. Development of new tools for testing, slicing, stretching, and thinning silicon wafers will be a cornerstone of the FHE MII. Device/sensor integrated printing and packaging: Such as high speed automated pick and place for precision placement of ultra-thin silicon devices, merging the high-performance printing industries for interconnects and data lines and imprinting processes for sensors. Integrating critical power storage, harvesting and system designs. System design tools: Software and hardware design capabilities to integrate novel manufacturing design rules in a collaborative software-space. The manufacturing capabilities will demonstrated through technology platform demonstrations that have both commercial DoD applications that include; Wearable Medical and Human Performance Monitoring Systems; Ubiquitous Sensing Systems for Asset Monitoring (Internet of Things), Flex-Hybrid Phase Array antenna Systems, Integrated Flexible and Stretchable Electronics Enabling Soft Robotics.

9836-46, Session 9
**Cut-and-paste manufacture of
 multifunctional epidermal electronic
 systems (Invited Paper)**

Nanshu Lu, The Univ. of Texas at Austin (United States)

Epidermal electronics is a class of noninvasive skin-mounted, tattoo-like sensors and electronics capable of continuous vital sign monitoring and long-term human-machine interface. They are considered the most intimate and comfortable wearable sensors for vital sign and physiology monitoring

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including electroencephalogram (EEG), electrocardiogram (ECG), electromyogram (EMG), skin temperature, skin hydration, respiratory rate, and so on. The high cost of manpower, materials, vacuum equipment and photolithographic facilities associated with its manufacture greatly hinders the widespread use of disposable epidermal electronics. We have invented a cost and time effective, completely dry, benchtop “cut-and-paste” method for the green, freeform and portable manufacture of multiparametric epidermal sensor systems (ESS) within minutes. The process begins with programmable cutting of blanket metallic and polymeric sensor sheets, followed by removal of unnecessary parts and pasting on target medical or tattoo adhesives. This versatile method works for all types of thin metal and polymeric sheets and is compatible with any tattoo adhesives or medical tapes. The resulting ESS are multimaterial and multifunctional and have been demonstrated to noninvasively but accurately measure EEG, ECG, EMG, skin temperature, skin hydration, as well as respiratory rate. In addition, planar stretchable coils exploiting double-stranded serpentine design have been successfully applied as wireless, passive epidermal strain sensors.

9836-47, Session 9

Wearable electronics for personalized diagnostic and physiological monitoring
(Invited Paper)

Ali Javey, Univ. of California, Berkeley (United States)

The number of interconnected devices, equipped with sensing and actuation functionalities, are expected to grow beyond thousands of units per person by 2020. Hence, personalized networks of devices can be realized, where the desired functionalities are fully integrated into the wearable and surrounding objects as per individuals’ needs, and the subsequently collected data can be used to keep the individuals informed of their daily activities and physical and health states. Accordingly, novel manufacturing processes are required for on-demand creation of smart objects, and non-invasive sensing methods are needed for continuous health monitoring of individuals. Aligned with this vision, we demonstrate a low-cost printing process that enables on-demand creation of personalized smart objects with integrated silicon ICs to achieve system-level functionalities. In one example system, we present a fully-integrated and wearable perspiration analyzer that simultaneously measures a panel of electrolytes and metabolites in sweat and can provide insight into the physiological state of individuals in real-time.

9836-48, Session 9

A flexible future for paper-based electronics
(Invited Paper)

Tongfen Liang, Xiyue Zou, Rutgers, The State Univ. of New Jersey (United States); Yunjian Cui, Rutgers University (United States); Aaron D. Mazzeo, Rutgers, The State Univ. of New Jersey (United States)

This paper will review the origins and state of the art in paper-based electronics, suggesting the stage is set for future promising applications. Current interest in paper-based electronics can trace its roots to recent developments in paper-based microfluidics. With a need to improve the reliability and sensitivity of paper-based microfluidics for certain tasks, there were natural efforts to begin embedding sensing electrodes into microfluidic devices. Recognizing the general benefits of paper as an advanced material (e.g., its environmental friendliness, bendable nature, and low cost), efforts in paper-based electronics also began to take a life of their own with demonstrations of transistors, batteries and devices for energy storage, energy harvesting, sensors to improve situational awareness, acoustics, and displays.

The state-of-the-art paper-based electronic devices have benefited and will continue to profit from technologies for printing or transferring electronic

functionality onto the surfaces of paper-based substrates. Nonetheless, the authors suggest that many future promising applications will go beyond using paper as a carrier/substrate for electronic components to explore tuning and patterning the electromechanical properties of the paper-based substrate itself. The most obvious efforts to tune the properties for paper-based electronics may be in the use of nano cellulose for optical transparency and high strength. At physically larger and potentially more economical scales, there have also been efforts to embed nanoparticles in micro-sized cellulosic fibers for building sensors responsive to mechanical force. In general, patterning substrates themselves will make use of the unused volumes of paper-based substrates to increase the density of packed electronic components. Patterning the internal regions of substrates will also move potentially strain-sensitive materials toward the neutral axis of bending to improve fatigue life. With these technical advances, paper-based electronics will move closer to economically viable killer applications.

9836-49, Session 9

Stretchable electronics for invasive and wearable healthcare devices
(Invited Paper)

Dae-Hyeong Kim, Seoul National Univ. (Korea, Republic of) and Institute for Basic Science (Korea, Republic of)

Recent advances in soft electronics have attracted great attention due in large to the potential applications in personalized, bio-integrated healthcare devices. The mechanical mismatch between conventional electronic/optoelectronic devices and soft human tissues/organs causes many challenges, such as the low signal to noise ratio of biosensors because of the incomplete integration of rigid devices with the body, inflammations and excessive immune responses of implanted stiff devices originated from frictions and foreign nature to biotic systems, and the huge discomfort and consequent stress to users in wearing/implanting these devices. Ultraflexible and stretchable electronic devices utilize the low system modulus and the intrinsic system-level softness to solve these issues. Here, we describe our unique strategies in the synthesis of nanoscale materials, their seamless assembly and integration, and corresponding device designs toward wearable and implantable healthcare devices. These implantable and wearable bioelectronic systems combine recent breakthroughs in unconventional soft electronics to address unsolved issues in the clinical medicine, which provides new opportunities the personalized healthcare.

9836-50, Session 9

Roll-to-roll processing for flexible devices and components utilized in wearable and mobile electronics
(Invited Paper)

Neil Morrison, Applied Materials GmbH (Germany)

Roll-to-Roll (R2R) production of flexible electronic devices (active matrix TFT backplanes, OLED frontplanes and touch screens) combine the advantages of the use of inexpensive, lightweight and flexible substrates with high throughput production to enable new form factor products with exceptional robustness and mechanical stability. Significant cost reduction opportunities can also be found in terms of processing tool capital cost, utilized substrate area and process gas flow when compared with batch processing systems. Nevertheless, material handling, device patterning and yield issues have limited widespread utilization of R2R manufacturing within the electronics industry. Recently, significant advances have been made in device patterning enabling the mass production of a variety of flexible electronic devices. These techniques are now so advanced that feature sizes of less than 40 nm can be produced on thin film layer stacks deposited on 50 μm thick polymeric substrates and features down to less

than 20 μm on thick film processed screen printed metal layers for narrow bezel applications. Significant challenges also exist in terms of the layer deposition technologies used in R2R manufacture of these devices. Unlike

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traditional semiconductor or display based cluster tool platforms, R2R systems require processing substrates in a continuous fashion with rolls up to several kilometers in length. Depending upon the process itself, this imposes a limitation in terms of the mean time before cleaning (MTBC) and in some cases the particle management strategy. A variety of different web handling and coating technologies/platforms to enable high volume R2R manufacture of both active and passive components utilized in display have been developed. The work presented in this paper therefore describes the principal challenges inherent in moving from lab/pilot scale manufacturing to high volume manufacturing. Results will be presented for both amorphous silicon and IGZO TFT backplanes, ITO based touch panel devices in addition to high barrier performance layers and stacks for both substrate encapsulation and barrier film for final device encapsulation. The paper also addresses areas where both thick and thin film processing technologies can be combined.

9836-51, Session 10

**Particle-tracking microrheology:
fundamentals and new applications**
(Invited Paper)

Denis Wirtz, Johns Hopkins Univ. (United States)

A multitude of cellular and subcellular processes depend critically on the mechanical deformability of the cytoplasm. We have recently introduced the method of particle tracking microrheology, which measures the viscoelastic properties of the cytoplasm locally and with high spatiotemporal resolution. Here we establish the basic principles of particle tracking microrheology, describing the advantages of this approach over more conventional approaches to cell mechanics. We present basic concepts of molecular mechanics and polymer physics relevant to the microrheological response of cells. Particle tracking microrheology can probe the mechanical properties of live cells in experimentally difficult - yet more physiological - environments, including cells embedded inside a 3D matrix, adherent cells subjected to shear flows, cells inside a developing embryo. Particle tracking microrheology can readily reveal the lost ability of diseased cells to resist shear forces. We will also present novel applications of particle-tracking microrheology to monitor phenotypic changes in tumors at the single-cell level in living subjects.

9836-52, Session 10

**Characterization of nanoparticle targeted
delivery and trans-endothelial capability
through a biomimetic microfluidic device**
(Invited Paper)

Yaling Liu, Lehigh Univ. (United States)

This talk covers multiscale characterization, evaluation, and design for adhesion dynamics of nanoparticles and cells. Nanoparticulate systems have been widely used in diagnostic imaging and targeted therapeutic applications in recent years. One of the major challenges in nanomedicine is to improve particle selectivity and adhesion efficiency under complex vascular flow conditions. We developed an integrated microvascular mimetic microfluidic testing platform to evaluate nanoparticle targeted delivery under vascular flow. A monolayer of endothelium cell is formed in the channel and activated locally through TNF- α to mimic the physiological diseased region. NP binding dynamics under a range of shear rates are characterized to evaluate the targeting efficiency. We aim to provide a systematic design and evaluation tool toward a virtual vascular platform for nanomedicine testing.

9836-53, Session 10

**Diamond-based multifunctional
nanosensing platform** *(Invited Paper)*

Jonathan S. Hodges, Florian Dolde, Ophir Gaathon,
Diamond Nanotechnologies, Inc. (United States)

For a variety of applications in biomedical research there is a need for better imaging and sensing tools that can report on activities at the nanoscale. In many instances, such as in neural activity imaging, it is desirable to record those dynamics in real time over a wide field of view while resolving features below the diffraction limit. This multi-scale challenge is compounded with performance issues of current probes such as photostability, cytotoxicity or low contrast. A potential candidate to overcome those barriers is the multifunctional diamond nanosensor. The unique sensing capabilities of diamond are derived from fluorescent atomic defect centers in the diamond lattice. One of those color centers is the nitrogen vacancy (NV) center. By optically interrogating the electronic spin state of those centers we can probe the local environment. To do so, we employ a specially designed rapid pulse sequences in a manner similar to magnetic resonance imaging (MRI) techniques but on normal optical microscopes. We can engineer these nanosensors to be non-bleaching optical reporters of small changes in charge density, electric and magnetic fields and temperature. Here we will discuss our recent development of electric field diamond nanosensors. We will also report on our efforts towards realizing a robust sensing and imaging platform that is based on these new kind of high performance diamond probes.

9836-54, Session 10

**Multifunctional combinatorial-designed
nanoparticles for nucleic acid therapy**
(Invited Paper)

Mansoor Amiji, Northeastern Univ. (United States)

Tremendous advances in molecular and personalized medicine also present challenges for translation of innovative experimental approaches into clinically-relevant strategies. To overcome some of these challenges, nanotechnology offers interesting solutions for disease prevention, diagnosis, and treatment. For many systemic diseases, overcoming biological barriers and target specific delivery are the key. Additionally, newer generation of molecular therapies, such as gene therapy, oligonucleotides, and RNA interference (RNAi) that use nucleic acid constructs require robust and highly specific intracellular delivery strategies for effective and clinically meaningful therapeutic outcomes. In this talk, I will cover several of our strategic approaches for development of multifunctional engineered nano-systems for targeted therapies in the treatment of cancer and inflammatory diseases. Specific examples will include: (1) overcoming tumor multidrug resistance using a combinatorial-designed engineered nano-systems for RNAi and chemotherapy, (2) genetic modulation of macrophage phenotype to promote anti-inflammatory effects in the treatment of rheumatoid arthritis, and (3) oral anti-TNF gene silencing therapy using multicompartamental delivery system for the treatment of inflammatory bowel disease.

In each of the above examples, we focus on challenging medical problems with innovative solutions that use safe materials and scalable fabrication methods in order to facilitate clinical translation and improve patient outcomes.

9836-55, Session 10

Cancer nanotheranostics *(Invited Paper)*

Xiaoyuan Chen, National Institutes of Health (United States)

Cancer nanotheranostics combines nanobiotechnology and cancer biology,

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aiming for early diagnosis, accurate molecular imaging, and precise treatment at the right timing and proper dose, followed by real-time monitoring of treatment efficacy. This talk provides an overview of the state-of-the-art of cancer nanotheranostics from the design of nanobiosensors for ultrasensitive biomarker detection in vitro, application of molecular imaging techniques for in vivo measurement of cancer hallmarks, image-guided cancer interventions, to nanoparticle platforms for co-delivery of imaging labels and therapeutic genes and drug molecules. The challenges of clinical translation of cancer nanotheranostic are also briefly discussed.

9836-56, Session 10

Ultra-high sensitivity imaging of cancer using SERRS nanoparticles *(Invited Paper)*

Moritz F. Kircher, Memorial Sloan-Kettering Cancer Ctr. (United States)

“Surface-enhanced Raman spectroscopy” (SERS) nanoparticles have gained much attention in recent years for in silico, in vitro and in vivo sensing applications. Our group has developed novel generations of biocompatible “surface-enhanced resonance Raman spectroscopy” (SERRS) nanoparticles as novel molecular imaging agents. Via rigorous optimization of the different variables contributing to the Raman enhancement, we were able to design SERRS nanoparticles with so far unprecedented sensitivity of detection under in vivo imaging conditions (femto-attomolar range). This has resulted in our ability to visualize, with a single nanoparticle, many different cancer types (after intravenous injection) in mouse models. The cancer types we have tested so far include brain, breast, esophagus, stomach, pancreas, colon, sarcoma, and prostate cancer. All mouse models used are state-of-the-art and closely mimic the tumor biology in their human counterparts. In these animals, we were able to visualize not only the bulk tumors, but importantly also microscopic extensions and locoregional satellite metastases, thus delineating for the first time the true extent of tumor spread. Moreover, the particles enable the detection of premalignant lesions. Given their inert composition they are expected to have a high chance for clinical translation, where we envision them to have an impact in various scenarios ranging from early detection, image-guidance in open or minimally invasive surgical procedures, to noninvasive imaging in conjunction with spatially offset (SESORS) Raman detection devices.

9836-57, Session 10

Nanoparticle formulations for image-guided drug delivery to brain tumors *(Invited Paper)*

Tyrone Porter, Boston Univ. (United States)

Nanoparticles have proven to be an invaluable resource for delivery of therapeutic agents to solid tumors. Nanoparticles enable the use of anticancer agents that suffer from poor solubility in blood or enzymatic degradation or rapid clearance from circulation. When administered systemically, nanoparticles can circulate for hours and extravasate through leaky tumor vasculature, ultimately increasing the drug dose delivered to malignant cells. While this strategy is effective against most solid tumors, nanoparticle-based drug delivery to brain tumors remains a monumental challenge. The presence and activity of the blood-tumor barrier (BTB) severely limits transport of nanoparticles from the bloodstream into the brain parenchyma. To overcome this hurdle, nanoparticles can be decorated with a mixture of ligands that facilitate receptor-mediated transcytosis RMT as well as target the drug carrier to malignant cells. Leveraging an innovative dynamic model, we are investigating RMT across the barrier as a function of nanoparticle size and ligand surface density. Alternatively, circulating microbubbles driven with ultrasound can temporarily disrupt the BTB, providing a pathway for nanoparticle diffusion. Ongoing studies will examine the relationship between nanoparticle penetration with ultrasound pressure, administered microbubble dose, and nanoparticle physicochemical properties. Moreover, the incorporation of contrast material into the

nanoparticle allows for monitoring extravasation and accumulation within intracranial tumors. Combining the proposed strategies for circumventing the BTB with novel multifunctional nanoparticles will expand the range of anticancer agents that may be utilized in the treatment of brain tumors.

9836-58, Session 10

Multifunctional nanoconstructs for biomedical applications *(Invited Paper)*

Tayyaba Hasan, Massachusetts General Hospital (United States) and Harvard Medical School (United States)

This presentation will introduce a new nanotechnology platform for cancer combination therapy that utilizes near infrared light activation not only for photodynamic damage but also as an extrinsic mechanism to initiate release of complimentary drugs to suppress dynamic bursts in molecular signaling networks that promote tumor cell survival and treatment escape. The goal is to achieve co-delivery with concomitant activity of photodynamic, molecular inhibitor and chemotherapeutic agents, selectively within the tumor. This approach overcomes challenges in achieving synergistic interactions using sequential drug delivery. Conventional drug delivery is compromised by the differential pharmacokinetics of individual agents and potentially antagonistic effects—such as vascular shutdown by one agent that limits delivery of the second. Here, photodynamic damage—which efficiently kills drug-resistant cells via damage of common proteins involved in drug-resistance (such as anti-apoptosis factors and drug-efflux transporters)—is synchronized spatially and temporally with the photo-initiated release of complimentary agents—to enable full interaction amongst the individual therapies. This spatiotemporal synchronization offers new prospects for exploiting time-sensitive synergistic interactions. Specific implementations of these concepts will be presented in preclinical models of cancer. Strategies to enable molecular-targeting of cancer cells via site-specific attachment of targeting moieties to the outer lipid shell of these nanovehicles will also be discussed. If successful in humans, this new paradigm for synchronized, tumor-focused combination therapy will ultimately supersede the present use of chronic drug injection by increasing efficacy per cycle whilst reducing systemic exposure to toxic drugs.

9836-59, Session 10

IGF-1 receptor targeted nanoparticles for image-guided therapy of stroma-rich and drug resistant human cancer *(Invited Paper)*

Hongyu Zhou, Weiping Qian, Emory Univ. (United States); Fatih M. Uckun, The Univ. of Southern California (United States); Liya Wang, Emory Univ. (United States); Andrew Y. Wang, Ocean NanoTech (United States); Hui Mao, Lily Yang, Emory Univ. (United States)

Low drug delivery efficiency and drug resistance from highly heterogeneous cancer cells and tumor microenvironment represent major challenges in clinical oncology. Growth factor receptor, IGF-1R, is overexpressed in both human tumor cells and tumor associated stromal cells. The level of IGF-1R expression is further up-regulated in drug resistant tumor cells. We have developed IGF-1R targeted magnetic iron oxide nanoparticles (IONPs) carrying multiple anticancer drugs into human tumors. This IGF-1R targeted theranostic nanoparticle delivery system has an iron core for non-invasive MR imaging, amphiphilic polymer coating to ensure the biocompatibility as well as for drug loading and conjugation of recombinant human IGF-1 as targeting molecules. Chemotherapy drugs, Doxorubicin and Cisplatin, were encapsulated into the polymer coating and/or conjugated to the IONP surface by coupling with the carboxyl groups. The ability of IGF1R targeted theranostic nanoparticles to penetrate tumor stromal barrier and enhance tumor cell killing has been demonstrated in human pancreatic cancer and triple negative breast cancer patient tissue derived xenograft (PDX) models.

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Repeated systemic administrations of those IGF-1R targeted theranostic IONP carrying chemotherapy drugs doxorubicin and/or cisplatin led to breaking the tumor stromal barrier and improved therapeutic effect. Near infrared (NIR) optical and MR imaging enabled noninvasive monitoring of nanoparticle-drug delivery and therapeutic responses. Our results demonstrated that IGF-1R targeted nanoparticles carrying multiple drugs are promising combination therapy approaches for image-guided therapy of stroma-rich and drug resistant human cancer, such as pancreatic and triple negative breast cancers. The development of this novel image-guided cancer therapeutic protocol using targeted theranostic nanoparticles has great potential for future translation into clinical applications for effective treatment of drug resistant cancer patients.

9836-60, Session 10

Early detection and longitudinal imaging of cancer micrometastases using biofunctionalized rare-earth albumin nanocomposites *(Invited Paper)*

Prabhas Moghe, Margot Zevon, Harini Kantamneni, Rutgers, The State Univ. of New Jersey (United States); Laura Higgins, Marco Mingozi, Rutgers University (United States); Vidya Ganapathy, Charles M. Roth, Richard E. Riman, Mark C. Pierce, Rutgers, The State Univ. of New Jersey (United States)

Metastatic cancer is the leading cause of almost 90% of cancer-related deaths. Current clinical imaging techniques are unable to detect micrometastases due to limited resolution. Their imaging capability is challenged by high tissue scattering and absorption of visible light, thus limiting resolution of deeper tissue lesions. Our approach utilizes rare earth (RE) nanoprobes that absorb near infrared (NIR) radiation and emit in the shortwave infrared (SWIR) spectrum (1000-3000 nm), allowing for greater depth of detection. In this study, we demonstrate the ability of CXCR4-targeting Rare Earth Albumin NanoComposites (ReANCs) to preferentially accumulate in tumor lesions and image lesion dynamics in an in vivo MDA-MB-231 derived lung metastatic model. Tumor burden in the lungs was assessed by MRI and compared to the SWIR signal from the nanoprobes. Longitudinal in vivo imaging confirmed improved accumulation of functionalized nanoprobes in tumor lesions compared to control ReANCs. Currently, there are no robust imaging modalities that can detect micro-metastases of breast cancer to the bone. We were able to demonstrate the ability of ReANCs to image micro-metastatic lesions in long bones and spine of animals prior to their detection via conventional imaging techniques such as CT. Findings from this study support the promise of the "new window" imaging platform and suggest future clinical translatability for nanomedicine. Given the multifunctional nature of ANCs as drug delivery vehicles, our imaging probes can also be adapted for pre-clinical pharmacogenomic screening, an emerging component of precision medicine.

9836-61, Session 10

Imaging and nanomedicine in inflammatory atherosclerosis *(Invited Paper)*

Zahi A. Fayad, Icahn School of Medicine at Mount Sinai (United States)

Atherosclerosis is a chronic progressive disease, affecting the medium and large arteries, in which lipid-triggered inflammation plays a pivotal role. The major clinical manifestations of atherosclerosis are coronary artery disease (CAD), leading to acute myocardial infarction (MI) and sudden cardiac death; cerebrovascular disease, leading to stroke; and peripheral arterial disease, leading to ischemic limbs and viscera. These complications of

atherosclerosis are leading causes of death worldwide. Despite progress in medical and re-vascularization therapies for atherothrombotic disease, the incidence of MI and stroke remain high under the current standard of care, and the past decade has generated few new medical therapies to prevent atherosclerosis-induced events. Similarly, current diagnostic approaches to atherosclerosis do not accurately identify those individuals who will suffer an ischemic complication. The field of atherosclerosis is therefore ripe for re-engineering in both the therapeutic and diagnostic arenas. Research into the process of atheroma lesion development and maturation has implicated many immune cells including lymphocytes, dendritic cells, and neutrophils. The most numerous cells in atherosclerotic plaque are macrophages, which are leukocytes that are central to the innate immunity. Because they play a major role in instigating plaque development and complication—both of which are inflammation-related disease processes—leukocytes are promising targets for more effective atherosclerosis treatments. However, the complexity of the immune system and its role as a defensive force against infection require novel tools to very precisely identify and treat the inflammatory cells that promote atherosclerosis. Biomedical engineering offers unique possibilities for diagnosing and treating atherosclerotic plaque inflammation. Thus, interfacing engineering with immunology will be essential to meaningful advances in disease management.

This talk will discuss how recent discoveries in atherosclerosis immunology can provide opportunities for diagnostic imaging of atherosclerotic plaques and cardiovascular complications of atherosclerosis, including translatable molecular imaging techniques. Integrated diagnostic modalities have uncovered new pathways that can serve as potential diagnostic and therapeutic targets, and show that these pathways can be specifically modulated by nanomedicine based interventions.

Objectives:

- 1) Define Nanomedicine and its opportunity in cardiovascular disease detection and treatment
- 2) Demonstrate the methods of plaque molecular imaging with MR Imaging, PET, CT.
- 3) Discuss the advantages and limitations of plaque molecular imaging using MR Imaging, PET, CT.
- 4) Discuss the preclinical and clinical relevance of plaque molecular imaging by MR Imaging, PET, CT.
- 5) Discuss novel methods for atherosclerotic plaque treatment using nanomedicine.

9836-62, Session 11

Vision-based obstacle avoidance for micro air vehicles using image space representations *(Invited Paper)*

Larry Matthies, Roland Brockers, Jet Propulsion Lab. (United States); Anthony Fragoso, California Institute of Technology (United States); Brandon Rothrock, Alexander Harmsen, Jet Propulsion Lab. (United States)

Micro air vehicles require obstacle avoidance capabilities that provide a wide field of regard for agile maneuvering in cluttered space and long range with high angular resolution for high-speed flight in open space. No single sensor available today adequately meets these requirements. For outdoor applications, which typically have highly textured surfaces, vision-based approaches are promising and have potential to enable perception systems with very low size, weight, and power (SWaP). We take a vision-based approach that draws inspiration from the visual fields of barn owls, which have a substantial binocular field of view and wide, monocular, peripheral fields of view. We previously introduced an adaptation of the concept of configuration space obstacles to inverse-range image space representations generated by stereo vision; we also showed how to use this for fast collision checking of 3-D trajectories generated by a closed-loop RRT-based path planning algorithm. In this paper, we generalize the image space representation to a cylindrical data structure centered on the vehicle ("egocylinder") that provides approximately a 180 degree horizontal field

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of regard by fusing 3-D perception from forward-looking stereo vision and peripheral structure from motion. This includes the image-space configuration-space expansion from our previous work. To reduce the computational cost of the path planner, we employ a reactive approach to obstacle avoidance that searches the egocylinder for feasible, collision-free flight segments. We have implemented this approach on quadrotors weighing in the range of 0.5 to 1 kg, with all computing done onboard. Experimental results show this approach to be promising.

9836-63, Session 11

The role of vision in perching and grasping for MAVs (*Invited Paper*)

Justin Thomas, Giuseppe Loiano, Univ. of Pennsylvania (United States); Kostas Daniilidis, University of Pennsylvania (United States); Vijay Kumar, Univ. of Pennsylvania (United States)

In this work, we provide an overview of vision-based control for landing, perching, and grasping for Micro Aerial Vehicles. We investigate visual servoing techniques for quadrotors to enable autonomous perching by hanging from cylindrical structures and also by landing or perching on flat, inclined, or vertical surfaces using only a monocular camera and an appropriate gripper for each specific case. The challenges of visual servoing are discussed, and we focus on the problems of relative pose estimation, control, and trajectory planning for maneuvering a robot with respect to an object of interest. Experimental results demonstrate the proposed techniques. Finally, we discuss future technological challenges to achieve fully autonomous landing, perching, and grasping in more realistic scenarios.

9836-64, Session 11

Vision-based fast navigation of micro aerial vehicles (*Invited Paper*)

Giuseppe Loiano, Vijay Kumar, Univ. of Pennsylvania (United States)

Autonomous fast navigation of Micro Aerial Vehicles in 3D environments, requires to plan trajectories, control and identify the vehicle's state at high rates, using either absolute or relative asynchronous on-board sensor measurements. These have to be fused, exploiting different rates and statistical sensor properties.

In this work, we present techniques in the area of planning, control and visual-inertial state estimation for fast navigation of MAVs. We demonstrate how to solve on-board, on a small computational unit, the pose estimation, control and planning problems for MAVs, using a minimal sensor suite for autonomous navigation composed of a single camera and IMU. Additionally, we show that a consumer electronic device such as a smartphone can alternatively be employed in a similar way both as computation as sensing unit.

Experimental results validate the proposed techniques. Any consumer, provided with a smartphone, can autonomously drive a quadrotor platform at high speed, without GPS, by downloading an app, and concurrently build 3-D maps.

9836-65, Session 11

Inertial-optical flow for fast deployable UAVs (*Invited Paper*)

Stephan Weiss, Alpen-Adria-Univ. Klagenfurt (Austria)

Miniature Aerial Vehicles (MAVs) attract much attention when it comes to research and development of mobile robots suitable for navigation in 3D space. Besides GPS, visual-inertial methods become very popular to control

and navigate these platforms. Known landmarks or visual maps built during the mission serve for MAV localization in 6 Degrees of Freedom (DoF). Since landmarks are not always known in advance and the built maps are prone to errors, we base our approach on using optical flow which is free of any type of map or (feature) history. Feature matches in each two consecutive images together with inertial cues are sufficient to estimate four of the 6 DoF and additionally allows to estimate the metric 3D vector of the vehicle velocity. Failures in the optical flow reading are detected using probabilistic consistency tests. Due to the temporal independence, optical flow failures can then be mitigated by simply discarding the erroneous frames and taking the next available ones. Inertial cues effectively bridge these short gaps in visual update information. In addition to the control states like position, attitude and velocity, we estimate the calibration states such as the camera-IMU transformation and IMU biases of the system online. We demonstrate that this not only creates a self-calibrating system for long-duration missions but also allows a quick system initialization without prior calibration procedures for fast platform deployment by unexperienced users: We dub this a throw-and-go MAV.

9836-66, Session 11

Multi-sensor fusion techniques for state estimation of micro air vehicles (*Invited Paper*)

Daniel Donavanik, Gregory Gremillion, Ryan M. Robinson, Joseph K. Conroy, William D. Nothwang, U.S. Army Research Lab. (United States)

Aggressive flight of micro air vehicles (MAVs) in unstructured, GPS-denied environments poses unique challenges for estimation of vehicle pose and velocity due to the noise, delay, and drift in individual sensor measurements. Maneuvering flight at speeds in excess of 10 m/s creates additional challenges even for active range sensors; in the case of LIDAR, an assembled scan of the vehicle's environment will in most cases be obsolete by the time it is processed. Multi-sensor fusion techniques which combine inertial measurements with passive vision techniques and/or LIDAR have achieved breakthroughs in the ability to maintain accurate state estimates without the use of external positioning sensors such as VICON. In this paper, we survey algorithmic approaches to exploiting sensors with a wide range of nonlinear dynamics using extended Kalman filter (EKF) and novel factor graph-based approaches for state estimation and optimal control. From this foundation, we propose a biologically-inspired framework for incorporating the human operator in the loop as a privileged sensor.

9836-67, Session 12

Human-machine Teaming for Effective Estimation and Path Planning (*Invited Paper*)

Michael J. McCourt, Univ. of Florida (United States); Siddhartha S Mehta, University of Florida (United States); Emily A Doucette, J. Willard Curtis, Air Force Research Laboratory (United States)

While traditional sensors provide accurate measurements of quantifiable information, humans often provide better assessments of qualitative information and holistic assessments. Sensor fusion approaches that team humans and machines can take advantage of the benefits provided by each while mitigating the shortcomings. These two sensor sources can be fused together using Bayesian fusion, which assumes that there is a method of generating a probabilistic representation of the sensor measurement. In the case of human sensors, training data can be used to generate a probability density function from all possible qualitative sensor measurements.

This general framework of fusing estimates can also be applied to joint human-machine decision making. In the simple case, binary decisions

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can be fused by using a probability of a positive action versus a negative action from each sensor source. These are fused together to arrive at a final probability of a positive action, which can be taken if above a specified threshold. In the case of path planning, rather than binary decisions being fused, complex decisions can be fused by allowing the human and machine to interact with each other's suggested paths to improve them. For example, the human can draw a suggested path while the machine planning algorithm can refine it to avoid obstacles and remain dynamically feasible. Similarly, the human can revise a suggested path to achieve secondary goals not encoded in the algorithm such as avoiding dangerous areas in the environment.

9836-68, Session 12

Dynamic inverse models in human-cyber-physical systems *(Invited Paper)*

Ryan M. Robinson, U.S. Army Research Lab. (United States); Dexter Scobee, Univ. of California, Berkeley (United States); Samuel A. Burden, Univ. of Washington (United States); S. Shankar Sastry, Univ. of California, Berkeley (United States)

Human interaction with the physical world is increasingly mediated by automation. This interaction is characterized by dynamic coupling between robotic (i.e. cyber) and neuromechanical (i.e. human) decision-making agents. Guaranteeing performance of such human-cyber-physical systems will require predictive mathematical models for this dynamic coupling. Toward this end, we propose a rapprochement between robotics and neuromechanics premised on the existence of internal models in the human agent. We hypothesize that, in telerobotic applications of interest, a human operator learns to invert automation dynamics by directly translating from desired task to required control input. By formulating the model inversion problem in the context of a tracking task for a nonlinear control system in control-affine form, we derive criteria for exponentially memoryless tracking and show that the resulting dynamic inverse model generally renders the physical system state unobservable from the human operator's perspective. Under stability conditions, we show that the human can achieve exponentially memoryless tracking without formulating an estimate of the system's state so long as they possess an accurate model of the system's dynamics. We then demonstrate that the automation can intervene to improve performance of the tracking task by solving an optimal control problem. Performance is guaranteed to improve under the assumption that the human performs dynamic model inversion, regardless of how this inversion is achieved. We illustrate these theoretical results using a teleoperation testbed wherein human subjects control a simulated quadrotor to execute a tracking task. Lastly, we conclude with a discussion of the implications for real-world applications that accommodate human performance limitations.

9836-69, Session 12

Human assisted robotic exploration *(Invited Paper)*

Benjamin T. Files, Jonroy D. Canady, U.S. Army Research Lab. (United States); Garrett Warnell, Computational and Information Sciences Directorate, Army Research Laboratory (United States); Ethan A. Stump, William D. Nothwang, Amar R. Marathe, U.S. Army Research Lab. (United States)

Distributed simultaneous localization and mapping (DSLAM) solutions are improved when loop closures are successfully detected, i.e. when an autonomous agent recognizes a location that was previously visited by itself or by another agent. Automated location recognition is an area of active research, but current solutions may be unreliable and expensive in terms of computation and communication. Here, we report on an experiment

showing that human location recognition is accurate, even with limited visual information.

Human participants were presented pairs of brief video clips recorded by autonomous exploration robots traversing a realistic urban environment. Pairs of video clips were presented in blocks by original recording length (2 levels: 180 and 360 frames at 30 frames per second) and down-sampling (2 levels: 3x and 6x). The ordering of clip types was counter-balanced across subjects so that effects of clip types could be examined separately from effects of learning. Clips were displayed in original color at a resolution of 320x280 pixels at 20 frames per second on a standard LCD monitor. Participants were asked to judge whether the clips were from the same or a different location by selecting strong non-match, weak non-match, weak match, or strong match. From these responses the area under the receiver operating characteristic (Az) was calculated for each clip type.

Performance is generally good even with the lowest frame density tested. Moreover, extended experience with a particular environment does not appear to be necessary for good performance. Significant variability across subjects was observed; individual variability could potentially be leveraged in future work. An additional set of participants did this experiment with simultaneous EEG and eye tracking in order to derive additional predictors of successful loop closure detection. The conclusion from the behavioral results is that incorporating humans into DSLAM solutions could increase the accuracy and reduce the cost when solving the loop closure problem.

9836-70, Session 12

Analysis of trust in autonomy for convoy operations *(Invited Paper)*

Gregory Gremillion, U.S. Army Research Lab. (United States); Jason S. Metcalfe, DCS Corp. (United States); Amar R. Marathe, U.S. Army Research Lab. (United States); Victor J. Paul, U.S. Army Tank-Automotive and Armaments Command (United States); James C. Christensen, Air Force Research Lab. (United States); Kim Drnec, U.S. Army Research Lab. (United States); Benjamin A. Haynes, U.S. Army Tank Automotive Research, Development and Engineering Ctr. (United States); Corey Atwater, DCS Corp. (United States)

The growing use of autonomous agents in civilian and military contexts introduces increasing need for effective human-autonomy collaborations. A major factor in determining the efficacy of human-autonomy teams is the human operator's level of trust in the autonomous agent. Deviations in the level of human trust in autonomy (TiA) away from the optimum can have significant detrimental effects on team performance. Specifically, a lack of TiA can lead to complete disuse of the autonomy, while excess trust can produce complacency, yielding a nearly unsupervised autonomous system. Failures therefore arise from TiA at either extreme. This work investigates human TiA in the context of an autonomy-assisted driving convoy-operations task, with the eventual goal of developing a feedback mechanism to appropriately modulate the human TiA level to yield improved team performance. In this experiment, human subjects performed a simulated driving task with an autonomous driving assistant in a leader-follower scenario. The subjects had control over the engagement of an autonomous lane keeping and active cruise control system of varying performance levels. A simultaneous button-press task was performed by the subjects to increase workload and thus encourage use of the autonomy in the driving task. Analysis of the experimental data was performed to identify contextual features of the simulation environment that correlated to instances of autonomy engagement and disengagement. Furthermore, inappropriate TiA levels were identified in the subject trials using estimates of momentary risk and agent performance, as functions of these contextual features. Inter-subject and intra-subject trends in autonomy usage and performance were also identified. This analysis indicated that for poorer performing autonomy, TiA decreases with time, while higher performing autonomy induces less drift toward diminishing usage. Subject use of autonomy is also largely influenced by course features, with higher usage in straightaways and

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decreasing usage as turn radius decreases, especially when lane keeping autonomy is utilized. Additionally, an autonomy level with both lane keeping and active cruise control is less likely to be used than an autonomy with only active cruise control. Future efforts will focus on utilizing physiological and behavioral measurements that were simultaneously collected during the experiment to identify biological antecedents to autonomy toggling for estimation and prediction of the underlying human trust state.

9836-71, Session 12

Measurement and inference of trust in driving autonomy as a function of reliability and workload using the ride motion simulator (*Invited Paper*)

Benjamin A. Haynes, Victor J. Paul, U.S. Army Tank Automotive Research, Development and Engineering Ctr. (United States)

The Measurement and Inference of Trust in Driving Autonomy as a function of Reliability and Workload experiment was conducted as a joint effort between the U.S. Army TARDEC's Ground Vehicle Simulation Laboratory (GVSL), The Army Research Laboratory-Human Research and Engineering Directorate (ARL-HRED), Air Force Research Laboratory (AFRL), and DCS Corporation. The experiment was conducted on the TARDEC's Ride Motion Simulator (RMS) in which participants completed driving and driving aid interaction tasks. The goal of this research is to determine how Trust in Autonomy (TiA), as reflected in measures of physiological and psychological state, varies with automation type and reliability. For instance, it is expected that a subject's trust will vary according to both the perceived reliability of the autonomy as well as the workload involved in the task. As such, we aim to identify relationships between these variables and computationally determined "states" (i.e. clustered or correlated values of individual variables) that enable prediction of the influence of task context on TiA and performance. These relationships are key to understanding the use of the human as a sensor in autonomous systems. An experiment based on the capabilities of the TARDEC RMS as a full featured driving simulator was designed and executed to collect qualitative and quantitative feedback, including eye-tracking, Electroencephalography, and simulation and driving characteristics and participant surveys. This report covers the test methodology, and execution. Analysis of the data is currently ongoing by AFRL and ARL-HRED and not presented here.

9836-72, Session 12

An efficient fusion approach for combining human and machine decisions (*Invited Paper*)

Hyungtae Lee, Heesung Kwon, Ryan M. Robinson, William D. Nothwang, Amar R. Marathe, U.S. Army Research Lab. (United States)

A novel approach for the fusion of heterogeneous object detection methods is proposed. In order to effectively integrate the outputs of multiple detectors, the level of ambiguity in each individual detection score is estimated using the precision/recall relationship of the corresponding detector. The main contribution of the proposed work is a novel fusion method, called Dynamic Belief Fusion (DBF), which dynamically assigns probabilities to hypotheses (target, non-target, intermediate state (target or non-target)) based on confidence levels in the detection results conditioned on the prior performance of individual detectors. In DBF, a joint basic probability assignment, optimally fusing information from all detectors, is determined by the Dempster's combination rule, and is easily reduced to a single fused detection score. Experiments on ARL and PASCAL VOC 07 datasets demonstrate that the detection accuracy of DBF is considerably greater than conventional fusion approaches as well as individual detectors

used for the fusion. Performance in integrating human perception ability with the detectors is also presented.

9836-73, Session 12

Image triage from EEG recordings using deep convolutional networks (*Invited Paper*)

Jared Shamwell, U.S. Army Research Lab. (United States)

We applied convolutional neural networks (CNNs) to the classification of single-trial target and non-target image presentations during a rapid serial visual presentation (RSVP) triage task. The low SNR of EEG inherently limits the accuracy of single-trial classification and when combined with the high dimensionality of EEG recordings, extremely large training sets are needed to prevent over fitting and achieve accurate classification from raw EEG data. To overcome these limitations, we implemented a novel feature extraction method to pre-process the raw EEG data and a CNN to classify target and non-target exemplars. We use a constrained, model-based dipole fitting method to map raw EEG data to a subspace of reduced dimensionality that corresponds to the anatomical structure of the brain. This map enables the application of task-specific heuristics that allow us to selectively extract features that correspond to brain regions believed most relevant for RSVP discrimination. Here we report results comparing this approach to other state of the art neural classification approaches.

9836-74, Session 13

Tensegrity robotics research at NASA Ames (*Keynote Presentation*)

Vytas SunSpiral, NASA Ames Research Ctr. (United States)

No Abstract Available

9836-75, Session 13

Soft wearable robotics for assisting mobility and manipulation (*Invited Paper*)

Christopher Atkeson, Carnegie Mellon Univ. (United States)

We describe some of the research on soft wearable robotics for assisting mobility and manipulation at Carnegie Mellon University. This includes work on inflatable structure and actuators, as well as a major emphasis on a range of sensors for robot skin. More information is available at www.cs.cmu.edu/~cga

9836-76, Session 13

Soft stimuli responsive untethered microbots (*Invited Paper*)

David H. Gracias, Johns Hopkins Univ. (United States)

Soft microrobots offer the possibility to create mechanized structures that have the touch and feel of biological organisms and structures. However there are significant challenges in the design, fabrication, energy harvesting and operation of soft microbots which are especially pronounced for untethered devices.

In the talk, I will describe results on the micro engineering of gradient cross-linked polymers and stimuli responsive hydrogels to realize devices such as micro grippers and sensors that actuate reversibly in response to stimuli such as temperature, pH, biomolecules and solvent exchange. Further, by combining these structures with magnetic nanoparticles or 2D

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layered materials, trackable and guidable microbots and sensors can be formed. I will discuss challenges in design of these differentially swelling materials to achieve large bandwidth and range of actuation. Further, I will highlight applications in sensing, drug delivery, closed-loop pick and place and surgery.

9836-77, Session 13

Soft robotics: from scientific challenges to technological applications *(Invited Paper)*

Cecilia Laschi, Scuola Superiore Sant'Anna (Italy)

Soft robotics is a recent and rapidly growing field of research, which aims at unveiling the principles for building robots that include soft materials and compliance in the interaction with the environment, so as to exploit so-called embodied intelligence and negotiate natural environment more effectively. Using soft materials for building robots poses new technological challenges: the technologies for actuating soft materials, for embedding sensors into soft robot parts, for controlling soft robots are among the main ones. This is stimulating research in many disciplines and many countries, such that a wide community is gathering around initiatives like the IEEE TAS TC on Soft Robotics and the RoboSoft CA – A Coordination Action for Soft Robotics, funded by the European Commission. Though still in its early stages of development, soft robotics is finding its way in a variety of applications, where safe contact is a main issue, in the biomedical field, as well as in exploration tasks and in the manufacturing industry. And though the development of the enabling technologies is still a priority, a fruitful loop is growing between basic research and application-oriented research.

9836-78, Session 13

System-level challenges in soft robotics *(Invited Paper)*

Cagdas D. Onal, Worcester Polytechnic Institute (United States)

As soft robotics becomes more popular with promising recent results, system integration remains an outstanding challenge. This talk will describe our research in the Worcester Polytechnic Institute (WPI) Soft Robotics Laboratory on theoretical modeling, design, fabrication, actuation, sensing, and control solutions for soft robotic systems. Inspired greatly by biology, we envision future robotic systems to embrace mechanical compliance with bodies composed of soft and hard components as well as electronic and sensory infrastructure, such that robot maintenance starts to resemble surgery. Our approach to enable these composite robotic bodies is to explore standardized design and fabrication techniques and processes. On the other hand, while offering many advantages in safety and adaptability to interact with unstructured environments, objects, and human bodies, mechanical compliance also violates many inherent assumptions in traditional robotics. Thus, a complete soft robot architecture requires new approaches to utilize accurate theoretical models that capture the nonlinear response of elastomeric materials, proprioception that provides rich sensory information while remaining flexible, and motion control under significant time delay. Our proposed solutions utilize analytical Ogden material models that predict motion and force output, composite magnetic deformation and force sensing, and sliding mode feedback control of soft actuation to address each of these issues. Multiple soft robotic systems covering a range of features and use cases will be presented to demonstrate and verify the proposed system integration techniques and solutions.

9836-79, Session 13

Next-generation soft wearable robots *(Invited Paper)*

Conor Walsh, Harvard School of Engineering and Applied

Sciences (United States)

Next generation wearable robots will use soft materials such as textiles and elastomers to provide a more conformal, unobtrusive and compliant means to interface to the human body. These robots will augment the capabilities of healthy individuals (e.g. improved walking efficiency, increased grip strength) in addition to assisting patients who suffer from physical or neurological disorders. This talk will focus on two different projects that demonstrate the design and fabrication principles required to realize these systems. The first is a soft exosuit that that can apply assistive joint torques to synergistically propel the wearer forward and provide support to minimize loading on the musculoskeletal system. Advantages of the suit over traditional exoskeletons are that the wearer's joints are unconstrained by external rigid structures, and the worn part of the suit is extremely light, which minimizes the suit's unintentional interference with the body's natural biomechanics. The second part of the talk will focus on the development of a soft robotic glove for hand rehabilitation that consists of a wearable textile with attached elastomeric fluid-powered actuators specially designed to match the natural movements of the fingers and thumb. A component of the research is to develop the knowledge and techniques required to design soft multi-material fluid-powered actuators. These actuators are of particular interest to the robotics community because they are lightweight, inexpensive, easily fabricated with emerging digital fabrication techniques and capable of producing complex three-dimensional outputs with simple control inputs. This is accomplished via a multi-step molding process where some combination of fillers (e.g. cloth, paper, particles and fibers) is integrated into a soft elastomeric matrix to create anisotropy in the bulk material properties. Upon pressurization, embedded channels or chambers in the soft actuator then expand in directions with the lowest stiffness and give rise to linear, bending, and twisting motions.

9836-80, Session 13

Sensors for soft robotics *(Invited Paper)*

Jamie Paik, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The latest wearable technologies within the scope of soft robotics have shown acute focus on improving the machine human interface. To achieve more sophisticated system, producing a comprehensive interface that can not only transfer various vital signals but also deliver feedback to the wearer is critical. Such advancement in the interface design requires robust solutions in realizing versatile and adaptable interface on soft and multi-degrees of freedom (DoF) working surface. Therefore, we are immediately confronted with strict mechanical parameter limitation in its flexibility and conformity without loosing any sensorial functionality compared to when they are placed on rigid and static surfaces.

In this talk I will describe how my lab has been solving such interface and sensor challenges. I will illustrate the design principle and the fabrication method of two distinctive sensor solutions and their experimental results. These sensors are not only distributable on substrate modules but are robust enough to undergo 30% overall strain.

Soft pneumatic actuator (SPA) embedded with piezoelectric (PZT) element can produce vibratory feedback while measuring high bandwidth input contacts. Due to its compact size (2 x 2 mm²) and the substrate design, they can eventually be distributed in large areas while measuring region specific contacts. I will also describe a sensor with high signal fidelity without drift and damping. The metal mesh-based sensor has a unique design that can be implemented in place of the PZT signals. I will also present how we control these sensors to minimize various errors for repeated application without time for recalibration.

9836-81, Session 13

Open loop adaptive robotic systems *(Invited Paper)*

Carl Vause, Soft Robotics, Inc. (United States)

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Adaptability and agility is considered one of the key traits necessary to enable the field of soft robotics has enabled new devices that bring a higher level of adaptability than traditional robotic systems while lowering the overall system complexity and eliminating the need for numerical computation. This is a paradigm shift whereby greater levels of agility are possible with reduced or no closed loop feedback systems. Through a synergistic combination of material science and fluid mechanics, open loop robotic actuators have been developed that enable robotic solutions in new application areas. Robotic applications. Traditionally robotic adaptability has been pursued through a combination of machine vision, complex mechanical design, sensor-based feedback and the utilization of computationally expensive algorithms. This talk will focus on current deployment of soft robotic systems in unstructured environments and a discussion of future areas of research.

9836-82, Session 13

Robot tongues in space: continuum surfaces for robotic grasping and manipulation (Invited Paper)

Ian Walker, Clemson Univ. (United States)

Grasping with traditional robots is currently largely achieved using simple parallel jaw gripper end effectors. However, the payloads and objects graspable with this technology are inherently restricted to scales and geometries which match those of the jaws of the grippers. In this paper, we introduce a novel continuously bending "robot tongue". We demonstrate its ability for unique and adaptive grasping of objects over a wide range of scales and geometries, and discuss the potential for use of such robot tongues in a variety of applications.

Continuously bendable and compliant robot tongues, focused in our research towards adaptive grasping in unstructured applications such as in Space, could also have potential terrestrial applications. Such adaptable robot end effectors could be highly useful in areas of defense and security, teleoperation in hazardous environmental conditions and even as an innovative option in traditional industrial automation.

A prototype continuum surface tongue was designed and constructed at Clemson University. The tongue was deployed (replacing the existing parallel jaw gripper) at the end of a KUKA industrial robot manipulator. The resulting system augments the precise positioning of the KUKA with unique capabilities for adaptive grasping afforded by the new robot tongue. The specifics of the new robot tongue design will be described and discussed in detail in the manuscript. We will illustrate the operation and potential applications of the new design via grasping and manipulation of a variety of objects, whose geometry would generally preclude grasping with traditional robot end effectors.

9836-83, Session 13

Moving beyond metal, the strength of soft machines (Invited Paper)

Kevin Albert, Pneubotics (United States)

Because they are easiest to understand and model, machines have until recently been almost exclusively constructed from stiff and rigid parts. We believe that a confluence of factors now makes it possible to shed this restriction and build machines that actively exploit the properties of soft materials. Such mechanisms promise to be dramatically cheaper, lighter, and more energy-efficient in construction and operation. They may therefore be better suited to tasks now performed by traditionally stiff machines, as well as enabling the automation of, or assistance with, tasks that were previously intractable. One of the attributes that is not frequently talked about is the strength of soft machines but, as we will explore, this is one of the key benefits of going soft. We will share our experience in building a new breed of robot that is both strong and gentle.

9836-84, Session 13

Active elastic skins for soft and wearable robots (Invited Paper)

Rebecca K. Kramer, Purdue Univ. (United States)

As advanced as modern machines are, the building blocks have changed little since the Industrial Revolution; structure, motors and gears are typically rigid, bulky and heavy. Future machines will be soft, elastically deformable and lightweight, lending them to applications such as soft robots, conformable wearable devices, and safe human-machine interfaces. Progress toward these next-generation soft machines is an interplay between the development of new soft active materials for actuation and sensing, adaptive controllers that will account for the non-linear and time-varying behaviors displayed by soft materials, and scalable manufacturing processes for soft materials. This talk will highlight the work of the Purdue Laboratory in developing processes, techniques, and tools for active elastic soft skins that will enable lightweight, compact, robust, and reconfigurable soft and wearable robots.

9836-102, Session PSWed

Bandgap engineering of graphene decorated with randomly distributed ZnO nano-seed

Chowdhury G. Al-Amin, Phani Kiran Vabbina, Mustafa Karabiyik, Raju Sinha, Nezh Pala, Florida International Univ. (United States)

We experimentally demonstrate bandgap opening of Graphene by decorating it with randomly distributed single crystalline ZnO nano-seeds. The ZnO nano-seeds were grown on top of single layer Graphene using Zinc acetate dihydrate ($Zn(O_2CCH_3)_2 \cdot 2H_2O$) (ZAD) by utilizing the effects of sonication to produce solution phase seeding in a solution exposed to the ambient. A 0.005M concentration of ZAD in isopropyl alcohol solution was prepared at room temperature. Single layer CVD Graphene grown on Copper sheet was transferred on SiO₂/Si substrate. 10 nm Ti and 100 nm Au were e-beam evaporated to pattern two contacts. The sample was cleaned with solvents before immersing into the solution. The solution with the immersed substrate then was irradiated using a commercially available high intensity ultrasound setup (750W ultrasonic processor, Sonics and Systems) for a single sonication cycles of 15 minutes duration and the amplitude of the 20 kHz ultrasonic probe was 75% of the maximum amplitude (-30 W.cm⁻²). The global temperature of the aqueous solutions did not exceed -70oC.

The Graphene and ZnO nano-seeds on Graphene were characterized by Raman spectroscopy using a 532 nm laser with a spot size of 1 μm². The 2-D/G ratio of Raman spectroscopy along with a peak at 432.39 cm⁻¹ confirmed the presence of single layer Graphene and ZnO on top, respectively. Also the Raman spectra of decorated Graphene sample confirmed a right-shift of G and 2-D peaks with respect to those of the undecorated one. The SEM image of the ZnO nano-seed decorated Graphene confirmed the average size of the nano-seeds to be ~ 10 nm. The AFM image of the decorated Graphene confirmed the RMS and average roughness of the surface to be 15.85 nm and 12.34 nm, respectively. The TEM data confirmed the single crystalline nature of ZnO nano-seeds.

To measure the bandgap of ZnO nano-seeds decorated Graphene, the temperature vs. conductivity of the samples were plotted (Arrhenius plot) and the slope was extracted. A commercially available vacuum probe station integrated with a precision thermal chuck and temperature control system, turbo pump and semiconductor parameter analyzer was used to measure the temperature vs. conductivity properties. At first, the current-voltage characteristics of the sample was measured inside a constant pressure (25 mBar) chamber at different temperatures starting from 0 oC to 110 oC with a step size of 5 oC, and at each temperature step, the sample was left for 5 minutes before the measurement was taken. A DC voltage was ramped starting from -500 mv to +500 mv with a step size of 10 mV,

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and both the hold time and delay time at each bias point were set at 20 ms. From the Arrhenius plot, slope was extracted and the bandgap was calculated to be 7.36 meV. The proposed method of bandgap opening can be further investigated varying nano-seed size, height, position with respect to Graphene (on top/bottom of Graphene) and density. Graphene with a moderate bandgap achieved by fine tuning this decoration process can be used for digital and logic devices.

9836-104, Session PSWed

Compact high-resolution micro-spectrometer on chip: spectral calibration and first spectrum

Thomas Diard, Florence de la Barrière, Yann Ferrec, Nicolas Guérineau, Sylvain Rommeluère, ONERA (France); Etienne P. Le Coarer, Guillermo Martin, Institut de Planétologie et d'Astrophysique de Grenoble (France)

There is a need for compact, hand-held, spectrometers for the measurement of spectral signatures of chemicals or objects. To achieve this goal, ONERA and IPAG have developed a new micro-spectrometer on chip operating in the visible spectral range with a high spectral resolution (near 2 cm⁻¹). It is directly inspired from the MICROSPOC infrared spectrometer, studied at ONERA in the past years. This spectrometer is made of a stair-step two-wave interferometer directly glued on a CMOS detector making it a very compact prototype. After calibrating the optical path difference, measurements of experimental spectra are presented.

9836-107, Session PSWed

Plasmonic resonance shift for various nanodevice geometries

David A. French, Stephen J. Bauman, Ahmad Darweesh, Desalegn Debu, Pijush K. Ghosh, Joseph B. Herzog, Univ. of Arkansas (United States)

Plasmonic nanodevices are metallic structures that exhibit plasmonic effects when exposed to light, causing scattering and enhancement of that light. These plasmonic effects make it possible for light to be focused below the diffraction limit. Dark-field spectroscopy has been used to capture the scattering spectra of these structures and examine the scattering and resonant frequencies of the devices. The geometries of the devices change which wavelengths of light are most readily able to couple to the device, resulting in a change in the wavelength of the scattered light. In this paper, we report our studies of the resonant frequencies produced by a variety of device geometries and configurations, including nanodiscs, nanowires, and plasmonic gratings. We also study double-width nanogap plasmonic gratings, created in our laboratory using a nanomasking technique. These new structures have features below the fabrication limit of electron-beam lithography, i.e. sub-10 nanometer features. We measured the polarization dependencies of these resonance modes and identified the relation between device geometry and wavelength. This allows the selection of geometry of the fabricated device based on the desired wavelength of light to be scattered. We also report preliminary results of our study of the device response and usefulness for surface-enhanced Raman spectroscopy.

9836-108, Session PSWed

Fractal aluminum Cayley trees to design a plasmonic ultraviolet photodetectors

Arash Ahmadvand, Raju Sinha, Mustafa Karabiyik, Serkan Kaya, Nezh Pala, Florida International Univ. (United States)

Plasmonic ultraviolet (UV) photodetectors have witnessed considerable enhancements in quantum efficiency and responsivity. Here, we go beyond regular plasmonic detectors by using periodic arrays of fractal aluminum nanostructures as Cayley trees deposited on various wide bandgap semiconductors including GaN, ZnO, Ga₂O₃ substrates to generate photocurrent. We show that the proposed aluminum Cayley trees are able to support and intensify strong broad plasmon resonant modes across the UV to the visible spectra. Investigating the plasmon response of aluminum nanostructures, it is shown that the Cayley trees can be tailored to facilitate strong absorption at high energies (short wavelengths), resulting with formation of hot electron-hole carriers. Having perfect comparability to operate at the UV spectrum, fractal aluminum structures and the substrates help increase the produced photocurrent at the terminal electrodes, remarkably. Presence of layer blue-shifts the peak of absorption to higher energies and helps to generate hot carriers at deeper UV wavelengths.

9836-109, Session PSWed

Novel fluidic packaging of gimbal-less MEMS mirrors for increased optical resolution and overall performance

Veljko Milanovic, Abhishek Kasturi, James Yang, Mirrorcle Technologies, Inc. (United States)

Two-axis quasistatic (point to point) MEMS mirrors with the ability to arbitrarily address and track targets and achieve uniform beam scanning for imaging have become established in a wide range of applications including 3D scanning, biomedical imaging, free-space communication, and short-range LiDAR. However, for many defense applications, the total Theta-D product (angle × mirror diameter), or optical resolution, of MEMS mirrors has not been large enough to address requirements for agile steering in large fields of regard and with a low beam divergence. Two key limitations have been the relatively low forces available in electrostatic combdrive actuators and the susceptibility of large-diameter MEMS mirrors to shock and vibrations.

In this work, we utilize special fluidic packages in which the driving portions of the MEMS mirror or the entire MEMS mirror device is immersed in a dielectric fluid with torque-increasing and damping properties. Replacing air in the rotating electrostatic combdrive actuators has an effect of nearly tripling the available torque, allowing for much stiffer MEMS supports. Furthermore, structural damping could be tuned to a nearly critically-damped point, reducing the overall quality factor of the device from almost 100 to below 1. The result is high tolerance for shock and vibrations, increased torque, increased beam stiffness, and increased mirror cooling. In the case of full device immersion, the increased scan angle due to the index of refraction of the fluid is an additional benefit. These numerous benefits of the fluidic packaging enabled us to double the previously achieved Theta-D product of two-axis quasistatic MEMS mirrors while still maintaining speeds applicable for many tracking, LiDAR, and related applications. This has been demonstrated with varied actuators and mirror sizes. One specific example is a mirror which achieves +/-8° of mechanical tip/tilt with a mirror diameter of 6.0mm with a 250Hz -3dB bandwidth.

The increased figure of merit does not change the compactness and low power-consumption of the MEMS-based beam-steering solution since the improved MEMS mirrors still consume <1mW in operation and drivers typically consume 100mW. The MEMS mirror PCB and its digital-input driver PCB are approximately 25mm x 25mm x 15mm in volume and weigh only <15g. One of the most exciting benefits of the packaging methodologies is that the damping dramatically increases shock and vibration tolerance. So far, units have passed 500G shock tests and are scheduled for testing at 1500G.

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9836-110, Session PSWed

Hybrid mode-locked fiber ring laser using graphene and charcoal nanoparticles as saturable absorbers

Hongyu Hu, Xiang Zhang, Wenbo Li, Niloy K. Dutta, Univ. of Connecticut (United States)

A fiber ring laser which implements hybrid mode locking technique has been demonstrated to generate pulse train at 20 GHz repetition rate. Graphene and charcoal nanoparticles acting as saturable absorbers are inserted in a rational harmonic mode-locked fiber laser to improve the performance. The pulse duration is shortened to ~ 3 ps, and the RF spectrum shows that noise is low in the presence of the saturable absorbers. Theoretical simulation of the pulse transmission has also been carried out using the split-step Fourier method.

9836-111, Session PSWed

Magnetic microsensor for harsh transportation applications

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the design of a magnetic microsensor for transportation applications in harsh environments. The sensor has a fast response and linear sensitivity to rapid external magnetic field variations. The structure of the sensor nullifies all odd harmonics and no magnetic filtering is being used. A Fourier analysis model is being used to process the sensor's output voltage. A Co-based implementation is presented using a new material previously unseen in magnetometric transportation applications. The choice of the material has increased significantly the response of the sensor to simulated abrupt magnetic field changing scenarios that are highly unlikely to occur during normal operation time and especially for ground-based transportation applications. Different sensor implementations have been tested and the optimum results are presented confirming that new reliable transportation applications can be realized.

9836-112, Session PSWed

Label-free water sensors using hybrid polymer-dielectric mid-infrared optical waveguides

Pao Lin, Texas A&M Univ. (United States)

A chip-scale mid-IR water sensor was developed using silicon nitride (SiN) waveguides coated with poly(glycidyl methacrylate) (PGMA). The label-free detection was conducted at $\lambda = 2.6\text{--}2.7 \mu\text{m}$ because this spectral region overlaps with the characteristic O-H stretch absorption while being transparent to PGMA and SiN. Through the design of a hybrid waveguide structure, we were able to tailor the mid-IR evanescent wave into the PGMA layer and the surrounding water and, consequently, to enhance the light-analyte interaction. A 7.6 times enhancement of sensitivity is experimentally demonstrated and explained by material integration engineering as well as waveguide mode analysis. Our sensor platform made by polymer-dielectric hybrids can be applied to other regions of the mid-IR spectrum to probe other analytes and can ultimately achieve a multispectral sensor on-a-chip.

9836-113, Session PSWed

MIRPHAB: a new European pilot line for mid-infrared devices fabrication

Thierry Robin, TEMATYS (France); Carlos Lee, EPIC

(France); Sergio Nicoletti, MINATEC (France)

The MIRPHAB (Mid InfraRed PHotonics devices fABrication for chemical sensing and spectroscopic applications) consortium will establish a pilot line to serve the growing needs of European industry in the field of analytical micro-sensors. The MIRPHAB Pilot Line is a 4-years Project supported by the European Commission through the Photonics PPP (Public Private Partnership).

Its main objectives are to: - provide a reliable supply of mid-infrared (MIR) photonic components for companies in particular QCL (Quantum Cascade Lasers), - reduce investment cost to access innovative MIR solutions for companies already active in the field of analytical sensors, but new to MIR photonics based sensing, - attract companies new to the field of analytical sensors, aiming to integrate micro-sensors into their products.

To fulfil those objectives, MIRPHAB is organized as a distributed pilot line formed by leading European industrial suppliers of MIR photonic components, complemented by first class European R&D institutes with processing facilities capable of carrying out pilot line production. MIRPHAB provides access to MIR photonic devices via mounted/packaged devices for laser-based analytical MIR sensors and to expert design for sensor components to be fabricated in the pilot line plus training services to its customers.

The platform will be organized such that new developments in MIR micro and integrated optic components and modules can be taken up and incorporated into the MIRPHAB portfolio.

MIRPHAB will become a sustainable source of key components for new and highly competitive MIR sensors, facilitating their effective market introduction and thus significantly strengthening the position and competitiveness of the respective European industry sector.

The partners of MIRPHAB are the following: CEA LETI, Fraunhofer Institutes: IAF, IPMS, & IPT, Nanoplus, Vigo System, IMEC, III-V Lab, Alpes Lasers, Norsk Elektro Optikk, CSTG, Quantared Technologies, CSEM, IQE, Cascade Technologies, MirSense, Phoenix BV, Robert Bosch, EPIC and TEMATYS.

In this paper, we will detail the MIRPHAB objectives, organization and roadmap.

9836-114, Session PSWed

Bias-tunable IR photodetector based on asymmetrically doped GaAs/AlGaAs double quantum well nanomaterial for remote temperature sensing

Xiang Zhang, Vladimir Mitin, Univ. at Buffalo (United States); Jae Kyu Choi, SK Hynix, Inc. (Korea, Republic of); Kimberly A. Sablon, Andrei Sergeev, U.S. Army Research Lab. (United States)

We fabricated multi-color IR photodetectors with asymmetrical doping of GaAs/AlGaAs double quantum wells (DQW) and measured spectral and noise characteristics at nitrogen temperatures. Dark current and responsivity of our devices are symmetrical and weakly dependent on the bias polarity because the asymmetry of doping compensates the effect of dopant migration in the growth direction. The bias voltage controls the electron distribution between the two wells in a DQW unit and in this way provides effective tuning of IR induced electron transitions. Therefore, the asymmetrical doping strongly enhances the selectivity and tunability of spectral characteristics by adjusting bias voltage. Spectral peaks contribution to photoresponse is shifted by varying the amplitude of negative or positive bias voltage: maximum detection wavelength moves from $7.5 \mu\text{m}$ to $11.1 \mu\text{m}$ by switching applied bias from -5 V to 4 V. Using the measured spectral characteristics we theoretically investigated the capability of temperature sensing. Modeling shows significant dependence of the photocurrent on the object temperature. We experimentally verified the feasibility of our devices for remote temperature sensing of the blackbody radiation from 300oC to 1000oC by measuring photoresponse in the range of -5 V to 5 V. The corresponding temperature sensitivity for our sensor at nitrogen temperature was found to be -0.2% per 1oC. Thus,

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our devices operating at nitrogen temperatures show the same sensitivity as complex multi-stack QWIP devices at helium temperatures. The interval of the measured temperatures can be broadened and/or changed by adjusting thickness of quantum wells, their separation and asymmetry of doping.

9836-85, Session 14

Single snapshot stand off detection using sub-microsecond tuning speed quantum cascade lasers (Keynote Presentation)

C. Kumar N. Patel, Pranalytica, Inc. (United States)

Grating tuned quantum cascade lasers have provided the needed tunable laser radiation covering $\sim 3.5 \mu\text{m}$ to $\sim 12.0 \mu\text{m}$ and are the commonly available systems because of the simplicity of construction and long history of grating tuned lasers covering UV, visible and infrared spectral regions. These systems, however, suffer from several critical disadvantages, including relative slow speed of scanning wavelengths or switching wavelengths, susceptibility to vibration and shock because of a macroscopic object, a diffraction grating, that needs to be angle tuned, and need for different gratings for covering different wavelength regions. There is an urgent need for fast tuning and ruggedness, which the grating tuned QCLs lack. In my presentation, I will describe a breakthrough in both of these areas, speed and ruggedness that we have achieved recently and which make the tunable QCLs extremely desirable for many practical applications that could not be addressed using the traditional grating tuned QCLs.

We have used acousto-optic modulator (AOM) for ultrafast tuning of QCLs. We have achieved wavelength switching speeds of $< 700 \text{ ns}$ for switching between any wavelengths within the lasing region of the quantum cascade laser. The switching speed is limited by the acoustic transit time through the optical beam traversing the AOM. In initial experiments we have demonstrated absorption measurements in $< 19 \mu\text{s}$ covering a wavelength scan of $> 1500 \text{ nm}$. The scan time is limited by the response time of the infrared detectors used in the demonstration. It is clear that the rapid switching and scanning capability opens up applications that are not accessible using traditional grating tuned QCLs.

Many spectroscopic applications require measurements of transient or rapidly changing spectra, such as in the study of combustion and explosion dynamics, the latter being very important for understanding and improving explosives. Many other applications require spectral data to be obtained in a finite, short period of time, such as standoff detection of IEDs and other suspicious objects from a platform that may be traveling at highway speeds. We have carried out initial demonstration of standoff detection of various substances that confirm the ability to identify targets in a single snapshot scan of $< 1 \text{ ms}$. The rapid detection of the signature of surface properties of IEDs and suspicious objects will provide the much needed protection in battlefield environments. I will present data for absorption measurements as well as standoff detection. The AOM tuned QCL systems, because they have no moving parts, are inherently rugged for applications in vibration prone environments such as when mounted on moving vehicles, aircraft and helicopters.

9836-86, Session 14

QCL-based standoff and proximal chemical detectors (Invited Paper)

Julia R. Dupuis, Joel M. Hensley, Bogdan R. Cosofret, Daisei Konno, Phillip Mulhall, Thomas Schmit, Shing D. Chang, Mark G. Allen, William J. Marinelli, Physical Sciences Inc. (United States)

The development of several longwave infrared quantum cascade laser (QCL) based surface contaminant detection platforms supporting government programs will be discussed. The detection platforms utilize reflectance spectroscopy with application to optically thick and thin materials including solid and liquid phase chemical warfare agents, toxic industrial chemicals

and materials, and explosives. Operation at standoff (10s of m) and proximal (1 m) ranges will be reviewed with consideration given to the spectral signatures contained in the specular and diffusely reflected components of the signal. The platforms comprise three variants: Variant 1 employs a spectrally tunable QCL source with a broadband imaging detector, Variant 2 employs an ensemble of broadband QCLs with a spectrally selective detector, and Variant 3 accomplishes spectral selectivity through a multi-heterodyne dual comb spectroscopy approach. Each variant employs a version of the Adaptive Cosine Estimator for detection and discrimination in high clutter environments. Detection limits of $10 \mu\text{g}/\text{cm}^2$ have been achieved through speckle reduction methods enabling detector noise limited performance.

Design considerations for QCL-based standoff and proximal surface contaminant detectors are discussed with specific emphasis on speckle-mitigated and detector noise limited performance sufficient for accurate detection and discrimination regardless of the surface coverage morphology or underlying surface reflectivity. Prototype sensors and developmental test results will be reviewed for a range of application scenarios. Future development and transition plans for the QCL-based surface detector platforms are discussed.

9836-87, Session 14

Broadband infrared imaging spectroscopy for stand-off detection of trace explosives (Invited Paper)

Christopher A. Kendziora, Robert Furstenberg, Michael R. Papantonakis, Viet Nguyen, Jeff M. Byers, R. Andrew McGill, U.S. Naval Research Lab. (United States)

We present the results of recent tests regarding standoff detection of trace explosives on relevant substrates using a mobile platform. We are developing a technology for detection based on active broadband infrared imaging spectroscopy. This approach leverages one or more micro-fabricated IR quantum cascade lasers, tuned to strong absorption bands in the analytes and directed to illuminate an area on a surface of interest. An IR focal plane array is used to image the surface response upon laser illumination. The broadband IR signal is processed as a hyperspectral image cube comprised of spatial, spectral and temporal dimensions as vectors within a detection algorithm. Increased sensitivity to explosives and selectivity between different analyte types is achieved by exploiting the surface response in the time domain. We have previously demonstrated standoff trace detection at several meters indoors and in field tests, while operating the lasers below the eye-safe intensity limit ($100 \text{ mW}/\text{cm}^2$). Sensitivity to explosive traces as small as a single grain ($\sim 1 \text{ ng}$) has been demonstrated. Analytes tested include RDX, TNT, ammonium nitrate and perchlorates. Relevant substrates include metal, plastics, glass and painted car panels.

References: C. Kendziora et al., in Laser-Based Optical Detection of Explosives, P. M. Pellegrino, E. L. Holthoff, and M. E. Farrell, eds. (CRC Press, 2015); C. Kendziora et al., Proc. of SPIE Vol. 9467 94672R (2015), C. Kendziora et al.; Proc. of SPIE Vol. 8709, 870900-1 (2013); R. A. McGill et al.; US Patent #8,101,915 B2 (2012). This research is sponsored by ONR/NRL.

9836-88, Session 14

Multi-modal, ultrasensitive detection of trace explosives using MEMS devices with quantum cascade lasers (Invited Paper)

Omid Zandieh, Seonghwan Kim, Univ. of Calgary (Canada)

Multi-modal chemical sensors based on microelectromechanical systems (MEMS) have been developed with an electrical readout. Opto-calorimetric infrared (IR) spectroscopy, capable of obtaining molecular signatures of extremely small quantities of adsorbed explosive molecules, has been realized with a microthermometer/microheater device using a widely

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tunable quantum cascade laser. A microthermometer/microheater device responds to the heat generated by non-radiative decay process when the adsorbed explosive molecules are resonantly excited with IR light. Monitoring the variation in microthermometer signal as a function of illuminating IR wavelength corresponds to the conventional IR absorption spectrum of the adsorbed molecules. Moreover, the mass of the adsorbed molecules is determined by measuring the resonance frequency shift of the cantilever shape microthermometer for the quantitative analysis. In addition, micro differential thermal analysis, which can be used to differentiate exothermic or endothermic reaction of heated molecules, has been performed with the same device to provide additional orthogonal signal for trace explosive detection and sensor surface regeneration. In summary, we have designed, fabricated and tested microcantilever shape devices integrated with a microthermometer/microheater which can provide electrical responses used to acquire both opto-calorimetric IR spectra and microcalorimetric thermal responses. We have demonstrated the successful detection, differentiation, and quantification of trace amounts of explosive molecules and their mixtures (trinitrotoluene (TNT), cyclotrimethylene trinitramine (RDX), and pentaerythritol tetranitrate (PETN)) using two orthogonal sensing signals which improve chemical selectivity.

9836-89, Session 14

**Imaging standoff trace detection
 of explosives using IR-laser based
 backscattering (Invited Paper)**

Frank Fuchs, Stefan Hugger, Jan P. Jarvis, Quankui K. Yang, Ralf Ostendorf, Christian Schilling, Wolfgang Bronner, Rachid Driad, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

Broadband tunable external cavity quantum cascade lasers (EC-QCL) have emerged as attractive light sources for mid-infrared (MIR) "fingerprint" spectroscopy for e.g. detection and identification of hazardous chemical compounds. We report on the use of EC-QCL for eye-safe standoff detection of explosives.

Imaging MIR backscattering spectroscopy has been shown to be a promising technique for non-contact detection of traces of explosives. Our laser-based imaging standoff spectroscopy system allows hyperspectral MIR image acquisition with 100 – 300 different spectral elements. Recording the backscattered light with a MIR camera at each illumination wavelength, the MIR backscattering spectrum can be extracted from the three-dimensional data set recorded for each spatial element within the laser illuminated area. Applying appropriate image analysis algorithms to this hyperspectral data set, chemically sensitive and selective images of the surface of almost any object can be generated. This way, residues of explosives can be clearly identified on the basis of characteristic fingerprint backscattering spectra and separated from the corresponding spectra of the underlying material. Using a MIR EC-QCL with a tuning range from 7.5 μm to 10 μm , detection of a large variety of explosives, e.g. TNT, PETN and RDX and precursor materials such as Ammonium Nitrate could be demonstrated. In a real world scenario stand-off detection over distances of up to 20 m could be successfully performed. This includes measurements in a post blast scenario demonstrating the potential of the technique for forensic investigations.

9836-90, Session 15

**Long-term operational testing of quantum
 cascade lasers (Invited Paper)**

Tanya L. Myers, Bret D. Cannon, Mark C. Phillips, Pacific Northwest National Lab. (United States); Carolyn S Brauer, Matthew S Taubman, Pacific Northwest National Lab (United States); Bruce E. Bernacki, Pacific Northwest National Lab. (United States)

We present the results of long-term operational testing of several quantum cascade laser (QCL) variants to illustrate their robustness and long lifetimes. The results from the several years' operation of a custom external cavity quantum cascade laser-based trace gas sensor are presented to highlight the reliable performance of QCL-based sensor systems. This sensor monitored the laboratory air for multiple chemicals and operated continuously for two years without any evidence of degradation in performance. The data from all of these experiments will be discussed to demonstrate the reliability and robust performance of QCLs.

9836-91, Session 15

**Monolithic design of quantum cascade
 lasers (Invited Paper)**

Kwok Keung Law, Naval Air Warfare Ctr. Weapons Div. (United States)

Quantum cascade lasers (QCLs) are increasingly incorporated into a variety of systems and sensing applications. Many advances have been made recently in mid-wave infrared and long-wave infrared quantum cascade lasers (QCLs) technologies. We will discuss in this presentation a portfolio of Navair's programs and efforts on significantly improving QCLs' performance, affordability and reliability by means of monolithic integrations.

9836-92, Session 15

**Recent progress in quantum cascade
 laser-based sources and systems for mid-
 infrared sensing applications (Invited
 Paper)**

Leigh J. Bromley, David B. Arnone, Daylight Solutions Inc. (United States); David B. Caffey, Daylight Solutions Inc (United States); William B. Chapman, Timothy Day, Allen Priest, Daylight Solutions Inc. (United States)

The presence of strong molecular absorptions in the mid-IR 'fingerprint' region is driving strong interest in a multitude of mid-IR-laser-spectroscopy-based sensing and imaging applications. Able to deliver high brightness, wide tuning, and narrow linewidth in compact form factors, quantum cascade laser (QCL)-based sources and sensor systems are ideally suited to meeting the requirements of mid-IR sensing applications. In this paper we survey recent advances in commercial sources and systems based on external cavity QCLs, and discuss sensing applications that benefit from these advances.

9836-93, Session 15

**Recent results on high-power and
 extended-tuning quantum cascade lasers
 (Invited Paper)**

Richard Maulini, Alfredo Bismuto, Stéphane Blaser, Tobias Gresch, Romain Terazzi, Yves Bidaux, Ilia Sergachev, Camille Tardy, Dana Turcinkova, Alpes Lasers SA (Switzerland)

We will present our latest results on high power and extended tuning quantum cascade lasers (QCLs). We report watt-level output power at wavelengths of 3.90, 4.55, 4.65, and 4.95 μm , from highly strained InGaAs/AlInAs QCLs processed in both ridge waveguide and buried heterostructure configurations and mounted epitaxial-side down on AlN submounts with AuSn solder. A maximum output power in excess of 3 W is observed at some wavelengths. We will compare the performance of these two types of

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devices, in terms of output power, wallplug efficiency, and beam quality, and discuss their respective advantages for volume production of high power QCLs. We also report extended tuning of single-frequency QCLs using integrated resistive micro-heaters. Emission frequency tuning in continuous-wave as large as 9 cm⁻¹ at 1270 cm⁻¹ and 14 cm⁻¹ at 2040 cm⁻¹ are observed, corresponding to an increase of the active region temperature of 90 K. Due to the close proximity of the heater to the active region, emission wavelength can be modulated at kHz frequencies with low drive power. The monolithic design without any moving parts guarantees the mechanical stability of the system.

9836-94, Session 16

High-power quantum cascade lasers and applications (*Invited Paper*)

Mariano Troccoli, AdTech Optics, Inc. (United States)

We will present our recent results on high power mid-IR generation from single-emitter QCL devices and discuss various applications related to the use of high power devices in the MWIR and LWIR ranges. We will address the different challenges associated with high power generation in the MWIR and LWIR spectral regions, usually identified with the 3-5um and 8-12um "spectral windows", respectively. In addition, besides their use as high power sources, the large nonlinearity associated with the inter-subband transitions of QC devices and the multi-stage engineering of the band structure makes QCLs a perfect tool for building multi-functional devices. Among the possible applications of band structure engineering are multi-wavelength and broadband emission, non-linear intra-cavity difference frequency generation for room temperature THz emission, double frequency generation, among others. Various applications of these approaches will be illustrated during the talk.

9836-95, Session 16

THz QCLs for heterodyne receivers and wavelength modulation spectroscopy (*Invited Paper*)

Alan W. Lee, Tsung-Yu Kao, Ian A. Zimmerman, LongWave Photonics LLC (United States); William T. Cole, Univ. of California, Berkeley (United States); Richard Thurston, University of California Berkeley (United States); Richard J. Saykally, Univ. of California, Berkeley (United States); Ningren Han, Qing Hu, Massachusetts Institute of Technology (United States)

On behalf of the SPIE DSS16 Micro-Nanotechnology Sensors, Systems, and Applications Conference committee, it gives me great pleasure to confirm your invited talk entitled, "THz QCLs for Heterodyne Receivers and Wavelength Modulation Spectroscopy," within the session on "Stand-off Detection," being organized by Dr. Michael Rafailov.

9836-96, Session 17

Technology trend in real-time uncooled image sensors for sub-THz and THz wave detection (*Keynote Presentation*)

Naoki Oda, NEC Corp. (Japan)

The author summarizes development of uncooled microbolometer focal plane arrays (FPAs) and real-time imagers for sub-THz and THz wave detection. The array formats are 320x240 and 640x480, and the imagers have several functions, such as lock-in imaging, external-trigger imaging, image processing (pixel binning and frame integration), beam profiling and

so forth. The FPAs are, roughly speaking, sensitive to sub-THz, THz and infrared regions.

Active imaging systems based on the imagers are described. One of them is a real-time transmission-type THz microscope which contains a THz imager and a quantum cascade laser (QCL). The other one is an active sub-THz imaging system which can easily be switched between a transmission imaging mode and a reflection imaging mode. Strong THz sources, such as far-infrared gas lasers and QCLs, are strongly coherent and often produce interference fringes in an image. A method of reducing the interference fringes is briefly presented, which employs Galvano mirrors.

Microbolometer FPAs developed by other groups, antenna-coupled CMOS FPA, array detectors based on GaAs high-mobility heterostructure and so forth are also summarized, which operate in real-time and at room temperature. A fair method of evaluating performance of detectors with different sizes and at different wavelengths is explained and the performances of the detectors are compared.

9836-97, Session 17

Recent developments in terahertz sensing technology (*Invited Paper*)

Michael S. Shur, Rensselaer Polytechnic Institute (United States)

Applications of terahertz sensing technology range from radio astronomy and earth remote sensing to non-destructive testing of VLSL, chemical analysis, explosive and mine detection, concealed weapons detection, moisture content determination, film uniformity and coating thickness control, structural integrity testing, and medical and biological applications. All these applications require efficient THz sources and sensitive detectors. I will discuss the potential from moving from the THz photonics technology to THz electronics for sensing applications. The well-established Schottky diode THz technology is now being augmented by high-speed THz transistor technology including Plasmonic FETs that demonstrated superior performance as room temperature THz detectors. New ideas of using van der Waals materials, such as graphene and MoS₂, involve using thin film transistors with and without grating gates, bilayer tunneling structures, and Hot Electron Transistors. This paper will review established and emerging applications of the THz sensing technology and will discuss emerging THz electronics for sensing applications.

9836-98, Session 17

System level challenges of THz and mm-wave imaging systems (*Invited Paper*)

Adrian J. Tang, Jet Propulsion Lab. (United States)

While THz and mm-wave imaging systems provide an interesting avenue for stand-off detection of concealed weapons and other threats without the need for ionizing radiation, there are many physical and technical obstacles which still prevent these systems from becoming commercially practical.

This paper describes the key tradeoff issues between power imaging and radar imaging including background masking and specular responses. Secondly for radar imaging, the paper discusses the tradeoffs between system parameters such as transmit power, receiver sensitivity and phase noise and how they affect corresponding physical behavior including aperture size, resolution, penetration and center frequency.

9836-99, Session 17

High effective THz-TDS method for the detection and identification of substances in real conditions (*Invited Paper*)

Vyacheslav A. Trofimov, Svetlana A. Varentsova, Vasiliy V. Tikhomirov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

As it is well-known, the detection and identification of explosives, drugs and other hazardous chemical and biological agents is one of the main security problems. To solve this problem, a THz radiation has been actively used during the past twenty years.

Currently, the standard method of the substance detection is a THz-TDS. The spectral characteristics (typically, these are substance absorption frequencies) of a substance under consideration are compared with standard absorption characteristic from the database and the identification is based on this comparison. Unfortunately, this method has obvious disadvantages. For example, many explosives have simulators - ordinary substances with the same absorption frequencies, which makes use of the THz-TDS method not effective enough. Opaque packaging, or substance surface inhomogeneity, and high humidity during the measurements also lead to low efficiency of this method. However, the THz-TDS method may be applicable with high efficiency for substance investigation in laboratory conditions.

In the present paper, we show fundamental limitations of the standard THz-TDS method for the detection and identification of substances in real conditions - at long distance of about 3.5 m and in ambient air with relative humidity of about 50% and in opaque material presence. For this purpose, we use a neutral substance - thick paper bag. Another example is the semiconductor identification in laboratory conditions - at short distance of about 30 cm and in dry air with relative humidity less than 2%. We show that the standard THz-TDS method detects the spectral features of hazardous substances in the neutral substances under consideration both in real and laboratory conditions.

9836-100, Session 17

Reflection imaging in the millimeter-wave range using a video-rate terahertz camera (*Invited Paper*)

Linda E. Marchese, Marc Terroux, Michel Doucet, Nathalie Blanchard, Ovidiu Pancrati, Alain Bergeron, INO (Canada)

The ability of millimeter waves (1-10 mm, or 30-300 GHz) to penetrate through dense materials, such as leather, wool, wood and gyprock, and to also transmit over long distances due to low atmospheric absorption, makes them ideal for numerous applications, such as body scanning, building inspection and seeing in degraded visual environments. Current drawbacks of millimeter wave imaging systems are they use single detector or linear arrays that require scanning or the two dimensional arrays are bulky, often consisting of rather large antenna-couple focal plane arrays (FPAs).

Previous work from INO has demonstrated the capability of its compact lightweight camera, based on a 384 x 288 microbolometer pixel FPA with custom optics for active video-rate imaging at wavelengths of 118 μm (2.54 THz), 432 μm (0.69 THz), 663 μm (0.45 THz), and 750 μm (0.4 THz). Most of the work focused on transmission imaging, as a first step, but some preliminary demonstrations of reflection imaging at these were also reported. In addition, previous worked also showed that the broadband FPA remains sensitive to wavelengths at least up to 3.2 mm (94 GHz). The work presented here demonstrates the ability of the INO terahertz camera for reflection imaging at millimeter wavelengths. Snapshots taken at video rates of obscured objects at near and approaching stand-off distances show the excellent quality of the images. This paper provides a description of the imaging system that includes the terahertz camera and millimeter source and an analysis of its sensitivity and resolving capability.

9836-101, Session 17

Antenna-coupled mmW staring arrays for imaging applications (*Invited Paper*)

Michael A. Gritz, Steven M. Lardizabal, Charles Wang, Leonard P. Chen, Robert Burkholder, Sean F. Harris, Raytheon Co. (United States)

Millimeter-wave (mmW)/sub-mmW/THz region of the electro-magnetic spectrum enables imaging thru clothing and other obscurants such as fog, clouds, smoke, sand, and dust. Therefore considerable interest exists in developing low-cost passive millimeter-wave imaging (PMMWI) systems. Previous PMMWI systems have evolved from crude mechanically scanned, single element receiver systems into very complex multiple receiver camera systems. Initial systems required many expensive mmW integrated-circuit low-noise amplifiers. In order to reduce the cost and complexity of the existing systems, attempts have been made to develop new mmW staring array focal plane arrays sensors employing direct detection arrays. In this presentation, we report on Raytheon's recent development of a W-band focal plane array technology. Raytheon's innovative approach enables low-cost production of 2D staring mmW focal plane arrays (mmW FPA), which not only have equivalent sensitivity and performance to existing millimeter wave systems, but require no mechanical scanning. We also present recently generated images of objects obscured under clothing.

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9837-1, Session 2

Non-GPS full position and angular orientation onboard sensors for moving and stationary platforms

Harbans S. Dhadwal, Jahangir Rastegar, Dake Feng, Philip Kwok, Omnitek Partners, LLC (United States); Carlos M. Pereira, U.S. Army Armament Research, Development and Engineering Ctr. (United States)

Angular orientation of both mobile and stationary objects continues to be an ongoing topic of interest for guidance and control as well as for non-GPS based solutions for geolocations of assets in any environment. Currently available sensors, which include inertia devices such as accelerometers and gyros; magnetometers; surface mounted antennas; radars; GPS; and optical line of sight devices, do not provide an acceptable solution for many applications, particularly for gun-fired munitions and for all-weather and all environment scenarios. We present a robust onboard full angular orientation sensor solution, which is based on a polarization scanning reference sources and polarized geometrical cavity orientation sensors. The full position of the object may also be independently determined using well known time-of-flight techniques.

Angular orientation and position of remotely located stationary or mobile assets in all-weather environments is an ongoing topic of research interests. High accuracy angle measurements in the mrad range are needed in many applications, particularly when measurements are to be made from relatively far distances. Such angular orientation measurements, particularly for stationary objects and about the direction of travel (roll angle in objects during the flight) is beyond the limits of existing techniques. Most angle measurement systems, suitable for all weather environments, essentially provide heading information and can provide resolutions of a few degrees. We present a solution, which combines a polarized geometrical cavity orientation sensors and scanning polarized reference sources, which has a demonstrated angular resolution of the order of 1 mrad.

The innovative design of the non-mechanical and fully electronic scanning reference source is described. With the present sensory system, direct measurement of angular orientation and position is made onboard the object in a coordinate system established by the scanning referencing sources. The sensor system provides a new non-GPS and non-inertial approach to angle measurements, with several key advantages over other methods including traditional phased-array antenna systems and the like. In this novel approach, the angular orientation information is coded into a time dependent pattern, which is insensitive to noise and while making the angle measurement independent of distance from the referencing sources. The manuscript presents design and analysis using a finite element based numerical solutions and supporting experimental measurement data taken in anechoic chamber are outdoors.

9837-2, Session 2

Optimal vehicle planning and the search tour problem

Thomas A. Wettergren, Naval Undersea Warfare Ctr. (United States); Matthew J. Bays, Naval Surface Warfare Ctr. Panama City Div. (United States)

We describe a problem of optimal planning for unmanned vehicles and illustrate two distinct procedures for its solution. The problem under consideration, which we refer to as the search tour problem, involves the determination of multi-stage plans for unmanned vehicles conducting

search operations. These types of problems are important in situations where the searcher has varying performance in different regions throughout the domain due to environmental complexity. The ability to provide robust planning for unmanned systems under difficult environmental conditions is critical for their use in search operations. The problem we consider consists of searches with variable times for each of the stages, as well as an additional degree of freedom for each stage to select from one of a finite set of operational configurations. As each combination of configuration and stage time leads to a different performance level, there is a need to determine the optimal configuration of these stages. When the complexity of constraints on total time, as well as resources expended at each stage for a given configuration, are added, the problem becomes one of non-trivial search effort allocation and numerical methods of optimization are required. We show two solution approaches for this numerical optimization problem. The first solution technique is to use a mixed-integer linear programming formulation, for which commercially available solvers can find optimal solutions in a reasonable amount of time. We use this solution as a baseline and compare against a new inner/outer optimization formulation. This inner/outer optimization compares favorably to the baseline solution, but is also amenable to adaptation as the search operation progresses. Numerical examples illustrate the utility of the approach for unmanned vehicle search planning.

9837-3, Session 2

Incremental learning in trust-based vehicle control

Robert E. Karlsen, Dariusz G. Mikulski, U.S. Army Tank Automotive Research, Development and Engineering Ctr. (United States)

In many multi-agent teams, entities fully trust their teammates and the information that they provide. But we know that this can be a false assumption in many cases, which can lead to sub-optimal performance of the team. In this paper, we build off of prior work in developing a simple model of estimating and responding to different levels of trust between team members. We have chosen to use a vehicle convoy application to generate data and test the operation of the trust estimation algorithm and its evolution. In the foundational work on the model, it was assumed that all team members had knowledge of the goals of the convoy, but, in more recent work, only the team leader (first vehicle in the convoy) knows the global goals of the convoy and the following vehicles must determine their level of trust and corresponding behavior response, based on observations of their immediate leader's performance, which may be different than that of the team leader. In this paper, we build on prior work and add more complex behaviors. For example, we recently implemented a simple learning algorithm for setting model parameters that is based on past performance. We expand on this simple model with a multi-resolution model that would weigh recent observations more highly than long past observations. We add some learning techniques to push the convoy towards higher performance when feedback mechanisms appear to be constraining the convoy to sub-optimal speeds. We also compare the performance of the existing model to other simple models of trust estimation.

9837-4, Session 2

Mobility versus terrain: a game theoretic approach

Paul L. Muench, David Bednarz, U.S. Army Tank Automotive Research, Development and Engineering Ctr.

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(United States)

Mobility and terrain are two sides of the same coin. You cannot describe mobility unless you describe the terrain. For example, if my world is trench warfare, the tank may be the ideal vehicle. If my world is urban warfare, clearing buildings and such, the tank may not be an ideal vehicle, perhaps an anthropomorphic robot would be better. We seek a general framework for mobility that captures the relative value of different mobility mechanisms. Game theory is positively the right way to analyze the interactions of rational players who behave strategically.

In this paper, we will describe the interactions between a mobility player, who is trying to make it from point A to point B with one chance to refuel, and a terrain player who is trying to minimize that probability by placing an obstacle somewhere along the path from A to B. In previous work, we used Monte Carlo methods to analyze this mobility game, and found optimal strategies for a discrete version of the game. Here we show the relationship of this game to a game of timing, and use solution methods from that literature to solve for optimal strategies in a continuous version of this mobility game.

9837-5, Session 2

Ant-based distributed protocol for coordination of a swarm of robots in demining mission

Floriano De Rango, Nunzia Palmieri, Univ. della Calabria (Italy)

Coordination among multiple robots has been extensively studied, since a number of practical real problem can be performed using a effective approach. In this paper it is investigated a collective task that requires a multirobot system to search for randomly distributed mines in an unknown environment and disarm them cooperatively. Communication among the swarm of robots influences the overall performance in terms of time to execute the task or consumed energy. To address this problem, a new distributed recruiting protocol to coordinate a swarm of robots in demining mission, is described. This problem is a multiobjective problem and two bio inspired strategies are used. The novelty of this approach lies in the combination of direct and indirect communication: on one hand an indirect communication among robots is used for the exploration of the environment, on the other hand a novel protocol is used to accomplish the recruiting and coordination of the robots for demining task. In the experiments, a wireless module for robot communication is used. If a mine is detected by a robot, it tries to recruit the others in its location in a minimum amount of time. This protocol attempts to tackle the question of how autonomous robots can coordinate themselves into an unknown environment relying on simple low-level capabilities. The strategy is able to adapt the current system dynamics if the number of robots or the environment structure or both change. The proposed approach has been implemented and has been evaluated in several simulated environments varying the dimension of swarm and complexity of tasks. We analyzed the impact of our approach in the overall performance of a robot team. Experimental results verify the effectiveness and efficiency of the proposed protocol to spread the robots in the environment.

9837-28, Session PSWed

An energy-efficient architecture for Internet of things systems

Floriano De Rango, Univ. della Calabria (Italy); Domenico Barletta, Alessandro Imbrogno, Spintel Inc. (Italy)

In this paper some of the motivations for energy-efficient communications in wireless systems are described by highlighting emerging trends and identifying some challenges that need to be addressed to enable novel, scalable and energy-efficient communications. So an architecture for internet of things systems is presented, the purpose of which is to minimize

energy consumption by communication devices, protocols, networks, end-user systems and data centers. Some electrical devices have been designed with multiple communication interfaces, such as RF or WiFi, using open source technology; they have been analyzed under different working conditions. Some devices are programmed to communicate directly with a web server, others to communicate only with a special device that acts as a bridge between some devices and the web server. Communication parameters, data size and device status have been changed dynamically according to different scenarios and specific quality of service required, such as the speed of response, in order to have the most benefits in terms of energy cost/quality ratio and to extend battery life. So the way devices communicate with the web server or between each other and the way they try to obtain the information they need to be always up to date change dynamically in order to guarantee always the lowest energy consumption, a long lasting battery life, the fastest responses and feedbacks and the best quality of service and communication for end users and inner devices of the system.

9837-30, Session PSWed

A fast and scalable content transfer protocol (FSCTP) for VANET-based architecture

Amilcare Francesco Santamaria, Francesco Scala, Cesare Sottile, Mauro Tropea, Pierfrancesco Raimondo, Univ. della Calabria (Italy)

In the modern Vehicular Ad-Hoc Network (VANET) based systems even more applications require lot of data to be exchanged among vehicles and infrastructure entities. Due to the mobility issues and unplanned events that may occurs it is important that contents should be transferred as fast as possible by taking into account consistence of the exchanged data and reliability of the connections. In order to face with these issues, in this work we propose a new transfer data protocol called Fast and Scalable Content Transfer Protocol (FSCTP). This protocol makes possible data transfer by using a bidirectional channel among content suppliers and receiver exploiting several cooperative sessions. Each session will be based on User Data Protocol (UDP) and Transmission Control Protocol (TCP) to send and manage data transfer. Often in urban area the VANET scenario is composed of several vehicle and infrastructures points. The main idea is to exploit ad-hoc connections between vehicles to reach content suppliers. Moreover, in order to obtain a faster data transfer more than one session is exploited to achieve a higher incoming rate. Of course it is important to manage data transfer between suppliers to avoid redundancy and resource wastages. The main goal is to instantiate a cooperative multi-session layer efficiently managed in a VANET environment exploiting the wide coverage area and avoiding common issues known in this kind of scenario. High mobility and unstable connections between nodes are some of the most common issues to address, thus a cooperative work between network, transport and application layers needs to be designed.

9837-31, Session PSWed

Implementation of a large solar collector for energy generation

Skye Leake, Thomas McGuire, Michael Parsons, Michael P. Hirsch, Jeremy Straub, Univ. of North Dakota (United States)

This paper evaluates the efficacy of using a parabolic mirror to concentrate solar flux for the purposes of power generation. This approach is compared to multiple other alternate approaches including the use of a similarly sized array of solar panels. Various uses for the concentrated flux are also considered, ranging from converting it to electric power using solar cells to using it to generate thermal energy directly. This evaluation is performed in the context of various (launch provider or otherwise imposed) constraints

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on space systems. Analysis of overall economic feasibility is performed with particular consideration to factors which impact the cost/benefit ratio. Factors under consideration include launch volume and mass, cost, efficiency once in a functioning configuration, and life expectancy. The comparative production time of the hardware for each approach is also considered.

Solar energy is conventionally harvested via solar panels. These panels receive the incident solar flux and provide an output of electric current; however, even leading solar panel technologies may lose two-thirds of the total flux energy to entropy (such as heat, which must be dissipated). Other approaches, however, are possible. With a large mirrored dish, solar energy can be collected, aimed and potentially utilized without conversion to electric charge and then to another type of energy required for the particular function, thus increasing efficiency by cutting out any intermediate steps. Potential target energy formats include thermal energy, electrical energy and kinetic energy.

However, the required mirrored solar concentrators are not without their own share of problems. Standard mirrored surfaces are inherently fragile (traditional solar power generations' photovoltaic cells are also fragile) and can be bulky. Low cost alternatives to this exist, such as inflatable options for mirrored collectors. However these tend to be less efficient. As a result of the large amount of raw solar energy being processed thermal stability is a significant concern. Radiative cooling can be used to manage thermal input and separate radiators can be used to dissipate excess thermal energy.

To compare the different approaches, research on the efficiency of the various systems and system configurations is presented. Multiple case studies related to several applications (differing in the type of energy needed as output, its use and the amount of energy required) are used to comparatively assess the different systems/configurations. They are compared in terms of expense, mass, volume, fragility (and other logistical considerations), conversion loss levels, heat generation (and other byproducts). The cost/output ratio, efficiency of each array, and lifespan are also considered.

From this work, a decision making framework for power system / configuration selection is presented. The paper concludes with a discussion of the potential mission types that are prospectively enabled by the various technologies and the presentation of a roadmap to several technologies' implementation.

9837-32, Session PSWed

Comparison of gradient methods for gain optimization of a PD controller applied on a quadrotor system

Jinho Kim, Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States); Stephen A. Wilkerson, U.S. Army Research Lab. (United States)

Many mechanical and electrical systems have utilized the proportional-integral-derivative (PID) control strategy. The concept of PID control is a classical approach but it is easy to implement and yields a very good tracking performance. Unmanned aerial systems (UAS) are currently experiencing a significant growth in popularity. Due to the advantages of PID controllers, UAS' are implementing PID controllers for improved stability and performance. An important consideration for the system is the selection of PID gain values in order to achieve a safe flight and successful mission. There are a number of different algorithms that can be used for real-time scheduling of gains. This paper presents two algorithms for gain scheduling, and are based on the method of steepest descent and Newton-Raphson minimization of an objective function. This paper compares the results of applying these two gain scheduling algorithms in conjunction with a PD controller on a quadrotor system.

9837-33, Session PSWed

LiPo battery energy management for improved flight performance of unmanned aerial systems

Kevin Chang, Univ. of Maryland, Baltimore (United States); Mark L. Bundy, Stephen A. Wilkerson, U.S. Army Research Lab. (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

Energy storage is one of the most important determinant of how long and far an electric powered unmanned aerial system (UAS) can fly. In the case of multi-rotors, lithium polymer (LiPo) batteries are the most commonly used form of energy storage due to their high energy density and high power output. However, even with the most advanced LiPo batteries, electric UAS mission plans are often dictated by the flight time of the vehicle. In most scenarios, this is generally limited to upwards of 30 minutes before battery protection measures activate and the craft must land. This paper addresses this problem by proposing a method of system identification and modeling of energy storage in electric UAS' to allow for energy storage to be used more effectively in planning autonomous missions. To achieve this, a set of experiments were designed to measure the energy consumption of a mid-size UAS multi-rotor. Several different flight maneuvers were considered: different lateral velocities, climbing, and hovering. The goal of this paper was to create a set of data that allowed each flight maneuver to be characterized with a certain rate of energy usage. Experimentation results demonstrate the feasibility and robustness of the proposed approach. Future work includes the development of mission planning algorithms that provide realistic estimates of possible mission flight times given a certain set of flight parameters.

9837-34, Session PSWed

Mathematical modeling and system identification of electric motors for unmanned systems

David Hanlon, Univ. of Maryland, Baltimore County (United States); Stephen A. Wilkerson, U.S. Army Research Lab. (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

Electric motors are becoming increasingly popular for the propulsion and control of unmanned systems. In order to optimize power generation and energy use for unmanned systems, it is important to understand the dynamics of electric motors and the corresponding powertrain. This paper studies commonly used electric motors for small unmanned ground and aerial systems. Mathematical models are derived for the most common types of motors, and system identification is performed using an electric dynamometer. The mathematical models are compared with experimental data, and verified in the laboratory setting. Future work will look at implementing the mathematical models in an unmanned ground system built for experimentation.

9837-6, Session 3

A new application for analyzing driving behaviour and environment characterization in transportation systems based on a fuzzy logic approach

Peppino Fazio, Amilcare Francesco Santamaria, Floriano De Rango, Mauro Tropea, Univ. della Calabria (Italy)

The physical security in transportation systems is becoming a serious

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issue in the last years, given the high number of accidents and emergency situations. With the huge arising of technological applications availability in vehicular environments, many efforts have been given in the scientific world, aimed at minimizing the probability of road accidents. In this paper, we propose a new platform able to discover dangerous driving behaviors. We based our application on the on-board diagnosis standard, able to provide all the needed information directly from the electronic control unit of the vehicle. The main goal of this work is represented by the characterization of the different driving styles in various environments, with the possibility of highlighting potentially dangerous behaviors. Our approach is based on the deployment of a Smart-Device (SD, a phone, a tablet, etc.) to acquire, process data and perform the characterization (nowadays, at least one SD is present in a vehicle). We integrated the received data with a fuzzy logic approach, obtaining a description of how the driver is behaving. In particular, for our purposes and to identify a particular driving style, we first need to pick out the environment in which the driver is located (such as urban, suburban or highway). The identification can be made by performing a statistical analysis on the speed data, acquired experimentally from the SD and the OBD-II. The overall system can take several initiatives (alarms, rpm corrections, etc.), in order to notify the bad behavior of the driver.

9837-7, Session 3

Probabilistic monitoring in intrusion detection module for energy efficiency in mobile ad hoc networks

Floriano De Rango, Andrea Lupia, Univ. della Calabria (Italy)

Two of the main issues regarding the Mobile Ad-hoc Networks (MANETs) are the security and the energy consumption. The communication through the wireless medium and the lack of an infrastructure lead to the chance of interfering in the communication among the nodes participating in the network by malicious agents. The nodes have limited amount of available energy to communicate each other, and the adoption of security measures introduces an increase in the energy consumption. Our work takes into account the relationship between these two issues, proposing an innovative approach in the security management through an energy-efficient Intrusion Detection System (IDS) based on a Trust Management Scheme (TMS). The monitoring operations needed to secure the communication between the nodes follow a probability function depending on the trust value of the nodes composing the route to the destination, reducing the usage of the promiscuous mode of the wireless interface and therefore the energy consumption of the nodes. We identified the constraints that need to be satisfied in order to keep an effective IDS, so our proposal dynamically tunes the parameters of the TMS obtaining the lowest possible energy consumption without damaging the effectiveness of the IDS. The results obtained through many simulations confirm the goodness of our approach, showing a decrease in the energy consumption maintaining the same effectiveness in malicious agents detection against the standard approach that monitors each transmitted packet.

9837-8, Session 3

Human guidance of mobile robots in complex 3D environments using smart glasses

Ryan Kopinsky, Aneesh Sharma, Nikhil Gupta, Camilo Ordonez, Emmanuel G. Collins, Florida State Univ. (United States); Daniel J. Barber, Univ. of Central Florida (United States)

In order for humans to safely work alongside robots in the field, the Human-Robot Interface (HRI), which enables bi-directional communication between human and robot, should be able to quickly and concisely express the robot's intentions and needs. While the robot operates mostly in

autonomous mode, the human should be able to intervene to effectively guide the robot in complex and/or risky scenarios. Finally, the HRI should enable the human and robot to form more of a peer-based relationship as opposed to the traditional hierarchical relationship.

While recent research [1] has focused on tablet-based interfaces, our research explores the use of smart glasses such as Google Glass to aid in HRI tasks. By using smart glasses, we seek to improve human guidance of mobile robots in complex environments while reducing interaction time and distractions during interaction with the robot. The current prototype utilizes Google Glass and the Husky platform from ClearPath Robotics. The user (i.e. soldier) can command the robot to follow a planned trajectory, abort the mission, and learn the model of the interaction between the terrain and the wheels or legs. In addition, the user can conveniently view mission critical information in real-time on the Heads Up Display (HUD) of Google Glass.

In order to compare the performance and effectiveness of smart-glass based HRI with tablet-based and more traditional teleoperated systems, several metrics are used. Interaction time is an important metric which is measured for a set of different scenarios. In addition, distraction during focus-critical missions is quantified.

[1] Barber, D., Abich IV, J., Phillips, E., Talone, A., Jentsch, F., Hill, S. (2015). Field assessment of multimodal communication for dismounted human-robot teams. In the proceedings of the 59th Human Factors and Ergonomics Society Annual Meeting.

9837-10, Session 3

Planning energy-efficient bipedal locomotion on patterned terrain

Ali Zamani, Pranav Bhounsule, Ahmad Taha, The Univ. of Texas at San Antonio (United States)

Energy-efficient bipedal walking is essential in realizing practical bipedal systems. However, current energy-efficient bipedal robots (e.g., passive-dynamics-inspired robots) are limited to walking at a single speed and step length—a significant research gap. Consequently, the objective of this work is to address this gap by developing a method of synthesizing energy-efficient bipedal locomotion on patterned terrain consisting of stepping stones using energy-efficient primitives.

A model of Cornell Ranger (a passive-dynamics inspired robot) is utilized to illustrate our technique. First, an energy-optimal trajectory control problem for a single step is formulated and solved. The solution minimizes the Total Cost Of Transport (TCOT) is defined as the energy used per unit weight per unit distance travelled) subject to various constraints such as actuator limits, foot scuffing, joint kinematic limits, ground reaction forces. The outcome of the optimization scheme is a table of TCOT values as a function of step length and step velocity. Next, we parameterize the terrain to identify the location of the stepping stones. Finally, the TCOT table is used in conjunction with the parameterized terrain to plan an energy-efficient stepping strategy.

9837-11, Session 3

High power free space optical link for rapid energy and data transmission

Harbans S. Dhadwal, Jahangir Rastegar, Philip Kwok, Omnitek Partners, LLC (United States)

Wireless transmission of power and data to local or remote devices and sensors is an ongoing challenge. For example, high precision motion control devices are traditionally powered by wiring harnesses attached to control electronics and power sources. While some of the control electronics can exploit wireless technology, the power delivery remains tethered. Detachment from tethers simplifies control circuitry and reduces weight and power requirements. Subsequently, enabling higher spatial resolution of the mobile platform. Energy needs remote sensors, other power sources are not available can be serviced by these types of photonic systems.

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Design and experimental data for a high power laser diode based free space point-to-point optical link is presented. In time critical power up applications, such as providing power and guidance information to a munition shell just prior to deployment, energy of the order of 100 J needs to be transferred in under 10 s. Current inductive technology is slow and broadcasts a radio-frequency signal which is undesirable for stealth operation. Rapid energy transfer times require high irradiance levels at the surface of the photovoltaic cells, typically, exceeding 1000X suns. Through efficient thermal design of heat sinks, high optical to electrical power conversion efficiencies of 50%, which are usually attainable at low power levels of 1 W, are achievable at these higher power levels (4 W). The result show that the energy transfer time is inversely proportional to the surface power density at a fixed short-circuit condition. Comparative data is presented for the two different type of photovoltaic cells power converters. One is a 16-cell array comprising of 2 mm 6V-PPC cells and the second is a single 1 cm² 2V PV cell.

9837-12, Session 4

Thermal polarization imager for road edge detection

David B. Chenault, Todd M. Aycock, Jonathan B. Hanks, Polaris Sensor Technologies, Inc. (United States)

Infrared polarization relies on surface temperature, roughness, material properties, aspect angle to the sensor, sky down-welling and background radiance reflecting from the target. Often times, the polarization signature of a manmade target is different than the surrounding background. Furthermore, that difference is often present even when the thermal signature of the same target blends into the background. Recent work has shown this to be true for paved and unpaved roads producing contrast enhancement between the road way, the edge of the road and obstacles. This phenomenology holds potential to significantly impact path planning and navigation functions for unmanned systems and to improve performance of perception and situational awareness

In this paper, we describe Pyxis, a microbolometer based imaging polarimeter that produces live polarimetric video of conventional, polarimetric, and fused image products. A polarization microgrid array integrated in the optical system captures all polarization states simultaneously and makes the system immune to motion artifacts of either the sensor or the scene. The system is battery operated, rugged, and weighs about a quarter pound. On board processing of polarization and fused images produce polarimetric signatures in real time. A top level description of Pyxis is given followed by performance characteristics and representative data of scenarios relevant to unmanned systems.

9837-13, Session 4

LWIR passive perception system for stealthy unmanned ground vehicle night operations

Daren Lee, Arturo L. Rankin, Andres Huertas, Jeremy Nash, Gaurav Ahuja, Larry Matthies, Jet Propulsion Lab. (United States)

Resupplying forward-deployed units in rugged terrain in the presence of hostile forces creates a high threat to manned air and ground vehicles. An autonomous ground vehicle (UGV) capable of navigating stealthily at night in off-road and on-road terrain for many kilometers from a safe landing zone could significantly increase the safety and success rate of such resupply missions for warfighters. Passive night-time perception of terrain and obstacle features is a vital requirement for such missions. As part of the ONR 30 Autonomy Team, the Jet Propulsion Laboratory developed a passive, low-cost night-time perception system under the ONR Expeditionary Maneuver Warfare and Combating Terrorism Applied Research program. Using a stereo pair of forward looking LWIR

uncooled VOX microbolometer cameras, the perception system generates disparity maps using a local window-based correlator to achieve real-time performance while maintaining a low power consumption profile. To overcome the lower signal-to-noise ratio and spatial resolution of LWIR thermal imaging technologies, a series of pre-filters were applied to the input images to increase the scene features. To overcome false positives generated by mixed pixels, noisy disparities from repeated textures, and uncertainty in far range measurements, a series of consistency, multi-resolution, and temporal based post-filters were employed to improve the fidelity of the output range measurements. The stereo processing leverages multi-core processors and runs under the Robot Operating System (ROS). The night-time passive perception system was tested and evaluated on fully autonomous testbed ground vehicles at SPAWAR Systems Center Pacific (SSC-Pac) and Marine Corps Base Camp Pendleton, California. This paper describes the challenges, techniques, and experimental results of developing a passive, low-cost perception system for night-time autonomous navigation.

9837-14, Session 4

Obstacles and foliage discrimination using LIDAR

Daniel D. Morris, Michigan State Univ. (United States)

A central challenge to autonomous off-road navigation is discriminating between obstacles that are safe to drive over and those that pose a hazard to navigation and so must be circumnavigated. Foliage, which can often be safely driven over, presents two important perception problems. First, foliage can appear as a large impenetrable obstacle, and so must be discriminated from other objects. Second, real obstacles are much harder to detect when adjacent to or partially occluded by foliage and tend to be misclassified if clustered with the nearby foliage.

This paper addresses both the discrimination of foliage, and the detection of obstacles among foliage using LIDAR. Our approach uses a generative model to explain sensor data including a statistical penetration model for foliage, a parts-based shape model for obstacles, and an range-error model for the measurements. This generative modeling accumulates probabilistic evidence for foliage and for multiple obstacle types in the vicinity of a moving platform. A discriminative model is trained to robustly fuse these multiple sources of evidence and obtain a reliable, real-time foliage discriminator and obstacle detector. Quantitative results are obtained, and a demonstration is shown of a robot populating a local traversability map with obstacles and regions of foliage.

9837-15, Session 4

Landmark-based robust navigation for tactical UGV control in GPS-denied communication-degraded environments

Yoichiro Endo, Jonathan Balloch, Alexander Grushin, Mun Wai Lee, David A. Handelman, Intelligent Automation, Inc. (United States)

Control of today's tactical unmanned ground vehicles (UGVs) is typically accomplished through two alternative modes of operations, namely, low-level manual control using joysticks and high-level planning-based autonomous control. Each mode has its own merits as well as inherent mission-critical disadvantages; low-level joystick control is vulnerable to communication delay and degradation, and high-level navigation often depends on uninterrupted GPS signals and/or emissive (non-stealth) range sensors such as LIDAR for localization and mapping. To address these problems, we have developed a mid-level control technique where the operator semi-autonomously drives the robot relative to visible landmarks that are commonly recognizable by both humans and machine such as closed contours and structured lines. Our novel solution relies solely on optical and non-optical passive sensors and can be operated under GPS-

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denied, communication-degraded environments. To control the robot using these landmarks, we developed an interactive GUI that allows the operator to select landmarks in the robot's view and direct the robot relative to one or more of the landmarks. The integrated UGV control system was evaluated based on its ability to robustly navigate through indoor environments. The system was also successfully field tested with QinetiQ North America's Tactical Robot Controller (TRC), a ruggedized operator control unit (OCU). We found that the proposed system is indeed robust against communication delay and degradation, and provides the operator with steady and reliable control of the UGV in realistic tactical scenarios.

9837-16, Session 5

Transitions for a dynamic multi-modal legged robot

Charles Carbiener, Charles Young, Max Austin, Jonathan Clark, Florida State Univ. (United States)

No Abstract Available

9837-17, Session 5

Linear and nonlinear optimal control methods for underactuated bipedal stance on a quadrupedal robot

Turner Topping, Vasileios Vasilopoulos, Avik De, Daniel E. Koditschek, Univ. of Pennsylvania (United States)

No Abstract Available

9837-18, Session 5

Running and obstacle traversal on Minitaur

Daniel Blackman, John Nicholson, Abby Brauer, Florida State Univ. (United States); Jonathan Clark, Univ. of Pennsylvania (United States)

No Abstract Available

9837-19, Session 5

Simulation tools for robotics research and assessment

MaryAnne Fields, Ralph Brewer, Harris L. Edge, Jason L. Pusey, U.S. Army Research Lab. (United States); Ed Weller, Dilip G. Patel, Charles A. DiBerardino, General Dynamics Land Systems (United States)

No Abstract Available

9837-20, Session 5

Interactive multi-objective path planning through a palette-based user interface

Meher T. Shaikh, Michael A. Goodrich, Daqing Yi, Joseph Hoehne, Brigham Young Univ. (United States)

In a problem where a human uses supervisory control to manage robot path-planning, there are times when human does the path planning, and if

satisfied commits those paths to be executed by the robot, and the robot executes that plan. In planning a path, the robot often uses an optimization algorithm that maximizes or minimizes an objective. When a human is assigned the task of path planning for robot, the human may care about multiple objectives. This work proposes a graphical user interface (GUI) designed for interactive robot path-planning when an operator may prefer one objective over others or care about how multiple objectives are traded off. The GUI represents multiple objectives using the metaphor of an artist's palette. A distinct color is used to represent each objective, and trade-offs among objectives are balanced in a manner that an artist mixes colors to get the desired shade of color. Thus, human intent is analogous to the artist's shade of color. We call the GUI an "Adverb Palette" where the word "Adverb" represents a specific type of objective for the path, such as the adverbs "quickly" and "safely" in the commands: "travel the path quickly", "make the journey safely". The novel interactive interface provides the user an opportunity to evaluate various alternatives (that trade-off between different objectives) by allowing her to visualize the instantaneous outcomes that result from her actions on the interface. In addition to assisting analysis of various solutions given by an optimization algorithm, the palette has additional feature of allowing the user to define and visualize her own paths, by means of way-points (guiding locations) thereby spanning variety for planning. The goal of the Adverb Palette is thus to provide a way for the user and robot to find an acceptable solution even though they use very different representations of the problem. Subjective evaluations suggest that even non-experts in robotics can carry out the planning tasks with a great deal of flexibility using the adverb palette.

9837-21, Session 5

Clustering social cues to determine social signals: developing learning algorithms using the "n-most likely states" approach

Andrew Best, Kate Kapalo, Samantha F. Warta, Stephen M. Fiore, Univ. of Central Florida (United States)

Human-robot teaming relies on the ability of machines to respond and relate to human social signals. Prior work in Social Signal Processing has drawn a distinction between cues (discrete, observable features) and signals (underlying meaning). For machines to attribute meaning to behavior, they must understand some probabilistic relationship between cues presented, and the potential signal being conveyed. An experiment was previously performed in which participants identified a set of salient social signals in a simulated scenario and indicated the cues related to the observed signals. In this paper, we detail a learning algorithm which uses this data to cluster social cue observations and define an "n most-likely states" set for each cluster. Since multiple signals may be co-present in a given simulation and a set of social cues often maps to multiple social signals, the "n most-likely states" approach provides a dramatic improvement over typical linear classifiers. We find that the target social signal appears in a "3 most-likely signals" set with an 80% probability. We detail our algorithm, our comparative results, and offer potential applications for robot social-signal detection and machine-aided human social signal detection.

9837-22, Session 6

A multimodal interface for real-time soldier-robot teaming

Daniel J. Barber, Univ. of Central Florida (United States); Thomas M. Howard, Univ. of Rochester (United States); Matthew Walter, Toyota Technological Institute at Chicago (United States)

Recent research and advances in robotics have led to the development of novel platforms leveraging new sensing capabilities for semantic navigation. As these systems becoming increasingly more robust, they support highly complex commands beyond direct teleoperation and waypoint finding

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facilitating a transition away from robots as tools to robots as teammates. Supporting future Soldier-Robot teaming requires communication capabilities on par with human-human teams for successful integration of robots. Therefore, as robots increase in functionality, it is equally important that the interface between the Soldier and robot advances as well. Multimodal communication (MMC) enables human-robot teaming through redundancy and levels of communications more robust than single mode interaction. Commercial-off-the-shelf (COTS) technologies released in recent years for smart-phones and gaming provide tools for the creation of portable interfaces incorporating MMC through the use of speech, gestures, and visual displays. However, for a multimodal interfaces to be successfully used in the military domain, they must be able to classify speech, gestures, and process natural language in real-time with high accuracy. For the present study, a prototype multimodal interface supporting real-time interactions with an autonomous robot was developed. This device integrated COTS Automated Speech Recognition (ASR), a custom gesture recognition glove, and natural language understanding on a tablet. This paper presents performance results (e.g. response times, accuracy) of the integrated device when commanding an autonomous robot to perform reconnaissance and surveillance activities in an unknown outdoor environment.

9837-23, Session 6

Technological evaluation of gesture and speech interfaces for enabling dismounted soldier-robot dialogue

Ravi Kiran Kattoju, Daniel J. Barber, Julian Abich IV, Jonathan T. Harris, Univ. of Central Florida (United States)

With increasing necessity for intuitive Soldier-robot communication in military operations and advancements in interactive technologies, autonomous robots have transitioned from assistance tools to functional and operational teammates that service an array of military operations. Despite improvements in gesture and speech recognition technologies, their effectiveness in supporting Soldier-robot communication is still uncertain. The purpose of the present study was to evaluate the performance of gesture and speech interface technologies to facilitate Soldier-robot communication during a simulated intelligence, reconnaissance and surveillance (ISR) mission. Gesture and speech semantically based spatial-navigation commands leveraged existing lexicons for visual and verbal communication from the U.S Army field manual for visual signaling and a previously established Squad Level Vocabulary (SLV). Visual signals were captured and classified using a custom wireless gesture glove and software. Speech commands were recorded by a Lapel microphone and Microsoft Kinect, and classified by commercial off-the-shelf automatic speech recognition (ASR) software. Participants in the experiment commanded a robot to complete a simulated ISR mission in a scaled down urban scenario by delivering a sequence of gesture and speech commands, both individually and simultaneously, to the robot. Performance and reliability of gesture and speech hardware interfaces and recognition tools were analyzed and reported. Analysis of experimental results demonstrated the employed gesture technology has significant potential for enabling bidirectional Soldier-robot team dialogue based on the high classification accuracy and minimal training required to perform gesture commands.

9837-24, Session 6

Learning object models from few examples

Ishan Misra, Yuxiong Wang, Martial Hebert, Carnegie Mellon Univ. (United States)

No Abstract Available

9837-25, Session 6

Incorporating polarization in stereo vision-based 3D perception of non-Lambertian scenes

Kai Berger, Rand Voorhies, Larry Matthies, Jet Propulsion Lab. (United States)

Specular and transparent surfaces are important classes of materials with non-Lambertian reflectance that are commonplace in urban areas. Many robotics applications will operate in urban areas, so it important to develop robotic perception systems that function well in the presence of such materials. Passive 3-D perception systems that do not explicitly allow for the presence of such materials perform poorly in these environments, and active ranging systems also have difficulty. This paper focuses on passive 3-D perception of specular scenes. Several techniques have potential to improve traditional stereo vision and structure from motion algorithms in this setting. We survey these possibilities, then focus on prospects for exploiting polarization phenomenology in this setting. Compact, relatively affordable cameras are now available that provide four simultaneously acquired channels of linear polarization filters, using micro-grid polarizers on a single focal plane. The measured angle of polarization at a pixel in the image constrains the corresponding surface normal in the scene to lie in the plane of the observed angle of polarization. This constraint can be incorporated into regularization-based stereo vision algorithms for 3-D reconstruction. We describe the theoretical foundations of this approach and present results to date on improving stereo vision-based 3-D perception of specular scenes by incorporating these constraints.

9837-26, Session 6

Improving image labeling using prior information

Ankit Laddha, Martial Hebert, Carnegie Mellon Univ. (United States)

No Abstract Available

9837-27, Session 6

Video-based convolutional neural networks for activity recognition from robot-centric videos

Michael S. Ryoo, Indiana Univ. (United States); Larry Matthies, Jet Propulsion Lab. (United States)

An ability to recognize human activities from a video input is very crucial for many robotics applications. It enables the robot to better understand the surroundings based on human actions and reactions (i.e., activity-level situation awareness) and also allow the robot to recognize intended activities targeting the robot by team members and other neutral/hostile individuals. In this paper, we discuss convolutional neural network (CNN)-based approach for human activity recognition. CNNs trained based on millions of images and videos (with the help from modern GPUs) are not only obtaining successful results in image-based object recognition but also are showing promising results on video-based activity recognition. Our objective is to investigate state-of-the-art CNN approaches and illustrate how they can be applied to robot videos. In particular, we investigate CNN architectures designed to capture temporal information in videos, including architectures with 3-D XYT convolutional filters, approaches using pooling operations on top of per-frame image-based CNN descriptors, and recurrent neural networks (RNNs) to learn temporal changes in per-frame CNN descriptors. We experimentally compare these different CNN approaches using first-person human activity videos, while especially focusing on those captured during human-robot interactions. Video datasets taken with wearable cameras and robot cameras are used for the experiments.?

Conference 9838: Sensors and Systems for Space Applications IX

Monday - Tuesday 18-19 April 2016

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9838-1, Session 1

Thinking telescopes: An autonomous robotic ecosystem for persistent space situational awareness and real-time response

W. Thomas Vestrand, Heath R. Davis, Przemek Wozniak, James Wren, Jeffrey J. Bloch, Eric Dors, Los Alamos National Lab. (United States)

We discuss the design and operation of a prototype telescope ecosystem called Thinking Telescopes that is designed to act as a fully autonomous Space Situational Awareness monitoring system. The system employs an ensemble of persistent full-sky monitors that scan the sky for space objects, recognize tracks in real time (and importantly, reject instrumental artifacts and non-satellite streaks such as airplanes and meteors), compare with properties of known space objects, and selects candidates for real time follow-up. The system then self-tasks itself to make interrogating observations with more powerful narrow field telescopes to obtain higher precision metric and photometric observations. The Thinking Telescopes system is designed to autonomously acquire LEO, MEO, HEO, or GEO satellite tracks, recognize anomalies, command higher precision measurements in real-time and report the results without prior tasking. This enables improved custody of objects and rapid recognition of photometric anomalies. The autonomous telescopes can also self-task and coordinate in real-time from geographically distributed sites to obtain, for example, range measurements with simultaneous parallax observations of space objects. The agility of autonomous systems, coupled with broad geographic distribution and a heterogeneous distribution of instrument capability, enables effective triage and a graduated response to SSA events of interest. The approach, which leverages new technology, offers an exciting, cost effective, approach with unique capabilities for space surveillance.

9838-2, Session 1

Accelerated space object tracking via graphic processing unit

Bin Jia, Kui Liu, Intelligent Fusion Technology, Inc. (United States); Khanh Pham, Erik Blasch, Air Force Research Lab. (United States); Genshe Chen, Intelligent Fusion Technology, Inc. (United States)

Space object tracking plays essential roles in communications, navigation, and observation. Many popular nonlinear filters have been used to estimate the positional state of the space object. In this paper, we focus on the particle filter due to its high accuracy in robust object tracking. The main drawback of the particle filter is that a large number of particles has to be maintained which leads to high computational demands. Hence, it is very inefficient when processed by conventional central processing unit (CPU). Fortunately, the trajectories of particles afford parallelized computations. Benefiting from this observation, we implement a classical particle filter using the graphic processing unit (GPU), such as the auxiliary particle filter with a simulated ground Electro-optical sensor tracking problem. The simulation results reveal that the particle filter implemented on the GPU is over 10x faster than that implemented on the CPU while maintaining the accuracy of a particle filter implemented on a CPU.

9838-3, Session 1

Investigating prior probabilities in a multiple hypothesis test for use in space domain awareness

Tyler Hardy, Stephen C. Cain, Air Force Institute of Technology (United States)

To goal of this research effort is to improve Space Situational Awareness (SSA) of current telescope systems through improved detection algorithms. Ground-based optical SSA telescopes are often spatially undersampled, or aliased. This fact negatively impacts the detection performance of traditionally proposed binary and correlation based detection algorithms. A Multiple Hypothesis Test (MHT) algorithm has been previously developed to mitigate the effects of the spatial aliasing. This is done by testing potential Resident Space Objects (RSO) against several sub-pixel shifted Point Spread Functions (PSF). A MHT has been shown to increase detection performance for the same false alarm rate. In this paper, the assumption of prior probability used in a MHT algorithm is investigated. First, an analysis of the pixel decision space is completed to determine alternate hypothesis prior probabilities. These probabilities are then implemented into a MHT algorithm tested against simulated RSOs. Results are reported with Receiver Operating Characteristic (ROC) curves and probability of detection, Pd, analysis.

9838-4, Session 1

Optical detection of closely spaced sources for improved space situational awareness

Patrick Cunningham, Stephen C. Cain, Air Force Institute of Technology (United States)

With the possibility of thousands of undetected pieces of space debris existing, it is possible for space debris to potentially damage or even destroy important space assets. Without the ability to detect these threats, we will have no way of initiating any kind of counter measure against them. Current detection methods are adept at locating a single object in space, as well as two objects that are greatly separated, but have difficulty finding a second object that is nearby. The problem is exacerbated if the second object appears much dimmer than the first object. This is because the point spread function of the brighter object can obscure that of the dimmer object, if they are in close proximity to one another.

The method proposed in this paper would work with the current method in that it waits for the current algorithm to detect something and then scans the area around it for a second object. In this case the algorithm looks at a pixel and determines how bright an object would be if there were an object in that pixel, then applies a binary hypothesis test to determine the probability that there an object of that brightness in the pixel, given the known object in its vicinity. In theory, this will have the greatest advantage over the original method when the objects are very close together or the second object is very dim. The algorithm has been tested on both simulated data and on a laboratory level test and outperformed the current method by a factor of up to three to one on measured data.

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9838-5, Session 1

A novel lightweight Fizeau infrared interferometric imaging system

Douglas Hope, Michael Hart, Olivier Durney, Stephen H. Warner, Robert C. Romeo, Hart Scientific Consulting International L.L.C. (United States)

Aperture synthesis imaging techniques using an interferometer provide a means to achieve imagery with spatial resolution equivalent to a conventional filled aperture telescope at a significantly reduced weight and cost, an important implication for air- and space-borne persistent observing platforms. These concepts have been realized in SIRII (Space-based IR-imaging interferometer), a new light-weight, compact SWIR and MWIR imaging interferometer designed for space-based surveillance. The sensor design is configured as a six-element Fizeau interferometer; it is scalable, light-weight, and uses structural components and main optics made of carbon fiber replicated polymer (CFRP) that are easy to fabricate and inexpensive. A three-element prototype of the SIRII imager has been constructed. The optics, detectors, and interferometric signal processing principles draw on experience developed in ground-based astronomical applications designed to yield the highest sensitivity and resolution with cost-effective optical solutions.

SIRII is being designed for detection of rocket plumes from geo-stationary orbit. It has an instantaneous 6 x 6 mrad FOV and the ability to rapidly scan a 6x6 deg FOV, with a minimum SNR that enables detection of solid and liquid fuel rocket plumes. The interferometric design can be scaled to larger equivalent filled aperture, while minimizing weight and costs when compared to a filled aperture telescope with equivalent resolution. This scalability in SIRII allows it address a range of IR-imaging scenarios.

9838-6, Session 2

COMSATCOM service technical baseline strategy development approach using PPBW concept

Tien M. Nguyen, The Aerospace Corp. (United States)

The U.S. Department of Defense (DoD) recently focused on modernizing existing space systems and development of new space systems using DoD and Congressional initiatives , Defense Innovation Initiative (DII), and Better Buying Power 3.0 (BBP 3.0) initiatives to improve innovation and acquisition efficiency. These initiatives impose four key requirements on the development of future space systems, including (i) making affordability a requirement, (ii) innovative solutions, (iii) increasing competition, and (iv) decreasing the time it takes to acquire a system. On the other hand, as indicated in the Space Modernization Initiative (SMI) Strategy, the modernization of existing space systems shall meet three Strategic objectives, namely, (i) design for low LCC/TOC for affordability, (ii) provide desired system capability to meet warfighter needs, and (iii) achieve resiliency to operate in contested environments. Strategic objectives and acquisition initiatives have posed conflicting acquisition requirements and a real challenge for DOD Acquisition Authority (DAA) to acquire affordable future space systems, including SATCOM5, SATOPS, and Space Navigation Systems (e.g., GPS), Space Sensors (weather, radar, etc).

Per DII instruction to reinvigorate war-gaming effort, recently the authors have investigated the feasibility of applying war-gaming concept to develop optimum technical baseline strategies for acquiring future space systems . The authors have proposed the use an Advanced Game-based Mathematical Framework (AGMF) employing Bayesian games with both complete and incomplete information cases to provide a recipe for compromising conflicting aforementioned acquisition requirements. This paper extends the AGMF concept to include the development of flexible and optimum acquisition strategies using war-gaming application concept. The paper describes how to incorporate the following BBP 3.0 initiatives⁴ into the Acquisition Action Spaces (A2S) of all potential players (e.g., DAA and potential contractors) when playing games to optimize the acquisition

strategies:

- (1) "Should" cost goal and required actions to achieve the goal,
- (2) Employ appropriate contract types, and increase the use of incentive type contracts (e.g., CPIF, FPIF) and provide guidelines for incentive fees to mitigate program risks,
- (3) Remove barriers to COTS technology using MOSA, (3) improve the ROI in DOD labs by developing required technology/capability roadmaps,
- (4) Incorporate contractor's IRAD results to reduce the bid prices, and provide incentive to allow the contractor to make IRAD an allowable cost,
- (5) Impacts of "Prototyping & Experimentation" on the acquisition strategy and its technical baseline,
- (6) Stimulate innovation using MOSA.

The extended AGMF described in this paper when implemented properly will provide an advanced acquisition tool capability to develop flexible, creative and optimum acquisition strategies that can simultaneously achieve affordability (i.e., low LCC/TOC), decreased acquisition time, innovative technical baseline solutions and meeting warfighter requirements. In addition, the paper will show that the extended framework can also allow to develop an acquisition strategy that optimally aligns and synchronizes the warfighter needs with the required innovative space technology enablers, which allow our warfighter to reestablish the asymmetric advantage for achieving the 3rd Offset Strategy.

9838-7, Session 2

War-gaming application for future space systems acquisition

Tien M. Nguyen, The Aerospace Corp. (United States)

The U.S. Department of Defense (DoD) recently focused on modernizing existing space systems and development of new space systems using DoD and Congressional initiatives , Defense Innovation Initiative (DII), and Better Buying Power 3.0 (BBP 3.0) initiatives to improve innovation and acquisition efficiency. These initiatives impose four key requirements on the development of future space systems, including (i) making affordability a requirement, (ii) innovative solutions, (iii) increasing competition, and (iv) decreasing the time it takes to acquire a system. On the other hand, as indicated in the Space Modernization Initiative (SMI) Strategy, the modernization of existing space systems shall meet three Strategic objectives, namely, (i) design for low LCC/TOC for affordability, (ii) provide desired system capability to meet warfighter needs, and (iii) achieve resiliency to operate in contested environments. Strategic objectives and acquisition initiatives have posed conflicting acquisition requirements and a real challenge for DOD Acquisition Authority (DAA) to acquire affordable future space systems, including SATCOM, SATOPS, and Space Navigation Systems (e.g., GPS), Space Sensors (weather, radar, etc).

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- (1) "Should" cost goal and required actions to achieve the goal,
- (2) Employ appropriate contract types, and increase the use of incentive type contracts (e.g., CPIF, FPIF) and provide guidelines for incentive fees to mitigate program risks,
- (3) Remove barriers to COTS technology using MOSA, (3) improve the ROI5 in DOD labs by developing required technology/capability roadmaps,
- (4) Incorporate contractor's IRAD results to reduce the bid prices, and

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provide incentive to allow the contractor to make IRAD an allowable cost,
(5) Impacts of "Prototyping & Experimentation" on the acquisition strategy and its technical baseline,
(6) Stimulate innovation using MOSA.

The extended AGMF described in this paper when implemented properly will provide an advanced acquisition tool capability to develop flexible, creative and optimum acquisition strategies that can simultaneously achieve affordability (i.e., low LCC/TOC), decreased acquisition time, innovative technical baseline solutions and meeting warfighter requirements. In addition, the paper will show that the extended framework can also allow to develop an acquisition strategy that optimally aligns and synchronizes the warfighter needs with the required innovative space technology enablers, which allow our warfighter to reestablish the asymmetric advantage for achieving the 3rd Offset Strategy.

9838-8, Session 2

The Joint Space Operations Center Mission System and the Advanced Research, Collaboration, and Application Development Environment Status Update 2016

Jeremy Murray-Krezan, Samantha Howard, Jae Kwak, Air Force Research Lab. (United States); Richard Kim, Stanford University (United States); Juan Echeverry, Tech 7 Consulting (United States)

The Joint Space Operations Center (JSpOC) Mission System (JMS) is a modern service-oriented architecture (SOA) infrastructure with increased process automation and improved tools to enhance Space Situational Awareness (SSA) performed at the US-led JSpOC. The Advanced Research, Collaboration, and Application Development Environment (ARCADE) is a test-bed maintained and operated by the Air Force to (1) serve as a centralized test-bed for all research and development activities related to JMS applications, including algorithm development, data source exposure, service orchestration, and software services, and provide developers reciprocal access to relevant tools and data to accelerate technology development, (2) allow the JMS program to communicate user capability priorities and requirements to developers, (3) provide the JMS program with access to state-of-the-art research, development, and computing capabilities, and (4) support JMS Program Office-led market research efforts by identifying outstanding performers that are available to shepherd into the formal transition process. In this paper we will share with the international remote sensing community some of the recent JMS developments that may contribute to greater SSA at the JSpOC in the future, and share technical areas still in great need.

9838-9, Session 2

Sensitivity analysis of a space-based multi-band infrared imager for GEO belt debris study

Jeremy Murray-Krezan, Air Force Research Lab. (United States)

Thousands of space objects in the Earth orbital-region known as the GEO belt are categorized as debris. Relatively little is known about the thousands of space debris objects. Remote sensing techniques offer the only viable opportunity to learn more about these objects. In this paper an analysis is performed for observations using a hypothetical space-based multi-band infrared instrument to measure characteristics of GEO belt space debris. The purpose of this study is to understand the limitations of such an instrument and sensing modality for studying GEO belt space debris. Although certain aspects of this study are analytical, the results are anchored with results from the NASA-WISE and MSX experiments.

9838-10, Session 3

MIMO SAR for automated position-keeping under a sea-clutter environment

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This paper presents a multiple-input and multiple-output (MIMO) synthetic aperture radar (SAR) imaging system with a sliding range window for automated position-keeping, which can be applied in vessel escorting, offshore support vessel servicing the deep-water drill ship, etc. The MIMO SAR system utilizes multiple switched transmit and receive antenna elements to synthesize an aperture instead of using sliding/moving antenna. The MIMO antenna array has 44 effective phase centers along the aperture with a spacing of a half of the carrier wavelength. A range-gated frequency modulated continuous wave (FMCW) radar architecture is employed to reduce the cost and increase the receiver sensitivity. The reduced data rate is also suitable for real-time SAR image processing. In the radar image processor, Range Migration Algorithm (RMA) has been used to focus a fine resolution SAR image. Under sea clutter environment, two issues has to be solved to get a successful detection. The first is determining the existence of sea clutters, which is removed by a sea clutter suppression algorithm; and the second is the additional motion of the radar system caused by the sea wave, which is solved by a motion compensation algorithm. With one 500MHz bandwidth 1W transmitter, one 10 kHz bandwidth receiver, a linear frequency modulated continuous waveform, eight receiving antennas, and thirteen transmitting antennas; a 0.3m range resolution and 1.3° angular resolution are achieved.

9838-11, Session 3

An airborne low SWaP-C UAS sense and avoid system

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This paper presents a proposal for an Airborne Low SWaP-C UAS Sense and Avoid (SAA) System based on a linear frequency modulated continuous wave (LFMCW) radar, which satisfies the constraint of the available sources on class 2/3 unmanned aircraft system (UAS). To obtain the desired SAA system working range, a narrow band frequency (range) scanning technique is applied for reducing the receiver noise floor to improve its sensitivity. Digital signal integration with fast Fourier transform and multiple-antenna beamforming are applied to enhance signal to noise ratio (SNR). The gate length and chirp rate are intelligently adapted to not only accommodate different object distance, speed and approaching angle conditions, but also optimize the detection speed, resolution and dynamic coverage range. To minimize the radar blind zone, higher chirp rate is applied at the near region. For speeding up the system update rate, lower chirp rates are applied for obtaining larger range scanning step length out of the near region, and single antenna signal is applied for target detection at the near region. To make the system work with a low power transmitter, multiple-antenna beamforming, digital signal integration with FFT, and a much narrower receiver bandwidth are applied at the far region. The working range of the airborne SAA system is projected to be 2 miles with a 1W transmitter and single antenna signal detection. When a 5W transmitter and 4-antenna beamforming (BF) are applied, its working range is projected to be 5 miles. The multiple target threat levels are assigned based on the projected collision times.

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9838-12, Session 3

Real-time WAMI streaming target tracking in fog

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Situation awareness (SAW) is essential for mission critical applications. As part of SAW, object assessment can be achieved from many sources such as cyber, linguistic and surveillance data using information fusion exploitation techniques. Target detection from surveillance data is often achieved through an exploitation of sensor data such as wide area motion imagery (WAMI) systems in a layered sensor environment. Real time detection is ideal since the more rapid targets are detected, the faster tracking and identification opportunities can be used to assess target activities. However, real-time tracking is difficult with big data. Cloud Computing has been considered promising to achieve big data integration from multi-modal sources. In many mission critical tasks, however, powerful Cloud technology cannot satisfy the tight latency tolerance as the servers are allocated far from the sensing platform, actually there is no guaranteed connection in the emergency situations. Therefore, data processing, information fusion, and decision making are required to be executed on-site (i.e., near the data collection). Fog Computing, a recently proposed extension and complement for Cloud Computing, aims at enabling applications on billions of devices and sensors networked by the Internet of Things (IoT). Fog Computing allows users to develop, deploy and execute applications on networked devices, such that computing tasks can be accomplished at the edge of a network without outsourcing jobs to a remote Cloud.

In this work, we chose WAMI as a case study to investigate whether or not it is feasible to support emergency response leveraging the Fog Computing paradigm. WAMI provides a site overview (e.g., of a city) and can be used to route traffic in an emergency situation. One of the key tradeoffs is that Fog nodes are less powerful. Embedded processors in mobile devices, or computers carried by UAVs, are not on the level of a Cloud server, leaving alone the server farms in Cloud Computing centers. Taking advantage of the temporal and spatial locality properties, a pseudo-real-time WAMI data stream analysis using Fog computing is a suggested strategy. Intuitively such a divide-and-conquer strategy matches the philosophy of the Fog computing. The main challenge lies in the gap between the large amount of dynamic data and limited computing power at the edge. Efficient use of computing resources is the critical for which a container-based virtualization (CBV) technique is adopted due to the excellent capability of live resource reallocation and ultra-low overhead and the near-native performance. Using a Fog-based CBV technique, a WAMI frame is divided into multiple sub-areas, each of which is assigned to a container-based virtual machine (VM). The sub-areas are processed independently of one another and the results are displayed in real-time to a human operator. In this manner, we can process certain "key" areas in real-time even though we still cannot process the entire frame in real-time. The experimental results are very encouraging that validated the effectiveness of our Fog approach to achieve real-time frame rates.

9838-13, Session 3

Vehicle classification in WAMI imagery using deep network

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Humans have a keen interest in understanding their surrounding environment. Thanks to recent progress in photography and breakthroughs in aviation, we are now able to capture tens of megapixels of ground imagery, namely with Wide Area Motion Imagery (WAMI), at multiple frames per second from unmanned aerial vehicles (UAVs). WAMI data serves as a great source for many applications including security, urban planning and digital earth. These applications require fast and accurate image understanding which is time consuming for operators, due to the large data volume, city-scale area coverage, and numerous moving objects. Therefore, automatic processing and understanding WAMI imagery has been gaining attention in both industry and research community. This paper focuses on an essential step in WAMI imagery analysis of vehicle classification; that is, deciding whether a certain image patch contains a vehicle or not. We collect a set of positive and negative sample patches using a standard data set, for training and testing the detector. Positive samples are 64x64 image patches centered on annotated vehicles. We generate two sets of negative images. The first set is generated from positive images with some location shift. The second set of negative patches is generated from randomly sampled patches. We also discard those patches if a vehicle accidentally located at the center of the patch. Both positive and negative samples are randomly divided into 9000 training images and 3000 testing images. We propose to train a deep convolution neural network (CNN) for classifying these patches. The classifier is based on a pre-trained AlexNet Model in the Caffe library, with adapted loss function for vehicle classification. The performance of our classifier surpasses several traditional image classifier methods, among which the best is the one using a support vector machine (SVM) and histogram of oriented gradients (HOG) feature. While the SVM+HOG method achieves an accuracy of 90.4%, the accuracy our deep network-based classifier reaches 97.9%.

9838-14, Session 3

Censoring distributed nonlinear state estimates in radar networks

Armond Conte, Ruixin Niu, Virginia Commonwealth Univ. (United States)

In a distributed radar track fusion system, it is desired to limit the communication rate between the sensors and the central node to only the most relevant information available. One way to do this is to use some metric that judges quantity of new information available, in comparison to that which has already been provided. The J-Divergence is a symmetric metric, derived from the Kullback-Liebler divergence, which performs a comparison of the statistical distance between two probability distributions. For the comparison between new and old data, a large J-Divergence can represent the existence of new information, while a small J-Divergence represents the lack of new information. Previous work included an application where the J-Divergence was used to limit data for scenarios in which the primary state estimator was an Extended Kalman Filter and used only Gaussian approximations at the local sensors. This paper expands the range of estimators to particle filters in order to account for situations where censoring is desired to be applied to non-linear/non-Gaussian environments. A derivation of the J-Divergence between probability density functions (PDFs) which are approximated by particles is provided for use in a non-feedback fusion case. An example application is given involving a 2D radar tracking scenario using the J-Divergences of a particle filter with the Gaussian approximation and a particle filter with the approximated discrete prior/posterior PDFs.

9838-15, Session 4

On simulation studies of advanced detection techniques against inside attacks

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With the explosive growth of network technologies, inside attacks have become a major issue to business and government operations on proprietary networks. As demonstrated by experiences from cyber defenders in the past, the threat landscape has rapidly evolved from simple and naive to complex and serious cyber warfare with interest from organized criminal and/or state-sponsored entities. Future infrastructure cyber attacks will become more sophisticated, more prevalent and more difficult to detect such as inside attacks. Generally speaking, the inside attacker refers to a legitimate user within an organization who is already compromised or an attacker who succeeds in stealing user's identity and impersonates a legitimate user. They both aim to negatively affect confidentiality, integrity, or availability of information over a long period of time while avoiding normal detection.

To better detect inside attacks marginally manipulating network traffic over time, we adopt a temporal-based detection using sequential hypothesis testing technique, called cumulative sum control chart (CUSUM) algorithm. To be specific, we are considering two hypothetical states. One is the null hypothesis that the collected data is from benign historical traffic and the other one is the alternative hypothesis that the measurement is under attack. The goal of such a detection scheme is to recognize the change within the shortest time by comparing the two hypotheses. To further enhance the defense and mitigation of inside attacks, we designed and implemented a multi-functional web display for the detection analysis of cumulative sum control chart (CUSUM) algorithm. Experiments using real-world traffic traces are used to evaluate the effectiveness of our proposed detection scheme. Our simulation validates that the cumulative sum control chart (CUSUM) algorithm can perform well in effectively detecting stealthy inside attacks.

9838-16, Session 4

Optimal space-time attacks on system state estimation under a sparsity constraint

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System state estimation in the presence of an adversary that injects false information into sensor readings has attracted much attention in wide application areas, such as target tracking with compromised sensors, secure monitoring of dynamic electric power systems, secure driverless cars, and radar tracking and detection in the presence of jammers. From a malicious adversary's perspective, the optimal strategy for attacking a multi-sensor dynamic system over sensors and over time is investigated. It is assumed that the system defender can perfectly detect the attacks and identify and remove sensors once they are corrupted by false information injected by the adversary. With this in mind, the adversary's goal is to maximize the covariance matrix of the system state estimate by the end of attacking period under a sparse attack constraint such that the adversary can only attack the system a few times over time and over sensors. The sparsity assumption is due to the adversary's limited resources and his/her intention to reduce the chance of being detected by the system defender. This becomes an integer programming problem and its optimal solution, an exhaustive search, is intractable with a prohibitive complexity, especially for a system with large number of sensors and over large number of time steps. Several suboptimal solutions, such as those based on greedy search and dynamic programming are proposed to find the attacking strategies. Examples and numerical results are provided in order to illustrate the effectiveness and the reduced computational complexities of the proposed attack strategies.

9838-17, Session 5

RFI modeling and prediction approach for SATOP applications: RFI detection and prediction models

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This paper is a follow-up to the initial effort on RFI modeling and prediction topic that we presented at the 2015 SPIE conference (Ref. 1). This paper describes our technical approach for the implementation of RFI detection and prediction models using carrier synchronization loop and the Time Factor (TF) when calculating Bit or Carrier SNR degradation due to interferences for (i) detecting narrow-band and wideband RFI signals, and (ii) estimating and predicting the behavior of the RFI signals.

The paper also presents analytical and simulation models and provides both analytical and simulation results on the performance of USB (Unified S-Band) waveforms in the presence of narrow-band and wideband RFI signals. The models presented in this paper will allow the future USB command systems to detect the RFI presence, estimate the RFI characteristics and predict the RFI behavior in real-time for accurate assessment of the impacts of RFI on the command Bit Error Rate (BER) performance. The command BER degradation model presented in this paper also allows the ground system operator to estimate the optimum transmitted SNR to maintain a required command BER level in the presence of both friendly and un-friendly RFI sources.

Ref. 1: Tien M. Nguyen, Hien T. Tran, et. al., "RFI Modeling and Prediction Approach for SATOP Applications," 2015 SPIE Proceedings, April 2015, Baltimore, MD.

9838-18, Session 5

Mitigation of weather on channel propagation for satellite communications

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This paper investigates the dynamic property of the channel model due to the weather effects on a satellite communication (SATCOM) link. Specifically, we discuss the rain attenuation in the Ka band and X band of the SATCOM link for both uplink and downlink scenarios. First, we describe a weather model for the SATCOM link using a Markov chain model. Next, the average probability and the transition probability for different states of weather are calculated, and the impact of dynamic weather on the SATCOM link channel propagation model is discussed. A Bayesian network is used to analyze the link budget and show the weather impact on the SATCOM link channel propagation model. Then, a mitigation scheme is proposed to limit the impact of dynamic weather on communications. This scheme makes use of a game theoretic framework based on space-ground link geometry and transmit power control to adapt to the dynamic weather. Finally, simulations are implemented for the weather, link channel propagation model, and the game theoretic framework in different scenarios. The simulation results validate the proposed weather model and channel model, and show the effectiveness of the game theoretic mitigation scheme

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9838-19, Session 5

Cyber security with interferences mitigation study for satellite systems

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Satellite systems including the Global Navigation Satellite System (GNSS) and the satellite communications (SATCOM) system provide great convenience and utility to human life including emergency response, wide area efficient communications, and effective transportation. Elements of satellite systems incorporate technologies such as navigation with the global positioning system (GPS), satellite digital video broadcasting, and information transmission with a very small aperture terminal (VSAT), etc. The satellite systems importance is growing in prominence with end users' requirement for globally high data rate transmissions; the cost reduction of launching satellites; development of smaller sized satellites including cubesat, nanosat, picosat, and femtosat; and integrating internet services with satellite networks. However, with the promising benefits, challenges remain to fully develop secure and robust satellite systems with pervasive computing and communications. In this paper, we investigate both cyber security and radio frequency (RF) interferences mitigation for satellite systems, and demonstrate that they are not isolated. The action space for both cyber security and RF interferences are firstly summarized for satellite systems, based on which the mitigation schemes for both cyber security and RF interferences are given. A multi-layered satellite systems structure is provided with cross-layer design considering multi-path routing and channel coding, to provide great security and diversity gains for secure and robust satellite systems. Network simulation results demonstrate the superiority of our proposed multi-layered system structure and cross-layer design as compared with a single-layered satellite systems with traditional signal processing schemes.

9838-20, Session 5

Dynamic spectrum access based security guarantee for 3D satellite wireless networks

Qixuan Zhu, Xi Zhang, Texas A&M Univ. (United States)

Data transmissions in three-dimensional satellite communication networks require for stringent security protections due to the open nature of wireless communications. The dynamic spectrum access (DSA) has been recognized as one of the candidate advanced techniques to overcome these security and reliability challenges by dynamically shifting the transmission spectrum according to the channel attack and interference conditions. We propose a frequency hopping based DSA scheme for satellite communications where the protected information transmissions are more robust against smart eavesdropping to significantly improve the privacy and secure reliability of satellite communications. Our proposed scheme mainly composes of three parts: spectrum sensing and accessing, security/privacy preservation through encryption/decryption, and frequency hopping mechanism. The first part applies a finite state Markov Chain framework to exploit the spectrum sensing capabilities for proactive detection of channel quality. Due to the quality of sensing channel, the satellite determines to access an available frequency or swap with a better quality frequency when its previous frequency exhibits high interferences. Then, in the security preserving key encryption/decryption part, the satellite encrypts it protected information with each destination's security preserving key, and distributes the encrypted data to the corresponding destinations. Each destination can only decrypt parts of the entire information with its own key, but can collect the rest of the decrypted information from other destinations. Finally during one of the destinations leaving phase, other destinations can use a dummy key, which could be provided by the

sender satellite, to replace an actual key so that other destinations are able to decrypt the entire protected information with the absence of one destination.

9838-21, Session 5

A distributed-toward-decentralized satellite communications (SATCOM) decision making approach

Wenjie Lu, Wenhao Xiong, Gang Wang, Xin Tian, Intelligent Fusion Technology, Inc. (United States); Khanh Pham, Erik Blasch, Air Force Research Lab. (United States); Dan Shen, Genshe Chen, Intelligent Fusion Technology, Inc. (United States)

This paper presents a distributed-toward-decentralized satellite communications (SATCOM) decision-making approach based on situational uncertainty modeling via non-parametric Bayesian causal relation learning of the SATCOM network in an operating environment with feedback delays. The decision model is developed using multi-objective optimization that concerns robustness against interference and jamming, and is based on decentralized partial observed Markov decision process (dec-POMDP) that represents the underlying phenomena of the SATCOM system and operating environment. The multi-objective model provides a unified and compact basis for distributed decision making via dec-POMDP, in order to overcome the curse of dimensionality and to reduce communication cost. This dec-POMDP model has two layers. i) The low-level layer formulates a multi-objective optimization problem within a shared objective space and solves the problem based on available information, resulting multi-value functions that present its estimated utility given its future state. ii) The high-level layer is the dec-POMDP with decentralized decision making capability when communication is blocked or turned off due to cost or privacy. It is shown that such a two-layer decision making scheme is robust to delay of communication quality feedback and to inconsistency knowledge of SATCOM network topology among decision makers. The performance assessment of the proposed algorithm is carried out in a system-level simulator with realistic channel models and system assumptions, where the objective space is defined over dimensions of Low Probability Interception (LPI), Low Probability Detection (LPD), and Low Communication Cost (LCC).

9838-22, Session 5

QoS-based quantum key distribution for security guarantees over 3D satellite networks

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Quantum cryptography is one of the most promising technologies for guaranteeing the absolute security in communications over various advanced networks, including fiber networks and wireless networks. In particular, quantum key distribution is an efficient encryption scheme on implementing secure satellite communications between satellites and ground stations. However, it faces many new challenges such as high attenuation and low polarization-preserving capability or extreme sensitivity to the environment. In order to guarantee the quality of service (QoS) provisioning of quantum communications over 3D satellite networks, we need to focus on the security problem and throughput efficiency through correcting the errors resulted from the objective and adversary influences. To overcome these problems, we model the noisy quantum channel and implement an efficient quantum error correction scheme to ensure the security and increase the quantum throughput efficiency in QKDbased satellite networks. The simulation results obtained show that our proposed efficient QEC scheme for QoS guarantee outperforms the other existing quantum error correction schemes in terms of security and the quantum throughput efficiency.

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9838-23, Session 6

Satellite control network upgrade with CDMA-based waveform

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Satellite Control Networks (SCN) have provided launch control for space lift vehicles; tracking, telemetry and commanding for on-orbit satellites; and, test support for space experiments since the 1960s. Currently, SCNs encounter a new challenge: how to maintain the high reliability of services when sharing the spectrum with emerging commercial services. To achieve this goal, this paper propose a code division multiple access (CDMA) based waveform for a SCN, which can greatly improve the spectrum efficiency and interference mitigation of the system. First, we provide the baseline CDMA waveform for a SCN system, which is particularly designed with low data rate but high reliability. The baseline includes the modulation, channel coding, roll-off factor, etc. Furthermore, this work investigates the spectrum efficiency of the new waveform in a SCN system, i.e., the number of supported users within desired performance degradation. Last, the capability of interference mitigation is studied, where we focus on the inter-operating interference with existing SCN systems, i.e., narrowband Frequency Division Multiple Access (FDMA) interference. Extensive numerical and simulation results are presented to illustrate the theoretical development.

9838-24, Session 6

SINR estimation for SATCOM in the environment with jamming signals

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In this paper we consider a problem of estimating the signal-to-interference-plus-noise ratio (SINR) for satellite transmission system in the presence of jamming signals. Additive white Gaussian noise (AWGN) channels are considered for baseband quadrature phase shift keying (QPSK) data transmission system. Two interference models are proposed with Gaussian or non-Gaussian interference signals in order to investigate the SINR for different satellite transmission jamming scenarios. Both non-data-aided moment-based and data-aided maximum likelihood SINR estimators are derived for the systems. The normalized mean square errors of the SINR estimation algorithms are examined by means of computer simulations. The numerical results show the robustness of derived SINR estimators. The development of the SINR estimators are applicable to a large number of applications utilizing satellite communication systems.

9838-25, Session 6

Improving performance of DVB-S2X through constellation shaping

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As the extension of the satellite digital video broadcasting standard, the 2nd generation satellite extensions (DVB-S2X) has been proven to achieve efficiency gain up to 50% when comparing with its predecessor DVB-S2. The

DVB-S2X improvements contain the Modulation and Coding (MODCOD) and Forward Error Correction (FEC) upgrades as well as increased granularity to provided more application-dependent satellite link choices. Constellation shaping is the strategy involving the transmission of lower-energy signals more frequently than higher-energy signals. Previous work has shown that shaping is effective for DVB-S2 waveform and the extra gain could be achieved by optimizing the Low-Density Parity Check (LDPC) information-theoretic codes in conjunction with shaped Amplitude and Phase-Shift Keying (APSK) modulation. In this paper, the constellation shaping technique is applied to the DVB-S2X physical layer and the simulation results validate its effectiveness. Additionally, information-theoretic analysis suggests affords choices among the MODCOD schemes as well as the shaping parameters under different system settings. The proposed solution brings efficiency closer to the theoretical Shannon limit thus attractive for satellite communication links.

9838-26, Session 6

Advanced beam forming power allocation for SATCOM LPI and LPD

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In this work, we propose a novel beamforming power allocation method for Satellite Communications (SATCOM) multiple-input multiple-output (MIMO) system to achieve better low probability of interception (LPI) and low probability of detection (LPD). Conventional solution may achieve LPI and LPD separately with different techniques. We propose to achieve the LPI and LPD simultaneously with one advanced beam formation power allocation method. The pre-coding and beamforming technique is a conventional way of avoid interception, By controlling the antenna beam, interference from certain direction can be mitigated. We propose a novel beamforming technique which considers the number of independent channels used and the transmitting power deployed to reduce and mitigate the intentional and unintentional interference effects. With the certain quality of service (QoS) for the SATCOM system, independent channels will be selected where it is desired to use fewer and stronger channels when possible. On the other hand, SATCOM systems often face the problem that adversary receiver overhears the signal which requires enhanced security. To enhance security, we propose a power allocation method that can efficiently reduce the received power at the adversary receiver. We measure the received signal at adversary receiver by interference temperature which quantizes the amount of information leak. Results demonstrate that the proposed power allocation method constrains the received signal power at adversary receiver

9838-27, Session 6

Analysis of a probability-based SATCOM situational awareness model for parameter estimation

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Emerging satellite communication (SATCOM) systems are envisioned to incorporate advanced capabilities for dynamically adapting link and network configurations to meet user performance needs. These advanced capabilities require an understanding of the operating environment as well as the potential outcomes of adaptation decisions. A SATCOM situational awareness and decision-making approach is needed that represents the cause and effect linkage of relevant phenomenology and operating conditions on link performance. Similarly, the model must enable a corresponding diagnostic capability that allows SATCOM payload managers to assess likely causes of observed effects.

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Prior work demonstrated the ability to use a probabilistic reasoning model for a SATCOM situational awareness model. It provided the theoretical basis and demonstrated the ability to realize such a model. This paper presents an analysis of the probabilistic reasoning approach in the context of its ability to be used for diagnostic purposes. A quantitative assessment is presented to demonstrate the impact of uncertainty on estimation accuracy for several key parameters. The paper also discusses how the results could be used by a higher-level reasoning process to evaluate likely causes of performance shortfalls such as atmospheric conditions, pointing errors, and jamming.

9838-28, Session 7

SERB, a nano-satellite dedicated to the Earth-Sun relationship

Mustapha Meftah, LATMOS (France)

The Solar irradiance and Earth Radiation Budget (SERB) mission is a future innovative proof-of-concept nano-satellite, with three ambitious science goals. The nano-satellite aims to measure on the same platform the different components of the Earth radiative budget, the absolute value of the total solar irradiance and its variability, and the UV solar spectral variability. SERB is proposed for the nano-satellite program of Polytechnic School (X-CubeSat II) and CNES for a flight in 2020-2021. SERB is a triple Cubesat, under development by students, mostly working at Polytechnic School. Critical components of instrumental payloads of future large missions (coatings, UV filters, etc.) can acquire the technical maturity by flying in a CubeSat. Nano-satellites represent also an excellent alternative of instrumentation testing, providing longer flights than rockets. Moreover, targeted science can be performed by nano-satellites. Thus, this paper is intended to present a future space mission enabled by the development of nano-satellites and the underlying technologies they employ.

9838-29, Session 7

Enablement of defense missions with in-space 3D printing

Michael Parsons, Thomas McGuire, Michael P. Hirsch, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

Earth's orbit represents the 'ultimate' high ground for many defense sensing applications. In addition to the ability to image vast areas of the Earth from a single spacecraft, orbital space is a good place to put surveillance equipment because its exact location and target can be obfuscated from the enemy. One consideration with using space for surveillance and defense logistics purposes is that significant expense is associated with the launch and deployment of spacecraft. Due to this, the latest capabilities may be unavailable until many years have passed after their development.

This paper proposes and evaluates the efficacy of using in-space 3D printing for enabling defense (principally remote sensing) missions. With an in-space 3D space printer, spacecraft deployment costs can be reduced significantly and missions can be designed around a rapid craft build-on-demand (and rapid-replacement) capability.

A variety of applications for an in-space 3D printer are discussed. For example, it could be used to build or repair satellites, to print parts for spacecraft, or to build mechanisms that might impair the functionality of adversary spacecraft. In the longer term, such a technology could also be used (from a technical perspective, there are obvious issues with this from the perspective of the Outer Space Treaty) to create responsive ordinance in-orbit for deployment to Earth.

Spacecraft construction in space provides several benefits. In addition to the ability to bring up a large supply of raw materials and components and determine what will be produced at a later time (and enjoy some volume savings from being able to launch material in a more compact form), significant structural benefits also exist. When a spacecraft is built on Earth for launch into orbit or beyond, it must be constructed to withstand both

terrestrial forces (during construction) and the forces that act upon it during launch. When building the spacecraft in space, in many cases less structural support is required allowing spacecraft to require less overall launch mass capability and allowing the creation of larger-size and differently-configured spacecraft.

Each prospective application is discussed and its efficacy as an enabling technology as well as its short, medium and long-term viability is considered. The paper concludes with a discussion of next steps in the design, development and testing of the in-space 3D printing concept.

9838-30, Session 7

A design for an in-space 3D printer

Thomas McGuire, Michael P. Hirsch, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

This paper presents a technology to reduce space mission costs. Specifically, it discusses in-space 3D printing. Using in-space 3D printing, spacecraft can be lighter, require less launch volume and be designed solely for orbital operations. The proposed technology is presented in detail. Then, several prospective spacecraft designs are discussed. Each design is evaluated in terms of its launch mass and volume requirements as well as its suitability for its corresponding mission. Designs are also evaluated to determine whether conventional (fabricate-and-launch) or in-space printing paradigms are best suited to its construction. From this, conclusions are drawn about the benefits of in-space 3D printing as well as the specific areas where it provides benefit.

The in-space 3D printing spacecraft is comprised of multiple subsystems which act together to prepare, position and extrude material. There are three main portions to this system: the energy collection system, the melting unit, and the printing unit. The energy collection system is comprised of a dual reflective array to focus energy onto a small area on the melting unit. This melting unit is essentially a small holding chamber where material is raised to a temperature where it is fully molten prior to printing. One the material is fully molten, it is transferred to the printing unit to be extruded. The printing unit forces the molten material through a print head which transfers the material onto a receiving platform (or, in most cases, onto layers of previously-printed material on top of the receiving platform). This platform and the printing unit are capable of orientating themselves relative to each other to facilitate printing in desired locations.

The proposed technology supports multiple materials, including aluminum, various plastics and other metals. A benefit of the multiple subsystem design is the ability to use multiple materials in a single print job. By switching to a new set of storage, melting, and printing units, an alternate material can be added to the component. This allows materials to be used interchangeably to create complex structures and systems, expanding prospective uses for the in-space 3D printing system.

The ability to fabricate spacecraft in orbit can provide significant benefit. Current spacecraft designs are significantly constrained by the process and rigors of launching them into orbit. They must be designed to support exposure to terrestrial gravity during fabrication, integration and storage and sustain the immense forces of launch. Once they are in space, much of the structural stability that was required for these prior phases is no longer required; however, additional components may be required to transition from a storage to operational state. By fabricating spacecraft in orbit, they no longer need to be designed around terrestrial and launch requirements. Additionally, spacecraft can be designed to include structures that would not be able to be fabricated on Earth and would not survive launch forces, but which are best suited to the spacecraft's primary purpose: on-orbit operations.

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9838-31, Session 7

A low-mass, low-power hyperspectral imaging concept for small satellite applications

Sarah T. Crites, Robert Wright, Paul G. Lucey, Jeremy Chan, Andrea Gabrieli, Harold Garbeil, Casey I. Honniball, Univ. of Hawai'i at Manoa (United States); Keith A. Horton, Amber K. Imai-Hong, Eric J. Pilger, Univ. of Hawai'i (United States); Mark Wood, Univ. of Hawai'i at Manoa (United States); Lance Yoneshige, Univ. of Hawai'i (United States)

At the University of Hawaii we have developed a novel design for low-mass, low-power long wave infrared (LWIR, 8-14 microns) hyperspectral imagers for small satellite applications. The design combines an extremely compact variable gap Fabry-Perot interferometer employed as a Fourier Transform spectrometer with low-power uncooled microbolometer arrays to collect the images, allowing relatively high spectral resolution and SNR measurements from space while limiting mass and power consumption. This design was first implemented in the form of SUCHI (the Space Ultra Compact Hyperspectral Imager), which was developed within strict mass (<9kg), power (<10 W), and volume (40 cm x 10 cm x 13 cm) limitations as the primary payload for the University of Hawaii-built 'HiakaSat' microsatellite (launching with ORS-4 in October 2015). We are currently completing fabrication of TIRCIS (the Thermal Infrared Compact Imaging Spectrometer) as a follow-on to SUCHI. TIRCIS takes lessons learned from SUCHI and applies them to a new design with improvements to spatial and spectral resolution. Like SUCHI, TIRCIS utilizes a variable-gap Fabry Perot interferometer to create the spectra, but three different interferometer wedges with varying slopes resulting in spectral resolution ranging from 65 cm-1 to 15 cm-1 will be tested to explore tradeoffs between spectral resolution and sensitivity. TIRCIS is designed to achieve 120 m spatial resolution, compared with 230 m for SUCHI, from a theoretical 500 km orbit. It will be used for ground and aircraft data collection but will undergo environmental testing to demonstrate its relevance to the space environment.

9838-33, Session 8

Initial relative-orbit determination using heterogeneous TDOA

Andrew J. Sinclair, Auburn Univ. (United States); Thomas A. Lovell, Air Force Research Lab. (United States)

Time-difference-of-arrival (TDOA) measurements, using ground or space-based receivers, have been widely studied for the geolocation of a ground-based RF transmitter. This paper investigates the novel problem of initial relative-orbit determination (IROD) of a space-based RF transmitter via TDOA. The use of a satellite formation to determine the unknown orbit of an RF transmitter has a wide array of military and civilian applications, including space situational awareness. The TDOA measurement is formed by comparing the signal received by two non-collocated receivers. By knowing the speed of the signal's propagation, the TDOA measurement can be related to the difference in the ranges from the transmitter to the two receivers. The analytic expression for this range difference places the transmitter on one sheet of a two-sheeted hyperboloid with the two receivers located at the foci. Determining the orbit of the transmitter requires six TDOA measurements over time, combined with a model for the relative motion of the transmitter with respect to the receivers.

This paper will investigate IROD via a linearized dynamics model referred to as DeVries equations, which in the special case of a circular reference orbit simplify to the Clohessy-Wiltshire equations. One measurement approach is to use a formation of four receivers that can instantaneously collect three independent TDOA measurements. Using three TDOA measurements, the instantaneous transmitter position can be calculated using solutions identical to those developed previously for fixed, ground-based transmitters. From solutions for the position at two instants in time, the state-transition

matrix can be used to solve for the relative velocity, and thus the relative orbit of the transmitter.

Alternatively, a formation of only two receivers can be considered, which provide a single TDOA measurement at each instant. This measurement can be expressed as a quadratic function of the receiver's instantaneous position components. Using the linear dynamics model, these equations can be rewritten as quadratic functions of the six initial position and velocity components. TDOA measurements at six instants in time produce a system of six quadratic equations for six unknowns. Calculating the Macaulay resultant can be used as an approach to solve this system of polynomial equations.

9838-34, Session 8

Passive optical sensing of atmospheric polarization for GPS denied operations

David B. Chenault, Todd M. Aycok, Art Lompado, Polaris Sensor Technologies, Inc. (United States)

There is a rapidly growing need for position, navigation, and timing (PNT) capability that remains effective when GPS is degraded or denied. Passive optical techniques are highly desirable so that they cannot be spoofed or jammed. Naturally occurring sky polarization was used as long ago as the Vikings for navigation purposes. With current polarimetric sensors, the additional polarization information measured by these sensors can be used to increase the accuracy and the availability of this technique. The Sky Polarization Azimuth Sensing System (SkyPASS) sensor measures this naturally occurring sky polarization to give absolute heading and attitude information to less than 0.1° and offers significant performance enhancement over digital compasses and sun sensors, availability enhancement over current celestial technologies and Size, Weight & Power (SWaP) enhancements over existing inertial technology. SkyPASS has been under development for some time for terrestrial applications, but we believe there is strong potential for use above the atmosphere as well and the performance specifications and SWaP are attractive for use as an additional pose sensor on a satellite. The SkyPASS system is a passive optical sensor that can operate at 10's of Hz, has no warm-up or calibration time, does not require leveling, and operates in GPS denied and magnetically challenged environments. SkyPASS is less than 5 cubic inches and weighs approximately 4 ounces. In this paper, we will describe the phenomenology, the sensor performance, and the latest test results and the potential for use above the atmosphere.

9838-35, Session 8

Using luminescent materials as the active element for radiation sensors

William A. Hollerman, Univ. of Louisiana at Lafayette (United States); Ross S. Fontenot, Naval Surface Warfare Ctr. Carderock Div. (United States); Stephen Williams, John Miller, Univ. of Louisiana at Lafayette (United States)

Ionizing radiation poses a significant challenge for Earth-based defense applications as well as human and/or robotic space missions. Practical sensors based on luminescence will depend heavily upon research investigating the resistance of these materials to ionizing radiation and the ability to anneal or self-heal from damage caused by such radiation. In 1951, Birks and Black showed experimentally that the luminescent efficiency of anthracene bombarded by alphas varies with total fluence (N) as $(I/I_0) = 1/(1 + AN)$, where I is the luminescence yield, I₀ is the initial yield, and A is a constant. The half brightness (N_{1/2}) is defined as the fluence that reduce the emission light yield to half and is equal to is the inverse of A. Broser and Kallmann developed a similar relationship to the Birks and Black equation for inorganic phosphors irradiated using alpha particles. From 1990 to the present, we found that the Birks and Black relation describes the reduction in light emission yield for every tested luminescent material

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except lead phosphate glass due to proton irradiation. These results indicate that radiation produced quenching centers compete with emission for absorbed energy. The purpose of this paper is to present results from research completed in this area over the last few years. Particular emphasis will be placed on recent measurements made on new materials such as europium tetrakis dibenzoylmethide triethylammonium (EuD4TEA). This groundbreaking research can be used to help determine if EuD4TEA-based materials can be used as a real-time sensor to detect ionizing radiation.

9838-36, Session 8

Applications of a dynamic tethering system to enable the deep space cam jointed observation bot

Skye Leake, Thomas McGuire, Michael Parsons, Michael P. Hirsch, Jeremy Straub, Univ. of North Dakota (United States)

The Deep Space Cam Jointed Observation Bot (DeSCJOB) provides the capability to collect imagery of a spacecraft that can serve to validate proper operations, help troubleshoot maloperation and provide imagery of the spacecraft in proximity to features of interest (for publicity and historical purposes). The DeSCJOB, thus enables detailed checks, either autonomously or remotely controlled, of key systems as well as the ability to identify damage and verify deployment of deployables. By collecting images that can be used for publicity (and are not just an artist's representation), an increased amount of interest within the media can be created. For example, there was significant media coverage of the Mars Curiosity Rover's selfie. This could lead to increased public engagement in space travel, similar to the public interest in the U.S. and U.S.S.R. space race.

This paper discusses a dynamic tether system (DyTS) that was designed to facilitate the operations of the DeSCJOB spacecraft in close proximity to its parent spacecraft. DyTS facilitates the repeated deployment of the DeSCJOB spacecraft and its retrieval without the use of consumables (like propellants) which would limit its mission lifespan.

The DyTS can manage its rigidity, based on the method and material used for tether creation. This allows it to provide precise positioning of a camera, for long exposures or continual monitoring of a specific part of a spacecraft, or to allow it to float with reduced interference to image objects not connected to the parent craft. The design and operations of the DyTS unit are presented, in detail, and the efficacy of different materials for tether use is evaluated. They utility of DeSCJOB and the DyTS for multiple prospective mission types is also discussed and evaluated using a number of case studies.

The DyTS also has prospective applications beyond its DeSCJOB camera use. These are also discussed. For example, scientific interments or experiments could be fitted to the tethering system, providing a significant (and variable) amount of distance between the instruments and the parent spacecraft. This is advantageous for a variety of sensors (such as magnetometers) which are affected by proximity to the parent craft.

With the various applications of the DeSCJOB's DyTS presented and evaluated and additional DyTS applications presented, focus then turns to a discussion of the technical viability of the DyTS system, which is evaluated from both design and operations perspectives. Finally, the paper concludes with a discussion of the remaining development work that must be completed and with a presentation of a prospective test mission for the DeSCJOB and DyTS.

9838-37, Session 8

Magnetic sensor for space exploration

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the design of a new type of magnetic sensor for Space exploration applications. Based on the new sensor, advanced spacecraft navigation systems can be built with significantly lower requirements

in terms of processing power. Tri-axial fluxgate magnetic sensors have traditionally been used for spinning and non-spinning spacecraft magnetometric applications. However, the proposed sensor is inheriting the virtues of a novel sensor design methodology. Modern materials have been selected to assist in the optimization process of the proposed sensor. The system's aggregate power consumption is significantly reduced, when compared to existing sensors for space navigation. The sensor is evaluated against existing sensors previously used for spacecraft navigation and the results are presented.

9838-38, Session 9

An investigation of image compression on NIIRS rating degradation through automated image analysis

Hua-Mei Chen, Intelligent Fusion Technology, Inc. (United States); Erik Blasch, Khanh Pham, Air Force Research Lab. (United States); Zhonghai Wang, Genshe Chen, Intelligent Fusion Technology, Inc. (United States)

The National Imagery Interpretability Rating Scale (NIIRS) is a subjective quantification of a static image widely adopted by the Geographic Information System (GIS) community. Efforts have been made to relate NIIRS image quality to sensor parameters using the general image quality equations (GIQE), which make it possible to automatically predict the NIIRS rating of an image through automated image analysis. In this paper, we first present an automated image analysis method to estimate the NIIRS rating of a given image with known ground sampling distance. Steps involved include straight edge detection, edge profile estimation, edge profile selection, and signal to noise ratio (SNR) estimation. Next, we investigate the effects of image compression on the degradation of an image's NIIRS rating. Specifically, we consider JPEG and JPEG2000 image compression standards. The extensive experimental results demonstrate the effect of image compression on the ground sampling distance, which is the major factor effecting NIIRS rating.

9838-39, Session 9

Google glass-based remote control of a mobile robot

Song Yu, Xi Wen, Tianjin Univ. (China); Wei Li, Tianjin Univ. (China) and California State Univ., Bakersfield (United States); Genshe Chen, Intelligent Fusion Technology, Inc. (United States)

The technology of human-machine interface (HMI) has made remarkable progresses, including text recognition, speech synthesis and recognition, image processing and pattern recognition, machine translation and so on, have found their practical applications. Currently, Google Glass, a new wearable intelligent device, provides a new way to remotely control robot systems. Google Glass projects images on the right eye lens through a micro projector and an oblique prism. The projector subtly uses an image stack to arrange real images and effectively displays an image with a distance away from a user about 2.4 meters on the 25 inch high-definition screen. Wearing it, the user equally carries an invisible high-definition screen without losing vivid sense of the surroundings. A touchpad on the right side of Google Glass is located between the temple and right ear. The user is able to control the time line of the user interface by sliding the touchpad. In this paper, we investigate the remote control of mobile robot systems using the clever projection technology due to its powerful computing capability and new touchpad input interface. By observing live video feedback, an operator chooses control commands and sends them to control a Surveyor robot in a virtual environment designed by the Webots simulator. In order to demonstrate the effectiveness of the proposed Google Glass-based remote controller, we conduct three study cases: navigating the mobile robot among obstacles with avoidance, controlling the robot to pass through a

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complicated maze and to track given trajectories accurately. In this paper, we design the user interface of the Google Glass-based control system, discuss how to use Webots to set up a simulation environment, describe the experimental process, and shows results of the experiment.

9838-40, Session PSTue

Embedded reconfigurable all-digital signal processing platform for prototyping space magnetometers

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the development of a new embedded magnetometer core for rapid prototyping of reconfigurable space magnetometers. The magnetometer core is connected to a new proven tri-axial fluxgate sensor, which measures the axial magnetic field density components of the Earth's magnetic field during testing. Superimposed on the Earth's magnetic field are signatures of heliospheric physics activity. The proposed system measures both. Other magnetometric applications can be implemented in the future by slightly modifying the existing sensor or by adding sensors for other types of magnetic measurements. Calibration procedures are still required to compensate for superimposed measurements, due to the local environmental magnetic conditions. An all-digital computer architecture methodology has been implemented, fulfilling the specifications of the corresponding receiver's hardware. This expedites testing of the new system-on-chip magnetometer.

Conference 9839: Degraded Visual Environments (DVE): Enhanced, Synthetic, and External Vision Solutions (ESXVS) 2016

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9839-2, Session 1

Flight test results of helicopter approaches with trajectory guidance based on in-flight acquired LIDAR data

Michael Zimmermann, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Topics related to helicopter landing on unprepared landing sites and in degraded visual environments have been studied intensively in the last decade.

This work discusses flight test results for in-flight calculated trajectory guidance using DLR's manned research helicopter. This highly modified EC135 is equipped with a commercial forward looking LIDAR sensor with a range of 1 km. During flight, LIDAR samples are acquired and combined with a priori database information. The resulting representation of the environment is used for generation of collision free trajectories during the approach. Once new samples by the LIDAR sensor are collected, the environment map is updated and the trajectory is changed if necessary. Since this work involves manual trajectory following by a pilot, a "Tunnel-In-The-Sky" head down display is used to provide visual cues for spatial and speed guidance.

A reference scenario for testing of this system has been defined by the research team and the responsible flight test crew early on. It consists of a predefined landing site at DLR's research airport and a shallow approach leading above a forested area next to the airport. Following a trajectory calculation based on database information only, the pilot is presented an initial solution. While flying with this guidance using the head down display, previously unmapped trees are detected. In case the distance of the active trajectory to the updated model of the environment decreases below safe margins, the pilot is given a new solution to follow.

A first version of the described system has been flight tested in mid 2013 during several approaches using aforementioned reference scenario. Based on the resulting records and pilot comments, improvements were identified, implemented and successfully evaluated during a second period of flight testing in mid 2015.

By assisting pilots with trajectory guidance in this critical phase of flight, this work continues research at DLR for flight under degraded visual environment for a full-scale helicopter.

9839-3, Session 1

Rotorcraft operations in degraded visual environments (DVE) and the sensor fusion challenge (*Invited Paper*)

Todd A. Dellert, U.S. Army Aviation Development Directorate (United States)

Overall, the U.S. Army considers the challenge of operating army rotorcraft in degraded visual environments (DVE) to be an aircraft handling qualities problem. Numerous personal engagements with government, academia and the vendor community have brought to light the fact that many individuals have difficulty making this connection. The normal response is, "Why ADS-33 (Aircraft Design Specification relating to aircraft handling qualities)? If I can merely see through the degraded visual environment, I will have overcome the challenge of operating in DVE in a satisfactory manner". This presentation outlines the methodology being executed by the RDECOM Rotorcraft DVE Mitigation Program (DVE-M). The objective is to inform

the aviation community of how the technical elements of the program fit together to merge with the structure of ADS-33. A primary focus will be the challenge of sensor fusion in order to present visually to the pilot the necessary information to allow pilotage in DVE.

9839-4, Session 1

Toward autonomous rotorcraft flight in degraded visual environments: experiments and lessons learned

Adam Stambler, Spencer Spiker, Marcel Bergerman, Sanjiv Singh, Near Earth Autonomy, Inc. (United States)

Unmanned cargo delivery to combat outposts will inevitably involve operations in degraded visual environments (DVE). The software and hardware enabling rotorcraft autonomy needs to be able to function when this unplanned DVE occurs. For clear air weather, Near Earth Autonomy established a baseline for rotorcraft perception performance in 2014. Near Earth's m3 sensor suite enabled autonomous no-hover landings onto unprepared sites populated with obstacles. The m3's long-range lidar scanned the helicopter's path, detected obstacles, and found safe locations to land. This clear air performance is now being tested against DVE.

In this paper we present the results of initial tests in a variety of DVE conditions and analyze them from the perspective of mission performance and risk for autonomy systems. Tests were conducted with the m3's lidar and a lightweight synthetic aperture radar in rain, smoke, snow, and controlled brown-out experiments. These experiments showed the capability to penetrate through mild DVE but the perception becomes degraded with the densest brownouts. The results highlight the need for not only improved ability to see through DVE, but also for improved algorithms to monitor and report DVE conditions.

9839-5, Session 1

Capability comparison of pilot assistance systems based solely on terrain databases versus sensor DB fused data systems

Thomas R. Muensterer, Juergen Scheuch, Philipp Voelschow, Michael Strobel, Michael Roth, Dennis Fadljevic, Airbus Defence and Space (Germany)

This paper compares the capabilities achievable with a pure database driven DVE system (NIAG class 4 system) with the capabilities of a database system fused with sensor information (NIAG class 2 system). Both systems will present the same 3D conformal symbology. To achieve terrain conformal representation with operational navigation systems and databases, specific compensation techniques are required. This applies especially for the pure database system. The sensor database fusion system on the other hand relies mainly on relative accuracies simplifying the required compensation techniques at the cost of additional sensors and fusion algorithms. Both system configurations were flight-tested on a test helicopter. The test results, specifics and basic limitations will be discussed and compared.

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9839-6, Session 1

Performance evaluation of active EO/IR systems in degraded visual environments (DVE)

Romain Ceolato, Nicolas Rivière, ONERA (France)

Abstract - This paper addresses the problem of critical operations in Degraded Visual Environment (DVE). DVE usually refers when the perception of a pilot is degraded by environmental factors, including the presence of obscurants from bad weather (e.g. fog, rain, snow) or accidental events (e.g. brownout, smoke). Critical operations in DVE is a growing field of research as it is a cause of numerous fatal accidents. Several artificial controlled DVE conditions are reproduced and controlled at ONERA facilities in order to investigate different systems performances. The purpose of this paper is to report performance evaluation results of potential Electro-Optical/InfraRed (EO/IR) systems dedicated to Enhanced Vision (EV) in DVE conditions. Different active and passive EO/IR optical systems will be investigated and evaluated in this study (e.g. 3D LADAR / LIDAR, LWIR camera) in controlled DVE conditions for a variety of obscurants. Simulations about obscurants penetration performances will be discussed along with experimental results will be discussed based on recent field experiments in our facilities.

9839-7, Session 2

The glass dome: low-occlusion obstacle symbols for conformal displays

Niklas Peinecke, Alvaro Chignola, Patrizia M. Knabl, Hartmut Friedl, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Contemporary helmet mounted displays integrate high-resolution display units together with precise head-tracking solutions. This combination offers the opportunity to show symbols in a conformal way. Conformality here means that a hazard symbol can be shown linked to the outside scenery, so that a pilot intuitively understands the connection between the symbol and its corresponding terrain feature, even if the feature is not fully visible due to degraded visual conditions. To accomplish this purpose the symbol has to be sufficiently noticeable in terms of size and brightness. However, this gives rise to the danger that parts of the outside scenery are occluded by the symbol. Furthermore, symbols should not clutter the display, in order not to distract the pilot.

We present a solution framework of highlighting obstacles by symbols that balance low occlusion against noticeability. Our concept allows including different representations for individual classes of obstacles in a unified way. We detail the implementation of the display symbols. Finally, we present results of a first acceptance test with pilots.

9839-9, Session 2

Amplifying the helicopter drift in a conformal HMD

Sven Schmerwitz, Patrizia M. Knabl, Thomas Lueken, Hans-Ullrich Doehler, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Helicopter operations require a well-controlled and minimal lateral drift shortly before ground contact. Any lateral speed exceeding this small threshold can cause a dangerous momentum around the roll axis, which may cause a total roll over of the helicopter. As long as pilots can observe visual cues from the ground, they are able to easily control the helicopter drift. But whenever natural vision is reduced or even obscured, e.g. due to night, fog, or dust, this controllability diminishes. Therefore helicopter operators could benefit from some type of "drift indication" that mitigates

the influence of a degraded visual environment.

Generally humans derive ego motion by the perceived environmental object flow. Shortly before ground contact pilots mainly gather this information by looking sideways or down through suitable windows. The visual cues perceived are located close to the helicopter, therefore even small movements can be recognized. This fact was used to investigate a modified drift indication. To enhance the perception of ego motion in a conformal HMD symbol set the measured own ship movement was used to generate a pattern motion in the forward field of view close or on the landing pad.

The paper will discuss the method of amplified ego motion drift indication. Further results from a high fidelity experiment will be provided and a set of part task experiments will be introduced with results concerning impact factors like visualization type, location, gain and more.

9839-10, Session 2

A concept for a virtual flight deck shown on an HMD

Johannes M. Ernst, Hans-Ullrich Doehler, Sven Schmerwitz, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

A combination of see-through head-worn or helmet-mounted displays (HMDs) and imaging sensors is frequently used to overcome the limitations of the human visual system in degraded visual environments (DVE). A visual-conformal symbology displayed on the HMD allows the pilots to see objects such as the landing site or obstacles being invisible otherwise. These HMDs are worn by pilots sitting in a conventional cockpit, which provides a direct view of the external scene through the cockpit windows and a user interface with head-down displays and buttons.

In a previous publication, we presented the advantages of replacing the conventional head-down display hardware by virtual instruments. These "virtual aircraft-fixed cockpit instruments" were displayed on the Elbit JEDEYE system, a binocular, see-through HMD. The idea of our current work is to not only virtualize the display hardware of the flight deck, but also to replace the direct view of the out-the-window scene by a virtual view of the surroundings. This imagery is derived from various sensors and rendered on an HMD, however without see-through capability.

This approach promises many advantages over conventional cockpit designs. Besides potential weight savings, this future flight deck can provide a less restricted outside view as the pilots are able to virtually see through the airframe. The paper presents a concept for the realization of such a virtual flight deck and states the expected benefits as well as the challenges to be met.

9839-11, Session 2

Helmet mounted display supporting helicopter missions during en route flight and landing

Thomas Lueken, Hans-Ullrich Doehler, Sven Schmerwitz, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Degraded visual environment is still a major problem for helicopter pilots especially during approach and landing. Complementary sensor data (e.g. Ladar, mmW, TV, and IR) can help the pilot by generating fused synthetic vision images on a Head-Down display. But particularly with regard to the landing phase, pilot's eyes must be directed outward in order to find visual cues as indicators for drift estimation. If lateral speed exceeds the limits it can damage the airframe or in extreme cases lead to a rollover. Since poor visibility can contribute to a loss of situation awareness and spatial disorientation, it is crucial to intuitively provide the pilot with the essential visual information he needs for a safe landing.

With continuous technology advancement helmet-mounted displays

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(HMD) will soon become a spreading technology, because look through capability is an enabler to offer both monitoring the outside view while presenting flight phase depending symbologies on the helmet display. Besides presenting primary flight information, additional information for obstacle accentuation or terrain visualization can be displayed on the visor. Virtual conformal elements like 3D pathway depiction or a 3D landing zone representation can help the pilot to maintain control until touchdown even during poor visual conditions.

This paper describes first investigations in terms of both enroute and landing symbology presented on a helmet mounted display system in the scope of helicopter flight trials with DLR's flying helicopter simulator ACT/FHS.

9839-12, Session 3

Present and future of vision systems technologies in commercial flight operations (*Invited Paper*)

Jim Ward, Gulfstream Aerospace Corp. (United States)

This talk will present an overview of the current state of vision system technologies in commercial flight operations. From this basis, the future applications of vision systems technologies will be discussed with emphasis on technology trends, benefits, and needs.

9839-13, Session 4

Assessing impact of dual sensor enhanced flight vision systems on departure performance

Lynda J. Kramer, NASA Langley Research Ctr. (United States); Timothy J. Etherington, Rockwell Collins, Inc. (United States); Kurt Severance, Randall E. Bailey, NASA Langley Research Ctr. (United States)

Flight deck-based vision system technologies, such as Synthetic Vision (SV) and Enhanced Flight Vision Systems (EFVS), may serve as game-changing technologies to meet the challenges of the Next Generation Air Transportation System and the envisioned Equivalent Visual Operations (EVO) concept – that is, the ability to achieve the safety of current-day Visual Flight Rules (VFR) operations and maintain the operational tempos of VFR irrespective of the weather and visibility conditions. One significant obstacle lies in the definition of required equipment on the aircraft and on the airport to enable the EVO concept objective. A motion-base simulator experiment was conducted to evaluate the operational feasibility, pilot workload and pilot acceptability of conducting departures on runways without centerline lighting in visibility as low as 300 ft runway visual range by use of onboard vision system technologies on a Head-Up Display (HUD) without need or reliance on natural vision. Twelve crews evaluated two methods of combining dual sensor (millimeter wave radar and forward looking infrared) EFVS imagery on pilot-flying and pilot-monitoring HUDs. In addition, the crews evaluated three combined vision system (SV and EFVS imagery) HUD concepts by assessing the impact of adding SV to the dual sensor EFVS imagery in terms of visual momentum. The impact of the presence or absence of runway centerline lighting was experimentally assessed. This paper presents the experimental results specific to crew taxi and takeoff performance, workload, and situation awareness while using EFVS on a HUD, with and without SV, during extremely low visibility terminal operations.

9839-14, Session 4

Measuring the denoising performance of the human visual system for optimum display quality

Kimberly E. Kolb, U.S. Army RDECOM CERDEC NVESD (United States)

The human visual system (HVS) uses a complex network of filters and algorithms to provide optimal balance between resolution and signal to noise for a given visual task. Temporal and spatial averaging, matched filter analysis, variable gain settings, real time adjustments and feedback – all of these are seamlessly available to the human observer to improve perception. Unfortunately, when viewing a scene through an imaging system and display, an observer is often forced to manually adjust display settings to improve viewing conditions. For many tactical imaging systems, these adjustments are either time-prohibitive or simply unavailable. In an ideal system, the optimal magnification, contrast, and denoising settings would be determined via adaptive algorithms and applied automatically. To guide the development of such algorithms, observer performance is measured using noise-limited target acquisition tasks. When combined with HVS-based performance models, this data establishes the algorithm settings for optimal display adjustment in a variety of noise-limited conditions.

9839-15, Session 4

Perceptual issues for color helmet-mounted displays: luminance and color contrast requirements

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Color is one of the latest design characteristics of helmet-mounted displays (HMDs). Its inclusion in design specifications is based on two suppositions: 1) color provides an additional method of encoding information, and 2) color provides a more realistic, and hence more intuitive, presentation of information, especially pilotage imagery. To some degree, these two perceived advantages have been validated with head-down panel-mounted displays, although not without a few problems associated with human vision physiology and visual perception. These problems become more prevalent when the user population expands beyond military aviators, where strict vision screening requirements are employed, to a general user population, of which a significant portion has color vision deficiencies. When color is implemented in HMDs, which are eyes-out, see-through displays, visual perception issues become an increased concern. A major confound with HMDs is their inherent see-through (transparent) property. The result is color in the displayed image combines with color in the outside (or in-cockpit) world, possibly producing a false perception of either or both images. While human-factors derived guidelines based on trial and error have been developed, color HMD systems still place more emphasis on colorimetric than perceptual standards. This paper identifies the visual and perceptual issues that must be considered in the design of color HMDs. These issues include color deficiencies, light and color adaptation, color contrast, and confusion, as well as illusions such as color constancy that can degrade performance in attention, search and recognition tasks.

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9839-16, Session 5

Wavelet-based image visibility enhancement of IR images

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Enhancing the visibility of infrared images obtained in degraded visibility environment is very important to many applications such as surveillance, visual navigation in bad weather and helicopter landing in brownout conditions. In this paper, we present an IR image visibility enhancement system based on adaptively modifying the wavelet coefficients of the images. In the proposed system, input images are first filtered by a histogram-based dynamic range filter in order to remove sensor noise and convert the input images into 8-bit dynamic range for efficient processing and display. By utilizing a wavelet transformation, we modify both the image intensity distribution and enhance image edges simultaneously. In the wavelet domain, low frequency wavelet coefficients contain original image intensity distribution while high frequency wavelet coefficients contain edge information of original images. To modify the image intensity distribution, an adaptive histogram equalization technique is applied to the low frequency wavelet coefficients; while to enhance image edges, an adaptive edge enhancement technique is applied to the high frequency wavelet coefficients. An inverse wavelet transformation is applied to the modified wavelet coefficients to obtain intensity images with enhanced visibility. Finally, a Gaussian filter is used to remove blocking artifacts introduced by the adaptive techniques. Since wavelet transformation uses down-sampling to obtain low frequency wavelet coefficients, histogram equalization of low-frequency coefficients is computationally more efficient than histogram equalization of the original images. We tested the proposed system with degraded IR images obtained from a helicopter landing in brownout conditions. Our experimental results show that the proposed system is effective for enhancing the visibility of degraded IR images.

9839-17, Session 5

A new optical system for low-profile HUD by using a prism waveguide

Masato Tanaka, Yoshiki Arita, Shimadzu Corp. (Japan)

A new approach for optical system with waveguides is presented. Recently, Large Area Displays (LAD) tend to be located to airplane cockpits. According to this trend, Low Profile Head Up Displays (HUD) are being developed, which can be installed to the cockpit avoiding interference with LAD by using holographic waveguides. However, the holographic waveguide has difficulties in realizing color display because of its own characteristics. We have succeeded to develop a new optical system for Low Profile HUD, which has wide field of view, small size, and excellent color performance, by using a prism waveguide.

9839-18, Session 5

Global vision systems regulatory and standard setting activities

Carlo L. Tiana, Rockwell Collins, Inc. (United States);
Thomas R. Muensterer, Airbus Defence and Space (Germany)

A number of committees globally, and the Regulatory Agencies they support, are active delivering and updating performance standards for vision system: Enhanced, Synthetic and Combined, as they apply to both Fixed Wing and, more recently, Rotorcraft operations in low visibility. We provide an update of recent activities and future goals of these efforts. In both domains the effort is going via an enhancement of situational awareness providing increased safety towards an extension of the operational envelope.

9839-19, Session 6

Characterization of the OPAL LiDAR under controlled obscurant conditions

Xiaoying Cao, Philip M. Church, Justin Matheson, Neptec Technologies Corp. (Canada)

Neptec Technologies' OPAL-120 3D Lidar is optimized for obscurant penetration. The OPAL-120 uses a scanning mechanism based on the Risley prism pair. The scan patterns are created by rotating two prisms under independent motor control. The geometry and material properties of the prisms define the conical field-of-view of the sensor, which can be set between 60 to 120 degrees. The OPAL-120 was recently evaluated using a controlled obscurant chamber capable of generating clouds of obscurants over a length of 22m. Obscurants used in this investigation include: Arizona road dust, water fog, and fog-oil. The obscurant cloud optical densities were monitored with a transmissometer. Optical depths values ranged from an upper value of 6 and progressively decreased to 0. Targets were positioned at the back of the obscurant chamber at a distance of 60m from the Lidar. The targets are made of a foreground array of equally spaced slats in front of a solid background. Reflectivity contrasts were achieved with background/foreground combinations of white/white, white/black and black/white. Data analysis will be presented on the effect of optical densities on range and cross-range resolution and accuracy. This will be done for the combinations of all obscurant types and target reflectivity contrasts.

9839-20, Session 6

Three-dimensional landing zone lidar

James C. Savage, Air Force Research Lab. (United States);
Hoyt B. Burns, H.N. Burns Engineering Corp. (United States)

Three-Dimensional Landing Zone (3D-LZ) refers to a series of Air Force Research Laboratory (AFRL) programs to develop high-resolution, imaging lidar to address helicopter approach and landing in degraded visual environments with emphasis on brownout; cable warning and obstacle avoidance; and controlled flight into terrain. Initial efforts adapted lidar systems built for munition seekers, and success led to a the 3D-LZ Joint Capability Technology Demonstration (JCTD) , a 27-month program to develop and demonstrate a lidar subsystem that could be housed with the AN/AAQ-29 FLIR turret flown on US Air Force Combat Search and Rescue (CSAR) HH-60G Pave Hawk helicopters. Following the JCTD flight demonstration, further development focused on reducing size, weight, and power while continuing to refine the real-time geo-referencing, dust rejection, obstacle and cable avoidance, and Helicopter Terrain Awareness and Warning (HTAWS) capability demonstrated under the JCTD. This paper summarizes significant lidar technology development milestones to date, individual LADAR technologies within 3D-LZ, and results of the flight testing.

9839-21, Session 6

Progress towards dual-mode active/passive millimeter-wave imaging receiver for brownout applications

Christopher A. Schuetz, Richard D. Martin, Thomas E. Dillon, Charles Harrity, Daniel G. Mackrides, Peng Yao, Phase Sensitive Innovations, Inc. (United States); Dennis W. Prather, Univ. of Delaware (United States)

For degraded visual environments, millimeter-wave wavelengths provide better penetration of most visible obscurants allowing sensing in a range of environments that are largely impenetrable to other wavelengths. While both passive imaging and active RADAR solutions have been explored

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at this wavelength, each provide unique advantages depending on the information desired. For example, while passive imaging provides diversity of illumination for more readily identifiable imagery, active provides the ability to derive range information, which is invaluable in low-contrast terrain environments. To this end, we present progress towards a photonically-enabled, dual-mode imager that either works as a passive millimeter-wave imager or as a 2-D RADAR imaging receiver potentially capable of providing range information for the full volume from a single pulse in a manner analogous to FLASH LIDAR. Results from the passive imager for brownout scenarios will be presented along with analysis of systems requirements necessary to yield the desired dual-mode operation. Additionally, photonic techniques for the generation of high-power, short-duration millimeter-wave transmit pulses will be described.

9839-22, Session 6

Mapping of ice, snow and water using aircraft-mounted LiDAR

Philip M. Church, Justin Matheson, Brett Owens, Neptec Technologies Corp. (Canada)

Neptec Technologies Corp. has developed a family of obscurant-penetrating 3D laser scanners (OPAL 2.0) that are being adapted for airborne platforms for operations in Degraded Visual Environments (DVE). The OPAL uses a scanning mechanism based on the Risley prism pair. Data acquisition rates can go as high as 200kHz for ranges within 230m and 25kHz for ranges exceeding 230m. The scan patterns are created by rotating two prisms under independent motor control producing a conical Field-Of-View (FOV). An OPAL laser scanner with 90 degrees FOV was installed on a Navajo aircraft, looking down through an aperture in the aircraft floor. The rotation speeds of the Risley prisms were selected to optimize a uniformity of the data samples distribution on the ground. Data was collected to evaluate the detection of wires when flying over water, snow and ice. Flight patterns simulating a landing approach over snow and ice in an unprepared Arctic environment were also done to evaluate the capability of the OPAL Lidar to map snow and ice elevation distribution in real-time and highlight potential obstacles. Main results and conclusions obtained from the flight data analysis will be presented.

9839-23, Session 6

Optical and imaging performance testing for an improved real-time passive millimetre-wave imager to be used in degraded visual environments

Colin D. Cameron, Rupert N. Anderton, Gordon N. Sinclair, James G. Burnett, QinetiQ Ltd. (United Kingdom)

This paper discusses the optical testing and imaging performance of the improved passive mm-wave imager design for use in degraded visual environments for base security and helicopter navigation reported in the 2014 conference.

The testing regime starts with optical component testing, to show whether each optical component conforms to its specification, and predict what effect each component will have on system performance. The testing described includes metrology of surface profiles, measurements of loss for each component, measurements of point spread functions and encircled energy of each component with optical power, and measurements of polarising efficiency on the polarising material and quarter-wave plate used in the system. The performance of the receivers is also measured in terms of noise equivalent temperature difference, frequency response and receiver feed horn beam pattern. Also described is the design of two corrector test lenses which allow either imager component with optical power to form a sharp image without the presence of the other component, and thus be tested individually.

Testing of the full optics is described, both using a single scanned receiver

and later the full receiver array. The former gives better sampled point spread functions; the latter better represents the full system. The loss, effective aperture, field of view, depth of field, narcissus, thermal and fixed-pattern noise are also measured. Iterative methods to set the tolerance compensation and optimise the scan conversion look up tables are described.

Finally testing of the system imaging performance on bar targets and simple scenes is described.

9839-24, Session 6

Display of real-time 3D sensor data in a DVE system

Philipp Voelschow, Thomas R. Muensterer, Michael Strobel, Michael Kuhn, Airbus Defence and Space (Germany)

This paper describes the implementation of displaying real-time processed lidar 3D data in a DVE pilot assistance system. The goal is to display to the pilot a comprehensive image of the surrounding world without misleading or cluttering information. 3D data which can be attributed, i.e. classified, to terrain or predefined obstacle classes is depicted differently from data belonging to elevated objects which could not be classified. Display techniques may be different for head-down and head-up displays to avoid cluttering of the outside view in the latter case. While terrain is shown as shaded surfaces with grid structures or as grid structures alone, respectively, classified obstacles are typically displayed with obstacle symbols only. Data from objects elevated above ground are displayed as shaded 3D points in space. In addition the displayed 3D points are accumulated over a certain time frame allowing on the one hand side a cohesive structure being displayed and on the other hand displaying moving objects correctly. In addition color coding or texturing can be applied based on known terrain features like land use.

9839-25, Session 7

Future certification standards for commercial avionics cockpit displays with touchscreen interfaces (Invited Paper)

Joseph L. Tchon, Rockwell Collins, Inc. (United States)

Electronic Display manufacturers in the commercial avionics display market are required to apply for TSO-C113A (Airborne Multipurpose Electronic Displays) to certify a product is ready for aircraft use. This standard calls out the minimum performance requirements for certification by the Federal Aviation Administration (FAA) in the United States. The emergence of touchscreen-enabled displays in the cockpit drives the need to ensure certification requirements include this new functionality. Industry committees are in the mode of updating standards and creating new documents that will ultimately establish a set of minimum performance standards for touchscreen-enabled electronic displays for use in commercial aircraft. In recent years, military system program offices have begun to leverage commercial standards and apply for TSO certification of display equipment. This trend is expected to continue as military programs continue to adopt commercial avionics for future platforms. A review of current electronic display commercial standards followed by a look at potential minimum performance standards for touchscreen-enabled avionics displays will be presented.

9839-26, Session 7

Cooling of organic light emitting diode display panels with heat pipes

Anita Sure, Gowtham Kumar Vankayala, Vaibhav Baranwal, Karthikeyan Paramanandam, Honeywell Technology

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Solutions Lab (India); Kalluri R. Sarma, Honeywell Technology (United States); Asokan Sundarrajan, Indian Institute of Science (India)

Organic light-emitting diode half life is a function of temperature and it decreases with increase in operating temperature. Hence thermal Management is important for the efficient operation of OLED based displays. High luminance applications like aerospace cockpit displays require high power densities which lead to increase in their operating temperatures. Passive cooling is the preferred choice in aerospace applications. In this work passive cooling option with heat pipes is studied and evaluated. It shows that it has potential to reduce the display temperature rise.

9839-27, Session 7

Recent commercial display technology advances and their potential impact on future avionics and military display systems designs

Kalluri R. Sarma, Honeywell Technology (United States)

Significant advances continue to be made in various display technologies including direct view displays, examples of which include displays in premium performance smart phones, Tablet PCs, Note Book PCs, Desktop monitors and TV, and virtual image displays examples of which include near to eye (NTE) displays and projection and waveguide based Head up Displays (HUD). The display media technologies such as LCD, OLED, and quantum dot (QD) technologies continue to make impressive advances. Similarly, advances in enabling technologies such as graphics processing, computation, optical technologies such as waveguide optics, free-form optics and holography, are supporting the development of augmented and virtual reality displays for entertainment, scientific visualization and education etc. In this paper we will first review the recent advances in commercial display technologies and then discuss their potential impact on future avionics and military display systems designs, including head down displays (HDD), HUDs, and wearable systems.

9839-30, Session 7

Symmetric bio-encryption to protect biometric templates

Obaidul Malek, Ctr. for Biometrics and Biomedical Research (United States)

Secrets have always been hard to keep. Due to the proliferation of changing technologies, demands from public and private institutions to protect these secrets in digital form have risen higher than ever. The advent of computer technology along with the rise in security and privacy concerns led to the emergence of biometric systems. Biometrics deals with sensitive physiological information that is extremely private for an individual. Security measures to protect this privacy are an extremely important component of biometric systems.

A limited number of biometric traits possess sensitive human information that is unique and cannot be revoked or reissued once compromised. The features extracted from the biometric traits are stored in the database during enrollment in order to compare and authenticate the legitimacy of an individual. The method of this stored data manipulation and representation technique is almost the same as any other traditional database system. Therefore, concerns about protecting the security and privacy of stored biometric templates are the crucial issues for the twenty first century.

Encryption in a biometric system is essentially a mathematical formulation. It is used to cryptograph the plain biometric features in such a way that encoding or decoding should not require too much effort for the legitimate user but must be difficult for the unintended user. The whole point of encryption is to transform biometric features into cipher-biometrics to keep biometric templates out of the hands of unauthorized individuals.

This paper proposes a novel biometric encryption method to protect the security and privacy of biometric templates. In the proposed system, a symmetric encryption method has been designed that addresses the challenges arising for biometric templates due to unlinkability attacks. Unlike current encryption methods, MultiBiometrics features are fused with a symmetric secret key to create a cryptographic bond. This cryptographic bond along with its data management system are used to protect not only the stored biometric templates, but also the secret key. The performance of the proposed method has been evaluated based on the Equal Error Rate, and the experimental results demonstrate the effectiveness of the proposed method.

In this paper, a encryption method has been proposed with the objective of providing multilayered security and privacy protection for the stored biometric templates from unlinkability attacks. Unlinkability implies the incapability of retrieving the information of one individual based on the information of another and is the core property for any authentication system. It has become an especially important phenomenon for biometric systems, because if the system becomes compromised it could lead to unprecedented security and privacy breaches of sensitive biometric systems.

In this method, a single 32-bit secret key is used for both encryption and decryption methods. Unlike current encryption methods, this secret key has been fused with extracted MultiBiometrics features to create a cryptographic bond. Furthermore, a data management architecture has been developed so that the cryptographic bond and data management system make it difficult for a third party recipient to access and retrieve not only the stored biometric templates but also the secret key.

9839-34, Session 7

Large area colour display performance improvements through the application of waveguide optical techniques

Paul L. Wisely, Aardvark Aerospace Ltd. (United Kingdom)

Cockpit displays for fighters have performance requirements that are far beyond the capabilities of commercial state-of-the-art flat panel displays.

Full sunlight readability and night vision compatibility are mandatory, requiring drive electronics that can achieve a minimum dimming range of 40:000:1 together with ultra-high reliability under the extreme environmental conditions specified for military equipment; these requirements cannot be satisfied by mass production products, hence displays need to be specially developed for military applications to meet these requirements.

Current AMLCD Displays struggle to meet the military requirements, are relatively bulky and heavy and suffer from obsolescence issues.

This paper describes a novel design approach base on waveguide optical design techniques that overcomes many of these problems and also incorporates an inherent touch screen capability.

9839-28, Session 8

Maximizing color detail differentiation of natural objects using inverse photopic spectra light

Gary W. Jones, NanoQuantum Sciences, Inc. (United States)

When on foot and off-pavement at night, improved situational awareness and more rapid identification of terrestrial hazards such as bumps, holes, or obstructions can provide considerable benefit to a wide range of military and civilian personnel. Many natural surfaces frequently appear as brown, grey, black, or other dark colors. These objects may appear similar to background surfaces or have internal patterns or structure. Faster object recognition is possible if differential color detail can be visually enhanced.

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Reflected spectral data from many natural terrestrial objects such as soils, fungi, minerals, and vegetation and a variety of ground hazards has been collected and analyzed to predict the best spectra illumination for the task of visually differentiating color detail in natural terrestrial objects. When this data was correlated with human visual sensitivity and light wavelengths from 385nm to 750nm, we found that the inverse of typical photopic vision sensitivity curves (with higher relative intensities in the shorter and longer wavelength portions of the visible light spectrum) could highlight differences in many dark color objects better than the typical LED personal flashlights and head-worn lamps used today that are spectrally dominated by yellow-green light and that contain minimal red, cyan, and violet-indigo spectral range light. Inverse Photopic Spectrum illuminated objects using camera and display systems appeared similar to incandescent illuminated images. This paper will relate this data to dark-adapted and not-dark-adapted human vision, review the benefits and weaknesses of various illumination spectra, review camera and display effects, and briefly discuss other parameters that are important for rapid recognition of physical and color detail in terrestrial objects.

9839-29, Session 8

Just noticeable color difference: a determination of 256 intensity difference thresholds

Daniel D. Desjardins, Northrop Grumman Corp. (United States); Patrick Gardner, Western Carolina Univ. (United States)

Leveraging research reported by the authors in an earlier paper, this paper shall pursue an improved and more in-depth approach for the determination of a full 256 Just Noticeable Color Differences (JNCDs) for red, green, and blue color primaries. An improved Display Under Test (DUT) shall be chosen capable of a sufficient black state such that for low luminance values the 1931 CIE x,y coordinates maintain a desired variance $< + 0.005$ units. The number of test subjects shall be expanded to 10, allowing a broader statistical validity. Testing shall be re-designed to allow a broader luminance range, e.g., 0 – 250 cd/m², and as many as 1,000 gray levels by which to determine 256 JNCD with sufficient granularity. Results shall be compared with the Munsell values (luminance %) recommended in the “Draft Standard for Color Active Matrix Liquid Crystal Displays In U.S. Military Aircraft” (WL-TR-93-1177). They shall also be compared with respect to color and/or gray “scale” performance criteria recommended in “Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft” (ARP4256A).

9839-31, Session 9

Combatant eye protection: an introduction to the blue light hazard

Morris R. Lattimore, U.S. Army Aeromedical Research Lab. (United States)

Introduction - Combat spectacles have successfully provided protection from penetrating ocular injury for over 5 years; the primary obstacle to their successful performance had been getting Soldiers to actually wear the protective gear. As success stories emerged (via photographic evidence), compliance rates approached 100%. The risk of functional eye injury resulting from visible solar radiation was less obvious. Moreover, the risk of functional ocular tissue injury from LED-generated radiant energy remains under scrutiny, because all LEDs (i.e., even those embedded within digital tactical display systems and flat panel instrument displays) can possess major energy outputs across the blue spectrum, independent of their apparent white or observational color. Methods - This report is based on current data-extrapolation from prior work that had quantified alterations in rabbit corneal metabolic activity secondary to in-vivo UV exposures. For each UV wavelength used (290 nanometers [nm], 300 nm, 310 nm, and 360 nm), the exposures varied from 0.05 J/cm² to 0.25 J/cm² (in 0.05 J/cm²

steps), based on maintaining environmental relevance. Micro-polarographic corneal oxygen uptake rates served as the in-vivo index of alteration in oxidative metabolic rate. Results - Analysis of variance exhibited an overall significant between-groups effect by wavelength ($p < 0.0001$), as well as an interactive effect between wavelength and radiant energy dose ($p < 0.005$). Control eyes were stable. Extrapolation of the nonlinear trend lines out into visible wavelengths reached baseline at 447 nm. Discussion - Evidence of metabolic vulnerability to visible light extending well into the blue spectrum is vitally important, as this is indicative of a moving, scalable effect, with no traditional threshold-delineating expectation of damage/no damage. Added stressors (e.g., increased altitude or contact lens wear) could shift the wavelength effects toward a more damaging clinical picture. Recent reports have indicated rod photo-pigment damage resulting from solar blue-light exposures, adversely affecting unaided night vision, a militarily important performance decrement. Conclusion - The incorporation of blue filters in conjunction with current protective eyewear represents one potentially proactive solution, but there are limits. A defined research program regarding establishment of human functional ocular parameter limits would be essential to overall safety. The activation wavelength for the daily synchronous setting of the Circadian Clock, which regulates the synchronization of all hormonal and organ systems throughout the body, falls within the blue light perceptual range. Thus, protection against blue light photo-damage cannot involve the application of a broad-band or full-time blue filter application. Ideally, a narrow-band blue filter should be developed, preceded by an applied research program to ensure the safe application of this proposed new filtering capability.

9839-32, Session 9

Head up, eye out in day and at night striker HMD: Evolution or revolution?

Alexander A. Cameron, Ross Hobson, BAE Systems (United Kingdom)

BAE Systems two-part Striker® helmet product family is a mature fully integrated helmet mounted display in volume production and used on multiple fixed wing and rotary platforms worldwide. The Striker® system on Typhoon, Gripen and Hawk provides a high accuracy off bore sight weapon cueing capability to the fast jet users in over 10 nations. The advanced all digital rotary wing variant of Striker® is a dedicated helicopter HMD which has already been extensively flight tested in a US, UK, and European platforms.

This visor projected HMD is therefore a mature, advanced integrated display helmet that has been specifically designed for high capability military HMD applications. The two part integrated helmet concept is also a mature design already in wide spread operational use. The combination of these features has enabled the core Striker® HMD design concept to be enhanced to meet the demand of both 5th Generation fixed wing platforms and enhanced capabilities for rotary wing users.

These top level needs may be summarized as:

- Provision of Enhanced Situational Awareness
- Capability to Operate in All Weathers and 24 Hours by providing enhanced vision.
- Seeing Through the Night, The Weather & Dust
- Improved Pilot & Mission Effectives
- Better Aircrew Safety and Comfort

This has resulted in the development of the Striker® II HMD, which although a new all-digital HMD design benefits from the maturity of the proven Striker® I product. It includes high definition digital display, and an integrated digital night vision camera which eliminates the need for separate night vision goggles. This means that the warfighter can transition from day to night operation at the flick of a switch, rather than having to remove and store the cumbersome NVGs. Striker® II also allows greater head movement, and (as it is lighter) causes less fatigue and enables the pilot to tolerate higher-G manoeuvring.

This paper charts the development of this next generation high capability HMD product, the operational drivers it was designed to satisfy, the key

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technologies that enabled it to be built and the implementation and flight evaluation of this ejection cleared production ready product.

9839-33, Session 9

**Performance and lifetime enhancements
to legacy analog head up displays systems
in military applications through affordable
digital upgrades**

Paul L. Wisely, Aardvark Aerospace Ltd. (United Kingdom)

Large numbers of military aircraft that were designed and manufactured in the last century remain in service today; world economics indicate that they are unlikely to be replaced in the foreseeable future. As their avionic systems age, in service support becomes increasingly expensive, hence ways need to be identified to control and reduce these costs.

This paper describes an affordable approach to reducing the costs associated with head up display pilots' display units, through novel design concepts; these concepts replace the cathode ray tubes and their associated electronics with an all-digital system that seamlessly interfaces, both optically and electronically, with the legacy components of the HUD display unit.

Though such schemes have been explored by several manufacturers in the past, they have struggled to achieve an ideal solution that would enable the HUDs to fully meet their original system design specifications; the challenges involved in achieving this goal are further discussed in this paper, and approaches to realize the ideal solution described.

Conference 9840: Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XXII

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9840-1, Session 1

Hyperspectral image analysis using deep learning: a survey

David K. J. Gustafsson, Hernik Petersson, FOI-Swedish Defence Research Agency (Sweden)

Hyperspectral image processing is a very progressive area in remote sensing and other applications. Among the key applications in hyperspectral image processing we find tasks such as using spectral signatures for material classification, target detection or scene segmentation at distance.

In machine learning and pattern recognition, 'Deep learning' is a relatively new approach which have given very promising results in many applications. In deep learning a hierarchical representation of increasing level of abstraction of the features is learned. A key concept in deep learning is the possibility to learn a hierarchical feature representation using unsupervised data. Extracting important regularities from unclassified data using unsupervised pattern recognition methods has made it possible to use the massive amount of unclassified data in the learning process. Auto-encoder is an important unsupervised technic frequently used for extracting key features from data in deep learning. An auto-encoder learn a mapping of the data onto itself through a latent representation of a lower dimensionality. The latent representation of lower dimensionality is a compact representation of the original data containing the most important features of the original data. Another key concept in deep learning is convolutional neural network (commonly called ConvNet). In ConvNet a hierarchical representation, composed of learned convolutional kernels, of the image data is automatically learned using supervised technics.

Deep learning methods have now begun to find use in hyperspectral images and on a number of application, such as material classification, segmentation, and target detection. In this paper, a survey on deep learning in hyperspectral imaging is presented. Key concept in deep learning is presented and discussed in relation to hyperspectral imaging. Deep learning methods for processing and classification using spatial information and spectral information in different application is described. Current practice in classification using deep learning in hyperspectral imaging and its performance in relation to state-of-the-arts methods are discussed.

9840-2, Session 1

A study of neural network parameters for improvement in classification accuracy

Avijit Pathak, Kailash Chandra Tiwari, Delhi Technological Univ. (India)

Hyperspectral data due to large number of spectral channels facilitates discrimination between large number cover classes; however, the advantage afforded by the hyperspectral data often tends to get lost in the limitations of convectional classifier techniques. Artificial Neural Networks in several studies have shown to outperform convectional classifiers. Objectives of the study are to investigate the effect of various Neural Network parameters on the accuracy of hyperspectral image classification. AVIRIS Hyperspectral Indian Pine dataset in 220 Bands acquired on June 12, 1992 has been used in the study. The bands covering the region of water absorption are removed leaving 200 bands for classification. Thereafter the maximal feature extraction technique of Principle component analysis is used to reduce the dataset to 10 bands preserving of 99.96% variance. The parameters selected for the study are - number of hidden layers, hidden Nodes, training sample size, learning rate and learning momentum. The training sample sizes selected for the study are 20, 40, 60, 80, and 100. Four testing classes

with 300 testing pixels from each class are selected to test the accuracy of the network after training. Four values of hidden nodes are selected 10, 20, 30, 40 are fixed for one and two hidden layer categories. The learning rate is variated in the range of 0.0004-0.4 and momentum varied in the range 0-1. Backpropagation method of learning is adopted. The overall accuracy of the network trained is assessed with testing samples of size 300. Total of 800 classifications are performed with various combinations of parameter set using adaptive learning rate. The performance of network is checked in terms of mean square error. The accuracies thus generated are plotted with their respective parameters and an attempt to investigate the relationship among them is made. The network is able to classify the data with high accuracies (>95%) even for smaller datasets thus outperforming several conventional methods. Parameters corresponding to such networks are studied thoroughly and necessary relations are derived for maximum classification accuracy with minimum size of input training set. All implementations are done on ENVI and MATLAB software.

9840-3, Session 1

Tensor subspace analysis for spatial-spectral classification of hyperspectral data

Lei Fan, David W. Messinger, Rochester Institute of Technology (United States)

Remotely sensed data fusion aims to integrate multi-source information generated from different perspectives, acquired with different sensors or captured at different times in order to produce fused data that contains more information than one individual data source. Recently, extended morphological attribute profiles (EMAPs) were proposed to embed contextual information, such as texture, shape, size and etc., into a high dimensional feature space as an additional data source complementary to the spectral image. Although EMAPs provide greater capabilities in modeling both spatial and spectral information, they lead to an increase in the dimensionality of the extracted features. Conventionally, a data point in high dimensional feature space is represented by a vector. For a hyperspectral image (HSI), this data representation has one obvious shortcoming in that only spectral knowledge is utilized without neighborhood information being exploited. Tensors provide a natural representation for HSI and EMAPs data points by incorporating local spatial information. A tensor-based Locality Preserving Projection (tensorLPP) algorithm was applied on HSI and EMAPs for dimensionality reduction before classification was performed. Results show that tensorLPP generates the highest classification accuracy compared to other vector-based dimensionality approaches such as PCA, LPP, LE and etc.

9840-4, Session 1

Classification performance of a hyperspectral data processing algorithm using a block-compressive sensing approach

Emmanuel Arzuaga, Fernando X. Arias, Univ. de Puerto Rico Mayagüez (United States); Heidy Sierra, Memorial Sloan-Kettering Cancer Ctr. (United States)

Compressive Sensing is an area of great recent interest for efficient signal acquisition, manipulation and reconstruction tasks in areas where sensor

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utilization is a scarce and valuable resource. The current work shows that approaches based on this technology can improve the efficiency of manipulation, analysis and storage processes already established for hyperspectral imagery, with little discernible loss in data performance upon reconstruction. It is our interest to evaluate the effects that compressive sensing technology might have on the classification of such data sets. We present the results of a comparative analysis of classification performance between hyperspectral data cubes acquired by traditional sensor systems, and those obtained through reconstruction from compressively sampled data points. To obtain a broad measure of the classification performance of compressively sensed cubes, we classify different scenes using a set of five classifiers commonly used in hyperspectral image classification. Global accuracy statistics are presented and discussed, as well as class-specific statistical properties of the evaluated data set.

9840-6, Session 2

Cross-calibration in the reflective solar bands of Terra MODIS and Landsat 7 ETM+ at desert, snow, and water surface types

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Using the Terra MODIS and Landsat 7 ETM+ reflectance measurements interchangeably is useful to extend analyses of Earth's land, ocean, and atmosphere system across global and regional geographic scales. Methodologies were previously developed by the MODIS Characterization Support Team (MCST) and the South Dakota State University (SDSU) Image Processing Lab to use the Libya-4 Saharan Desert site as a long-term stable reference to inter-compare sensor TOA calibration. The methodologies characterized sensor spectral response sensitivity mismatch, mitigated effects of atmospheric water vapor absorption features, and minimized the site-dependent surface BRDF variability of Libya-4. The two methodologies agreed to within 1-5% across six spectrally matching reflective solar bands in the MODIS and ETM+ instruments. However, methodologies specific to the Libya-4 site for cross-calibration do not achieve adequate signal level variation to comprehensively analyze the calibration accuracies across the full dynamic range of the instruments. As such, this study adapted the methodologies to an extended range of target surface types, including the brighter Dome-C target and the darker Lake Tahoe target. Using Earth Observing One (EO-1) Hyperion as the reference spectral input, uncertainties caused due to different spacecraft overpass times coupled with short-term instability of the surface types were characterized and removed. The results give new insight into the suitability of the models at different sites for analyzing the gain and biases inherent to the calibration approaches of the instruments over their on-going mission lifetimes.

9840-7, Session 2

Tracking the on-orbit spatial performance of MODIS using ground targets

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Nearly-identical MODIS instruments are operating onboard both the NASA EOS Terra and Aqua spacecraft. Each instrument records earth-scene data using 490 detectors divided among 36 spectral bands. These bands range in center wavelength from 0.4 μm to 14.2 μm to benefit studies of the entire earth system including land, atmosphere, and ocean disciplines. Many of

the resultant science data products are the result of multiple bands used in combination. Any mis-registration between the bands would adversely affect subsequent data products. The relative registration between MODIS bands was measured pre-launch and continues to be monitored on-orbit via the Spectro-radiometric Calibration Assembly (SRCA), an on-board calibrator. Analysis has not only shown registration differences pre-launch, but also long-term and seasonal changes. While the ability to determine registration changes on-orbit using the SRCA is unique to MODIS, the use of ground targets to determine relative registration has been used for other instruments. This paper evaluates a ground target for MODIS spatial characterization using the MODIS calibrated data product. Results are compared against previously reported findings using MODIS data and the operational on-board characterization using the SRCA.

9840-8, Session 2

Quantitative analysis of errors from keystone and smile in hyperspectral imagers

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Keystone and smile are optical distortions in slit spectrometer-based hyperspectral imagers that degrade the quality of hyperspectral data. There is a consensus in the hyperspectral community that these distortions must be held to sub-pixel levels to maintain sufficient data quality. However, evidence to support this consensus is difficult to find. This article presents the initial steps toward a framework for quantitative analysis of the effects of keystone and smile. The ultimate goals of this analysis are to predict the degree of degradation in hyperspectral data for given magnitudes of keystone and smile, and substantiate the keystone and smile requirements levied in hyperspectral sensor design documents. A model of the measured irradiance in a hyperspectral sensor is developed that allows the errors due to keystone and smile to be calculated. Several simulated scenes are used to reveal the effects of keystone and smile. Various metrics are used to quantify the effects of keystone and smile, including a signal-to-noise ratio metric and the root-mean-square signal error. We show that keystone and smile contribute very little error in portions of the scene with slow spatial and spectral variability, respectively. Conversely, they cause significant error around sharp spatial and spectral features. These errors are compared to errors from other sources to calculate thresholds for the acceptable magnitudes of keystone and smile. For a concrete example, we present distortion measurements from a hyperspectral sensor to illustrate keystone and smile trends, and how these distortions impact sensor performance.

9840-9, Session 2

New applications of Spectral Edge image fusion

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In this paper, we present several new applications of the Spectral Edge image fusion method. The Spectral Edge image fusion algorithm creates a result which combines details from any number of multispectral input images with natural color information from a visible spectrum image.

Spectral Edge image fusion is a derivative-based technique, which creates an output fused image with gradients which are an ideal combination of those of the multispectral input images and the input visible color image. This produces both maximum detail and natural colors.

We present two new examples of RGB-NIR image fusion. Firstly, a real-

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time implementation of Spectral Edge fusion on a prism-based 2CCD multispectral camera, which simultaneously acquires perfectly-registered visible spectrum and near-infrared images. This RGB-NIR fusion runs at 31 FPS (the limit of the camera) at VGA resolution, and 20 FPS at 720p resolution. Secondly, we fuse RGB-NIR information from a sensor with a modified Bayer pattern, which captures visible and near-infrared image information on a single CCD.

We also present an example of RGB-thermal image fusion, using a thermal camera attached to a smartphone, which captures both visible and low-resolution thermal images. These images are then fused to produce a natural color image which also has detail transferred from the thermal image. We also present a false-color fusion, with hotter objects appearing towards the yellow-orange end of the spectrum, and cooler objects appearing blue.

We present images and videos of the results of these fusion implementations, as well as comparisons with other image fusion methods.

9840-62, Session 2

Metamaterial based narrow bandwidth angle-of-incidence independent transmission filters for hyperspectral imaging

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In this work hyperbolic metamaterials are integrated within Bragg transmission filters with the purpose of eliminating the dependence of the center wavelength of a narrow bandwidth transmission peak on the angle of incidence of the incoming TM polarized beam. This structure allows the filtering of light that is necessary for hyperspectral imaging systems because the center-wavelength of transmission of the narrow bandwidth transmission peak does not change as a function of angle of incidence. Hence, lenses can be used to collect a larger amount of light to increase the sensitivity of the system without sacrificing spectral resolution. The structure is composed of a combination of a type of hyperbolic metamaterial called a wire mesh array or Fakir's bed and a traditional Bragg stack. The array of metal wires vertically penetrates the multiple dielectric layers of the Bragg stack. Two types of modeling methods are used to simulate the optical properties of the structure, a coupled wave algorithm that uses a transfer matrix method, and finite element modeling. It is shown that ultra narrow band transmission filters can be designed such that the center wavelength of the transmission peak for TM polarized incident light does not change as the angle of incidence of an incoming beam changes from 0 degrees up to close to 90 degrees. The method is applied to different hypothetical structures operating in the near infrared, mid wave infrared and long wave infrared. In particular, filter structures operating at wavelengths of 1.5 micrometers, 4 micrometers and 9 micrometers are described. Applications to hyperspectral imaging are discussed.

9840-10, Session 3

Developing a confidence metric for the Landsat land surface temperature product

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Land Surface Temperature (LST) is an important Earth system data record that is useful to fields such as change detection, climate research, environmental monitoring, and many smaller scale applications like agriculture. Earth-observing satellites can be used to derive this metric, with the goal that a global product can be established. Through the support of the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS), a LST product for the Landsat series of satellites has been developed. Currently, it has been validated for scenes in North America, with plans to expand to a trusted global product. As the product approaches public release, it is important to develop a quality

map that will report the expected LST error on a per-pixel level. Due to the complexity of the atmospheric propagation component of this LST process, performing error propagation is a difficult task. Instead, we propose to use the relationship between cloud proximity and the error seen in the LST process to develop a confidence metric. This method involves calculating the distance to the nearest cloud from a pixel of interest in a scene, and recording the LST error at that location. Performing this calculation for hundreds of scenes allows us to observe the average LST error for different ranges of distances to the nearest cloud. The paper will describe this process in full, as well as present results for a large set of Landsat scenes.

9840-12, Session 3

Detecting red blotch disease in grape leaves using hyperspectral imaging

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Red Blotch Disease (RBD) is a viral disease that affects grapevines. Symptoms appear as irregular blotches on grape leaves with pink and red veins on the underside of the leaves. RBD causes a reduction in the accumulation of sugar in grapevines affecting the quality of grapes and resulting in delay in harvest. Detecting and monitoring this disease early is important for grapevine management. This work focuses on the use of hyperspectral imaging for detection and monitoring RBD in grape leaves. Grape leaves with known red blotch disease have been imaged with the portable SOC710 hyperspectral imaging system both on and off the vine to investigate the spectral signature of red blotch disease as well as to quantify the diseased areas on the leaves. Spectral bands corresponding to 566 nm (green) and 628 nm (red), and spectral band ratios obtained from 566 and 628 nm as well as 680 and 738 nm were selected as effective features. These effective features were utilized to differentiate red blotch from healthy-looking and dry leaf. The two bands and two band ratios were then used to train the SVM classifier in a supervised learning scheme. Once the SVM classifier was defined, two-class classification was achieved for independently collected grape leaf hyperspectral images. Identification and quantification of the RBD on grape leaves as well as its progression using hyperspectral imaging are presented in this paper.

9840-13, Session 3

Spectral feature characterization methods for blood stain detection in crime scene backgrounds

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Blood-stains are one of the most important types of evidence for forensic investigation as they contain valuable DNA information. The use of spectral signatures in analyzing blood samples are important both for forensic analysis and laboratory testing as the spectrum contains unique reflectance and absorption features. Therefore, a good knowledge of the reflectance properties of blood under different crime scene backgrounds in the Visible (VIS), Near Infrared (NIR) and Short Wave Infrared (SWIR) spectrum is crucial in the detection and recognition tasks. Age of blood-stains provides crucial temporal evidence as it refers to the time passed by since people or animals at the scene began bleeding. This paper analyzes the signatures of blood in the range of 350 nm - 2500 nm under different circumstances such as pure blood with various thicknesses, mixed blood with different colors and materials of fabrics, carpet, wall, wood, and various light sources with proper calibration, all of which are examined to provide extra evidence for detecting blood in a realistic crime scene. Specifically, the blood samples were examined for their spectral reflectances for different periods of deposition time varying from seconds to hours and days. This provides a

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fairly accurate estimate of the age of blood, both pure and mixed, using the selected ratio of unique reflectance peaks and valleys of blood spectra. Conclusions are made for the spectral variability characterization of blood both pure and mixed with various backgrounds, light sources and aging within a couple of hours from the blood spectrum.

9840-14, Session 3

Monitoring forest biodiversity using imaging spectroscopy based on leaf biochemical variations in subtropical forest

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Forest biodiversity is a key element in the provision of ecosystem service, function and stability. Monitoring forest biodiversity is essential to the conservation and management of forest resource. In the past two decades, imaging spectrometry technique has been widely applied in forest biodiversity mapping or tree species identification. A new technology and method called "spectranomics" that maps forest species richness based on leaf chemical and spectroscopic traits using imaging spectroscopy, has been developed. In this paper, this method would be used for detecting the relationship among the spectral, biochemical and taxonomic diversity of tree species based on 20 dominant canopy species collected in the Shennongjia National Forest Nature Reserve. Firstly, sixteen leaf biochemical components including pigments, water, Specific Leaf Area (SLA), nitrogen, phosphorus, cellulose, lignin and trace elements are standardized to indicate the unique combinations for each species. The hierarchical cluster analysis based on spectral reflectance signatures in 400-2400nm are applied to divide forest species to different clusters. Furthermore, the Constrained Partial Least Squares (PLS-PRESS) regress analysis is used to establish the relationship between biochemical and spectral signatures. Finally, a Monte-Carlo simulation model is used to find the species richness changes caused by the biochemical and spectral properties. The results show that the biochemical components could be well quantified by spectral signatures ($R^2 > 0.43$, $P < 0.01$; excluding the trace elements) for identifying the subtropical forest species richness.

9840-15, Session 4

Hard solids: Addressing spectral challenges through modeling

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Current techniques for material detection and identification using spectral data often involve comparing a measured spectrum with a reference or library spectrum. However, the complex physics that governs the behavior of the reflectance/emittance properties of solid materials makes their detection and identification difficult. Morphology, particle size, surface roughness and other surface optical properties can each impact the spectral reflectivity/emissivity of solid materials. Measuring reference spectra for materials that adequately span the space of physical parameters (e.g. morphology, particle size, surface roughness) requires time and resources that are often not feasible. An alternate approach would be the development of validated, physics-based models and simulations that can be used to generate synthetic spectra under a wide variety of physical parameters.

To this end, the Department of Energy, Nuclear Nonproliferation Security Administration, Office of Nuclear Nonproliferation Research and Development (DNN R&D) initiated a multi-laboratory investment in 2014. The HARD Solids venture project includes researchers from Sandia, Livermore, Los Alamos, and Pacific Northwest National Laboratories.

Through a multidisciplinary effort, the project will develop and validate models for predicting and understanding the optical properties of solid materials, with direct application to hyperspectral image (HSI) analysis. Work will directly impact the field in terms of 1) physics-based models to compute spectra of complex solid materials, 2) algorithms leveraging these models and spectral signature libraries, and 3) measurements that can be used to provide input data for models, validate models and enable new models.

9840-16, Session 4

Ideal system morphology and reflectivity measurements for model development and validation

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A detailed understanding of light reflectance from granular solids (e.g., soils, minerals) is critical to the remote sensing of such materials by hyperspectral imaging. The reflectance spectrum of a packed solid is determined by radiative transfer among its constituent grains, a process that includes both optical scattering and absorption by the intimately contacted particles. The nature of the transfer is determined by the complex refractive indices of the material, as well as by the morphology of the system. The latter includes the size and shape distribution of the particles, as well as the manner in which they are arranged.

We present the results of an effort to develop "ideal" granular solid systems with well-characterized morphological and optical properties. This work is contributing to the generation and validation of radiative transfer models and/or electromagnetic scattering computations. It is being pursued because available reflectance data, such as the ASTER database, is often lacking in precise description (e.g., the particle shape distribution) of the material system measured. To date, two materials have been used - sieved fused silica and γ -alumina created by aluminum alkoxide hydrolysis. The individual-particle size and shape distributions are measured by laser scattering and automated single-particle imaging. Their packing is characterized by micro-scale x-ray tomography, which generates three-dimensional images of the packed solid and allows calculation of density distributions, such as the pair-distribution function.

Model comparisons and validations are conducted using hemispherical diffuse reflectance spectra measured using these solids. In the future, this work will be extended to the measurement of angularly resolved polarized reflectance.

9840-17, Session 4

Experimental effects on IR reflectance spectra: particle size and packing

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For geologic and extraterrestrial samples it has been known for many years that both particle size and morphology can have a strong effect on their infrared reflectance spectra; the spectra cannot be predicted from the absorption coefficients alone. This is because the light scattering of reflectance spectroscopy is both a surface as well as a bulk phenomenon, incorporating both dispersion as well as absorption effects. The spectral features may be observed as either maxima or minima: The effects depend on particle size and preparation, as well as the relative amplitudes of the optical constants n and k , i.e. the real and imaginary components of the complex refractive index, respectively. While partially oversimplified,

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upward-going peaks in the reflectance spectrum usually result from surface scattering, which are rays that have reflected from the surface without penetration, whereas downward-going peaks are due to either absorption or volume scattering, i.e. rays that have penetrated or refracted into the sample interior and are not reflected. While the effects have been well known, we report seminal measurements that include both the reflectance and the quantified particle size of the samples, as obtained from optical microscopy measurements. The size measurements are correlated with the reflectance spectra in the 1.3 – 16 micron range for various bulk materials that have a combination of strong and weak absorption bands in order to understand the effects on the spectral features as a function of the mean grain size of the sample. We report recent results for both sodium sulfate Na₂SO₄ as well as ammonium sulfate (NH₄)₂SO₄, for the latter the optical constants have been measured. We also investigate other samples such as elemental sulfur and the effects of sample preparation on the spectra. The studies have shown that particle size has an enormous influence on the measured reflectance spectra of such materials; successful identification requires sufficient representative reflectance data to include the particle sizes of interest.

9840-18, Session 4

**A next generation field-portable
goniometer system**

Justin Harms, Charles M. Bachmann, Rochester Institute of Technology (United States)

Various field portable goniometers have been designed to capture in-situ measurements of a material's bi-directional reflectance distribution function (BRDF), each with a specific scientific purpose in mind. [1,2,3,4] The Rochester Institute of Technology's (RIT) Chester F. Carlson Center for Imaging Science recently created a novel instrument incorporating a wide variety of features into one compact apparatus in order to obtain very high accuracy BRDFs of short vegetation and sediments, even in undesirable conditions and austere environments. This next generation system integrates a dual-view design using two VNIR/SWIR spectroradiometers to capture target reflected radiance, as well as incoming radiance, to provide for better optical accuracy when measuring in non-ideal atmospheric conditions or when adjacency effects are non-negligible. The new, fully automated device also features a laser range finder to construct a surface roughness model of the target being measured, which enables the user to include inclination information into BRDF post-processing and further allows for roughness effects to be better studied for radiative transfer modeling. The highly portable design features automatic leveling, a precision engineered frame, and a variable measurement plane that allow for BRDF measurements on rugged, un-level terrain while still maintaining true angular measurements with respect to the target, all without sacrificing measurement speed. Despite the expanded capabilities and dual sensor suite, the system weighs less than 75 kg, which allows for excellent mobility and data collection on soft, silty clay or fine sand.

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9840-19, Session 4

**Retrieval of sediment fill factor from
hyperspectral BRDF measurements of
coastal sediments**

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The Hapke model has been used extensively to describe scattering from granular media.[1] It is an approximate but analytical solution to the radiative transfer equation that has been widely applied to problems ranging from planetary regoliths to earth remote sensing. Coastal sediments are complex intimate mixtures, and our recent results contain modifications that we have made to more faithfully describe the observed hyperspectral bi-directional reflectance distribution function (BRDF) of coastal sediments. [2] This study builds on our earlier work in which constrained hyperspectral goniometer measurements were used to isolate and study the fidelity of the multiple scattering term to describe real coastal sediments under controlled conditions. By constraining hyperspectral BRDF data collections to measurements at constant phase angle, single scattering contributions are constant when properly normalized, thus isolating the impact of multiple scattering. In this paper, we also consider a second type of constraint that is always collected whenever a BRDF scan is completed over a hemisphere: constant illumination and observation zenith angles. Measurements of this type provide a varying single scattering contribution but the multiple scattering term remains fixed when properly normalized. The overall goal is to develop a repeatable means of retrieving geophysical parameters such as the fill factor, which also parameterizes the model. This study uses the hyperspectral goniometer system, the Goniometer of the Rochester Institute of Technology (GRIT), designed for both field and laboratory settings, to compare observed BRDF measurements with outcomes predicted by the approximate radiative transfer solutions.

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9840-20, Session 5

**NEFDS contamination model parameter
estimation of powder contaminated
surfaces**

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Hyperspectral signatures of powdered contaminated surfaces are challenging to characterize due to intimate mixing between materials. Most radiometric models have difficulties in recreating these signatures due to non-linear interactions between particles with different physical properties. The Nonconventional Exploitation Factors Data System (NEFDS) contamination model is capable of recreating longwave hyperspectral signatures at any contamination mixture amount, but only for a limited selection of materials currently in the database. A method has been developed to invert the NEFDS model and perform parameter estimation on emissivity measurements from a variety of powdered materials on substrates. This model was chosen for its potential to accurately determine contamination coverage density as a parameter in the inverted model. Emissivity data were measured using a Designs and Prototypes fourier transform infrared spectrometer model 102 for different levels of contamination. Temperature emissivity separation was performed to convert data from measure radiance to estimated surface emissivity. Emissivity curves were then input into the inverted model and parameters were

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estimated for each spectral curve. A comparison of measured data with extrapolated model emissivity curves using estimated parameter values assessed performance of the inverted NEFDS contamination model. This paper will present the initial results of the experimental campaign and the estimated surface coverage parameters.

9840-21, Session 5

Radiative transfer modeling of surface chemical deposits

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Remote detection of a surface-bound chemical relies on the recognition of a pattern, or “signature,” that is distinct from the background. Such signatures are a function of a chemical’s fundamental optical properties, but also depend upon its specific morphology. Importantly, the same chemical can exhibit vastly different signatures depending on the size of particles composing the deposit. We present a parameterized model to account for such morphological effects on surface-deposited chemical signatures. This model leverages computational tools developed within the planetary and atmospheric science communities, beginning with T-matrix and ray-tracing approaches for evaluating the scattering and extinction properties of individual particles based on their size and shape, and the complex refractive index of the material itself. These individual-particle properties then serve as input to the Ambartsumian invariant imbedding solution for the reflectance of a particulate surface composed of these particles. The inputs to the model include parameters associated with a functionalized form of the particle size distribution (PSD) as well as parameters associated with the particle packing density. The model is numerically inverted via Sandia’s Dakota package, optimizing agreement between modeled and measured reflectance spectra, which we demonstrate on data acquired on five size-selected silica powders over the 3.6-16 μm wavelength range. Agreements between modeled and measured reflectance spectra are assessed, while the optimized PSDs resulting from the spectral fitting are then compared to PSD data acquired from multiple particle size measurement approaches.

9840-22, Session 5

Hierarchical multi-scale approach to validation and uncertainty quantification of hyper-spectral image modeling

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The primary goal of the HARD Solids Venture program is to build upon the hyper-spectral imaging (HSI) technique to model and predict the optical properties of solid materials. Validating the predictive models and quantifying uncertainties inherent in the modeling process is a critical component of the program. The current validation and uncertainty quantification (V/UQ) research focuses on validating physics-based models that predict the optical properties of mixed-solid materials for arbitrary surface morphologies and characterizing the uncertainties in these models. To that end, we employ a systematic and hierarchical V/UQ approach by designing physical experiments and comparing the experimental results with the outputs of computational predictive models. This approach divides the complex system into several progressively smaller scales—system scale, pixel scale, micro scale, and intrinsic properties—to identify and quantify the simulation errors measured in relation to experimental data and to provide a quantitative assessment of uncertainties. We illustrate this approach through an example that compares a micro-scale forward model to an idealized solid-material system. By continually and methodically validating physical and mathematical models with experimental data at various scales,

and characterizing and quantifying uncertainties in the modeling process, the V/UQ research thrust contributes to enhanced detection reliability of the HSI technique, helps broaden the range of conditions under which solid materials can be detected, and elevates the level of confidence in model utilization and model outputs by users and stakeholders.

9840-23, Session 5

Advancing the retrievals of surface emissivity by modelling the spatial distribution of temperature in the thermal hyperspectral scene

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The retrieval of Surface Temperature (ST) and Surface Emissivity (SE) of objects from thermal hyperspectral imaging (THI) are common procedures. However, retrieving ST and SE from THI data is not an easy task because it presents an ill-posed problem, i.e., $N + 1$ unknowns which are determined from a set of N equations provided by the N measured radiances. One way to solve it is to reduce the number of unknowns used to represent the emissivity spectrum. Nonetheless, in the case of heterogeneous surfaces as in an urban area, where the spatial distribution of temperature largely varies in space and time, the radiance is more dependent on the local variation of the temperatures than on the difference between emissivities (i.e., the spectral difference of materials). Moreover, most of the Temperature and Emissivity Separation (TES) algorithms assume that the observed image is flat and contains a lambertian surface (i.e. emissivity = reflectivity), while an urban scene contains heterogeneous 3-D structures, materials and landscape which increase the standard deviation of the temperature.

This study creates a model which predicts the spatial distribution of the temperature in the scene and addresses a relevant correction to the TES procedure. Specifically, data from very high resolution orthophoto, 3D LIDAR, thermal and THI of an urban area were combined for the creation of the model and for its validation. Information about the materials, reflectivity, temperature, structures and positions of the objects were extracted from the images and integrated to allow better prediction of the radiative transfer model and the spatial distribution of the temperature in the scene. The model was tested using several images from various daily times and was validated using in-situ measurements. The model proposes a robust solution for the retrieval of ST and SE of objects in a complex urban THI scene.

9840-24, Session 5

Modeling and analysis of LWIR signature variability associated with 3D and BRDF effects

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Algorithms for retrieval of surface reflectance, emissivity or temperature from a spectral image almost always assume uniform illumination and horizontal surfaces with Lambertian reflectances. When these algorithms are used to process real 3-D scenes, the retrieved “apparent” quantities reflect the strong, spatially dependent variations in illumination as well as surface bidirectional reflectance distribution function (BRDF) effects. This is especially problematic in oblique or horizontal views, where many observed surfaces are vertical, and where horizontal surfaces can show strong specularity. The goals of the present study are to characterize long-wavelength infrared (LWIR) signature variability in a HSI 3-D scene and develop practical methods for estimating the true surface quantities. We

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take advantage of synthetic horizontal imagery generated with the high-fidelity MuSES model, and present retrievals of temperature and directional-hemispherical reflectance from the FLAASH-IR algorithm, including a variant that incorporates MuSES-based non-uniform illumination. Approximating the illumination as local mixtures of clear sky and blackbody radiances facilitates the use of a single MuSES simulation to analyze HSI data over a range of atmospheric conditions and local surface types.

vehicles moving throughout the scene in varying solar-target-observer geometries. We also use the model to analyze recently collected VIS-SWIR hyperspectral imagery of vehicles and panels collected at Rochester Institute of Technology during a fall 2015 measurement campaign. This paper will discuss the variation of vehicle signatures under varying viewing geometries, using measured and modeled data, and consequences of these signature variations on subsequent target detection.

9840-25, Session 5

Solid target spectral variability in LWIR

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We continue to highlight the pattern recognition challenges associated with solid target spectral variability in the longwave infrared (LWIR) region of the electromagnetic spectrum for a persistent imaging experiment. The experiment focused on the collection and exploitation of LWIR hyperspectral imagery. We emphasize the inherent challenges associated with using remotely sensed LWIR hyperspectral imagery for material recognition, and show that this data type violates key data assumptions conventionally used in the scientific community to develop detection or ID algorithms, i.e., normality, independence, identical distribution. We treat LWIR hyperspectral imagery as longitudinal data and aim at proposing a more realistic framework for material recognition as a function of spectral evolution through time, and discuss limitations. The defining characteristic of a longitudinal study is that objects are measured repeatedly through time and, as a result, data are dependent. This is in contrast to cross-sectional studies in which the outcomes of a specific event are observed by randomly sampling from a large population of relevant objects in which data are assumed independent. Researchers in the remote sensing community generally assume the problem of object recognition to be cross-sectional. But through a longitudinal analysis of a fixed site with multiple material types, we quantify and argue that, as data evolve through a full diurnal cycle, pattern recognition problems are longitudinal in nature and that by applying this knowledge may lead to better algorithms.

9840-26, Session 5

Detection of spectrally varying BRDF materials in hyperspectral imagery

Timothy Perkins, Steven M. Adler-Golden, Leonid Muratov, Robert Sundberg, Spectral Sciences, Inc. (United States); Emmett J. Lentilucci, Rochester Institute of Technology (United States); Wesam A. Sakla, Air Force Research Lab. (United States)

Hyperspectral imaging (HSI) sensors have the unique ability to identify objects based on the spectral signatures of their surface materials. Many targets of interest, such as vehicles, exhibit specular (non-Lambertian) surfaces composed of multiple materials and surface angles. This complexity, combined with possible changing atmospheric/illumination conditions and viewing geometries, can produce significant fluctuations in the observed signatures from measurement to measurement, making detection and/or reacquisition challenging. Here we address the detection of complex, non-Lambertian targets under varying solar and observer geometries. To investigate the signature variations for this class of targets, we have developed a rapid imaging tool to effectively predict the signature behavior of complex 3D objects using spectral-BRDF material models. The simulation tool quickly estimates a target signature using physical representations of the reflective surfaces, such as the Modified Beard-Maxwell (MBM) spectral-BRDF model, combined with a geometric shape description of the object and a directional model of the environmental illumination. Target detection studies can be performed by embedding these effective, whole-object signatures into VIS-SWIR imagery to represent

9840-27, Session 5

Instance influence estimation for hyperspectral target signature characterization using extended functions of multiple instances

Sheng Zou, Alina Zare, Univ. of Missouri (United States)

Extended Function of Multiple Instances (eFUMI) is a generalization of Multiple Instance Learning (MIL). In eFUMI, only bag (i.e. set) level labels are needed to estimate target signatures from mixed data. The training bags in eFUMI are labeled positive if any data point in a bag contains or represents any proportion of the target signature and are labeled as a negative bag if all data points in the bag do not represent any target. From these imprecise labels, eFUMI has been shown to be effective at estimating target signatures in hyperspectral subpixel target detection problems. One motivating scenario for the use of eFUMI is where an analyst circles objects/regions of interest in a hyperspectral scene such that the target signatures of these objects can be estimated and be used to determine whether other instances of the object appear elsewhere in the image collection. The regions highlighted by the analyst serve as the imprecise labels for eFUMI. Often, an analyst may want to iteratively refine their imprecise labels. In this paper, we present an approach for estimating the influence on the estimated target signature if the label for a particular input data point is modified. This "instance influence estimation" guides an analyst to focus on (re-)labeling the data points that provide the largest change in the resulting estimated target signature and, thus, reduce the amount of time an analyst needs to spend refining the labels for a hyperspectral scene. Results are shown on both simulated and real hyperspectral sub-pixel target detection data sets.

9840-28, Session 5

Graph-based and statistical approaches for detecting spectrally variable target materials

Amanda K. Ziemann, James P. Theiler, Los Alamos National Lab. (United States)

In discriminating target materials from background clutter in hyperspectral imagery, one must contend with variability in both. Most algorithms focus on the clutter variability, but for some materials there is considerable variability in the spectral signatures of the target. This is especially the case for solid target materials, whose signatures depend on morphological properties (particle size, packing density, etc.) that are rarely known a priori. In this paper, we investigate detection algorithms that explicitly take into account the diversity of signatures for a given target. In particular, we demonstrate a graph theory and manifold learning based approach to target detection that incorporates multiple spectral signatures of the target material of interest; this is built upon previous work that used a single target spectrum. We first build an adaptive nearest neighbors (ANN) graph on the data and target spectra, and use a biased locally linear embedding (LLE) transformation to perform nonlinear dimensionality reduction. This biased transformation results in a lower-dimensional representation of the data that better separates the targets from the background. In these lower-dimensional coordinates, we then apply standard subspace target detection approaches, such as rank-based spectral angle mapper (SAM) and subspace adaptive cosine estimator (ssACE). Results will be shown on hyperspectral images using implanted targets as both full and mixed pixels.

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9840-29, Session 5

**Identification of solid materials using HSI
spectral oscillators**

Cory Lanker, Milton O. Smith, Lawrence Livermore National Lab. (United States)

Our research aims to characterize solid materials through LWIR reflectance spectra in order to improve compositional exploitation in a hyperspectral imaging sensor data cube. Specifically, we aim to reduce false alarm rates when identifying target materials without compromising sensitivity. We employ dispersive analysis to extract the material oscillator resonances from reflectance spectra with a stepwise fitting algorithm to estimate the Lorentz or Gaussian oscillators effectively present in the HSI spectral measurements. The proposed algorithm operates through nonlinear least squares minimization through a grid search over potential oscillator resonance frequencies and widths. Experimental validation of the algorithm is performed with published values of crystalline and amorphous materials. Our aim is to use the derived oscillator parameters to characterize the materials that are present in an HSI pixel. We demonstrate that there are material-specific properties of oscillators that show subtle variability when considering changes in morphology or measurement conditions. The experimentally verified results include variability in material particle size, measurement angle, and atmospheric conditions for six mineral measurements. Once a target material's oscillators are characterized, we apply statistical learning techniques to form a classifier based on the estimated spectral oscillators of the HSI pixels. We show that this approach has good initial identification results that are extendible across localized experimental conditions. This research is part of the DoE HARD Solids multi-lab venture.

9840-30, Session 6

**Anomaly detection schemes across varied
scene content**

Emily E. Berkson, David W. Messinger, Rochester Institute of Technology (United States)

Anomaly detection (AD) of hyperspectral imagery has been used for disaster response efforts, tracking landscape modifications, and surveillance purposes, to name just a few applications. We attempt to quantify differences in the distributions of anomalous pixels found with two multivariate statistics-based algorithms (RX and subspace-RX), and one algorithm based on graph theory (TAD). Outliers in statistical ADs are predicted to approximate a chi-squared distribution; however, the expected distribution of outliers found with TAD is unclear. We also look for general trends in performance with varied scene content, where we expect cluttered scenes to have more outliers of a different statistical distribution than simple scenes. Three separate scenes were extracted from the hyperspectral MegaScene image taken over downtown Rochester, NY with the VIS-NIR-SWIR ProSpecTIR instrument: urban, suburban, and rural. Each scene was run through the three aforementioned ADs, and the distributions of the most anomalous 5% of pixels were compared. Results will show statistical characterizations of anomalies detected by these three methods. This will lead to better understanding of these algorithms and their applicability across scenes of varying clutter content.

9840-31, Session 6

**Target detection for hyperspectral imaging
with small sample size**

Edisanter Lo, Susquehanna Univ. (United States); Emmett J. Ientilucci, Rochester Institute of Technology (United States)

In hyperspectral imaging, the number of spectral bands in each pixel is in the hundreds so a large number of background observations are typically needed. When an application such as target detection is applied to a small local area in an image, there may not be a sufficient number of background pixels to form a full-rank covariance matrix. Conventional detection algorithms cannot be used in this case because the algorithms require an inverse of the covariance matrix, which will not be of full rank. The logistic regression model, which does not require the inverse of the covariance matrix, is proposed in this paper as a target detection algorithm with a small sample of background pixels. Experimental results show that the logistic regression model can work when the number of background pixels is fewer than the number of spectral bands.

9840-32, Session 6

**Comparison of algorithms for blood
stain detection applied to forensic
hyperspectral imagery**

Jie Yang, David W. Messinger, Jobin J. Mathew, Roger R. Dube, Rochester Institute of Technology (United States)

Blood-stains are one of the most important evidences in forensic investigation as they contain valuable DNA information. The method used for detecting blood-stains in a crime scene is important, and the destructive nature of manual sample-collection and laboratory testing should not be considered as the highest priority. Hyperspectral imaging might be a potential method to detect blood-stains because it is non-contact and provides substantial spectral information which can be utilized for a more elaborate analysis. The range of material-types and conditions containing blood-stains at a crime scene is vast and some are hard to see with unaided eyes for crime scene investigators. The hyperspectral imaging of a crime scene before human intervention adds an extra layer of blood-stain detection while physical effect on the samples is seldom. Efficient algorithms can process these images to identify the blood-stains while the hyperspectral domain enhances the detection in complex backgrounds. In this paper we utilize a hyperspectral imaging system, which generates images in the 400 nm - 700 nm ranges with a spectral resolution of 10 nm. Three sets of 31 band images for a simulated indoor crime scene were generated, in which blood-stains were present on clothes and walls. To detect the blood stains in the scene, Principal Component Analysis (PCA), Subspace RX (SRXD), and Topological Anomaly Detection (TAD) algorithms were used. Comparison of the three algorithms indicates that TAD is most suitable for detecting visible and latent blood stains and can be further applied to related detection tasks in forensic imagery.

9840-33, Session 6

**Biased normalized cuts for target
detection in hyperspectral imagery**

Xuewen Zhang, Leidy P. Dorado-Munoz, David W. Messinger, Nathan D. Cahill, Rochester Institute of Technology (United States)

Target detection in hyperspectral imagery (HSI) is vital in many military and civilian applications. A major challenge in target detection is that the distribution of the spectra of pixels containing targets may be highly non-Gaussian due to a variety of factors, including varying illumination/shadows, non-Lambertian targets, and mixtures of target with non-target materials in a single pixel. In the computer vision community, the Biased Normalized Cut (BNC) algorithm has become a popular technique for detecting targets or objects in RGB imagery: BNC highlights pixels/regions sufficiently close to priors as measured in a low-dimensional representation of the data constructed via nonlinear dimensionality reduction.

In this paper, we propose modifying BNC for the purpose of target detection in HSI. By using Laplacian Eigenmaps as a basis for the nonlinear dimensionality reduction step, the BNC target detection algorithm has

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some similarities to the previously proposed Schroedinger Eigenmaps (SE) algorithm that encodes target information with cluster potentials prior to dimensionality reduction. A key difference, however, is that the BNC algorithm encodes target information after dimensionality reduction, enabling a user to pre-perform the costly dimensionality reduction step and then use it as a basis to detect different targets in interactive mode.

To assess the proposed BNC algorithm, we utilize HSI from the SHARE 2012 data campaign. We explore the relationship between the number and the position of expert-provided target labels and the precision/recall of remaining targets in the scene, and we discuss advantages and disadvantages of BNC as compared to SE with cluster potentials.

9840-34, Session 6

Methods and challenges for target detection and material identification for longwave infrared hyperspectral imagery

Blake M. Rankin, National Research Council (United States) and Wright-Patterson Air Force Base (United States); Joseph Meola, Air Force Research Lab. (United States); David L. Perry, Leidos, Inc. (United States); Jason R. Kaufman, Univ. of Dayton Research Institute (United States)

Hyperspectral imaging (HSI) combined with target detection and identification algorithms require spectral signatures for target materials of interest. The longwave infrared (LWIR) region of the electromagnetic spectrum is dominated by thermal emission, and thus, estimates of target temperature are necessary for emissivity retrieval through temperature-emissivity separation or for conversion of known emissivity signatures to radiance units. Therefore, lack of accurate target temperature information poses a significant challenge for target detection and identification algorithms. Previous studies have demonstrated both LWIR target detection using signature subspaces and visible/shortwave subpixel target identification. This work compares adaptive coherence estimator (ACE) and subspace target detection algorithms for various target materials, atmospheric compensation algorithms, and imagery domains (radiance or emissivity) for several data sets. Preliminary results suggest that target detection in the radiance and emissivity domains is complementary, in the sense that certain material classes may be more easily detected using subspaces, while others require conversion to emissivity space. Furthermore, a radiance domain LWIR material identification algorithm that accounts for target temperature uncertainty is presented. The latter algorithm is shown to effectively distinguish between materials with a high degree of spectral similarity.

9840-35, Session 6

Vector tunnel anomaly detection algorithm for hyperspectral imagery

Suleyman Demirci, Turkish Air Force Academy (Turkey); Isin Erer, Istanbul Technical Univ. (Turkey); Okan K. Ersoy, Purdue Univ. (United States)

The aim of detection is to search the unknown pixels of a hyperspectral data cube for specific material. Detection algorithms for hyperspectral imaging data can be grouped into two categories which are target detection and anomaly detection. Target detection algorithms try to identify the similarity of unknown spectral signature of test pixels with the expected spectral information. Anomaly detection algorithms are carried out by using a local or global background. The pixels, whose spectral responses do not fit one of these models, are treated as candidates of anomaly pixels.

In general, there are four different types of anomaly detection algorithms in literature. They are statistical, kernel, projection, and segmentation based methods. The most common anomaly detection algorithm is Reed-Xiaoli

(RX) Algorithm which was developed for detecting unknown spectral distribution against a background distribution. The RX Algorithm is now accepted as the benchmark anomaly detection algorithm for hyperspectral image application. Among many types of RX algorithms, there are two commonly used types. They are Global RX (GRX) and Local RX (LRX) algorithms.

In previous studies, spectral similarity based Vector Tunnel Algorithm (VTA) was used as target detection and classification purposes. The aim of this work is to understand whether the VTA method can be used as an anomaly detection algorithm. In this method, the hyperspectral image data is characterized in terms of their spectral features. As being a spectral similarity based technique, the VTA algorithm try to predict the level of upper and lower spectral boundaries of all hyperspectral image pixel spectral signatures. For prediction of VTA level, the Weighted Chebyshev Distance (WCD) measure using means and standard deviations of the hyperspectral data cube is employed. Each test pixel spectral signature in the image is compared with the mean of all hyperspectral data by using WCD measures. The pixels having biggest WCD values are labeled as being the most likely anomaly pixels. Then, the result of the method is compared with GRX and LRX algorithms.

In summary, there are four steps of the proposed WCD algorithm as follows:

Step 1: The mean and standard deviation vectors of the image data cube are calculated.

Step 2: The WCD measures are calculated for all pixels in the hyperspectral image.

Step 3: Each test pixel is labeled according to their WCD values.

Step 4: According to Generalized-Likelihood Ratio Test (GLRT), all pixels having the bigger WCD values than threshold level are labeled as a candidate of anomaly pixels.

The proposed method is tested on AVIRIS Indiana's Pine data with simple back ground and HYDICE Urban data with complex back ground. According to the visual results of algorithms, the VTA algorithm is better than for both hyperspectral images. Considering the implementation time of the algorithms, the VTA method is far better than the GRX and the LRX methods.

9840-36, Session 7

Agile multi-scale decompositions for automatic image registration

James M. Murphy, Duke Univ. (United States); Omar N. Leija, Univ. of Nevada, Las Vegas (United States); Jacqueline J. Le Moigne, NASA Goddard Space Flight Ctr. (United States)

In recent works, the first and third authors developed an automatic image registration algorithm based on a multiscale hybrid image decomposition with anisotropic shearlets and isotropic wavelets. This method showed strong performance, improving robustness over registration with wavelets alone. However, this method imposed a strict hierarchy on the order in which shearlet and wavelet features were used in the registration process, and also involved a mixture of MATLAB and C code.

In this paper, we introduce a more agile model for generating features, in which an adaptive mix of shearlet and wavelet features are computed. Compared to the previous prototype, this method introduces a flexibility to the order in which shearlet and wavelet features are used in the registration process. Moreover, the present algorithm is now fully coded in C, making it simpler to use than the MATLAB and C prototype. We demonstrate the versatility and computational efficiency of our approach by performing registration experiments and timing studies with our fully-integrated C algorithm. The timing studies allow for a meaningful analysis of the computational costs of the flexible feature extraction. Examples of multi-modal and multi-temporal images shall be investigated.

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9840-37, Session 7

**Schroedinger eigenmaps with knowledge
propagation for target detection**

Leidy P. Dorado-Munoz, David W. Messinger, Rochester
Institute of Technology (United States)

It has been widely shown the applicability of Laplacian Eigenmaps (LE) and Schroedinger Eigenmaps (SE) in the processing of hyperspectral imagery. Specifically, we have previously shown that SE has a promising performance in spectral target detection. SE, unlike LE, could include prior information or labeled data points into a barrier potential term that steers the transformation in certain directions making the labeled points and the similar points pulled toward the origin in the new space. We have also noticed that the barrier potentials generated from a few labeled points may affect in a brittle manner the dimensionality in the Schroedinger space and in turn, the target detection performance. In this paper, we show that the number of SE used in the detection could be increased without affecting the detection performance by adding spatial and spectral constraints on the individual labeled points and propagating this knowledge to nearby points through a modified Schroedinger matrix. We apply our algorithm to hyperspectral data sets with several target panels and different complexity in order to have a wide framework of assessment. We also use the false alarm rates and ROC curves to quantitatively evaluate the proposed methodology.

9840-38, Session 7

**A review on hyperspectral image
exploitation methodologies, their
limitations, the mathematics and lessons
learned**

Edward H. Bosch, Univ. of Maryland, College Park (United
States)

For more than twenty years the development of hyperspectral sensors along with the novel theoretical techniques derived from ground-breaking research has led to results that have significantly impacted the exploitation of remotely-sensed data. Many of these techniques have addressed problems such as the detection, identification and classification of natural and manmade objects, pixel demixing and abundance estimation, super resolution and fusion, generation of spectral libraries, atmospheric correction which requires specific knowledge of the physics of electromagnetic radiation, background and noise suppression, and many other applications. The processing of hyperspectral data has been successfully employed in military and civilian applications to include precision farming, classification of tree species in forests, resource management while the biomedical community often uses these for obtaining information and facilitating the diagnostic of tissue physiology, morphology and composition.

The objective of this talk is to present a review on hyperspectral image exploitation methodologies, their limitations, the mathematics and lessons learned via an open discussion. We will discuss application performance which depends on a variety of factors such as model employed, model requirements (e.g., assumptions made on the data such as type of distribution), data complexity, ground pixel coverage, atmospheric conditions, the problem being considered and other confounding factors. Also, we will discuss the methods used to measure application performance which depending on the problem can be given by confusion matrices and receiving operating curves. Ultimately, choosing a technique that produces well-founded results can be challenging. However, when properly employed, these methods have demonstrated that they can perform exceptionally well.

9840-39, Session 7

**Building robust neighborhoods
for manifold learning based image
classification and anomaly detection**

Timothy J. Doster, Colin C. Olson, U.S. Naval Research Lab.
(United States)

Sensors are continually evolving to offer finer spatial and spectral resolution. This improvement allows for the development of more exact data representation models which are vital for image classification and anomaly detection in complex maritime scenes. Manifold-learning-based approaches have been shown to offer superior results over what is possible with traditional statistics-based techniques in this domain. These manifold-based techniques can all be broadly summarized as performing three distinct tasks: measuring distances between pixels, building a weighted graph representation of those distances, and solving a minimization problem defined by the graph relationships. The first two steps of the manifold learning algorithm are where we will depart from the classical implementations to improve results. We first add local neighborhood information to the graph representation structure by forming super-pixels (including the spatially neighboring pixels when measuring distances). We then expand upon this by examining techniques from harmonic analysis and image processing to make these local neighborhoods robust to affine transformations. By transforming the local neighborhoods using rotation operators, Fourier, Mellin-Fourier, and Wavelet Packet transforms we develop robust graph structures. We also develop local and semi-global distances to bias graph construction. By building more accurate graph (and thus manifold) representations of our data, products derived from these representations will show improvements. We compare our various neighborhood techniques to standard neighborhood constructions from manifold learning methods as well as established algorithms in the field of remote sensing such as RX and sub-space RX.

9840-40, Session 7

**A parametric study of unsupervised
anomaly detection performance in
maritime imagery using manifold learning
techniques**

Colin C. Olson, Timothy J. Doster, U.S. Naval Research Lab.
(United States)

We investigate an unsupervised anomaly detection framework that uses manifold learning techniques to learn a better model of the non-anomalous data. The algorithm begins by uniformly sampling a small subset of the data under the assumption that anomalous data is by definition rare relative the rest of the data set. The operating assumption is that the ratio of anomalous to non-anomalous data in the subset is small and will have little effect on the learned background model. A manifold is then constructed from the adjacency matrix built solely from the subsampled data. The algorithm proceeds by using out-of-sample extension methods (e.g., the Nystrom extension) to project the remaining data into the manifold space. The distance of each projected point from the manifold is approximated by, for example, finding the distance to its nearest neighbor on the manifold. The selected distance measure is then thresholded under the assumption that background data will project close to the manifold while anomalous data will map farther from the manifold.

We consider here data constructed from tiled panchromatic maritime imagery. Comparing tiles rather than single-pixel intensities (or filter outputs) allows for better use of spatially-coherent statistics in the background model. We investigate the effect of tiling parameters such as neighborhood size and degree of neighborhood overlap (ranging from disjoint tiling to neighborhoods associated with every pixel) as well as embedding parameters such as kernel bandwidth and subsampling percentage on the overall detection performance of the algorithm. Results are then compared to more traditional detection techniques.

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9840-41, Session 7

**Use of high-dimensional model
representation in dimensionality reduction:
application to hyperspectral image
classification**

Gül?en Ta?kin Kaya, Istanbul Technical Univ. (Turkey)

Hyperspectral Imaging (HSI) provides very high dimensional data with hundreds of spectral channels ranging from the visible to the short wave-infrared region of the electromagnetic spectrum. Although HSI enables a detailed separation of similar surface materials, the spectral features are correlated especially in adjacent bands, thus providing redundant information. The large number of redundant features, when performing supervised learning in high dimensional feature space, results in a poor classification performance when a limited number of training samples is considered which is referred as curse of dimensionality (or Hughes phenomenon) in the literature. To avoid Hughes phenomenon due to high dimensionality of the data, dimensionality reduction, that are feature selection or feature extraction, is required for both improving the classification accuracy and reducing the computational load.

In this work, a new wrapper based feature selection procedure is introduced. The novelty of the proposed method is to incorporate a well-known global sensitivity analysis tool named High Dimensional Model Representation (HDMR), which was first developed by Sobol in order to analyze the sensitivity of nonlinear mathematical models, which requires to determine the individual and cooperative effects of the model variables on the model output. The purpose is to determine most important features in a hyperspectral remote sensing image in order to improve classification performance. Several experiments on synthetic and hyperspectral datasets were carried out in order to show the performance of the proposed algorithm as compared to the following four well-known feature selection algorithms: SVM-RFE, sequential forward selection, Branch and Bound feature selection and feature selection and feature selection with Bhattacharya distance in terms of both computational effectiveness and classification accuracy.

9840-42, Session 7

**Gaussian processes and self-organizing
maps for possibilistic, robust, ambiguity
preserving (PRAM) classification and
regression with spectral data**

Paul D. Gader, Univ. of Florida (United States) and Univ. of California, Santa Barbara (United States); Leila Kalantari, Univ. of Florida (United States); Hichem Frigui, Univ. of Louisville (United States)

Hyperspectral data sets are growing rapidly in size, requiring more automated processing. Data will be measured in unconstrained environments. Two problems that plague systems in such environments are robustness and ambiguity. Human experts resolve these using interactive software. Massive data sets require computer programs to resolve problems without human input.

Suppose needs to classifier to classify patterns from C classes. Many classifiers that perform equally well assuming that the input sample is from one of the C classes. If the input sample is not, then classifiers may perform much differently. Many will aggressively classify all patterns with high confidence. They are not robust, they don't respond appropriately on samples from non-training distributions. SVM classifiers are not robust as observed by comparing classification rate vs. the outlier rejection rate.

Possibility theory is a branch of measure theory relying on different axioms than Probability theory. Possibilistic classifiers are excellent tools for representing ambiguity because possibilities of different species can all be high and labeling outliers because the possibilities of all species can

be low. Producing possibilities mitigates the need for binary decisions at intermediate processing stages, consistent with David Marr's "principle of least commitment".

We present PRAM classification results using using 1-class Gaussian Processes and Kohonen's Self Organizing Feature Map (SOFM). The fundamental idea is to represent lower-dimensional surfaces in the measured high-dimensional spectral domain to provide useful information to algorithms. For regression, target training outputs are set using k-nearest neighbors.

9840-43, Session 7

**Graph MBO method for multi-class
segmentation of hyperspectral stand-off
detection video**

Ekaterina Merkurjev, Univ. of California, San Diego (United States); Andrea L. Bertozzi, Univ. of California, Los Angeles (United States); Justin Sunu, Claremont Graduate Univ. (United States)

We consider the challenge of detection of chemical plumes in hyperspectral image data. Segmentation of gas is difficult due to the diffusive nature of the cloud. The use of hyperspectral imagery provides non-visual data for this problem, allowing for the utilization of a richer array of sensing information. In this paper, we present a method to track and classify objects in hyperspectral videos. The method involves the application of a new algorithm recently developed for high dimensional data. It is made efficient by the application of spectral methods and the Nystrom extension to calculate the eigenvalues/eigenvectors of the graph Laplacian. Results are shown on plume detection in LWIR standoff detection.

9840-44, Session 7

**A nonlinear modeling framework for
the detection of underwater objects in
hyperspectral imagery**

David B. Gillis, U.S. Naval Research Lab. (United States)

The detection of underwater objects of interest (or targets) in hyperspectral imagery is a challenging problem, with a number of complications that are not present in land-based hyperspectral target detection.

The main challenge in underwater detection is that, in contrast to land, where the observed spectrum of an associated target is largely independent of the surrounding background (e.g. the signature of a tank looks more or less the same whether it is on a road or in a field of grass), the observed spectrum of an underwater target is a highly nonlinear function of the background - that is, the optical properties of the water body that the object is submerged in, as well as the depth of the target. As a result, the same object in different types of water and/or at different depths will in general have very different observed spectral signatures.

In this work, we present a general overview of the various challenges involved in underwater detection, and present a novel approach that fuses forward radiative-transfer modeling, ocean color predictions, and nonlinear mathematical techniques (manifold learning) to model both the background and target signature(s) and perform detection over a wide range of environmental conditions and depths.

9840-45, Session 7

**Spatial-spectral deep wavelet scattering
for multispectral image analysis**

Matthew Hirn, Univ. of Maryland, College Park (United States)

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Classification of grayscale and RGB images relies on stable feature extraction algorithms that encode translation and rotation invariants while taking advantage of the multiscale nature of images. Convolutional deep networks leverage modern computing power and the vast number of images available for training to learn a cascade of alternating linear convolutional filters and nonlinear maps that encode complex features at multiple scales, obtaining unprecedented classification rates.

Multispectral images present not only the same challenges as traditional images, but have several added complexities, most notably the spectral dimension and its interplay with the spatial dimensions. Furthermore, relative to traditional images, there are significantly fewer multispectral images for training machine learned models. Thus to circumvent the curse of dimensionality, features must be designed, rather than learned, to encode rotation and translation invariants, and be stable to small deformations of the image.

A wavelet transform of a multispectral image X consists of a collection of linear filters that encode directional features at different scales, both spatially and spectrally, and which are covariant to translations, rotations, and deformations of X . The scattering transform builds nonlinear invariants by composing the wavelet transform with the complex modulus operator, and then cascading this alternating sequence of linear and nonlinear maps while extracting invariant features at each level with a low pass filter:

The scattering transform has been successfully used for image classification, 2D texture classification, and quantum energy regression of molecules. In this talk we explore the utility of the scattering transform for multispectral imagery tasks, and how to adapt the wavelet filters to the specific nature of multispectral data.

9840-68, Session PWed

Lossless compression of hyperspectral images based on the prediction error block

Yongjun Li, Yunsong Li, Juan Song, Weijia Liu, Jiaojiao Li, Xidian Univ. (China)

A lossless compression algorithm of hyperspectral image based on distributed source coding is proposed, which is used to compress the spaceborne hyperspectral data effectively. In order to make full use of the intra-frame correlation and inter-frame correlation, the prediction error block scheme and multi-band prediction scheme are introduced. Compared with the scalar coset based distributed compression method (s-DSC) proposed by E.Magli et al., that is the bitrate of the whole block is determined by its maximum prediction error, and the s-DSC-classify scheme proposed by Song Juan that is based on classification and coset coding, the prediction error block scheme and multi-band prediction scheme could reduce the bitrate efficiently. Experimental results on hyperspectral images show that the proposed schemes can offer both high compression performance and low encoder complexity and decoder complexity, which are available for on-board compression of hyperspectral images.

9840-69, Session PWed

Serial and parallel implementations of spatially adaptive constrained non-negative matrix factorization for hyperspectral unmixing

Miguel A. Goenaga-Jimenez, Univ. del Turabo (United States)

This paper proposes the serial and parallel implementations of a spatially adaptive constrained Nonnegative Matrix Factorization (sacNMF) for unmixing of hyperspectral imagery. The image is decomposed into spectrally homogeneous regions using Quadtree region partitioning and then is processed using the constrained Nonnegative Matrix Factorization

(cNMF) to the individual image tiles to perform spectral endmember extraction. The extraction of Spectral endmembers is performed in each tile simultaneously then are clustered into endmember classes that enhance the capture of the endmember spectral variability across the image. Then the abundances are estimated using a serial algorithm, showing that by decomposing the image into spatially and spectrally homogeneous regions, the convex structure of the spectral cloud and the of mixing material constraints imposed by the spatial relation between materials are finer captured. A computational framework in MATLAB is developed to implement the proposed approach. The performance of this serial and parallel algorithm is compared with the normal sacNMF using real hyperspectral data from the AVIRIS sensor. Operational times in both algorithms are compared to show their performance. Results show that combination of serial and parallel sacNMF performs faster the unmixing process.

9840-70, Session PWed

Superpixel segmentation for hyperspectral unmixing

Jiarui Yi, Miguel Velez-Reyes, The Univ. of Texas at El Paso (United States)

This paper presents an approach to incorporate spatial information in endmember extraction for hyperspectral unmixing using superpixels. The spatial information is incorporated by over-segmenting hyperspectral images to obtain locally spectrally homogeneous regions (or superpixels) that can be used as candidates for spectral endmembers. Once spectral endmember signatures are extracted, they are clustered into endmember classes. These classes represent the different spectral components of the image as well as their spectral variability. The usefulness of the method is illustrated on the AVIRIS image captured over Fort AP Hill, Virginia. A comparison of the method with other unmixing techniques is also included.

9840-71, Session PWed

Minimum removal and maximum normalization of VNIR hyperspectral image for shade and specular invariance

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The anomaly detection in hyperspectral images (HSI) is useful for a wide range of applications including camouflaged target detection, skin cancer detection, and bruised fruit detection. However, the detection performance is frequently limited by illumination effects such as shades, shadows, and highlights given a xed illuminant. Most HSI-based target detection methods use spectral preprocessing to reduce the illumination effects.

A band ratio (BR) method is usually used because of its simplicity and effectiveness. The band ratioing is an enhancement process in which the digital number values of one band is divided by that of any other band. In this paper, a novel hyperspectral image normalization method was developed to make the hyperspectral profile invariant to illumination. The well-known band-ratio method shows unstable spectral profile to shades and highlights. The proposed minimum removal and maximum normalization method is simple but can reduce the spectral variations caused by shades and highlights effectively, which leads to enhanced abnormal region detection performance in VNIR hyperspectral images.

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9840-72, Session PWed

FPGA implementation of nonlinear diffusion approaches for multi-scale representation and classification of hyperspectral imagery

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Multiscale representation based on nonlinear diffusion can improve the classification accuracy of hyperspectral imagery. However, nonlinear diffusion requires the successive solution of nonlinear partial differential equations which have an expensive computational cost for high dimensional data such as hyperspectral images. The need to near real-time algorithms for the processing of hyperspectral remote sensing data has been identified for several researchers. A way to obtain these processing times is the use of reconfigurable computing systems such as field-programmable gate arrays (FPGAs). This paper presents the implementations of two nonlinear diffusion schemes over FPGA to obtain multiscale representation of hyperspectral image. A comparison of both schemes in terms of performance and the use of hardware resources is presented. The multiscale representations of Indian Pines image obtained by the two schemes are used to show that the hardware implementation preserve the classification accuracy.

9840-73, Session PWed

A generalized representation-based approach for hyperspectral image classification

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Sparse representation-based classifier (SRC) is of great interest recently for hyperspectral image classification. It is assumed that a testing pixel is linearly combined with atoms of a dictionary. Under this circumstance, the dictionary includes all the training samples. The objective is to find a weight vector that yields a minimum L2 representation error with the constraint that the weight vector is sparse with a minimum L1 norm. The pixel is assigned to the class whose training samples yield the minimum error. In addition, collaborative representation-based classifier (CRC) is also proposed, where the weight vector has a minimum L2 norm. The CRC has a closed-form solution; when using class-specific representation it can yield even better performance than the SRC. Compared to traditional classifiers such as support vector machine (SVM), SRC and CRC do not have a traditional training-testing fashion as in supervised learning, while their performance is similar to or even better than SVM. In this paper, we investigate a generalized representation-based classifier which uses Lq representation error and Lp weight norm. The classification performance of Lq and Lp combinations is evaluated with several real hyperspectral datasets. Based on these experiments, the selection of the best values of q and p is recommended.

9840-74, Session PWed

Multispectral image fusion based on diffusion morphology for enhanced vision applications

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Multispectral vision is a promising solution that can contribute a lot to a

further development of Enhanced Vision technology. It provides informative image of the outside world in a broader range of visibility conditions owing to data fusion from sensors that operate with the use of different physical principles.

The paper proposes a new approach for multispectral image fusion based on the combination of morphological image analysis and diffusion maps theory. The motivation for such approach is that existing morphological models for image fusion are quite sensitive to the quality of image segmentation, since they traditionally express the geometrical idea of image shape as a label image and therefore not sufficiently robust to noise and high frequency distortions. On the other hand, there are a number of methods in dimensionality reduction and data comparison that allows one to omit image segmentation by applying diffusion maps techniques.

It is shown that all techniques for morphological shape analysis can also be used in diffusion morphology by substituting a morphological projector to a diffusion kernel.

The developed real-time image fusion algorithm is implemented for a prototype of multispectral Enhanced Vision System (EVS) that uses three imagery sensors: a TV camera, a short-wave and an uncooled long-wave IR. A set of flight experiments in different weather conditions was performed with the EVS prototype. The results of tests, which were performed on images acquired in flight experiments, show that the algorithm is robust enough and meets to DO-315 requirements related to flight visibility of runway markings, lighting, and aerodrome objects.

9840-75, Session PWed

Compressive hyperspectral and multispectral imaging fusion

Óscar Espitia, Sergio Castillo, Henry Arguello, Univ. Industrial de Santander (Colombia)

Image fusion is a valuable framework which consists in fusing two or more images of the same scene from one or multiple sensors, allowing to improve the resolution of the images and increase the interpretable content. Hyperspectral (HS) and multispectral (MS) remote sensing images fusion results in high spectral and spatial resolution scenes. Fusion of multi-sensor images has been a very active research topic during recent years, however fusion of HS and MS images is not fully explored because their acquisition involves large amount of data which is also often redundant, which ignore the highly correlated structure of the datacube along the spatial and spectral dimensions. Compressive HS and MS systems compress the spectral data in the acquisition step allowing to reduce the data redundancy by using different sampling patterns. This work presents a compressed HS and MS image fusion approach. A joint sparse model is formulated by combining HS and MS compressive acquisition models. The high spectral and spatial resolution image is reconstructed by using sparse optimization algorithms. Different fusion spectral image scenarios are used to explore the performance of the proposed scheme. Several simulations with synthetic and real datacubes show promising results and improvements in the image reconstruction of the proposed method compares with fusion based on sparse representation up to 2 dBs with 50% of the measurements.

9840-76, Session PWed

On Validating Remote Sensing Simulations Using Coincident Real Data

Mingming Wang, Wei Yao, Rochester Institute of Technology (United States); Adam Goodenough, Scott Brown, Jan van Aardt, Rochester Institute of Technology, Chester F. Carlson Center for Imaging Science (United States)

The remote sensing community often requires data simulation, either via spectral/spatial downsampling or through virtual, physics-based models,

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to assess systems and algorithms. The Digital Imaging and Remote Sensing Image Generation (DIRSIG) model is one such first-principles, physics-based model for simulating imagery for a range of modalities. As scene rendering technology and software advanced, simulation of complex vegetation environments has become possible. This in turn has created questions related to the validity of such complex models, with potential multiple scattering, bidirectional distribution function (BRDF), etc. phenomena in the case of complex vegetation scenes.

We selected three sites, located in the Pacific Southwest domain (Fresno, CA) of the National Ecological Observatory Network (NEON). These sites represent oak savanna, hardwood forests, and conifer-manzanita-mixed forests. We constructed corresponding virtual scenes, using airborne LiDAR and imaging spectroscopy data from NEON, ground-based LiDAR data, and field-collected spectra to characterize the scenes. Imaging spectroscopy imagery for these virtual sites then was generated using the DIRSIG simulation environment. This simulated imagery was compared to real AVIRIS imagery (18m spatial resolution; nine pixels/scene) and NEON Airborne Observation Platform (AOP) data (1m spatial resolution; six thousand and four hundred pixels/scene). These tests were performed using a distribution-comparison approach for select spectral statistics, e.g., established indices and the spectra's shape (derivatives), for each distribution pair (simulated vs. real).

The initial comparison results of the spectral distributions indicated that the shapes of spectra between the virtual and real sites were closely matched. These results and those related to narrow-band indices will be presented at the conference.

9840-78, Session PWed

Spectral signature verification using statistical analysis and text mining

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A major problem for spectral scientists and analysts is having a metric for validated signatures. This has been an area of great discussion and debate in the spectral science community. In this paper, a method that validates the textual metadata and numerical spectral data associated with the spectral signatures stored in the large Signature Database (SigDB) of vis/nir/swir (VNR) and long wave infrared (LWIR) is proposed. A multi-dimensional procedure that is robust statistically, analytically, and contextually is presented. Originally, spectra are validated based on statistical properties derived from an ideal population set representing the unique material. The quality of each individual spectrum is ranked based on a spectral angle mapper (SAM) comparison to the mean spectrum derived from the unique material's population. This numerical method acts as a first pass filter to identify and flag low and high quality signatures based on the signal to noise ratio (SNR), and a measurement of precision compared to an accepted population set. Additionally, a method to validate signatures using text mining on the metadata is presented. Text mining allows for the capability of learning local features at lower stages and abstract features at a higher level of the network. Text mining algorithms have successfully been implemented for speech and image recognition. In this paper, we used a text mining approach to understand the patterns of the contextual data associated with spectral data in order to develop a model to differentiate metadata associated with high and low quality sample material. This sample model, for each material, together with metadata acts as a second pass filter to allow an in depth quantitative analysis to define the validity of a spectral signature. From this analysis, signatures with low validation scores are flagged for further validation from a spectral subject matter expert. This method has been compared to other validation methods accepted by the spectral science community [1]. The APL Spectral Validation Method has provided promising results when a baseline spectral signature is present for comparison. In the paper the APL Spectral Validation Method is described from an analytical and practical application. It has been compared to the

Tripartite Harmonized ICH Guideline which identifies validation parameters needed for a variety of analytical methods, as well as to the development and validation of near-infrared (NIR) spectral signatures as they pertain to counterfeit drug detection [1,2].

[1] International Conference On Harmonisation Of Technical, ICH Expert Working Group, Requirements For Registration Of Pharmaceuticals For Human, and Use. "ICH HARMONISED TRIPARTITE GUIDELINE." V ALIDATION OF A NALYTICAL P ROCEDURES : T EXT AND M ETHODOLOGY (1994): n.

[2] Kalyanaraman, Ravi. "Near-Infrared (NIR) Spectral Signature Development and Validation for Counterfeit Drug Detection Using Portable Spectrometer." American Pharmaceutical Review. N.p., n.d. Web.

9840-79, Session PWed

Analyzing hyperspectral images into multiple subspaces using Gaussian mixture models

Clay Spence, SRI International Sarnoff (United States)

I propose an alternative problem to blind unmixing of hyperspectral data. I argue that the spectra in a datacube will usually lie in several low-dimensional subspaces, and that the data gives a more robust estimate of these subspaces than of the endmembers. I present an algorithm for estimating the subspaces and pixel membership in the subspaces. The algorithm fits the data with a Gaussian mixture model, in which the means and covariance matrices are expressed in terms of the subspaces. The dimensionality of each subspace is given as part of the model fitting, and the number of mixture components is chosen with the minimum description length criterion. Although this does not give the endmembers, the results are useful. The locations of materials can be inferred by computing the angle between their library spectra and the subspaces of each segment. I also demonstrate material detection with a modification of the algorithm. This has greater sensitivity and specificity than standard algorithms such as ACE, and runs in real time.

9840-80, Session PWed

Toward prediction of hyperspectral target detection performance after lossy image compression

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Hyperspectral imagery (HSI) offers numerous advantages over traditional sensing modalities with its high spectral content that allows for classification, anomaly detection, target discrimination, and change detection. However, this imaging modality produces a huge amount of data, which requires transmission, processing, and storage resources; hyperspectral compression is a viable solution to these challenges. Previous work has demonstrated that lossy compression of hyperspectral imagery (HSI) can impact hyperspectral target detection. In previous experiments, when the spectral correlation coefficient between the original and compressed imagery dropped below 0.999, target detection performance suffered. However, it was also observed that a small amount of lossy compression can slightly improve target detection performance, depending on the targets and backgrounds under test. Here we examine lossy compressed hyperspectral imagery from data-centric and target-centric perspectives. The compression ratio (CR), the signal to noise ratio (SNR), and the spectral correlation coefficient (SCC) are computed directly from the imagery and provide insight to how the imagery has been affected by the lossy compression process. When targets are present, we perform target detection on the decompressed imagery and evaluate the change in

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target detection performance by examining receiver operating characteristic (ROC) curves and the target signal-to-clutter ratio (SCR). We observe relationships between the data- and target-centric metrics for visible/near-infrared to shortwave infrared (VNIR/SWIR) HSI data from SHARE 2012 and Bobcat 2013 that motivate potential prediction of change in target detection performance as a function of compression ratio.

9840-81, Session PWed

Comparing performance of standard and iterative linear unmixing methods for hyperspectral signatures

Travis Gault, Melissa E. Jansen, Mallory DeCoster, Samantha K. Jacobs, Eric D. Jansing, Benjamin M. Rodriguez, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

Hyperspectral sensors measure incident electromagnetic energy over a large number of small wavebands, resulting in a measured spectral signature of the material(s) in each pixel's instantaneous field of view. All objects within a pixel's field of view contribute to the measured spectra. If the area being imaged by the pixel contains only a single material, then a pure spectrum is collected. However, there are often multiple diverse materials within the field of view, and all materials will contribute to the energy incident on the pixel. This results in the measurement of a mixed spectral signature made up of contributions from each of the independent materials being imaged. Linear unmixing is a method of decomposing the mixed signature to determine the component materials that are present in the field of view, along with the abundances at which they occur. Traditional unmixing methods take advantage of adjacent pixels in the decomposition algorithm. In addition, an assumption is made that the energy from the materials in the field of view is mixed in a linear fashion across the spectrum of interest.

In this paper, we explore both standard and iterative methods for linear unmixing, and examine their effectiveness at identifying the individual signatures that make up simulated single pixel mixed signatures, along with their corresponding abundances. The major hurdle addressed in the proposed method is that no neighboring pixel information is available for the spectral signature of interest. Testing is performed using two collections of spectral signatures from the Johns Hopkins University Applied Physics Lab's Signatures Database software (SigDB): a hand-selected small dataset of 25 distinct signatures from a larger dataset of approximately 1600 pure Vis/NIR/SWIR spectra. Simulated spectra are created with three and four material mixtures randomly drawn from the database, where the abundance of one material is swept in 10% increments from 10%-90% with the abundances of the other materials equally divided amongst the remainder. For the smaller dataset of 25 signatures, all combinations of three or four materials are used to create simulated spectra, from which the accuracy of materials returned, as well as the correctness of the abundances, is compared to the inputs. The experiment is expanded to include the signatures from the larger dataset of 1400 signatures. Due to the large size of the dataset, Monte Carlo runs with 5000 draws of three or four materials are used to create the simulated mixed signatures. The spectral similarity of the inputs to the output component signatures is calculated using the spectral angle mapper. Results show that iterative methods significantly outperform the traditional methods under the given test conditions.

9840-82, Session PWed

Middle infrared (wavelength range: 8 μm -14 μm) 2-dimensional spectroscopy (total weight with electrical controller: 1.7 kg, total cost: less than 10,000 USD) so-called hyper-spectral camera for unmanned air vehicles like drones

Naoyuki Yamamoto, Tsubasa Saito, Satoru Ogawa, Ichiro Ishimaru, Kagawa Univ. (Japan)

We developed the palm size (optical unit: 73[mm] \times 102[mm] \times 66[mm]) and light weight (total weight with electrical controller: 1.7[kg]) middle infrared (wavelength range: 8[μm]-14[μm]) 2-dimensional spectroscopy for UAV(Unmanned Air Vehicle) like drone. And we successfully demonstrated the flights with the developed hyperspectral camera mounted on the multi-copter so-called drone in 15/Sep./2015 at Kagawa prefecture in Japan.

We had proposed 2 dimensional imaging type Fourier spectroscopy that was the near-common path temporal phase-shift interferometer. We install the variable phase shifter onto optical Fourier transform plane of infinity corrected imaging optical systems. The variable phase shifter was configured with a movable mirror and a fixed mirror. The movable mirror was actuated by the impact drive piezo-electric device (stroke:4.5[mm], resolution: 0.01[μm], maker: Technohands Co.,Ltd., type:XDT50-45, price: around 1,000USD). We realized the wavefront division type and near common path interferometry that has strong robustness against mechanical vibrations. Without anti-mechanical vibration systems, the palm-size Fourier spectroscopy was realized. And we were able to utilize the small and low-cost middle infrared camera that was the micro borometer array (un-cooled VOxMicroborometer, pixel array: 336 \times 256, pixel pitch: 17[μm], wavelength range: 7.5-13.5[μm], frame rate 60[Hz], maker: FLIR, type: Quark 336, price: around 5,000USD). And this apparatus was able to be operated by single board computer (Raspberry Pi.). Thus, total cost was less than 10,000 USD.

We joined with KAMOME-PJ (Kanagawa Advanced MOdule for Material Evaluation Project) with DRONE FACTORY Corp., KUUSATSU Corp., Fuji Imvac Inc., And we successfully obtained the middle infrared spectroscopic imaging with multi-copter drone.

9840-83, Session PWed

Monitoring of urban heat island in Shenzhen, China, with remotely-sensed and ground measurements

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In the past three decades, the Shenzhen region experienced a rapid urbanization process characterized by sharp decrease in farmland and increases in urban area. This rapid urbanization is one of the main causes of many environmental and ecological problems including urban heat island. Therefore, the monitoring of rapid urbanization regions and the environment is of critical importance for their sustainable development. In this study, four Landsat TM images, which were acquired on 1980, 1990, 2000 and 2010, are used to monitor urban heat island. An object-based classification algorithm is employed to detect the change of land cover of Shenzhen in past 30 years. Urban heat island index (UHII) are calculated with ground meteorological observations. Surface urban heat island index (SUHII) and urban heat island ratio index (URI) are computed for ten districts of Shenzhen based on Landsat data. A correlation analysis is conducted between heat island index (including UHII, SUHII and URI) and land coverage. Socio-economic statistics (including total population, GDP and population density) also are included in this analysis. The results show

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that, the change of land cover is the main cause of urban heat island. A weak relationship between urban heat island and socio-economic statistics are found based on the analysis.

9840-46, Session 8

A Hyperspectral Vehicle BRDF Sampling Experiment

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Target detection of non-Lambertian objects with complex geometries such as vehicles can be challenging due to the aggregation of specular surfaces whose spectra are highly sensitive to sun-target-sensor geometry. To address these issues and better understand the problem domain, Hyperspectral imagery was taken of four vehicles from a roof at RIT at various vehicle orientations in illumination conditions dominated by direct solar radiation in order to explore and model the bi-directional reflectance functions (BRDF) of 3D objects. The imagery was taken with two line scanning instruments resulting in 1,984 contiguous bands from 0.4 to 2.5 microns and a spatial resolution on the order of 5cm GSD.

The four vehicles were rotated and imaged through the span of a single day resulting in many combinations of vehicle orientation, source azimuth, and source zenith. In addition to the general rotation of vehicles and sampling of in-scene BRDF, three experiments were designed and executed to fully understand the factors contributing to the vehicle BRDFs. The first experiment was designed to determine the effect of vehicle color on the BRDF of a vehicle. In this experiment two vehicles of the same make and model but different colors were rotated together and imaged at various sun-target-sensor geometries throughout the day. The second experiment was designed to determine the effect of vehicle shape on the observed BRDF of a vehicle. In this experiment two vehicles of the same make and color but vastly different shapes were rotated together and imaged at various sun-target-sensor geometries throughout the day. The third experiment was designed to determine the contribution of background onto the surface of a vehicle. In this experiment a vehicle was moved in front of two different backgrounds, asphalt and grass and imaged at various times of the day. The background adjacency contributions were further examined by adding a Lambertian black panel in front of the vehicle for the two backgrounds.

During the collect the scene illumination conditions were characterized using three different instruments. Downwelling radiance was measured using a hyperspectral down looking radiometer. The direct and solar terms were characterized with a sun-shadowing radiometer. And a sky cam imaged the visible distribution of clouds in the sky. The background BRDFs and vehicle material DHRs were also characterized via a goniometer and a spectrometer with an attached contact probe respectively.

The data from this experiment will aid in understanding the contributions shape, color, and background in the sensor reaching radiance of vehicles under in scene illumination conditions dominated by direct solar radiation. The data will also aid in the validation of synthetically generated imagery and lead to better target detection algorithms for 3D targets with complicated BRDFs.

9840-47, Session 8

Calculation of vibrational and electronic excited state absorption spectra of arsenic water complexes using density functional theory

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Calculations are presented of vibrational and electronic excited-state absorption spectra for As-H₂O complexes using density function theory (DFT) and time-dependent density functional theory (TD-DFT). DFT and TD-DFT can provide interpretation of absorption spectra with respect to molecular structure for excitation by electromagnetic waves at frequencies within the IR and UV-visible ranges. The absorption spectrum corresponding to excitation states of As-H₂O complexes consisting of relatively small numbers of water molecules should be associated with response features that are intermediate between that of isolated molecules and that of a bulk system. DFT and TD-DFT calculated absorption spectra represent quantitative estimates that can be correlated with additional information obtained from laboratory measurements and other types of theory based calculations. The DFT software GAUSSIAN was used for the calculations of excitation states presented here.

9840-48, Session 8

Modeling of forest canopy BRDF using DIRSIG

Rajagopalan Rengarajan, John R. Schott, Rochester Institute of Technology (United States)

The characterization and temporal analysis of multispectral and hyperspectral data to extract the biophysical information of the Earth's surface can be significantly improved by understanding its anisotropic reflectance properties, which are best described by a Bi-directional Reflectance Distribution Function (BRDF). The advancements in the field of remote sensing techniques and instrumentation have made hyperspectral BRDF measurements in the field possible using sophisticated goniometers. However, natural surfaces such as forest canopies impose limitations on both the data collection techniques, as well as, the range of illumination angles that can be collected from the field. These limitations can be mitigated by measuring BRDF in a virtual environment. This paper presents an approach to model the spectral BRDF of a forest canopy using the Digital Image and Remote Sensing Image Generation (DIRSIG) model. A synthetic forest canopy scene is constructed by modeling the 3D geometries of different tree species using OnyxTree software. The field collected spectra from the Harvard forest is used to represent the optical properties of the tree elements. The canopy radiative transfer is estimated using the DIRSIG model for specific view and illumination angles to generate BRDF measurements. A full hemispherical BRDF is generated by fitting the measured BRDF to a semi-empirical BRDF model. The results from fitting the model to the measurement indicates a root mean square error of less than 5% (2 reflectance units) relative to the forest's reflectance in the VIS-NIR-SWIR region. The process can be easily extended to generate a spectral BRDF library for various biomes.

9840-49, Session 8

Imaging of gaseous oxygen through DFB laser illumination

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A Tunable Diode Laser Absorption Spectroscopy setup with Wavelength Modulation has been used together with a synchronous sampling imaging sensor in order to obtain two-dimensional transmission mode images of oxygen content.

Diffuse, modulated laser light from a 760nm DFB source has been used to illuminate a scene from the back while image frames were acquired with a high dynamic range camera.

Thanks to synchronous timing between the imaging device and laser light modulation, the traditional lock-in approach used in Wavelength Modulation

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Spectroscopy was replaced by image processing techniques, and many scanning periods were averaged together to allow resolution of small intensity variation over the already weak absorption signals from oxygen absorption band.

After proper binning and filtering, the time-domain waveform obtained from each pixel in a set of frames representing the wavelength scan was used as the single detector signal in a traditional TDLAS-WMS setup, and so processed through a software defined digital lock-in demodulation and a second harmonic signal fitting routine.

In this way the WMS artifacts of a gas absorption feature were obtained from each pixel together with intensity normalization parameter, allowing a reconstruction of oxygen distribution in a two-dimensional scene regardless from broadband transmitted intensity.

As a first demonstration of the effectiveness of this setup, oxygen absorption images of similar containers filled with either oxygen or nitrogen were acquired and processed.

9840-50, Session 8

Towards an improved understanding of the influence of subpixel vegetation structure on pixel-level spectra: a simulation approach

Wei Yao, Rochester Institute of Technology (United States); Martin van Leeuwen, Univ. College London (United Kingdom); Paul Romanczyk, Dave Kelbe, Mingming Wang, Scott D. Brown, Adam A. Goodenough, Jan A. N. van Aardt, Rochester Institute of Technology (United States)

The planned NASA HypSIIRI mission, equipped with an imaging spectrometer that has the capability of monitoring ecosystems globally, will provide unprecedented opportunity to address scientific challenges related to ecosystem function and change. However, uncertainty remains around the impact of sub-pixel vegetation structure in combination with the point spread function on pixel-wise imaging spectroscopy data. We will extract structural information from HypSIIRI spectral data, with the goal of assessing the impact of sub-pixel vegetation structural variation on the per-pixel imaging spectroscopy data.

The variability of real vegetation structure makes this a challenging endeavor. Therefore, we utilized a simulation-based approach to counter the time-consuming and often destructive sampling needs of vegetation structural analysis and to simultaneously generate synthetic HypSIIRI data pre-launch. Three virtual scenes were constructed, corresponding to the actual vegetation structure in the National Ecological Observatory Network's (NEON) Pacific Southwest Domain (Fresno, CA). These included an oak savanna, a dense coniferous forest, and a conifer-manzanita-mixed forest. Simulated spectroscopy data for these scenes were then generated using the Digital Imaging and Remote Sensing Image Generation (DIRSIG) model. Simulations first were used to verify the physical model, virtual scene geometrical information, and simulation parameters. This was followed by simulations of HypSIIRI data where per-pixel structural variability was introduced, e.g., by iteratively changing tree density and placement, clustering, leaf area index (LAI), etc., between simulation runs for the virtual scenes. Finally, narrow-band vegetation indices (VIs) were extracted from the data to quantify the impact of the vegetation structural variability on spectral signals.

We constructed regression models of LAI ($R^2=0.92$) and forest density ($R^2=0.97$) with narrow-band VIs via this simulation approach. Detailed models will be presented, which ultimately are intended to improve the HypSIIRI mission's ability to monitor global vegetation structure.

9840-51, Session 9

How many spectral bands are necessary to describe the directional reflectance of beach sands?

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Spectral variability in the visible, near-infrared and shortwave directional reflectance factor of beach sands and freshwater sheet flow is demonstrated using principal component and correlation matrix analysis of in situ measurements. In previous work we concluded that the hyperspectral bidirectional reflectance distribution function (BRDF) of beach sands in the absence of sheet flow exhibit weak spectral variability, the majority of which can be described with three broad spectral bands with wavelength ranges of 350–450 nm, 700–1350 nm, and 1450–2400 nm (Doctor et. al, 2015). Observing sheet flow on sand we find that a thin layer of water enhances reflectance in the specular direction at all wavelengths and that spectral variability may be described using four spectral band regions of 350-450 nm, 500-950 nm, 950-1350 nm, and 1450-2400 nm. Spectral variations are more evident in sand surfaces of greater visual roughness than in smooth surfaces, regardless of sheet flow.

9840-52, Session 9

Simultaneously sparse and low-rank hyperspectral image recovery from coded aperture compressive measurements via convex optimization

Tatiana Gelvez, Univ. Industrial de Santander (Colombia); Hoover F. Rueda, Univ. of Delaware (United States); Henry Arguello, Univ. Industrial de Santander (Colombia)

A hyperspectral image (HSI) can be described as a set of images with spatial information across different spectral bands. Compressive spectral imaging techniques (CSI) permit to capture a 3-dimensional hyperspectral scene using 2 dimensional coded and multiplexed projections. Recovering the original scene from very few number of compressive measurements can be valuable in applications such as remote sensing, video surveillance and biomedical imaging. Typically, hyperspectral images (HSI) exhibit high correlations both in the spatial and spectral dimensions. Thus, exploiting these correlations from the scene allows to accurately recover the original scene from compressed measurements. Traditional approaches exploit the sparsity of the scene when represented in a proper basis. For this purpose, an optimization problem that seeks to minimize a joint L2-L1 norm is solved to obtain the original scene. However, there exists some HSI with an important feature which does not have been widely exploited; HSI are commonly low rank, thus only a few number of spectral signatures are presented in the image. Therefore, this paper proposes an approach to recover a simultaneously sparse and low rank hyperspectral image by means of exploiting both features at the same time. The proposed approach solves an optimization problem that seek to minimize the L2 norm, penalized by the L1 norm to force the solution to be sparse, and penalized by the nuclear norm to force the solution to be low rank. Theoretical analysis along with a set of simulations over different data sets show that simultaneously exploiting low rank and sparse structures enhance the quality of the recovered image.

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9840-53, Session 9

Schrödinger eigenmaps for semi-supervised manifold alignment of hyperspectral imagery

Juan Johnson, Charles M. Bachmann, Nathan D. Cahill,
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A common issue that occurs when collecting aerial hyperspectral imagery is that the sun-target-sensor angle can change significantly over the course of the acquisition. Multi-angular images can be extremely difficult to accurately classify without adequate preprocessing that characterizes and compensates for BRDFs of various materials in the scene. One promising classification approach, Semi-Supervised Manifold Alignment (SSMA), clusters similar classes together whilst pushing different classes apart, all while preserving the original geometric structure of each local data set independently.

In SSMA, geometric structure is incorporated via the Laplacian Eigenmaps (LE) algorithm, a popular dimensionality reduction algorithm based on preserving distances between pixels that are close to each other in a spectral sense. In previous research into hyperspectral image classification, the LE algorithm has been extended in a variety of ways to incorporate spatial as well as spectral information in the dimensionality reduction process. Spatial-Spectral Schrödinger Eigenmaps (SSSE) is a particularly noteworthy extension to the LE family of manifold learning algorithms, as it encodes spatial information through the simple addition of a “cluster potential” matrix to the graph Laplacian that encodes spectral information, and it additionally enables semi-supervision through the inclusion of a small set of manually-provided class labels.

In this paper, we extend the SSMA methodology for classifying multi-angular hyperspectral imagery by using SSSE instead of LE to preserve geometric structure. We assess its impact on the classification accuracy of a variety of multi-angular hyperspectral images captured over Hog Island in the Virginia Coast Reserve.

9840-54, Session 9

Deep sub-space mapping in hyperspectral imaging

David K. J. Gustafsson, Niclas Wadströmer, Henrik Petersson, FOI-Swedish Defence Research Agency (Sweden)

Hyperspectral imaging is an efficient technic for analyzing materials from a distance. Hyperspectral images are composed of a large number of spectral channels in which many materials can be identified and recognized due to their unique spectral properties. The large number of spectral bands is challenging in many signal processing applications. Hence there is a need to find a representation of the hyper spectral signal in a space of lower dimensionality without losing the discriminatory capacity.

We propose a novel deep learning approach using auto-encoders to map the spectral bands to a space of lower dimensionality while preserving the information that makes it possible to discriminate different materials. Deep learning is a relatively new pattern recognition approach which has given very promising result in many applications. In deep learning a hierarchical representation of increasing level of abstraction of the features is learned. Auto-encoder is an important unsupervised technic frequently used in deep learning for extracting important properties of the data. In auto-encoding a data vector x of dimension n is mapped on to itself through a latent space of lower dimensionality. The latent representation of lower dimensionality of the original data use few dimensions while allowing approximate reconstruction of the original data from the low dimensionality representation. The learned, using an auto-encoder, latent representation of the original data is a highly non-linear mapping of the original data which potentially preserve the discrimination capacity.

The proposed novel method using auto-encoding to learn a latent

representation of low dimensionality of the data, is compared with classical combination methods and subspace projection methods. The new method will also be evaluated as a way to reduce the dimensionality of hyperspectral data to allow visual presentation of the data and relevant properties of the data.

9840-55, Session 10

Chemical plume detection with an iterative background estimation technique

Eric Truslow, Steven E. Golowich, Dimitris G. Manolakis,
MIT Lincoln Lab. (United States)

The detection of chemical vapor plumes using passive hyperspectral sensors operating in the longwave infrared is a challenging problem with many applications. For adequate performance, detection algorithms require an estimate of a scene’s background statistics, including the mean and covariance. Diffuse plumes with a large spatial extent are particularly difficult to detect in single-image schemes because of contamination of background statistics by the plume. To mitigate the effects of plume contamination, a first pass of the detector can be used to create a background mask. However, large diffuse plumes are typically not removed by a single pass. Instead, contamination can be reduced by using smoothed detection results as a background mask.

In the proposed procedure, a detector bank is run on the cube, and a threshold applied to produce a binary image. The binary image can be modeled as a spatial point process consisting of high density and low density regions. By applying a spatial filter to the detection image, regions with overall higher intensity are detected as containing plume and can be removed from background statistic estimates. The key intuition is that regions with a higher density of hits are more likely to contain plume since plumes are spatially contiguous. We demonstrate with real plume data that this method can drastically improve detection performance over the single-pass method, and explore tradeoffs between different filter sizes and thresholds.

9840-56, Session 10

Flag-based detection of weak gas signatures in long-wave infrared hyperspectral image sequences

Timothy Marrinan, Ross Beveridge, Bruce Draper, Michael J. Kirby, Chris Peterson, Colorado State Univ. (United States)

We present a flag manifold based method for detecting chemical plumes in long-wave infrared hyperspectral movies. The technique leverages knowledge of the radiance of the background scene, taken from a frame of a hyperspectral movie at a time known to be free of chemical agents, to improve the detection of chemical signatures in other frames of the movie. The method utilizes a map between hyperspectral pixels and points on a Grassmann manifold $G(k,n)$, that is, the manifold whose points parameterize all k -dimensional subspaces of an n -dimensional vector space.

Given a finite set of linear subspaces, there is a natural way to associate a flag of vector spaces (i.e. a nested sequence of vector spaces) that lies most central to the set of subspaces. This representation is achieved through an optimization procedure that can be implemented on large data sets, and is flexible enough to represent collections of subspaces of possibly differing dimensions. The vector spaces within the flag are each the optimal subspace of that particular dimension. Thus, much like the singular value decomposition, if a low dimensional representation is sought, the earlier elements in the flag are most relevant. The additional structure of the representation makes it possible to observe signals in the earlier elements of the flag that may be washed out by noise in later elements. In our approach, a flag is associated with each pixel of a hyperspectral image, and detections are performed by measuring the principal angle between a library signature

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for the chemical agent and the appropriate element from the flag. Thus, temporal information contained in this subspace representation and spatial information shared by adjacent pixels are encoded as points on a flag manifold, that is, the manifold whose points parameterize all flags (of a given type) in an n-dimensional vector space.

The technique used to create the flags pushes information about the background clutter, ambient conditions, and potential chemical agents into the leading elements of the flags. The result of exploiting this temporal information by way of the flag structure is a novel algorithm for detecting gas plumes that appears to be sensitive to the presence of weak plumes. Detection results from this method are compared qualitatively to existing techniques and on real data. In addition, detection results are compared quantitatively on synthetic data where precise ground truth is available.

9840-57, Session 10

**Temperature-emissivity separation for
 LWIR sensing using MCMC**

Joshua N. Ash, Wright State Univ. (United States); Joseph Meola, Air Force Research Lab. (United States)

Signal processing for long-wave infrared (LWIR) sensing is made complicated by unknown surface temperatures in a scene which impact measured radiance through temperature-dependent black-body radiation of in-scene objects. The unknown radiation levels give rise to the temperature-emissivity separation (TES) problem describing the intrinsic ambiguity between an object's temperature and emissivity. In this paper we present a novel Bayesian TES algorithm that produces a probabilistic posterior estimate of a material's unknown temperature and emissivity. The statistical uncertainty characterization provided by the algorithm is important for subsequent signal processing tasks such as classification and sensor fusion. The algorithm is based on Markov Chain Monte Carlo (MCMC) methods and exploits conditional linearity to achieve efficient block-wise Gibbs sampling for rapid inference. In contrast to existing work, the algorithm optimally incorporates prior knowledge about in-scene materials via Bayesian priors which may optionally be learned using training data and a material database. Examples from synthetic and measured LWIR data demonstrate the efficacy of the Bayesian algorithm.

9840-58, Session 10

**Polarimetric assist to HSI atmospheric
 compensation and material identification**

Mark C. Gibney, Harris Corp. (United States)

In this effort, we investigated how polarimetric Hyper Spectral Imaging (p-HSI) data might benefit specified Material Identification of diffuse materials in the VNIR. The experiment was designed to compare paint reflectivities extracted from polarimetric hyper spectral data acquired in the field to a database of truth reflectivities measured in the lab. Both the polarimetric hyper spectral data and the reflectivities were acquired using an Ocean Optics spectrometer which was polarized using a fast filter wheel loaded with high extinction polarizers. During the experiment, we discovered that the polarized spectra from the polarimetric hyper spectral data could be used to estimate the relative spectral character of the field source (the exo-atmospheric sun plus the atmosphere). This benefit relies on the natural spectral flatness of the polarized spectrum that originates in the spectral flatness of the index of refraction in the reflective regime. Using this estimate of the field source, excellent per pixel estimates of the paint reflectivities (matching 10 paint reflectivities to $\leq 0.5\%$) were obtained.

The impact of atmospheric upwell on performance was then investigated using these ground based polarimetric hyper spectral data in conjunction with modeled atmospheric path effects. The path effects were modeled using the high fidelity Polarimetry Phenomenology Simulation (PPS) plate model developed by AFRL, which includes polarized Modtran. We conclude with a discussion of actual & potential applications of this method, and how best to convert an existing VNIR HSI sensor into a p-HSI sensor for an airborne Proof Of Concept experiment.

9840-59, Session 10

**A spectral climatology for atmospheric
 compensation of hyperspectral imagery**

John H. Powell, George Mason Univ. (United States);
 Ronald G. Resmini, The MITRE Corp. (United States)

Most Earth observation hyperspectral imagery (HSI) detection and identification algorithms depend critically upon a robust atmospheric compensation capability to correct for the effects of the atmosphere on the radiance signal. Atmospheric compensation methods typically perform optimally when ancillary ground truth data are available, e.g., high fidelity in situ radiometric observations or atmospheric profile measurements. When ground truth is incomplete or not available, additional assumptions must be made to perform the compensation. Meteorological climatologies are available to provide climatological norms for input into the radiative transfer models; however no such climatologies exist for empirical methods.

The success of atmospheric compensation methods such as the empirical line method suggests that remotely sensed HSI scenes contain comprehensive sets of atmospheric state information within the spectral data itself. It is argued that large collections of empirically-derived atmospheric coefficients collected over a range of climatic and atmospheric conditions comprise a resource that can be applied to prospective atmospheric compensation problems. A previous study introduced a new climatological approach to atmospheric compensation in which empirically derived spectral information, rather than sensible atmospheric state variables, is the fundamental datum. The current work expands the approach across an experimental archive of 127 airborne HSI datasets spanning nine physical sites to represent varying climatological conditions. The representative atmospheric compensation coefficients are assembled in a scientific database of spectral observations and modeled data.

Improvements to the modeling methods used to standardize the coefficients across varying collection and illumination geometries and the resulting comparisons of adjusted coefficients are presented. The climatological database is analyzed to show that common spectral similarity metrics can be used to separate the climatological classes to a degree of detail commensurate with the modest size and range of the imaging conditions comprising the study. The study closes with a notional application example and a discussion of the potential benefits, shortfalls and future work to fully develop the new technique.

9840-60, Session 10

**Generation of remotely sensed reference
 data using low altitude, high spatial
 resolution hyperspectral imagery**

McKay Williams, Jan A. N. van Aardt, John P. Kerekes,
 Rochester Institute of Technology (United States)

Exploitation of imaging spectroscopy (hyperspectral) data using classification and spectral unmixing algorithms is a major research area in remote sensing, with ground truth maps required to assess algorithm performance. However, we are limited by our inability to generate rapid and accurate ground truth, thus making quantitative algorithm analysis difficult. As a result, many investigators present either limited quantitative results, use synthetic imagery, or provide qualitative results using real imagery. Existing truth maps typically classify large swaths of imagery pixel-by-pixel, per cover type. While this type of mapping provides a first order understanding of scene composition, it is not detailed enough to include complexities such as mixed pixels, intra-endmember variability, and scene anomalies. The creation of more detailed ground truth maps based on field work, on the other hand, is complicated by the enormous spatial scale of common hyperspectral data sets. This research presents a solution to this challenge via classification of low altitude, high spatial resolution (1m GSD) National Ecological Observatory Network (NEON) hyperspectral imagery, on a pixel-by-pixel basis, to produce sub-pixel truth maps for high altitude, lower spatial resolution (15m GSD) AVIRIS imagery. This classification is

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performed using traditional classification techniques, augmented by (1m GSD) NEON light detection and ranging (lidar), and (0.3m GSD) NEON RGB data. Our results, along with strategies to address challenges related to the fusion of multiple remote sensing modalities (e.g., varying scene illumination, sensor look angles, spatial registration, etc.); will be presented at the conference.

9840-63, Session 11

An imaging spectro-polarimeter for measuring hemispherical spectrally resolved down-welling sky polarization

David B. Chenault, Joseph L. Pezzaniti, Polaris Sensor Technologies, Inc. (United States)

A full sky imaging spectro-polarimeter has been developed that measures spectrally resolved (~2.5 nm resolution) radiance and polarization (s₀, s₁, s₂ Stokes Elements) of natural sky down-welling over approximately 2π sr between 400nm and 1000nm. The sensor is based on a scanning push broom hyperspectral imager configured with a continuously rotating polarizer (sequential measurement in time polarimeter). Sensor control and processing software (based on Polaris Sensor Technologies Grave' camera control software) has a straight-forward and intuitive user interface that provides real-time updated sky down-welling spectral radiance/polarization maps and statistical analysis tools. Sensor data products, design and example data sets will be presented.

9840-64, Session 11

UAV-embedded hyperspectral camera in the mid-infrared spectral range

Armande Pola Fossi, Yann Ferrec, Christophe Coudrain, ONERA (France); Nicolas Roux, Sagem (France); Nicolas Guérineau, ONERA (France); Emmanuel Kling, Sagem (France)

As an answer to the increasing the demand of compact optical sensor for UAVs, we are testing the use of birefringent lateral shearing interferometers (BLSI) for static Fourier transform hyperspectral imaging system in the mid-infrared. BLSI present the advantage of being free of beamsplitters and therefore might lead to highly compact interferometer in contrary of commonly used interferometers (Michelson, Sagnac and so on). A first prototype, SIBI, has been realized and tested during a ground based measurement campaign and we are currently upgrading it to make a UAV-embedded version which is expected for the beginning of 2016.

9840-65, Session 11

Compact multispectral multi-camera imaging system for small UAVs

Hans Erling Torkildsen, Thomas-Olsvik Opsahl, Atle Skaugen, Trym V. Haavardsholm, Urmila Datta, Torbjørn Skauli, Norwegian Defence Research Establishment (Norway)

Multi- and hyperspectral imaging is an attractive sensing modality for small unmanned aerial vehicles (UAV) in numerous civilian and military applications, including target detection and precision agriculture. Cameras based on patterned filters in the focal plane, such as conventional color cameras, represent the most compact architecture for spectral imaging. Compactness is key to building payloads with multiple multispectral cameras arranged in different directions to cover a large field of view. Such payloads can provide large area coverage rate at high spatial resolution,

with potential for highly cost-effective operations. On a moving platform, multiple filters can be scanned over the scene by the platform movement, typically by arranging multiple bandpass filters as stripes across the image sensor of each camera, perpendicular to the flight direction. By image coregistration and resampling, it is possible to assemble a spectral image in software. Since different bands are recorded at different times and in different viewing directions, there is a risk of spectral artifacts in the image, resulting from temporal variability and parallax effects in the scene. At FFI we investigate a camera configuration where six bandpass filters are arranged in a periodically repeating pattern. The resulting repeated sampling of bands enables consistency checks on the individual pixel spectra, with potential for significantly improved spectral integrity. In addition, an unfiltered region permits conventional 2D imaging for video, panchromatic mosaics and image-based navigation. We have built a sensor payload with multiple such cameras combined with automated recording in an onboard computer. The payload is carried by an octocopter UAV with automated waypoint navigation. The recorded imagery demonstrates the potential for large area coverage with good spectral integrity.

9840-66, Session 11

Software defined multi-spectral imaging for Arctic sensor networks

Sam Siewert, Embry-Riddle Aeronautical Univ. (United States) and Univ. of Colorado at Boulder (United States); Vivek Angoth, Ramnarayan Krishnamurthy, Karthikeyan Mani, Univ. of Colorado at Boulder (United States); Kenrick Mock, Univ. of Alaska Anchorage (United States) and Arctic Domain Awareness Ctr. (United States); Saurav Srivistava, Chris Wagner, Univ. of Colorado at Boulder (United States); Ryan Claus, Matthew D. Vis, Embry-Riddle Aeronautical Univ. (United States); Surjith B Singh, University of Colorado Boulder (United States)

Availability of off-the-shelf infrared sensors combined with high definition visible cameras has made possible the construction of a Software Defined Multi-Spectral Imager (SDMSI) combining long-wave, near-infrared and visible imaging. The SDMSI requires a real-time embedded processor to fuse images and to create real-time depth maps for opportunistic uplink in sensor networks. Researchers at Embry Riddle Aeronautical University working with University of Alaska Anchorage at the Arctic Domain Awareness Center and the University of Colorado Boulder have built several versions of a low-cost drop-in-place SDMSI to test alternatives for power efficient image fusion. The SDMSI is intended for use in field applications including marine security, search and rescue operations and environmental surveys in the Arctic region. Based on Arctic marine sensor network mission goals, the team has designed the SDMSI to include features to rank images based on saliency and to provide on camera fusion and depth mapping. A major challenge has been the design of the camera computing system to operate within a 10 to 20 Watt power budget. This paper presents a power analysis of three options: 1) multi-core, 2) field programmable gate array with multi-core, and 3) graphics processing units with multi-core. For each test, power consumed for common fusion workloads has been measured at a range of frame rates and resolutions. The paper will present detailed analysis from our power efficiency comparison for workloads specific to stereo depth mapping and sensor fusion. Preliminary mission feasibility results from testing with off-the-shelf long-wave infrared and visible cameras in Alaska and Arizona will also be presented to demonstrate the value of the SDMSI for applications such as ice tracking, soil moisture, animal and marine vessel detection and tracking. The goal is to select the most power efficient solution for the SDMSI for use on UAVs and other drop-in-place installations in the Arctic. The prototype selected will be field tested in Alaska in the summer of 2016.

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9841-1, Session 1

An outlook for land remote sensing in support of civil applications

Peter J. Doucette, Timothy Newman, Raymond Byrnes, U.S. Geological Survey (United States)

Land remote sensing (LSR) for the purposes of Earth observation and monitoring in support of civil applications is rapidly evolving across multiple fronts. Central issues on the table of discourse include the future commoditization of space, the incorporation of emerging system approaches (e.g., CubeSat and UAS), data access and user rights, commercial marketplace economics vis-à-vis government sponsorship, international collaboration, and policy development. In this paper we offer a comprehensive perspective among these interrelated issues to prescribe workable paths toward meeting diverse community needs into the future. The goal is to both inform and motivate community discussion. We first provide a retrospective on the development of land remote sensing policy in the U.S., followed by a synopsis on the current state of affairs within the international arena. We then lay out a framework in which evolving user requirements can be assessed against an ever broadening portfolio of remote sensing capabilities. We conclude with an outlook for leveraging land change science and monitoring via temporal data cubes to project possible outcomes for use by decision makers to assess land management policy consequences. Thoughtful application of the full breadth LRS capabilities has considerable potential to inform a wide range of emerging regional and global issues related to changing climate stressors on water, food, and energy consumption.

9841-2, Session 1

On the feasibility of a temporal data cube for arctic assessment

Peter J. Doucette, Kevin Foley, U.S. Geological Survey (United States)

Rapidly receding ice in the Arctic has motivated considerable interest in understanding the future impact and risk assessment to the region from a policy making perspective. This paper is intended to study the feasibility and utility of a publically accessible temporal land data cube via an internet portal for the Arctic region. As a primary data source, the study considers the civil remote sensing community's considerable geospatial imagery archive at the U.S. Geological Survey's Earth Resources Observation and Science (EROS) Center. Several commercial entities are re-hosting partial collections of the EROS data set for specific applications. A key aspect of this study is to assess the relative value of time series data (collected over many years) to users, as well as assessing how well existing capabilities (e.g., pre-processing by the data host) and data can meet user requirements. The ultimate goal is to motivate new approaches to scientific discovery and operational products in support of national and international policy making communities in the Arctic.

9841-3, Session 1

In-scene parameter estimation for application of the general image quality equation (GIQE)

Nobuhiko Yamagishi, Mariko Sato, Mitsubishi Electric Corp.

(Japan); Charles A. McPherson, John M. Irvine, Draper Lab. (United States)

Numerous methods exist for quantifying the information potential of imagery analyzed by a human observer. The National Imagery Interpretability Ratings Scale (NIIRS) is a useful standard for intelligence, surveillance, and reconnaissance (ISR) missions. One property that greatly enhances the utility of NIIRS is the ability to predict the NIIRS level of an image prior to the acquisition of the image based on parameters related to the sensor and imaging conditions. The general image quality equation (GIQE) is a standard model which predicts the NIIRS of the image using sensor parameters such as the ground sample distance (GSD), the relative edge response (RER), edge overshoot, and signal-to-noise ratio (SNR). Typically, these parameters are derived from controlled experiments, such as images of calibration targets. For many situations, however, these controlled data are not available and it becomes necessary to estimate these parameters from information available in the imagery. We present methods for estimating the RER, edge overshoot, and SNR through analysis of the scene and demonstrate how to fold these values into NIIRS predictions using the GIQE.

9841-5, Session 2

Looking at earth observation impacts with fresh eyes: a Landsat example

Zhuoting Wu, Greg Snyder, Greg Stensaas, Bruce Quirk, U.S. Geological Survey (United States); Carolyn Vadnais, Michael Babcock, Integrity Applications, Inc. (United States); Peter J. Doucette, U.S. Geological Survey (United States)

US Geological Survey (USGS) initiated the Requirements, Capabilities and Analysis for Earth Observations (RCA-EO) project in the Land Remote Sensing (LRS) program, collaborating with the National Oceanic and Atmospheric Administration (NOAA) to jointly develop the supporting information infrastructure - The Earth Observation Requirements Evaluation Systems (EORES). RCA-EO enables us to collect information on current data products and projects across the USGS and evaluate the impacts of Earth observation data from all sources, including spaceborne, airborne, and ground-based platforms. EORES allows users to query, filter, and analyze usage and impacts of Earth observation data at different organizational level within the bureau. We engaged over 500 subject matter experts and evaluated more than 1000 different Earth observing data sources and products. USGS has maintained Landsat satellite records for over 4 decades, and is continuously providing more than 1000 images a day to support agriculture, forestry, land cover/land use monitoring, water resources management, global change and ecosystem modeling, and various mapping efforts. RCA-EO provides a comprehensive way to evaluate Landsat impacts within USGS through the survey of 345 key USGS products and services. We summarized our results by application area, spectral band, data record length, and compared various aspects of Landsat impacts within the organizational structure of the USGS. We paid special attention to user feedback about Landsat data and Landsat-derived products to inform decision making on continuous Landsat missions. We believe the approach and philosophy of RCA-EO can be applied in much broader scope to derive comprehensive knowledge of Earth observing systems impacts and usage and inform data products development and remote sensing technology innovation.

9841-6, Session 2

Addressing fundamental architectural challenges of an activity-based intelligence and advanced analytics (ABIAA) system

Matthew F. Pellechia, Harris Corp. (United States)

The domain of Intelligence Analysis is rapidly shifting into a paradigm to enable Activity Based Intelligence (ABI) from Multi-INT, Multi-Source, and the infamous "Big Data Cloud". Collectively, these data sources provide the community with tremendous opportunity to enable Integrated Intelligence, where automation of correlation of structured and unstructured data, predictive analytics to understand activities/behaviors, and with higher confidence/measured uncertainty. We propose an Activity Based Intelligence and Advanced Analytics (ABIAA) framework, with system level requirements that advantage high-performance computing resources, enable easier and faster search and discovery of data catalogs, with automated rule-based workflows to ease operator burden, while providing a level of affordability. Approaching an ABIAA system in a traditional architectural serial workflow (tasking, collection, processing, exploitation and dissemination) may produce short-term concept implementations, however, will inhibit longer-term barriers in realizing the intent of the true ABIAA system. The ABIAA systems we propose exhibit advanced algorithms with logic to automatically flag features and activities that humans don't have time to find, and in places that humans would not have been looking, all while maintaining integrity and product quality. Our presentation provides an overview of an ABIAA system, with several demonstrations of components and differentiation against legacy systems. ABIAA architectural considerations will be discussed, exploring the trades and issues between the hardware computing environment and advanced software processing components. The domain of Intelligence Analysis is rapidly shifting into a paradigm to enable Activity Based Intelligence (ABI) from Multi-INT, Multi-Source, and the infamous "Big Data Cloud". Collectively, these data sources provide the community with tremendous opportunity to enable Integrated Intelligence, where automation of correlation of structured and unstructured data, predictive analytics to understand activities/behaviors, and with higher confidence/measured uncertainty. We propose an Activity Based Intelligence and Advanced Analytics (ABIAA) framework, with system level requirements that advantage high-performance computing resources, enable easier and faster search and discovery of data catalogs, with automated rule-based workflows to ease operator burden, while providing a level of affordability. Approaching an ABIAA system in a traditional architectural serial workflow (tasking, collection, processing, exploitation and dissemination) may produce short-term concept implementations, however, will inhibit longer-term barriers in realizing the intent of the true ABIAA system. The ABIAA systems we propose exhibit advanced algorithms with logic to automatically flag features and activities that humans don't have time to find, and in places that humans would not have been looking, all while maintaining integrity and product quality. Our presentation provides an overview of an ABIAA system, with several demonstrations of components and differentiation against legacy systems. ABIAA architectural considerations will be discussed, exploring the trades and issues between the hardware computing environment and advanced software processing components. Our presentation concludes with a recommended strategy and incremental approach to the continued thought leadership, research, development and delivery of an ABIAA paradigm.

9841-7, Session 2

Gender classification of running using full body kinematics

Christina M. Williams, Khan M. Iftekharuddin, Old Dominion Univ. (United States)

Determining gender classification using full body kinematics offers relevancy to many applications such as security, sports, military applications and high-level character animation, to name a few. For this paper, full-body motion

capture data was collected from 25 males and 24 females for analysis. Motion capture data has been analyzed in similar experiments to distinguish between age, shod/barefoot conditions and injuries. The motion capture system used for this experiment has the ability to capture complex motion with extreme accuracy. Insight into the ways in which men and women differ while running, allows for a better understanding of occurrences such as increased injuries in one gender versus another. This paper provides an analysis and comparison of several pattern recognition techniques used to best determine the classification of men and women while running. Techniques are formed by implementing preprocessing steps using principle component analysis in conjunction with linear discriminant analysis, support vector machines, and decision-tree with AdaBoost. The dataset used consists of 49 subjects (25 males, 24 females, 2 trials each) all equipped with approximately 80 retroreflective markers. The trials are reflective of the subject's entire body moving unrestrained through a capture volume at a self-selected running speed, thus producing highly realistic data. By means of experimental testing, classification accuracy using leave-one-out cross validation for the 49 subjects is improved from 66.33% using linear discriminant analysis to 86.74% using the nonlinear support vector machine. Results are further improved to 87.76% by means of implementing a decision tree with AdaBoost. In support of previous experiments, the results obtained suggest that linear classification approaches are inadequate in classifying gender for a large dataset captured in a moderately uninhibited environment.

This work has been approved for public release (clearance number 88ABW-2015-4816).

9841-8, Session 2

Regional-scale incident-supporting visual cloud computing with software-defined networking

Prasad Calyam, Dmitrii Chemodanov, Rengarajan Pelapur, Kannappan Palaniappan, Univ. of Missouri (United States)

In the event of natural or man-made disasters, providing rapid situational awareness through video/image data collected at salient incident scenes is often critical to first responders. However, computer vision techniques that can process the media-rich and data-intensive content obtained from civilian smartphones or surveillance cameras require large amounts of computational resources or ancillary data sources that may not be available at the geographical location of the incident. Additionally, scalable processing of media-rich visual data and the subsequent visualization with high user Quality of Experience (QoE) demands new cloud computing and thin-client desktop delivery approaches. In this paper, we describe an incident-supporting visual cloud computing solution by defining a collection, computation and consumption (3C) architecture supporting fog computing at the network-edge close to the collection/consumption sites, which is coupled with cloud offloading to a core computation cloud. Our architecture assumes that fogs are capable of handling small instance video processing functions which are integrated with a core public cloud infrastructure for handling large instance video processing functions, utilizing software-defined networking (SDN). We describe how our 3C architecture and the provisioning and placement algorithms used for routing and selecting fog-cloud locations can be parameterized in the context of a regional-scale application for tracking objects in aerial full motion video and large scale wide-area motion imagery. We evaluate our 3C architecture and algorithms using a realistic virtual environment testbed to demonstrate the use of SDN for on-demand compute offload with congestion-avoiding traffic steering to enhance remote user QoE in the regional-scale application. The optimization between fog computing at the network-edge with core cloud computing for managing visual analytics reduces latency, congestion and increases throughput.

9841-9, Session 2

Smart phone orientation estimation comparisons using three axis gimbal

Kevin G. Gaquin, MaryAnne Fields, U.S. Army Research Lab. (United States)

Smartphones have put powerful sensor arrays in nearly everyone's pockets, this has driven research on smartphone based localization and orientation. In the past year a few comparative studies were published investigating the accuracy of smartphone based orientation estimation algorithms. Many of these studies utilized systems such as Xsens or high degree of freedom robotic manipulators. While these systems have a high degree of accuracy, they allow for both linear and angular velocities. In this study a 3 axis gimbal is utilized to better classify the accuracy of various smartphone based orientation algorithms. By using a gimbal all planar velocities can be removed so the device is only rotating about its center. By removing linear acceleration we can verify the accuracy of each algorithm with respect solely to estimation of the device's orientation. This will remove extraneous variables and allow us to determine where the algorithms' faults lie, where they begin to break down, and to what degree they break down. To compare the algorithms the gimbal repeats the same movements for each algorithm while progressively increasing the acceleration and velocity about each axis. In the results we compare the factors affecting each algorithm's performance including: computational complexity, delay in determining accurate orientation, and both maximum velocity and acceleration prior to degradation.

9841-10, Session 2

Geopositioning with a quadcopter: extracted feature locations and predicted accuracy without a priori sensor attitude information

John T. Dolloff, Bryant Hottel, David Edwards, Integrity Applications, Inc. (United States); Peter J. Doucette, U.S. Geological Survey (United States); Henry Theiss, Aaron Braun, Integrity Applications, Inc. (United States)

This paper presents an overview of the Full Motion Video Geopositioning Test Bed (FMV-GTB) developed to investigate algorithm performance and issues related to the registration of motion imagery and subsequent extraction of feature locations along with predicted accuracy. A case study is included corresponding to a video taken from a quadcopter. Registration of the corresponding video frames is performed without the benefit of a priori sensor attitude (pointing) information. In particular, tie points are automatically measured between adjacent frames using standard optical flow matching techniques from computer vision, an a priori estimate of sensor attitude is then computed based on supplied GPS sensor positions contained in the video metadata and a photogrammetric/search-based structure from motion algorithm, and then a Weighted Least Squares adjustment of all a priori metadata across the frames is performed. Extraction of absolute 3D feature locations, including their predicted accuracy based on the principles of rigorous error propagation, is then performed using a subset of the registered frames. Results are compared to known locations (check points) over a test site. Throughout this entire process, no external control information (e.g. surveyed points) is used other than for evaluation of solution errors and corresponding accuracy."

9841-11, Session 3

Automated scene generated background context for near-nadir look angles

Jonathan D. Tucker, Lockheed Martin Corp. (United States)

Multi-INT fusion of GEOINT and IMINT can enable performance optimization of target detection and target tracking problem domains, amongst others. Contextual information, which defines the relationship of foreground to background scene content, is a source of GEOINT for which various online repositories exist today including but not limited to the following: Open Street Maps (OSM) and the United States Geological Survey (USGS). However, as the nature of the world's landscape is dynamic and ever-changing, such contextual information can easily become stagnant and irrelevant if not maintained. In this paper we discuss our approach to providing the latest relevant context by performing automated scene generated background context segmentation and classification for near-nadir look angles for the purpose of defining roadways/parking lots, buildings, & natural areas. This information can be used in a variety of ways including augmenting context data from repositories, performing mission pre-planning, and for real-time missions such that GEOINT and IMINT fusion can occur and enable significant performance advantages in target detection and tracking applications in all areas of the world.

9841-13, Session 3

Textured object video segmentation using temporal coherency

Surya Prasath, Rengarajan Pelapur, Kannappan Palaniappan, Univ. of Missouri (United States); Gunasekaran Seetharaman, U.S. Naval Research Lab. (United States)

Deformable and articulated objects are hard to segment and track over time. Purely motion based techniques such as optical flow can produce good results in terms of segmenting motion, however they do not incorporate salient object features. In this work, we propose a textured object segmentation method using temporal coherency in videos. We utilize color and texture feature fusion within a fast globally convex active contour method to obtain multiscale intra frame segmentations. A long distance optical flow based point trajectories is then combined with frame segmentations to obtain label propagation along the temporal direction. Total variation regularization is applied to obtain well-defined object boundaries and a dual minimization implementation is undertaken for solving the overall energy minimization. Preliminary experimental results shows that we obtain dense segmentations even with sparse and noisy initial label sets.

9841-14, Session 3

Multi-focus and multi-modal fusion: a study of multi-resolution transforms

Soundararajan Ezekiel, Indiana Univ. of Pennsylvania (United States)

Automated image fusion would have wide ranging applications across a multitude of fields. Automation in the field of image fusion is difficult because there are many types of imagery data that need to be fused together at times, many types of multi-resolution transforms that can provide coefficients for fusion, and many fusion algorithms that can be used to complete the fusion. This creates a large number of possibilities for fusion. In this study we stride toward understanding how automation could be conceived, starting in the multi-focus and multi-modal image subdomains. We complete the identification of the best transforms to be used with both. Our study analyzes the greatest effectiveness for each subdomain, as well as identifying one or two that are most effective across the union of the two. We compare all types to find a correlation between the fusion input characteristics and the optimal transform. This assessment is completed through the use of no-reference image fusion metrics including information theory based, image feature based, and structural similarity based methods.

9841-15, Session 4

Optimal multi-focus contourlet-based image fusion algorithm selection

Soundararajan Ezekiel, Indiana Univ. of Pennsylvania (United States)

Abstract - Multi-Focus image fusion is becoming increasingly prevalent, as there is a strong initiative to maximize visual information in a single image for viewing by fusing the salient data from multiple images. This allows an analyst to make decisions based on a larger amount of information in a more efficient manner because multiple images need not be cross-referenced. The contourlet transform has proven to be an effective multi-resolution transform for both denoising and image fusion through its ability to pick up the directional and anisotropic properties while being designed to decompose the discrete two-dimensional domain. Many studies have been done to develop and validate algorithms for wavelet image fusion but the contourlet has not been as thoroughly studied. When we substitute the contourlet coefficients for the wavelet coefficients in these algorithms, we can perform contourlet image fusion. There are a multitude of methods for fusing these coefficients together, and our research shows if there is a superior method or methods for fusing coefficients together in the contourlet domain when using Multi-Focus images. Our method compares the algorithms with a variety of no reference image fusion metrics, including information theory based, image feature based, and structural similarity based assessments.

9841-16, Session 4

Bandelet-based image fusion: a comparative study for multi-focus images

Soundararajan Ezekiel, Indiana Univ. of Pennsylvania (United States)

There is a strong initiative to maximize visual information in a single image for viewing by fusing the salient data from multiple images. There exist a lot of multi-focus imaging systems that would be able to provide better image data if these images are fused together. This would allow an analyst to make decisions based on a single image rather than cross-referencing multiple images. The bandelet transform has proven to be an effective multi-resolution transform for both denoising and image fusion through its ability calculate geometric flow in localized regions and decompose the image based on an orthogonal basis in the direction of the flow. Many studies have been done to develop and validate algorithms for wavelet image fusion but the bandelet has not been as thoroughly studied. When we substitute the bandelet coefficients for the wavelet coefficients in modified versions of these algorithms, we can perform bandelet image fusion. There are a multitude of methods for fusing these coefficients together, and our research show if there is a superior method or methods for fusing coefficients together in the bandelet domain when using Multi-Focus images. Our method compares, the algorithms with a variety of no reference image fusion metrics, including information theory based, image feature based, and structural similarity based assessments.

9841-17, Session 4

Interactive target selection in aerial imagery using elastic body splines

Sachin Meena, Kannappan Palaniappan, Univ. of Missouri (United States); Guna Seetharaman, U.S. Naval Research Lab. (United States)

Tracking a target (i.e. moving vehicle, human being, object, animal) in airborne aerial imagery is a challenging task. Targets are often small in size, target appearance changes with viewpoint including shape distortions,

illumination differences and specularities also significantly influence target appearance, targets may be camouflaged, dynamic backgrounds, complex cluttered backgrounds, etc. Occlusions, presence of other moving targets and additional complexities pose further difficulties. This makes fully automatic detection and segmentation of the target a difficult task. Tracking is iterative and appearance based trackers are sensitive to input bounding boxes. In this work we study an elastic body spline based interactive target selection method which has proven to be robust even when the input consists of only a few pixels that belong to the object of interest. Elastic body spline belongs (EBS) to family of splines and have been applied for the task of biomedical image registration. It models the elastic deformation of homogeneous isotropic elastic body subjected to external forces. Our proposed method allows the user to select a target by marking only 4-6\$ pixels and performs an accurate segmentation of the target. The sparse interaction of labeling very few pixels by the user is less cumbersome than drawing an accurate bounding box and leads to fast target detection and segmentation. . EBS based target segmentation can be incorporated in the semi automatic tracker like LOFT where the target segmentation is a challenging task for the reasons mentioned above and the EBS based interactive target segmentation can help target segmentation to a great extend in such scenario.

9841-18, Session 5

Multi-scale focus-driven segmentation using elastic body splines

Sachin Meena, Rengarajan Pelapur, Surya Prasath, Kannappan Palaniappan, Univ. of Missouri (United States)

We study a method for extracting blurred or sharp regions of interest (ROI) that could help in initializing an interactive segmentation method using elastic body splines. Accurate salient region detection and segmentation can help many vision applications. In order to detect the ROI we first classify each pixel in an image as either sharp or blurred based on the second order derivative response. Using multiple scales of filters to compute the second order partial derivative matrix also known as the Hessian matrix helps us generalize the method to objects of varying sizes and across different imaging modalities. Areas in the image with blur respond differently while computing the derivatives. The absolute magnitude of the frobenius norm of such a multiscale Hessian matrix would be low in areas of blur relative to the areas that are sharp and in-focus. We use this basic property to mask out the ROI and initialize our novel elastic body splines based interactive segmentation technique. Elastic body splines belong (EBS) to a family of splines and have been applied for the task of biomedical image registration. It models the elastic deformation of homogeneous isotropic elastic body subjected to external forces. Our initial set of experiments of using a focus driven EBS interactive segmentation method shows promise and has vastly improved the quality of the segmentation over just the Hessian based ROI detection. The robustness of the method will be confirmed using standard metrics in literature such as F-measure and Jaccard similarity coefficient.

9841-19, Session 5

Selecting the ideal no-reference performance evaluation metric for multi-modal fusion algorithm validation

Soundararajan Ezekiel, Indiana Univ. of Pennsylvania (United States)

Image fusion is currently being used for a variety of applications for the consolidation of visual information from multiple sources. One way that image fusion can be particularly useful is when fusing imagery data from multiple modalities. Different modalities resulting from different sensors can provide a great deal of visual information enhancement to analysts. With the constantly increasing wealth of imagery data available today, it is important to automate the evaluation of the fused images to determine whether they are relevant for analysis. Many no-reference metrics, such as

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information theory based, image feature based, and structural similarity based, have been developed recently to do this. Not all of these metrics have been validated because it is hard to scale an accurate assessment of visual quality. In order to do this, human perception based validation methods have been developed, particularly dealing with the use of receiver operating characteristic (ROC) curves and the area under them (AUC). Our study uses these to analyze the effectiveness of no-reference image fusion metrics applied to multi-resolution fusion methods in order to determine which should be used when dealing with multi-modal data.

9841-20, Session 5

A comparative study of multi-focus image fusion validation metrics

Soundararajan Ezekiel, Indiana Univ. of Pennsylvania (United States)

Fusion of visual information from multiple sources is very relevant for current applications in fusion of imagery data. One way that image fusion can be particularly useful is when fusing imagery data from multiple levels of focus. Different focus can create different visual qualities for different regions in the imagery, which can provide much more visual information to analysts when fused. It is important to automate the evaluation of the fused images to determine whether they are they have fused the properly focused regions of each image, otherwise the fusion is useless. Many no-reference metrics, such as information theory based, image feature based, and structural similarity based, have been developed to accomplish this. It is hard to scale an accurate assessment of visual quality; hence there is still much work to be done in the validation of these metrics for different types of applications. In order to do this, human perception based validation methods have been developed, particularly dealing with the use of receiver operating characteristic (ROC) curves and the area under them (AUC). Our study uses these to analyze the effectiveness of no-reference image fusion metrics applied to multi-resolution fusion methods in order to determine which should be used when dealing with multi-focus data.

9841-21, Session 5

Interacting with target tracking algorithms in a gaze-enhanced motion video analysis system

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Motion video analysis is a challenging task, especially in real-time applications. It is therefore an important issue how to provide suitable assistance for the human operator. Given that the use of customized video analysis systems is more and more established, one supporting measure is to provide system functions which perform subtasks of the analysis. Recent progress in the development of automated image exploitation algorithms allows, e.g., real-time moving target tracking. Another supporting measure is to provide a user interface which strives to reduce the perceptual, cognitive and motor load of the human operator for example by incorporating the operator's visual focus of attention. A gaze-enhanced user interface is able to help here.

This work extends prior work on automated target recognition, segmentation, and tracking algorithms [1] as well as about the benefits of a gaze-enhanced user interface for interaction with moving targets [2]; we also proposed a prototypical system design aiming to combine both the qualities of the human observer's perception and the automated algorithms in order to improve the overall performance of a real-time video analysis

system [3]. In this contribution, we address two novel issues analyzing gaze-based interaction with target tracking algorithms. The first issue extends the gaze-based triggering of a target tracking process, e.g., investigating how to best relaunch in the case of track loss. The second issue addresses the initialization of tracking algorithms without motion segmentation where the operator has to provide the system with the object's image region in order to start the tracking algorithm.

[1] Teutsch, M., & Krüger, W. (2012, September). Detection, segmentation, and tracking of moving objects in UAV videos. In *Advanced Video and Signal-Based Surveillance (AVSS)*, 2012 IEEE Ninth International Conference on (pp. 313-318). IEEE.

[2] Hild, J., Brüstle, S., Heinze, N., & Peinsipp-Byma, E. (2013, May). Gaze interaction in UAS video exploitation. In *SPIE Defense, Security, and Sensing* (pp. 87400H-87400H). International Society for Optics and Photonics.

[3] Hild, J., Krüger, W., Brüstle, S., Trantelle, P., Unmüßig, G., Heinze, N., Peinsipp-Byma, E., & Beyerer, J. (2015, May). Collaborative real-time motion video analysis by human observer and image exploitation algorithms. In *SPIE Defense+ Security*(pp. 94630C-94630C). International Society for Optics and Photonics.

9841-22, Session 5

Mosaicing with Poisson blending regularization for wide area motion imagery

Surya Prasath, Raphael Viguier, Kannappan Palaniappan, Univ. of Missouri (United States); Gunasekaran Seetharaman, U.S. Naval Research Lab. (United States)

We study mosaicing for wide area motion imagery (WAMI) data using poisson blending regularization. Exploitation of full motion video and WAMI data is crucial for change detection, target tracking, activity-based recognition and 3D reconstruction. Creating a mosaicing of WAMI data is challenging due to problems such as blurring, ghosting due to parallax and varying image exposures. In this work we review image alignment and panoramic mosaicing techniques for WAMI data and identify corresponding challenges for these existing methods. We describe mosaicing with Poisson blending based regularization which helps avoid blending of colors from different frames. Experimental results show that we obtain seamless mosaics from full motion videos without artifacts associated with existing approaches.

9841-23, Session 5

Evaluation of H.264 and H.265 full motion video encoding for small UAS platforms

Christopher McGuinness, David Walker, Univ. of Dayton Research Institute (United States); Clark N. Taylor, Kerry Hill, Marc Hoffman, Air Force Research Lab. (United States)

Of all the steps in the image acquisition and formation pipeline, compression is the only process that degrades image quality. A selected compression algorithm succeeds or fails to provide sufficient quality at the requested compression rate depending on how well the algorithm is suited to the input data. Applying an algorithm designed for one type of data to a different type often results in poor compression performance. This is mostly the case when comparing the performance of H.264, designed for standard definition data, to HEVC (High Efficiency Video Coding), which the Joint Collaborative Team on Video Coding (JCT-VC) designed for high-definition data. This study focuses on evaluating how HEVC compares to H.264 when compressing data from small UAS platforms. To compare the standards directly, we assess two open-source traditional software solutions: x264 and x265. These software-only comparisons allow us to establish a baseline of how much improvement can generally be expected of HEVC over H.264.

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Then, specific solutions leveraging different types of hardware are selected to understand the limitations of commercial-off-the-shelf (COTS) options. Algorithmically, regardless of the implementation, HEVC is found to provide similar quality video as H.264 at 40% lower data rates for video resolutions greater than 1280x720, roughly 1 Megapixel (MPx). For resolutions less than 1MPx, H.264 is an adequate solution though a small (roughly 20%) compression boost is earned by employing HEVC. New low cost, size, weight, and power (CSWAP) HEVC implementations are being developed and will be ideal for small UAS systems.

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9842-1, Session 1

B-spline image representation for image tracking

Bhashyam Balaji, Rajiv Sithiravel, Defence Research and Development Canada (Canada); Sreeraman Rajan, Carleton Univ. (Canada)

Visual image tracking (VIT) has been extensively investigated for security, medical, robotics, space exploration, undersea explorations. The core of VIT is to obtain meaningful and accurate measurements about the location of moving targets. This is done for each image frame, which is then fed into a tracking algorithm. The tracker generates tracks that visualize the temporal history of moving targets' position in the image sequences.

However, background information in the images is a challenging problem for VIT. Examples of backgrounds could be natural objects like lake, ocean, forest and man-made objects like building, roads, and image jitter. The objects of interest in such applications, like vehicles and people appear much smaller in relation to the background.

The VIT can be implemented by two well known methods, namely tracking by detection and tracking by matching. Tracking by detection involves the use of a strong object recognition model which is capable of uniquely identifying the object of interest in each frame. A track is constructed using the sequence of object detection results from each frame. Tracking by matching uses a suitable motion model. Given the position of an object in a certain frame, the objective is to use this motion model to estimate the position of the object in a subsequent frame. Most of the VIT implementations use the detection of motion as the initial procedure.

The straightforward way to isolate the moving targets in a sequence of images can be done by using

background subtraction (BS). A simple approach to the background subtraction is the frame differencing (FD). The frame differencing method can be a static camera observing any scene with the assumption the sensor noise is negligible. Between any consecutive images any significant deviation in the intensity in any location of the images contribute to moving targets.

When the sensor noise is insignificant, the FD method cannot be used. In those cases, other BS-based methods (e.g., modelled background using Mixture of Gaussian, 3-frame subtraction, median image subtraction), can be used. All of the BS methods have uncertainty due to the fact that the detected motion might not come from the desired targets. Also, the apparent motion of the background objects, errors attributed to variations in illumination, image registration and dropped frames adversely effect the output.

Any arbitrary geometrical, numerical or statistical shapes can be represented by B-Spline, including images.

The main focus of this paper is the B-Spline based tracking by detection. The novel method models the background using the B-Spline followed by a tracking by detection algorithm. The newly proposed algorithm represents the images in terms of B-Splines. Using a few knots pixel intensity in the image can be represented and an optimal knot selection can be used to get a smooth and accurate representation of the image. The newly proposed B-Spline based VIT's performance is evaluated for two real-time vehicle tracking scenarios.

9842-2, Session 1

Landmark-based navigation for airborne sensor systems

Bhashyam Balaji, Rajiv Sithiravel, Anthony Damini, Defence Research and Development Canada (Canada)

The problem of tracking and multi-sensor data fusion in the context of airborne multisensor systems is well-studied. The tracking and fusion algorithms assume that the platform location is known. The navigation sensor systems may be broadly categorized as dead reckoning (e.g., inertial navigation), externally dependent (e.g., GPS) and database matching (e.g., celestial navigation).

In this paper, we consider the case when the location of the platform is not known from the navigation sensors. For instance, it could be due to the absence or denial of GPS or a GPS/INS integrated navigation system, or a malfunction in an INS. In this case it is assumed that the sensors are able to image and identify landmarks whose precise locations are known from a database. The problem then is to solve this externally dependent navigation problem in the absence of any other information.

The problem is formulated and solved in a Bayesian framework. For definiteness, we consider the case of an EO/IR sensor. The state model describes the dynamics of the moving platform. The measurements are the bearing and elevation measurements of each landmark. Note that the dimension of the measurement model is twice the number of landmarks. Furthermore, in contrast to most of the previous work, the problem of estimation of the complete kinematic state of the airborne platform is considered, not just the position and/or range to the targets. In addition, it is assumed that the platform is far more agile and capable of rapid manoeuvres than are possible by a surface target. Finally, as the landmarks disappear from the field of view quickly, and new landmarks are identified, the measurement model is formulated as capable of changing dynamically.

The problem of platform state estimation is then solved using common Bayesian algorithms, such as the extended Kalman filter. Simulations will be carried out that take into account the sensor field of view of the specified landmarks. The filter performance will be assessed in terms of RMSE and the NEES.

9842-3, Session 1

A Bayesian tracker for multi-sensor passive narrowband fusion

Ryan J. Pirkl, Jason M. Aughenbaugh, Applied Research Labs., The Univ. of Texas at Austin (United States)

We demonstrate the detection and localization performance of a multi-sensor, passive sonar Bayesian tracker for underwater targets emitting narrowband signals in the presence of realistic underwater ambient noise. Our evaluation focuses on recent advances in the formulation of the likelihood function used by the tracker that provide greater robustness in the presence of both realistic environmental noise and imprecise/inaccurate a priori knowledge of the target's narrowband signal. In the former, robustness is achieved by use of a physics-based noise estimation procedure for broadband ambient noise. In the latter, robustness is achieved through a new likelihood maximization over frequency. These improvements enable the tracker to reliably detect and localize narrowband emitters for a broader range of propagation environments, target velocities, and inherent uncertainty in a priori knowledge.

We evaluate the tracker's detection and localization performance by use of

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high-fidelity ray-based underwater acoustic simulations of a narrowband emitter moving through a distributed field of passive sensors in the presence of anisotropic noise and discrete interferers. The sensors' beam-level outputs are mapped to likelihood functions, which are used to update the 4-D probability density grid-based state-space of a Bayesian tracker spanning 2-D Cartesian position and velocity. The incorporation of a source-level model for the target's narrowband emissions that accommodates imprecision in a priori knowledge enables the likelihood functions to provide the joint bearing and range information necessary for fusing the different sensors' measurements in the tracker's Cartesian state-space. Target motion is handled within the tracker through a computationally efficient hybrid particle-grid motion update that incorporates a birth-death model for targets moving into and out of the tracker's state-space.

9842-4, Session 1

Trackability: Resolvability of Two Closely-Spaced Targets

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Recent research has developed a novel framework for determining target trackability using the Maximum Likelihood Probabilistic Multi-Hypothesis Tracker (ML-PMHT). This framework allows for the calculation of the PDF of the peak point in the ML-PMHT log-likelihood ratio (LLR) due to clutter as well as the PDF of the peak point in the ML-PMHT LLR due to the target. If it is possible to statistically discriminate between the peak target PDF and the peak clutter PDF, then the target is able to be tracked. We seek to expand on this framework by adding a second target and determining the conditions under which both targets can be individually tracked. For this to be possible, each target must have a peak PDF that is statistically differentiable from clutter as well as the other target. As the targets move closer and closer to one another, their peaks will start to overlap; at some point, the two distinct peaks will merge into one combined peak, and the targets will no longer be able to be tracked individually. We seek to quantify this: as two targets approach each other, how close can they get before they are no longer trackable?

9842-59, Session 1

Assignment and EM approaches for passive localization of multiple transient emitters

Wenbo Dou, Univ. of Connecticut (United States); Jemin George, Lance M. Kaplan, U.S. Army Research Lab. (United States); Richard Osborne, Yaakov Bar-Shalom, Univ. of Connecticut (United States)

This paper investigates the problem of localizing an unknown number of transient emitters using a network of passive sensors measuring angles of arrival in the presence of missed detections and false alarms. It is assumed that measurements within a certain time window of interest have to be associated before they can be fused to estimate the emitter locations. Two measurement models—either that any target can generate at most one measurement per sensor or that any target can generate several measurements per sensor — are possible within this time window. These two measurement models lead to two different problem formulations: one is an S-D assignment problem and the other is a cardinality selection problem. The S-D assignment problem can be solved by the Lagrangian relaxation algorithm efficiently with a high degree of accuracy when a small number of sensors are used. The sequential m-best 2-D assignment algorithm, which is resistant to the ghosting problem due to the estimation of the emitter signal's emission time, is developed to solve the problem when the number of sensors becomes large. Simulation results show that the sequential m-best 2-D assignment algorithm is suitable for real time processing with

reliable associations and estimates. The cardinality selection formulation models a list of measurements as a Poisson point process and is solved by applying the expectation-maximization (EM) algorithm and an information criterion. The convergence of the EM algorithm to the desired global maximum needs an initialization, which is close to the truth. Localization using passive sensors makes it difficult to obtain such an initial estimate. An assignment-based initialization approach is therefore presented. Simulation studies showed that the EM algorithm based on the assignment initialization is able to estimate the number of targets, target locations and directions with a high degree of accuracy.

9842-7, Session 2

Tracking interdependent target motion using the PHD filter

Krishanth Krishnan, Ratnasingam Tharmarasa, Thia Kirubarajan, McMaster Univ. (Canada)

This paper addresses the problem of tracking multiple pedestrians whose motion is dependent on one another.

In target tracking literature, it is commonly assumed that a target's motion follows a nearly constant velocity, constant turn or a constant acceleration model independent of the motion of other targets. But the actual behavior of a pedestrian may be more intricate than that and it is often affected by the motion of other pedestrians, obstacles in the surrounding and his/her intended destination. Hence, a more sophisticated motion modeling technique, which integrates the various factors that affect the motion of pedestrians, is needed. In this paper, a social force based motion model integrated into the Probability Hypothesis Density (PHD) framework is proposed. The social force concept has previously been used to model pedestrian motion when there are interactions among pedestrians. In this paper, the Sequential Monte Carlo (SMC) technique and the Gaussian Mixture (GM) technique are used to implement the proposed Social Force PHD (SF-PHD) filter and its multiple model variant in pedestrian tracking scenarios. A particle labeling approach is used in the SMC technique while a Gaussian component labeling approach is used in the Gaussian mixture technique for this purpose. Also, a modified performance measure based on the PCRLB for targets whose motion is dependent on each other is derived. Simulation and real data-based results show that both the SMC implementation and the Gaussian mixture implementation of the proposed SF-PHD filter outperform existing filters that assume independent motion among ground targets.

9842-8, Session 2

JPDA and traffic models for ground target tracking

Qingsong Wu, Ratnasingam Tharmarasa, Thia Kirubarajan, McMaster Univ. (Canada)

Tracking multiple closely-spaced ground targets, even if they are resolved in sensor's field of view, is challenging for traditional tracking approaches. In the Joint Probabilistic Data Association (JPDA) algorithm and the Multiple Hypothesis Tracking (MHT) algorithm as well as their variants, data association and prediction are carried out with a mutual independence assumption among target states. This is true for most other target tracking algorithms as well. However, the motion of a ground target has high correlation or interaction with that of its neighbors. Ignoring vehicle state dependency during the association and prediction steps in existing approaches will result in erroneous associations, track impurity and track coalescence. To solve this problem, this paper introduces a novel technique with emphasis on improving data association without the target state independence assumption as well as on improving state prediction with an explicit dependent target motion model. For data association in the presence of targets with explicit state dependence assumption, a Markov Random Field (MRF) graphical probabilistic model is introduced to model the association probabilities for such targets. Using the MRF, driving

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behavior models, road conditions and motion constraints are integrated into the tracking algorithm. The driving behavior models are used to calculate the joint association probability for two neighboring targets and as well to predict and estimate target states. Then data association and state update are resolved within a coupled JPDA framework. Through Monte Carlo simulations, it is shown that the proposed joint MRFPA algorithm can improve tracking results and alleviate issues like track impurity and coalescence in realistic ground target tracking scenarios. The proposed tracker outperforms standard trackers that assume state independence among targets.

9842-9, Session 2

Reconnaissance blind multi-chess: an experimentation platform for ISR sensor fusion and resource management

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This paper introduces the game of reconnaissance blind multi-chess (RBMC) as a paradigm and test bed for understanding and experimenting with autonomous decision making under uncertainty and in particular managing a network of heterogeneous ISR sensors to maintain situational awareness informing tactical and strategic decision making. The intent is for RBMC to serve as a common reference or challenge problem in fusion and resource management of heterogeneous sensor ensembles across diverse mission areas. The authors have defined a progression of RBMC versions with increasing complexity, are creating a software realization to serve as an experimentation platform, and are beginning to develop machine intelligence approaches to playing it.

The game of chess has been used very successfully for several decades as a test bed for machine intelligence algorithms. However, chess is not a suitable experimentation platform for understanding and improving tactical and strategic decision making in warfare because it lacks the key elements of fog and friction (as per Clausewitz), management of limited resources, and multiple, competing objectives. The game of RBMC introduces these factors as dominant elements of the competition. It is inspired by a chess variant known as kriegsspiel, which was used in 19th century Germany to train military officers. The key differentiators of RBMC are the elements of incomplete information, competing priorities, and taskable sensors. The controllable reconnaissance element is new within the universe of chess variants and is the driver of this research problem. It is envisioned that the tactics and strategy for RBMC are fundamentally different than for chess; and consequently therefore machine intelligence algorithms for RBMC will be a new area of research.

In RBMC, the players are not able to directly view the chess board. The chess board can be observed only through sensing actions, and situational awareness can be achieved only through inferences made on those observations. Each player is allocated a limited supply of sensing resources to interrogate the chess board. The player's sensor ensemble is heterogeneous, noisy, and has some predefined spatial, informational, and temporal agility. The authors have developed a rule set governing definition and allocation of sensing resources, described in this paper. In RBMC, there are a number of blind chess games running concurrently. This introduces the element of multiple, competing objectives, which is also a key element of warfare. This represents the problem that a commander at a certain echelon has in dividing attention and resources among multiple missions and goals. We can also introduce the element of friction by injecting a degree of randomness into the outcomes of moves.

It is envisioned that RBMC will serve as a common reference or challenge problem in fusion and resource management of heterogeneous sensor ensembles with applications to important mission-relevant problems across military domains and mission threads (land, maritime, air, space, and cyber).

Such reference or challenge problems have a long and very useful history in science and engineering (e.g., fruit fly, inverted pendulum, chess, DARPA Robotic Challenge, etc.). Because each tactical situation or mission is different, specific applications of sensor fusion and resource management techniques derived from the vast literature on that subject tend to be situation specific. The RBMC paradigm will provide an experimentation platform where information valuation and the sensor management trade-offs can be studied within a structured well-understood framework. Extensions will additionally permit the study of ISR effectiveness against countermeasures and in anti-access / area-denial environments.

9842-10, Session 2

Cloud4ISR: Large-scale intelligence, surveillance, and reconnaissance from cloud to mobile platforms

Arun Kirubarajan, TrackGen Solutions Inc. (Canada) and Gordon Graydon Memorial Secondary School (Canada)

Due to recent technological advances in compact, affordable and high-precision sensors, it is possible to collect large amounts of data from a multitude of devices such as cameras, radars, acoustic sensors and GPS receivers. With the voluminous data from these sensors, it is possible to detect, track and identify mobile objects using data fusion techniques. It is possible to predict the motion of those objects and classify their nature as well. There are many civilian and military applications of this surveillance technology.

In some cases, the surveillance may be local where the objects are restricted to a small area (e.g., mall, field) or distributed where they are geographically scattered over a large area (e.g., maritime, air). In both cases, the number of targets may be in the thousands and the volume of data may be in terabytes, which necessitates high computational and network resources. In particular, with high-resolution video data, the communication and processing power may be beyond the realm of a single desktop computer. With cloud computing being a flexible affordable solution for high performance computing (HPC), it is possible to handle large-scale Intelligence, Surveillance and Reconnaissance (ISR) problems by paying a subscription fee to access remote computing resources as needed. That is, remote computing resources are utilized only based on the needs of the scenario under consideration at any given time without having to invest in expensive HPC resources.

At the other end of the spectrum, the end-users visualizing and analyzing the output from the data fusion system have become mobile, switching to smart phones and tablets away from desktops. Today's tablets and smart phone have the computational and graphical power to handle demanding applications. With this cloud and mobile combination, users can perform complex large-scale ISR tasks like tracking, fusion and classification on remote cloud computers on-demand and access the results on their mobile or desktop devices at will. This combination provides the power and the flexibility required for large-scale ISR systems with large number of targets, sensors and end-users.

In this paper, we present a comprehensive architecture for large-scale ISR systems that takes advantages of computational platforms from cloud computing to smart phones for an end-to-end solution. Preliminary results on running multitarget trackers, multisensor fusion engines and classification algorithms on the cloud and visualizing the results on mobile platforms are presented as well.

9842-11, Session 3

Multitarget tracking using sensors with known correlations

Ronald P. S. Mahler, Random Sets, LLC (United States)

This paper is the fourth in a series aimed at weakening the independence assumptions that are typically presumed in multitarget tracking. Specifically,

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we assume that, in a multisensor scenario, the sensors are not necessarily independent but, rather, have known correlations (i.e., their joint single-target joint likelihood function is known). From this, we construct a very general multitarget measurement model for sensors with known correlations. From this general model we derive—as an illustrative example—the filtering equations for a probability hypothesis density (PHD) filter for sensors with known correlations. We emphasize the two-sensor case of this filter, for which the measurement-update equations involve an intuitively appealing summation over all measurement-to-measurement associations between the two sensors.

9842-12, Session 3

Tracking correlated, simultaneously evolving target populations

Ronald P. S. Mahler, Random Sets, LLC (United States)

This paper is the fifth in a series aimed at weakening the independence assumptions that are typically presumed in multitarget tracking. Specifically, analyses of two simultaneously-evolving multitarget populations typically presume that their evolutions are independent. In an earlier paper, we assumed that the target populations are correlated but approximately Poisson, and that their correlations can be approximately modeled as a bivariate Poisson process. Under certain assumptions, we derived a PHD-type filter for simultaneously evolving and correlated multitarget populations, but the measurement-update equation is combinatorial. In this paper we derive a tractable PHD-type filter for correlated populations, instead assuming that the correlation between two multitarget populations can be approximately modeled as a Poisson process on the product state-space of the two target populations.

9842-13, Session 3

Particle flow implementations of random finite set filters

Lingling Zhao, Harbin Institute of Technology (China); Mark Coates, Yunpeng Li, McGill Univ. (Canada); Junjie Wang, Harbin Institute of Technology (China)

The random finite set filtering methodology, as pioneered by Mahler, has proved extremely successful for performing multi-target tracking in a wide variety of challenging settings. Most implementations of the filters build on Gaussian mixture models or particle filters. The Gaussian mixture model approaches can struggle when the measurements or dynamics of targets are highly non-linear or non-Gaussian. The performance of particle filtering implementations can deteriorate when the measurements are highly informative or when the dimension of the state-space associated with a single target remains relatively large.

Particle flow filters, introduced recently by Daum and Huang, can perform significantly better than particle filters in high-dimensional settings or when there are highly informative measurements. These filters replace the importance sampling step of the standard particle filter, and involve the derivation of differential equations that specify a flow that can be applied to gradually migrate the particles from the prior to the posterior. Recently, we have proposed a novel filtering approach that incorporates particle flow within a standard particle filtering framework. The particle flow is used to derive the importance distribution rather than used to directly migrate the particles themselves. The resultant particle flow particle filters (PF-PFs) retain the desirable properties of particle filters (theoretical stability and known convergence behavior) but acquire the improved practical performance for the scenarios of high state dimension and very informative measurements.

In this paper, we will describe how particle flow methods and particle flow particle filters can be used to construct implementations of random finite set filters, including the (cardinalized) probability hypothesis density filter and the multi-Bernoulli filter. We will explore through numerical simulation how the performance compares with algorithms based on Gaussian

mixture models and particle filters, identifying tracking scenarios where the approach can prove beneficial. We will also examine how the filters compare in terms of the trade-off between computational requirements and accuracy.

9842-14, Session 3

Optimal SSN tasking to enhance real-time space situational awareness

Islam Hussein, Applied Defense Solutions, Inc. (United States); Robert SiVilli, Air Force Research Lab. (United States); Joe Gerber, Applied Defense Solutions, Inc. (United States); Paul Zetocha, Air Force Research Lab. (United States); John Ferreira, Applied Defense Solutions, Inc. (United States)

In this paper we develop a scalable simulation environment that implements a finite set statistical (FISST) information-based centralized tasking of a modernized Space Surveillance Network (SSN) in order to improve Space Situational Awareness (SSA). The environment models a population of space objects and sensors representative of diverse types of SSN sensors. Observations collected by the sensors are used to maintain and update a probabilistic representation of the state (the “information state”) of the space objects. Currently, this state is the position and velocity of all objects. This state is then used by a centralized scheduler to task the sensors over a future finite horizon. In order to do this, the scheduler propagates this state into the future to predict the state using a candidate schedule over the scheduling horizon. The performance of a candidate schedule is evaluated based on the amount of information gained during the collection process. Because the information gain is based on FISST, the gain reflects phenomena such as miss-detections (e.g., due to space object dimness), and false alarms. To ensure a real-time schedule computation, we use a fast stochastic optimization algorithm called the Information State Receding Horizon Control (ISRHC). Current results demonstrate the performance improvement (in information gain and true tracking error) of the FISST/ISRHC solution. As one would expect, for example, tracking error grows as the schedule gets “older” (closer to the end of the scheduling horizon) and as each new schedule gets implemented, a significant drop in error occurs.

9842-15, Session 4

Source credibility assessment using conflict measurement in information fusion

Pan Wei, John E. Ball, Derek T. Anderson, Mississippi State Univ. (United States)

In information fusion, information from multiple sources is combined together aiming for a result that is better than the ones produced by each source alone. To more effectively combine these sources for a better result, the credibility of each source needs to be taken into account when combining the data from multiple sources. In some scenarios, the credibility of sources can be obtained from external knowledge such as the inherent sensor capabilities; however, there are other scenarios in which no external knowledge is given. In this latter case, one would like to use the information provided by sources themselves to estimate and assess their credibility. In this paper, we propose an algorithm for calculating a measure of conflict, which is then used to estimate inter-source credibility. In order to facilitate better decisions, sources having higher conflict with other sources will be assigned to a lower credibility, and we can diminish the influence of those sources with lower credibility and put more trust on those sources that have higher credibility. We examine our algorithm by fusing information from different sources in both simulated examples and real-world examples, such as temperature estimation using thermal sensors at different nearby locations (a 1D problem), human target tracking using multiple security cameras (a 2D problem). The results show that conflict measurement can be an indication of source credibility, and the final results are improved by adding the credibility of each source to some information fusion algorithms.

9842-16, Session 4

Multi-performance fusion of classification systems

Mark E. Oxley, Christine M. Schubert Kabban, Air Force Institute of Technology (United States); Steven N. Thorsen, The Perduco Group (United States)

Given two legacy exploitation systems, whose performances are known, one might wish to determine if combining these together using some rule would yield a new exploitation system with improved performance. This is the fusion process. Often there are several performance objectives one would consider in this process. We investigate the fusion process based upon multiple performances. This is related to multi-objective optimization, but is different in some aspects. In this paper we pose a multi-performance problem for combining two classifications systems and derive the multi-performance fusion theory. A classification system with M possible output labels will have $M(M-1)$ possible errors. The Receiver Operating Characteristic (ROC) manifold was created to quantify all of these errors. The assumption of independence is usually made to simplify the mathematics of combining the individual systems into one system. Boolean rules do not exist for multiple symbols, thus, Boolean-like rules were created that would yield label fusion rules. An M-label system will have M! consistent rules. The formula for the resultant ROC manifold of the fused classification systems which incorporates the individual classification systems previously was derived. For the multi-performance problem we show how the set of permutations of the label set is used to generate all of the consistent rules and how the permutation matrix is incorporated into a single formula for the ROC manifold. Examples will be given that demonstrate how the solution to the multi-performance fusion problem relates to the solution of the single performance fusion problem.

9842-17, Session 4

The N-principle

Frederick E. Daum, Raytheon Co. (United States)

We derive a simple back-of-the-envelope formula for the error in particle flow caused by errors in the normalization of the conditional probability density. We know from numerical experiments that very small errors in the normalizing constant can completely destroy the estimation accuracy of the filter. Moreover, this same phenomenon is observed in other applications, such as adaptive meshing for weather prediction, where one needs to compute the normalization to machine precision (Emily Walsh ICIAM talk 2011)!!! It is very surprising that this effect is not well known. It is not so easy to derive a simple formula to quantify such errors, because a first order error analysis (like the Cramér-Rao bound) fails completely, owing to the lack of existence of a solution if the normalization is not perfect. There are interesting and useful physical analogies, such as the instability of plasmas and the extremely strong force of electrical charge compared with gravity. Our analysis uses the adjoint method to derive error bounds in the Banach space of unbounded linear differential operators rather than the usual perturbation analysis of numerical functions. Moreover, the relevant PDE has no chance of having a unique solution, and a large chance of not existing; hence we use a method due to Gromov for partial differential relations rather than PDEs. The mathematical techniques are somewhat edifying, but the results give deep insight into what is actually going on. We ruthlessly exploit the simple fact that the formal adjoint of the divergence is minus the gradient operator.

9842-18, Session 4

A plethora of open problems in particle flow research for nonlinear filters, Bayesian decisions, Bayesian learning and transport

Frederick E. Daum, Jim Huang, Raytheon Co. (United

States)

We derive four new particle flows using exact solutions to the Fokker-Planck equation that generalize the exponential family. We ask for finite dimensional solutions in which the dimension is allowed to grow with time, in contrast with the boring old exponential family in which the dimension is fixed with time. The four new solutions correspond to four distinct assumptions that are combinations of the following two conditions: (1) likelihood in the exponential family or not, and (2) prior density in the exponential family or not. This derivation is inspired by the exact solutions to the Zakai equation and the Fokker-Planck equation (Daum 1986-1987). Moreover, we exploit the recent work on particle flow and progressive Bayes' algorithms (Hanebeck, Morelande, Hagmar, Jirstrand & Svensson), which is a hybrid of particle flow and the flow of parameters of conditional probability densities. The hybrid particle-parameter flow is designed with the solution of a linear first order partial differential equation, analogous to particle flow. We know that it is crucial to avoid explicit normalization of the conditional probability density, analogous to the Zakai equation and the Kalman filter and Bene? filter and exact Daum filters. We enforce this condition using group renormalization flow ideas borrowed from quantum field theory. This new theory can be applied to design nonlinear filters as well as Bayesian decision and learning algorithms and transport algorithms.

9842-19, Session 4

Some remarks on quantum physics, stochastic processes, and nonlinear filtering theory

Bhashyam Balaji, Defence Research and Development Canada (Canada)

Quantum mechanics and special theory of relativity forms the foundation of the fundamental laws of nature. The union of quantum mechanics and relativity leads to quantum field theory (QFT). The successful theories of the fundamental interactions are all well described by quantum field theories. The notable exception of gravity, though quantum gravity effects are negligible in the length scales that can be explored. Furthermore, string theory the richest and most promising route beyond QFT, still assume the validity of quantum physics and relativity.

While the astonishing successes of quantum field theory as a description of nature is remarkable by itself, it is even more interesting to note that quantum physics has illuminated many areas of pure and (increasingly) applied mathematics. A major reason for that is the heuristic and mathematically nonrigorous Feynman path integral (FPI) formulation of quantum mechanics.

Since quantum mechanics is counter-intuitive, attempts have been made to understand it in terms of classical physics, such as hidden variable theory and Nelson's quantum mechanics. While there are deep and unbridgeable conceptual differences, there are some interesting mathematical similarities that has been well known. For instance, the relationship between the Fokker-Planck equation and Schrodinger equation has been well-known, though the solutions have very different meanings.

Recently, interesting new relationships have been shown between quantum mechanics and other areas by mathematicians and statistical physicists. The mathematics that arises quantum theory of interacting particles is closely related that arising in stochastic Petri nets in computer science to describe a collection of randomly interacting entities, as well as models in population biology and epidemiology. Some of the old and newer mathematical similarities are reviewed and possible connections to filtering theory discussed.

9842-20, Session 4

Improved landmine detection through context-dependent score calibration

Brandon Smock, Joseph N. Wilson, Univ. of Florida (United

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States); Martin Milner, CoVar Applied Technologies, Inc. (United States)

Algorithms developed for the detection of landmines must be able to characterize a wide variety of objects in a diverse array of environmental conditions. However, the potential performance of a detection algorithm may be underestimated by evaluating it in batch on a large, diverse dataset. This is because environmental—or in general, contextual—factors may contribute significant variance to the output of a detection algorithm across different contexts. One way to view this is as a problem of mis-calibration: within each context, the output scores of a detection algorithm can be seen as mis-calibrated relative to the scores produced in the other contexts. As a result of this mis-calibration, the observed receiver operating characteristic (ROC) curve for a detector can have a sub-optimal area-under-the-curve (AUC). One solution, then, is to re-calibrate the detector within each context. In this work, we identify multiple sets of contexts in which landmine detection algorithms exhibit significant output variance and, consequently, mis-calibration. We then apply a monotonic calibration strategy that maximizes AUC and demonstrate the gain in observed performance that results when a landmine detection algorithm is properly calibrated within each context.

9842-21, Session 5

Issues and challenges of the applications of context to enhance information fusion: panel summary

Erik Blasch, Air Force Research Lab. (United States); Ivan Kadar, Interlink Systems Sciences, Inc. (United States); Chee-Yee Chong, Consultant (United States); Alex L. Chan, U.S. Army Research Lab. (United States); Ronald P. S. Mahler, Random Sets, LLC (United States); Shanchieh J. Yang, Rochester Institute of Technology (United States); Alan Stenberg, Consultant (United States); Paul Tandy, Defense Threat Reduction Agency (United States); Laurie H. Fenstermacher, Air Force Research Lab. (United States)

During the 2015 SPIE DSS conference, nine panelists were invited to highlight the trends and use of context for information fusion. This paper will highlight the common issues and trends presented from the analysts. The different panelists highlighted methods of filtering, metrics for analysis, data for aggregation, and the importance of context for real-time analytics. Using the discussions from the panelists, the review will organize the trends towards a common assessment and review, content and context enrichment from information fusion, as well areas of future analysis.

9842-22, Session 5

An integrated model of hard and soft context in sensor management

Kenneth Hintz, George Mason Univ. (United States) and Perquire Research (United States); Ivan Kadar, Interlink Systems Sciences, Inc. (United States)

No Abstract Available

9842-23, Session 5

Learning patterns of life from intelligence analyst chat

Michael K. Schneider, BAE Systems (United States); Mark G. Alford, Air Force Research Lab. (United States); Olga

Babko-Malaya, BAE Systems (United States); Erik Blasch, Air Force Research Lab. (United States); Lingji Chen, Valentino Crespi, Jason C. Handuber, Philip J. Haney, BAE Systems (United States); James Nagy, Air Force Research Lab. (United States); Michael S. Richman, Greg Von Pless, Howie Zhu, Bradley J. Rhodes, BAE Systems (United States)

Our Multi-INT Data Association Tool (MIDAT) learns patterns of life (POL) of a geographical area from video analyst observations called out in textual reporting. Typical approaches to learning POLs from video make use of computer vision algorithms to extract locations in space and time of various activities. Such approaches are subject to the detection and tracking performance of the video processing algorithms. Numerous examples of human analysts monitoring live video streams annotating or ‘calling out’ relevant entities and activities exist, such as security analysis, crime-scene forensics, news reports, and sports commentary. This user description typically corresponds with textual capture such as chat. Although the purpose of these text products is primarily to describe events as they happen, organizations typically archive the reports for extended periods. This archive provides a basis to build POLs. Such POLs are useful for diagnosis to assess activities in an area based on historical context, and for consumers of products, who gain an understanding of historical patterns. MIDAT combines natural language processing, multi-hypothesis tracking, and Multi-INT Activity Pattern Learning and Exploitation (MAPLE) technologies in an end-to-end lab prototype that processes textual products produced by video analysts, infers POLs, and highlights anomalies relative to those POLs with links to ‘tracks’ of related activities performed by the same entity. MIDAT technologies perform well, achieving, for example, a 90% F1-value on extracting activities from the textual reports. An evaluation by analysts concluded that MIDAT would benefit user productivity, especially by automating analysis of weeks of data they regularly collect.

9842-24, Session 5

Collaborative mining of open-source text media: learning knowledge patterns from multiple sources

Georgiy M. Levchuk, Aptima, Inc. (United States)

Today’s battlefields are shifting to “denied areas,” where the use of U.S. Military air and ground assets is limited. To succeed, the U.S. intelligence analysts increasingly rely on available open-source intelligence (OSINT). Multiple OSINT sources are available, including local news, blogs, online investigations, social media reports, etc. They often describe the same events and actors, but present complementary information and thus must be analyzed together to obtain complete and reliable situation understanding. OSINT sources provide diverse and ambiguous mentions of same entities, making automated cross-document co-reference a very challenging task (Singh et al., 2011), and contain large amounts of erroneous information due to observer biases, accidental errors, second-hand reporting, and intentional information manipulation for propaganda and personal gains. Correctly identifying and completely discarding unreliable sources is neither feasible nor beneficial, since even propaganda news reports often contain information with unique details crucial to reconstructing the true situation on the ground.

Open source analysts require automated tools to analyze multi-source text data, answering queries, learning frequent (and thus normal) knowledge patterns, and discovering malicious or anomalous activities. These tools must deal with mention ambiguity and resolve vast amounts of knowledge conflicts present in OSINT data. In addition, the tools are needed that can fuse different complementary and only partially correlated fragments of knowledge across multiple sources. Recent advances in information extraction (IE) solutions (Manning et al., 2014), particularly generation of entities, events, relations, and comprehensive syntactic and semantic attributes, allow converting unstructured text into attributed knowledge graphs encoding semantic and syntactic information (Fig. 1). Use of attributes on both nodes and relations is a key innovation providing more

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contextualized (and consequently more accurate) knowledge comparison and fusion than the methods relying on only presence of entity connections (Wu et al., 2014; Yang et al., 2014). Higher accuracy of IE tools allow practitioners to go from theoretical and manual definitions of knowledge structures (Prentice, and Shapiro, 2011) to automate generation of complete, meaningful, and consistent knowledge graphs (Levchuk and Blasch, 2015). Using graph mining tools, researchers and OSINT analysts can fuse disparate sources and modalities of data, execute cross-source queries, and detect known or anomalous activities (Levchuk et al., 2015).

In this paper we present a model to learn and reconstruct the knowledge from multiple text sources when each source might have only a fragment of knowledge. Traditional machine learning algorithms assume that each source of data is a meaningfully complete instance of a model or pattern that generated it. This is not the case with general multi-source multi-modal data mining, such as OSINT, where individual sources mostly contain only partial information about overall situation that they report on. Our algorithms also extend the use of source reliability, traditionally applied to multi-source retrieval (Huang et al., 2012) and joint entity-relation extraction (Li, and Ji, 2014), to the case of multi-source knowledge pattern learning and reconstruction. Our models are based on collaborative mining methods and thus can be executed in distributed environments with and without support of Cloud infrastructure.

9842-25, Session 5

Agile battle management efficiency for command, control, communications and information (C3I)

Erik Blasch, Air Force Research Lab. (United States); Peter Houghton, Glen K. Hart, Defence Science and Technology Lab. (United Kingdom); Micheline Belanger, Defence Research and Development Canada, Valcartier (Canada); Nourbou Buchler, Air Force Research Lab. (United States)

Various operations such as civil-military (CIMIC) affairs require orchestration of communications, assets, and people. A key component includes technology support to enable coordinating analysts the ability to know where things are, who to coordinate with, and open and consistent lines of communication. In this paper, we explore concepts of battle management (BM) between military, civilian, and non-governmental organizations in support of a high-tempo emergency response scenario. Three concepts include sensor orchestration, a battle management language (BML), and command and control; which require coordination and de-confliction. In the this paper, we highlight the concepts, current trends on, and needs of BM for efficient command, control, communications, and information (C3I) to coordinate data and people for efficient and effective operations. The focus would be on the controlling analysts that supports a commander in an interoperable coalition disaster action response team (DART).

9842-26, Session 6

iCrowd: agent-based behavior modeling and crowd simulator

Vassilios I. Kountouriotis, Manolis Paterakis, Stelios C. A. Thomopoulos, National Ctr. for Scientific Research Demokritos (Greece)

Initially developed in the context of the TASS (Total Airport Security System) FP-7 project, the Crowd Simulation platform of the Integrated Systems Lab of the Institute of Informatics and Telecommunications in NCSR Demokritos has evolved into a complete agent-based behavior simulator with an emphasis on crowd behavior and building evacuation simulation. Under continuous development, it reflects an effort to implement a multithreaded, data-oriented simulation engine employing latest state-of-the-art programming technologies. It is based on an extensible architecture that

separates core services from the individual layers of agent behavior, offering a concrete simulation kernel designed for high-performance and stability. Its primary goal is to deliver an abstract platform to support facilitated implementation of Agent-Based Simulation solutions with potential applicability in several domains of knowledge, such as:

- Crowd behavior simulation, [in/out] door evacuation.
- Non-Player Character AI for Game-oriented applications and Gamification activities.
- Maritime surveillance simulation (vessel traffic modelling).
- Urban and Highway Traffic and Transportation Simulations.
- Social Behavior Simulations.

Currently, the platform is being developed in the context of the PYRONES (PYRo-mOdelliNg and Evacuation Simulation system) project, part of a Bilateral R&D Cooperation between Greece and Israel. It is planned to be integrated into the AF3 (Advanced Forest Fire-Fighting) FP7 project, as well as the FLYSEC (Optimising time-to-FLY and enhancing airport SECURITY) H2020 project R&I project.

9842-27, Session 6

Group activity scene understanding based on fusion of spatiotemporal imagery data

Vinayak Elangovan, The College of New Jersey (United States); Amir Shirkhodaie, Tennessee State Univ. (United States)

Understanding of Group Activities (GA) can be valuable for both military and civilian surveillance applications. A commonly practiced approach for understanding of GA is that of spatiotemporal analysis of video imagery data. However, constructing mindful evidence out of video imagery is a real challenge since the associated data may contain fragmented information, which complicates data processing, data association and correlation, and data fusion. A cognitive processing model is, therefore, required to assist in analyzing imagery data with varying degree of contextual details, extract and inference spatiotemporal information pertaining to correlated GA observations, and generate a summary annotation of occurred GA events. In this paper, we present an ontology-based approach for characterization and tracking of GA events based on a Hidden Markov Model (HMM) technique. The ontology-based HMM provides an inference for incremental perception for GA scene understanding as the associated events are dynamically evolved overtime. To verify and validate the performance of this GA inference method, a set of outdoor GA experiments with latent contexts and under different settings were conducted. The videos of scenarios were employed to track and tag participating persons in each GA spatiotemporally. Then, this information was used for generation of GA complimentary semantic messages partially describing refinements such as: human attributes, object attributes, individual/group activity attributes, and events spatiotemporal attributes. Fusion of these semantic messages takes place at each refinement stages, which significantly helps in describing a GA with appropriate traceability.

9842-28, Session 6

WayGoo recommender system: personalized recommendations for events scheduling, based on static and real-time information

Giorgos Konstandinos Thanos, Stelios C. A. Thomopoulos, National Ctr. for Scientific Research Demokritos (Greece)

WayGoo is a fully functional application whose main functionalities include event scheduling, and immersive navigation. However, significant information about events do not reach users' attention, either because of the size of this information or because some information comes from

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real - time data sources. The purpose of this work is to facilitate event management operations by prioritizing the presented, based on users' interests using both, static and real - time data. Through the WayGoo interface, users select conceptual topics that are interesting for them. These topics constitute a browsing behavior vector which is used for learning users' interests implicitly, without being intrusive. Then, the system estimates user preferences and return an events list sorted from the most preferred one to the least. User preferences are modeled via a Naïve Bayesian Network which consists of: a) the 'decision' random variable corresponding to users' decision on attending an event, b) the 'distance' random variable, modeled by a linear regression that estimates the probability that the distance between a user and each event destination is not discouraging, c) ' the seat availability' random variable, modeled by a linear regression, which estimates the probability that the seat availability is encouraging d) and the 'relevance' random variable, modeled by a clustering - based collaborative filtering, which determines the relevance of each event users' interests. Finally, experimental results show that the proposed system contribute essentially to assisting users in browsing and selecting events to attend.

9842-29, Session 6

Swarm-based heterogeneous aerial sensor network for monitoring indoor applications

Rajani Muraleedharan, Alexander D. Shibilski, Roan Woodruff, Saginaw Valley State Univ. (United States)

Recent development in sensor technology demands secure, reliable, and cost effective sensor based network application. In this research paper, a heterogeneous aerial sensor network (HASN) is deployed to perform data gathering and prediction analysis for indoor application such as air quality, emergency response and evacuation. The availability of heterogeneous nodes enables extensive sensor coverage (mobile and ad-hoc), varied sensor functionality, application adaptability, longevity and robustness. The HASN framework comprises of (a) Heterogeneous aerial sensor network architecture and (b) Distributed data communication and networking. There are some challenges involved in HASN based application such as, (i) deploying HASN autonomously require appropriate number of sensors (stationary, mobile and wireless) for continuous sensor coverage, (ii) tracking sensor's resource availability to maintain sensor lifetime and application reliability, (iii) maintain sensor functionality such as nodes dedicated for sensing, data dissemination and control the network to avoid data redundancy, (iv) communicating reliable messages among nodes (stationary, mobile and wireless) using multi-hop feature for congestion control and fairness, and (v) routing messages based on prioritization i.e., emergency response vs. air quality for smart message propagation. The main contribution of this research paper is (1) aerial sensor networking architecture (2) integrating hardware design using off-the shelf sensor components and open source software, (3) demonstrating HASN for air quality and simulated emergency rescue environment, and (4) robustness of swarm algorithm during multiple node failure. The autonomous and adaptability of HASN can reduce human intervention and automated emergency rescue mission as compared to existing stationary sensor network.

9842-30, Session 6

OCULUS fire: a control and command system for fire management with crowd sourcing and social media interconnectivity

Stelios C. A. Thomopoulos, Dimitris M. Kyriazanos, Alkiviadis Astyakopoulos, Vassilis Lampropoulos, Kostantinos Dimitros, Christos Margonis, National Ctr. for

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AF3 (Advanced Forest Fire Fighting, <http://af3project.eu/>) is a European FP7 research project that intends to improve the efficiency of current fire-fighting operations and the protection of human lives, the environment and property by developing innovative technologies to ensure the integration between existing and new systems. To reach this objective, the AF3 project focuses on innovative active and passive countermeasures, early detection and monitoring, integrated crisis management and advanced public information channels.

Oculus Fire is the innovative control & command system developed within AF3 as a monitoring, GIS and Knowledge Extraction System & Visualization Tool. Oculus Fire includes (a) an interface for real-time updating and reconstructing of maps to enable rerouting based on estimated hazards and risks, (b) processing of GIS dynamic re-construction and mission re-routing, based on the fusion of airborne, satellite, ground and ancillary geolocation data, (c) visualization components for the C&C monitoring system, displaying and managing information arriving from a variety of sources and (d) mission and situational awareness module for Oculus Fire ground monitoring system being part of an Integrated Crisis Management Information System for ground and ancillary sensors.

Oculus Fire will also process and visualise information from public information channels, social media and also mobile applications by helpful citizens and volunteers. Social networking, community building and crowdsourcing features will enable a higher reliability and less false alarm rates when using such data in the context of safety and security applications.

9842-31, Session 6

FlySec: a risk-based airport security management system based on security as a service concept

Dimitris M. Kyriazanos, Andreas Zalonis, Olga E. Segou, George Vardoulas, Stelios C. A. Thomopoulos, National Ctr. for Scientific Research Demokritos (Greece)

Complementing the ACI/IATA efforts, the FLYSEC European H2020 Research and Innovation project (<http://www.fly-sec.eu/>) aims to develop and demonstrate an innovative, integrated and end-to-end airport security process for passengers, enabling a guided and streamlined procedure from the landside to airside and into the boarding gates, and offering for an operationally validated innovative concept for end-to-end aviation security.

FLYSEC ambition turns through a well-structured work plan into: (i) innovative processes facilitating risk-based screening, (ii) deployment and integration of new technologies and repurposing existing solutions towards a risk-based Security paradigm shift, (iii) improve passenger facilitation and customer service, bringing security as a real service in the airport of tomorrow, (iv) achieving measurable throughput improvement and a whole new level of Quality of Service.

On the technical side, FLYSEC achieves its ambitious goals by integrating new technologies on video surveillance, intelligent remote image processing and biometrics combined with big data analysis, open-source intelligence and crowdsourcing. Repurposing existing technologies is also in the FLYSEC objectives, such as mobile application technologies for improved passenger experience and positive boarding applications (i.e. services to facilitate boarding and landside/airside way finding) as well as RFID for carry-on luggage tracking and quick unattended luggage handling.

In this paper, the authors will describe the risk based airport security management system which powers FLYSEC intelligence and serves as the backend on top of which FLYSEC's front end technologies reside for security services management, behaviour and risk analysis.

9842-32, Session 6

Dempster-Shafer information measures in category theory (*Invited Paper*)

Joseph J. Peri, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

In the Dempster Shafer context, one can construct new types of information measures based on belief and plausibility functions. These measures differ from those in Shannon's theory because, in his theory, information measures are based on probability functions. Other types of information measures were discovered by Kampe de Fariet and his colleagues in the French and Italian schools of mathematics. The objective of this paper is to construct a new category of information. I use category theory to construct a general setting in which the various types of information measures are special cases.

9842-5, Session PSTue

Tracking based on electro-optical and infrared sensors: evaluation of several algorithms

Balakumar Balasingam, Peter K. Willett, Yaakov Bar-Shalom, Univ. of Connecticut (United States)

We consider the problem of tracking point targets based on images from electro-optical (EO) and infrared (IR) sensors.

Sequential outputs of these sensors are assumed available in the form of energy density in a two dimensional sensor array, known as the focal plan array (FPA). In a target tracking context, the FPA images contain the azimuth and elevation information of targets and clutter in a rectangular field of view. We consider the following approaches of tracking point targets using FPA images: the first one is to hard-detect the measurements and to use them in a conventional tracking algorithm, such as the probabilistic data association (PDA) based tracker or the probabilistic multi hypothesis tracker (PMHT); the second approach is to model the (point) target in the FPA image with the use of a point spread function (PSF), i.e., to use the model of the optics that generated the image in the FPA, and to employ track before detect (TBD) type tracking algorithms, such as Viterbi (for slow-moving targets), multi-Bernoulli, maximum likelihood histogram PMHT (ML-HPMHT) etc.

Even though the second approach has some advantages over the first one, due to the fact that it does not need to employ measurement detection or data association, there are no objective performance comparisons of these two.

The goal of this paper is to look at these two types of tracking algorithms and to objectively compare their performance.

9842-51, Session PSTue

Addressing the vulnerabilities of pass-thoughts

Amanda S. Danko, Gabriel C. Fernandez, USAA (United States)

As biometrics become increasingly pervasive, consumer electronics are reaping the benefits of improved authentication methods. Leveraging the physical characteristics of a user reduces the burden of setting and remembering complex passwords while enabling stronger security. Multimodal systems lend further credence to this model, increasing security via multiple passive data points.

In recent years, expansion of this concept has lead to investigations into leveraging brainwaves as a next biometric for authentication. The feasibility of unique signals and even "pass-thoughts" is attracting more attention in the research community, and peeking into the consumer electronics space.

Physically unique to an individual, brain signals can also be changed by the user at will, making them more robust than static physical characteristics. While the consumer-level EEG technologies are nascent and limited, they are a promising start to a new line of wearables ready to deliver this functionality.

This work examines the security considerations of leveraging one's brainwaves for authentication purposes, and considers the vulnerabilities of exposing these signals to consumer electronics in general. Brain signals evaluated during known tasks can be interpreted in increasingly rapid manners. Therefore there are security concerns not only around the acquisition and transfer of brain signals, but additionally in a new line of phishing attacks; a user shown an image of an ATM, for example, may involuntarily recall their PIN. A primary consideration of this work then is to discuss the feasibility of such attacks, while outlining and implementing strategies for defense.

Next, existing consumer EEG devices are evaluated from consumer and security perspectives. A series of experiments on technology in this space is designed to investigate whether data is properly secured. Acknowledging that the current functionality of each device is generally guided meditation, some minor enhancements are made and shown to greatly improve security.

A system for biometric authentication via brain signals is next developed, leveraging consumer EEG technology to authenticate with a mobile device. Vulnerabilities exposed by the APIs of these devices are demonstrated in a series of attacks. A group of test subjects will undergo EEG biometric enrollment and authentication tasks; subsequently, an 'attacker' will perform a series of attacks to include replay and impersonation of the subject's EEG biometric.

Finally, a multimodal system combining EEG with additional factors is implemented to demonstrate improved performance against attacks. As a result, the system becomes more resilient to replay and impersonation attacks.

9842-52, Session PSTue

Supervised target detection in hyperspectral images using one-class Fukunaga-Koontz Transform

Hamidullah Binol, Abdullah Bal, Yildiz Technical Univ. (Turkey)

A novel hyperspectral target detection technique based on Fukunaga-Koontz transform (FKT) is presented. FKT offers significant properties for feature selection and ordering. However, it can only be used to solve two-pattern classification problems. Target detection may be considered as a two-class, i.e., target versus background, classification problem. Nevertheless, background clutter typically contains different types of materials. That's why; target detection techniques are different than classification methods by way of modeling clutter. To avoid the modeling of the clutter, we have improved one-class FKT for target detection. The statistical properties of target training samples are used to define tunnel-like boundary of the target class. Non-target samples are then created synthetically as to be outside of the boundary. Thus, only limited target samples become adequate for training of FKT. The hyperspectral image experiments confirm that the proposed one-class FKT technique provides an effective means for target detection.

Brief Information About Experimental Work:

In this work, we have chosen an airborne remote sensing data, captured by the HYperspectral Digital Imagery Collection Experiment (HYDICE) sensor, for experiments. The HYDICE data, gathered over the Washington, DC Mall, has seven labeled classes and 1208 lines with 307 pixels each. The HYDICE sensor originally contains 210 bands covering the 400-2400 nm portion of the spectrum. After removing noisy bands due to water absorption, 191 out of 210 bands were used in the experiments. All 7 classes of HYDICE DC Mall have been independently tested via conventional and suggested type of FKT, and the comparisons in terms of area under the recall-false positive rate curves (AUCs) are obtained. According to detection results, one-class FKT has satisfying performance without needing to utilize negative class (background clutter) samples.

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9842-53, Session PSTue

Characterizing sensor performance in statistically-represented signal propagation environments

Daniel J. Breton, D. Keith Wilson, U.S. Army Engineer Research and Development Ctr. (United States)

Most tactical decision aids (TDAs) employ physics-based models to estimate or predict environmental (i.e. terrain, weather, etc.) effects on sensor system performance. These models are necessarily deterministic and typically ingest single-valued representations of the environment, making the significant assumption that the relevant environmental parameters are perfectly known.

Recognizing that perfect knowledge is rarely the case, we seek to use statistical representations of both the environment and sensor-environment coupling to better understand the impact of imperfect knowledge on sensor performance estimation, and identify simplifying approximations when they exist.

We have conducted numerical experiments to simulate the effects of an uncertain environment on radiofrequency signal propagation and detection. These experiments couple the results from GPU-driven FDTD simulations of many different but statistically related realizations into a sensor model. The FDTD model focuses on capturing the statistical distribution of received signal energy as a result of changes in the material makeup of the propagation environment, while the sensor model includes variations in impulse response (to simulate variability in sensor-environment coupling) and background noise.

All of these variations in the source-environment-sensor chain have an impact on the final probability of detection, and we discuss the relative sensitivity of the results to variability in each of these areas. We also report on the apparent transition from a "linear" regime to a "saturated" regime in the context of increasing material and geometric variability in the propagation environment.

9842-54, Session PSTue

A comprehensive comparison of sigma-point Kalman filters applied on a complex maneuvering road

Mohammad Al-Shabi, Univ. of Sharjah (United Arab Emirates); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

Sigma-point Kalman filters (SPKFs) are well known estimation methods for highly nonlinear systems and measurements. These methods are popular for a number of reasons, including: first-order Taylor series expansions are no longer required to linearize the nonlinearities, a variety of different noise types can be overcome, more robust compared to the extended Kalman filter, and are not computationally heavy. In this paper, a comprehensive comparison is made of the following sigma-point Kalman filters: unscented Kalman filter (UKF), cubature Kalman filter (CKF), and the central difference Kalman filter (CDKF). A simulation based on a complex maneuvering road (an s-path) is used as a benchmark problem. This paper studies the response, stability, robustness, convergence, and computational complexity of the filters. Future work will look at implementing the methods on a robot built for experimentation.

9842-55, Session PSTue

Multi-Bernoulli filtering for initially unresolved targets in clutter

Qin Lu, Univ. of Connecticut (United States); Karl

Granström, Chalmers Univ. of Technology (Sweden); Yaakov Bar-Shalom, Peter K. Willett, Univ. of Connecticut (United States)

Multiple target tracking (MTT) is a challenging task that it aims to estimate the number of targets and their states in the presence of process noise, measurement noise and data association uncertainty.

This paper considers a special MTT problem characterized by additional complexity. In this problem, multiple targets are launched simultaneously in nearby locations at the same speed with slightly different directions. As the distances between the initial locations of these targets are smaller than the resolution of the sensor, this results in merged measurements, i.e., unresolved tracks at the very beginning. To deal with this problem, the recently proposed multi-Bernoulli (MB) filter is applied. Using a model for the merged measurements, simulation results with 2-D Cartesian measurements in clutter show that the initially unresolved tracks become resolved with MB filtering a few time steps after the measurements become resolved. Thus, the MB filter is capable of keeping track of the number of targets and their corresponding states when they are initially unresolved.

9842-56, Session PSTue

Low-cost attitude determination system using an extended Kalman filter (EKF) algorithm

Fernando Martignone Esteves, Georges Nehmetallah, Jandro Abot, The Catholic Univ. of America (United States)

Attitude determination is one of the most important subsystems in spacecraft, satellite or scientific balloons missions, since it can be combined with actuators to provide rate stabilization and pointing accuracy for payloads. In this paper, we discuss a low-cost attitude determination system with a precision in the order of arc-seconds that uses commercial off-the-shelf sensors, which includes a set of uncorrelated MEMS gyroscopes, two inclinometers and a magnetometer in a hierarchical manner, i.e., the faster and less precise sensors are updated by the slower, but more precise ones through an Extended Kalman Filter (EKF)-based data fusion algorithm. A revision of the EKF algorithm fundamentals and its implementation to the current application, along with an analysis of sensors noise, are presented. Finally, the results from the data fusion algorithm implementation are discussed in details.

9842-57, Session PSTue

ECG Holter with alert system and mobile application

Miguel A. Goenaga-Jimenez, Abigail C. Teron, Pedro A. Rivera-Hernandez, Univ. del Turabo (United States)

According to the Center for Disease Control and Prevention in United States around 610,000 people die of heart disease, that's 1 of every 4 deaths. For us, life is everything, and we should do something to maintain it. This paper propose the creation of a portable Electrocardiogram (ECG) Holter that will alert the user by detecting abnormal heart beats or any alteration at the moment of the occurrence. This device eliminate the unwanted frequencies and detect the heart arrhythmias such as: bradycardia, tachycardia using digital signal processing software. This is the first Holter monitor of this kind that will impact the society by giving an alert and awareness to the person that his/her heart is having electrical changes and will provide time for immediate medical assistance in order to prevent any serious complication or even death. The equipment is very simple, comfortable and small in size that fit the hand. It can be used at any time and any moment by placing three leads to the person's chest which is connected to an electronic circuit. The ECG data will be transmitted via Bluetooth to the memory of a selected mobile phone using a special application that will store the collected data for up to 24 hrs.

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9842-58, Session PSTue

Information fusion for the Gray Zone

Laurie H. Fenstermacher, Air Force Research Lab. (United States)

United States Special Operations Command (SOCOM) recently published a white paper describing the “Gray Zone”, security challenges characterized by “ambiguity about the nature of the conflict, opacity of the parties involved...competitive interactions among and within state and non-state actors that fall between the traditional war and peace duality.” Ambiguity and related uncertainty about actors, situations, relationships, and intent require new approaches to information collection, processing and fusion. General Votel, the current SOCOM commander, during a recent speech on “Operating in the Gray Zone” emphasized that it would be important to get left of the next crises and stated emphatically, “to do that we must understand the Human Domain.”

This understanding of the human domain must come from making meaning based on different perspectives, including the “emic” or first person/participant and “etic” or third person/observer perspectives. Much of the information currently collected and processed is etic. Incorporation and fusion with the emic perspective enables forecasting of behaviors/events and provides context for etic information (e.g., video). Gray zone challenges are perspective-dependent; for example, the conflict in Ukraine is interpreted quite differently by Russia, the US and Ukraine. Russia views it as war, necessitating aggressive action, the US views it as a security issue best dealt with by economic sanctions and diplomacy and the Ukraine views it as a threat to its sovereignty. General Otto in the Air Force ISR 2023 vision document stated that Air Force ISR is needed to anticipate strategic surprise, congruent. Anticipatory analysis enabling getting left of a crisis inherently requires a greater focus on information sources that elucidate the human environment an new methods that elucidate not only the “who’s” and “what’s”, but the “how’s and “why’s”. Methods that extract patterns and subtle cues useful for forecasting behaviors and events; for example discourse patterns related to social identity and integrative complexity. AFRL has been conducting research to enable analysts to understand the “emic” perspective based on discourse analysis methods and/or text analytics. Previous results demonstrated the value of fusion of emic and etic information in terms of improved accuracy (from 39% to 86%) in forecasting violent events. This paper will describe new work to extend this to anticipatory analysis in the gray zone.

9842-33, Session 7

A baseline for the scene understanding challenge problem

Gregory Arnold, Matrix Research Inc. (United States); Jared L. Culbertson, Todd Rovito, Air Force Research Lab. (United States); Euvondia Barto, Mary Ann Harrison, Stephen Walls, Matrix Research Inc. (United States)

A Scene Understanding Challenge Problem was released by AFRL at this conference in 2015 in response to DARPA’s Mathematics of Sensing, Exploitation, and Execution (MSEE) program. We consider a scene understanding system as a generalization of typical sensor exploitation systems where instead of performing a narrowly defined task (e.g., detect, track, classify, etc.), the system can perform general user-defined tasks specified in a query language.

That paper laid out the general challenges and methods for developing scene understanding performance models. This is an enormously challenging problem, so now AFRL is illustrating the methods with a baseline system primarily developed by UCLA during the MSEE program. This system will be publicly available for others to utilize, compare, and contrast with related methods.

This paper will further explain and provide insights into the challenges, illustrating them with examples from a publicly available data set. Our intent is that these tools will relieve the requirement for developing an entire

system and enable progress to occur by focusing on individual elements of the system. Finally, we will provide details as to how interested researchers may obtain the system and the data.

9842-34, Session 7

Real-time adaptation of spatial resolution for high-resolution space cameras

Ralf Reulke, Andreas Eckardt, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Due to the budget pressure we expect that dual-use satellite high-resolution imaging systems will be developed in the near future, which are able to provide data with 20 cm ground sample distance (GSD) or better. To open the door for selling the data under commercial aspects directly from the downlink of the satellite, it is necessary to re-sample it to e.g. 35 cm for the time being with reference to the NGA requirement. In case of a German satellite for example the re-sampling should be realized to 50 cm GSD because of the German image data distribution law.

The situation is similar when swinging out the satellite perpendicularly to its flight direction. The GSD is variable then with the angle to Nadir direction. The problem is the continuous adaptation to a predetermined GSD and the simultaneous prevention of aliasing errors due to incorrect aggregating of the pixels.

In this paper, there is a method proposed for adjusting the resolution adaptively according to given requirements to meet the MTF requirement on Nyquist as well as to real time processing capabilities in case of direct downlink mode. The opposite case, the up sampling or super-resolution, will be also shown as well as the influence on SNR and MTF will be affected by the proposed method.

9842-35, Session 7

Evaluation of the repeatability of a Landolt-C based automated sensor resolution assessment methodology

Alan R. Pinkus, Air Force Research Lab. (United States); David W. Dommert, Air Force Research Lab. (United States); Harry L. Task, Task Consulting (United States)

This paper describes a novel sensor resolution assessment chart and procedure based on the Landolt C. This automated resolution assessment procedure does not rely on human vision as the primary means of interpreting resolution chart results. Seven sensors across four different spectral bands and several geometric resolutions were assessed a total of five times each to determine the repeatability (confidence interval) for this automated procedure. The results are presented and compared with previous studies.

9842-36, Session 7

Neural network for IRST long-range low false alarm classifier real-time

Jorge Gimenez Romo, Jesus Gonzalez, TECNOBIT (Spain)

The IRST systems ability to work under clutter and structured scenarios resides in its capacity of reduce the FAR and maintain a reasonable detection thresholds.

The real time application of the traditional algorithms requires a huge amount of resources and penalizes the overall system performance.

A novel approach based upon neural network based classifier has been implemented and tested allowing a real system performance in typical

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operational scenarios with good tradeoff between sensitivity and false alarm rates.

This approach makes use of modeling and real data gathering for neural network training to tailor the design of the networks to the signatures characteristics. The joint operation of detection algorithms specifically designed to look for long range in a FPGA application in real time targets and classifier based neural network in a processor has demonstrated they performance and suitability for embedded application thanks to the HPEC boards.

9842-37, Session 7

Decision level fusion of neutron backscattering and microgravity for landmine detection

Mohamed Elkattan, Mostafa Rabei, Nuclear Materials Authority (Egypt); Ahmed M. Osman, Egyptian Atomic Energy Authority (Egypt) and Al-Jouf Univ. (Saudi Arabia)

Several sensor technologies have been considered for the detection of landmines. However, Current mine clearance technology predominantly relies on conventional sensors like metal detectors. The commonly used metal detector fails to detect plastic landmines that have almost no metal content, and offers limited discrimination ability versus nonmine objects.

Therefore, Because of the diverse physical properties that can be measured by different sensor technologies, multisensor fusion is an attractive approach to combine the strengths of individual sensors to create a sensing system that as a whole achieves better performance than any of the individual sensors.

A nuclear technique based on the measurement of thermal neutrons produced from the moderation of fast neutrons by elastic scattering with hydrogen nuclei is effective for distinguishing explosive material from other nonhydrogenous materials "i.e. metal". However, this technique cannot stand alone for distinguishing landmines.

In this paper, we present the potential advantage of using a multisensor system containing a nuclear technique represented by neutron backscattering system and geophysical technique that depends on the detection of density of the buried object represented by the gravimeter.

The proposed approach is tested using antitank and antipersonnel landmines, with metal and plastic "i.e. metal free" casing with different explosive content, buried at different depths. Also, we applied the algorithm on a buried steel cylinder, represents a common clutter in the real battlefield. The results are promising in discriminating the landmine signature from the surrounding clutter. Furthermore, we present a hardware implementation for the proposed approach using an inexpensive microcontroller chip.

9842-38, Session 7

Toward automated face detection in thermal and polarimetric thermal imagery

Christopher Gordon, The Catholic Univ. of America (United States) and U.S. Army Research Lab. (United States); Mark Acosta, U.S. Army Research Lab. (United States); Nathan Short, Booz Allen Hamilton, Inc. (United States); Shuowen Hu, Alex L. Chan, U.S. Army Research Lab. (United States)

Visible spectrum face detection software perform reliably under controlled lighting conditions; however, variations in illumination and application of cosmetics can distort the features used by face detectors, thereby decreasing detection performance. Thermal and polarimetric thermal facial imaging are relatively invariant to illumination and robust to the application of makeup, due to the measurement of emitted radiation versus reflected. The objective of this work was to evaluate a government off-the-shelf

wavelet based naïve-Bayes face detection algorithm and a commercial off-the-shelf Viola-Jones cascade face detection algorithm on face imagery acquired in different spectral bands. New classifiers were trained using the Viola-Jones cascade object detection framework with preprocessed facial imagery. Preprocessing using Difference of Gaussians (DoG) filtering reduces the modality gap between facial signatures across the different spectral bands, enabling more correlated histogram of oriented gradients (HOG) features to be extracted from the preprocessed thermal and visible face images. Since the availability of training data is much more limited in the thermal spectrum than in the visible spectrum, it is not feasible to train a robust multi-modal face detector using thermal imagery alone. A large training dataset was formed with both DoG filtered visible and thermal imagery, and then used to generate a custom trained Viola-Jones detector. A 40% increase in the true detection rate was achieved on a dataset consisting of 100 thermal images containing faces as compared to the pre-trained/baseline face detector. Insight gained in this research may enable the development of more robust multi-modal face detectors

9842-39, Session 8

Skin subspace color modeling for daytime and nighttime group activity recognition in confined operational spaces

Amir Shirkhodaie, Azin Poshtyar, Tennessee State Univ. (United States); Alex L. Chan, Shuowen Hu, U.S. Army Research Lab. (United States)

In many military and homeland security persistent surveillance applications, the capability to detect different skin colors accurately in varying observability and illumination conditions is a very valuable component in supporting the overall imagery analytics performance. One of those applications is In-Vehicle Group Activity (IVGA) recognition, in which significant changes in observability and illumination may occur during the course of a specific human group activity of interest. Most of the existing skin color detection algorithms, however, are unable to perform satisfactorily in confined operational spaces with partial observability and occultation, as well as under diverse and changing levels of illumination intensity, reflection, and diffraction. In this paper, we investigate the salient features of ten popular color spaces for skin subspace color modeling. More specifically, we examine the advantages and disadvantages of each of these color spaces, as well as the stability and suitability of their features in differentiating skin colors under various illumination conditions. The salient features of different color subspaces are methodically discussed and graphically presented. Furthermore, we present robust and adaptive skin color algorithms for skin color detection based on this analysis. Through examples, we demonstrate the efficiency and effectiveness of these new color skin detection algorithms and discuss their applicability for skin detection in IVGA recognition application using both real and synthetic imagery datasets.

9842-41, Session 8

Hand gesture recognition in confined spaces with partial observability and occultation constraints

Amir Shirkhodaie, Tennessee State Univ. (United States); Alex L. Chan, Shuowen Hu, U.S. Army Research Lab. (United States)

Human activity detection and recognition capabilities have broad applications for military and homeland security Persistent Surveillance Systems (PSS). These tasks are very complicated, however, especially when multiple persons are performing concurrent activities in confined spaces that impose significant obstruction, occultation, and observability uncertainty. In this paper, our primary contribution is to present a dedicated taxonomy and kinematic ontology that are developed for in-vehicle group human activities (IVGA). Secondly, we describe a set of hand-observable

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patterns that represents certain IVGA examples. Thirdly, we propose three classifiers for hand gesture recognition and compare their performance individually and jointly. Finally, we present a variant of Hidden Markov Model for Bayesian tracking, recognition, and annotation of hand motions, which enables spatiotemporal inference to human group activity perception and understanding. To validate our approach, synthetic (graphical data from virtual environment) and real physical environment video imagery are employed to verify the performance of these hand gesture classifiers, while measuring their efficiency and effectiveness based on the proposed Bayesian Hidden Markov Model for tracking and interpreting dynamic spatiotemporal IVGA scenarios.

9842-42, Session 8

In-vehicle group activity modeling and simulation in sensor-based virtual environment

Amir Shirkhodaie, Durga P. Telagamsetti, Azin Poshtyar, Tennessee State Univ. (United States); Alex L. Chan, Shuowen Hu, U.S. Army Research Lab. (United States)

Human group activity recognition is a very complex and challenging task, especially when we are dealing with In-Vehicle Group Activities (IVGA) that occur inside a vehicle with limited visual observability and often under severe occlusion. In this paper, we present an IRIS 3D Virtual Environment Simulation Model (VESM) that is uniquely developed for the modeling and simulation of interactive human group activities inside a vehicle. VESM enables accurate modeling of articulated animated characters or humanoids with human-like physical appearances and attributes, which are vivified by harmonious hand and postural gesture controls, realistic facial impression rendering, and deterministically choreographed behaviors. VESM facilitates the creation of interactive scenarios consisting of multiple humanoids with different personalities and intentions, which are capable of performing complicated human activities within the constrained space inside of a typical vehicle. Furthermore, we demonstrate the efficiency and effectiveness of VESM in terms of its capability to seamlessly generate synchronized, multi-source, and collocated imagery datasets of numerous IVGA scenarios, which are very useful for the training and testing of multi-source full motion video processing and annotation architectures. In this paper, we provide an effective technique for full motion video processing of such simulated scenarios under different operational contextual constraints.

9842-43, Session 8

PYRONES: Pyro-modelling and evacuation simulation system

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Structural fires continue to pose a great threat towards human life and property. Due to the complexity and non-deterministic characteristics of a building fire disaster, it is not a straightforward task to assess the effectiveness of fire protection measures embedded in the building design, planned evacuation strategies and potential modes of response for mitigating the fire's consequences. In addition, currently, there is a lack of means for realistically and accurately recreating the conditions of building fire disasters for purposes of training personnel in order to be sufficiently prepared when vis-a-vis with such an environment. The way that a fire propagates within a building, the diffusion of its volatile products, the behaviour of the occupants and the sustained injuries not only exhibit non-linear behaviours as individual phenomena, but are also entangled in a web

of co-dependencies to each other.

The PYRONES system has been developed to address all these aspects through a comprehensive approach that relies on accurate and realistic computer simulations of the individual phenomena and their interactions. PYRONES offers innovative tools and services to strategically targeted niches in two market domains. In the domain of building design and engineering, PYRONES is seamlessly integrated within existing engineering Building Information Modelling (BIM) workflows and serves as a building performance assessment platform, able to evaluate fire protection systems. On another front, PYRONES penetrates the building security management market, serving as a holistic training platform for stakeholders in evacuation strategy planning, fire-fighting, first response and building occupancy both at a Command & Control and at an individual trainee level.

9842-44, Session 8

People counting and re-identification using fusion of video camera and laser scanner

Bo Ling, Santiago Olivera, Migma Systems, Inc. (United States); Raj Wagley, Federal Transit Administration (United States)

We present a system for people counting and re-identification. This system can be used by transit and homeland security agencies. For the transit application, it can count the number of passengers boarding and alighting transit vehicles, and re-identify them. For homeland security, it can help the law enforcement agencies quickly identify suspects who enter and leave critical facilities at different entrances.

There are many issues an effective passenger counting and re-identification system must solve, which include passenger occlusion, reliable biometrics and statistical classification and fusion. Under FTA SBIR program, we have developed a system for transit passenger counting and re-identification using a laser scanner and video camera. Laser scanner has been successfully applied for outdoor people counting (Ling 2010, Olivera 2015) and video camera has demonstrated to be effective for people detection (Ling 2009, Ling 2007a and Ling 2006). Advanced image processing techniques (Ling 2007b) can classify targets using their signatures. Here the laser scanner is used to identify the locations of passenger's head and shoulder in imagery, which is often a challenging task in a crowded environment. It can also estimate passenger height without prior calibration, which is another challenging task. Various color models have been applied to form color signatures. Finally, using a statistical fusion and classification scheme, passengers are counted and re-identified.

We will also present test results using data collected at a transit bus and a commercial office building entrance. The results have shown that the system can achieve high accuracy in both counting and re-identification. References:

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9842-6, Session 9

Estimation error bounds for pixelated sensing

Christopher Kreucher, Integrity Applications, Inc. (United States); Kristine Bell, Metron, Inc. (United States)

This paper discusses the problem of estimating the state of an object using sensor measurements with special attention to “pixelization”. Pixelization refers to the fact that processed sensor data is typically provided to an estimation algorithm on a discrete grid of pixels. For example, Electro-Optical (EO) data is typically a 2D spatial grid, with resolution defined by the wavelength and lens diameter, among other things. Likewise, SAR data is typically processed to a range/cross-range grid with resolution defined by the bandwidth and the angle subtended during the collect.

Pixelization is not typically treated explicitly in detection, tracking, and estimation algorithms. This leads to sub-optimality in the estimator. In particular, pixelization imparts the following three interesting properties that are usually ignored: First, the measurement likelihood is uniform over the pixel, rather than Gaussian. In other words, when a pixel is detected, the implication is that we have learned only that the state of the target maps into that pixel. Second, point estimators are not unbiased unless the target happens to map to the center of the cell. Finally, because of the step-change in likelihood as cell boundaries are crossed, the log likelihood function is not differentiable, making analysis using the ordinary Cramer-Rao bound not possible.

This paper includes two contributions. First, we derive the minimum mean square error estimator (MMSE) for a generic pixelated sensor. Next, we compare the difference between this bound for the case where we elect to threshold the data before performing estimation (for the purposes of minimizing communication bandwidth, for example) to the case where the “raw” (i.e., non-thresholded) measurements can be used. We show a 4dB SNR “gain” when using raw measurements under one set of conditions.

9842-45, Session 9

WayGoo: A platform for geolocating and managing indoor and outdoor spaces

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WayGoo is a platform for Geolocating and Managing indoor and outdoor spaces and content with multidimensional indoor and outdoor Navigation and Guidance. Its main components are a Geographic Information System, a back-end server, front-end applications and a web-based Content Management System (CMS). It constitutes a fully integrated management system that creates repository constituted of database, content components and administrative data. wayGoo can connect to any third party database and event management data-source. The platform is secure as the data are only available through a Restful web service using https security protocol in conjunction with an API key used for authentication. To enhance users experience wayGoo makes the content available by extracting components out of the repository and constructing targeted applications.

The wayGoo platform supports geo-referencing of indoor and outdoor information and use of metadata. It also allows the use of existing information such as maps and databases. The platform enables planning through integration of content that is connected either spatially, temporally or contextually and provides immediate access to all spatial data through interfaces and interactive 2D and 3D representations. wayGoo constitutes a mean to document and preserve assets through computerized techniques and provides a system that enhances the protection of your space, people and guests when combined with wayGoo notification and alert system. It constitutes a strong marketing tool providing staff and visitors with an immersive tool for navigation in indoor spaces and allowing users to organize their agenda and to discover events through wayGoo event

scheduler and recommendation system. Furthermore, the wayGoo platform can be used in Security applications and event management, e.g. CBRNE incidents, man-made and natural disasters, etc., to document and geolocate information and sensor data (off line and real time) on one end, and offer navigation capabilities in indoor and outdoor spaces.

9842-46, Session 9

SYNAISTHISI: An IoT-powered smart visitor management and cognitive recommendations system

Giorgos Konstandinos Thanos, Christina Karafylli, Maria Karafylli, National Ctr. for Scientific Research Demokritos (Greece); Dimitris Zacharakis, National Ctr for Scientific Research Demokritos (Greece); Apostolis Papadimitriou, Kostantinos Dimitros, Dimitris M. Kyriazanos, Stelios C. A. Thomopoulos, National Ctr. for Scientific Research Demokritos (Greece)

Location-based and navigation services are really needed to help visitors and audience of big events, complex buildings, shopping malls, airports and large companies. However, the lack of GPS and proper mapping indoors usually renders location-based applications and services useless or simply not applicable in such environments.

SYNAISTHISI introduces a mobile application for smartphones which offers navigation capabilities outside and inside buildings and through multiple floor levels. The application comes together with a suite of helpful services, including personalised recommendations, visit/event management and a helpful search functionality in order to navigate to a specific location, event or person. As the user finds his way towards his destination, NFC-enabled checkpoints and bluetooth beacons assist him, while offering re-routing, check-in/out capabilities and useful information about ongoing meetings and nearby events. The application is supported by a backend GIS system, which can provide a broad and clear view to event organisers, campus managers and field personnel for purposes of event logistics, safety and security.

SYNAISTHISI system comes with plenty competitive advantages including (a) Seamless Navigation as users move between outdoor and indoor areas and different floor levels by using innovative routing algorithms, (b) connection to and powered by IoT platform, for localisation and real-time information feedback, (c) dynamic personalised recommendations based on user profile, location and real-time information provided by the IoT platform and (d) Indoor localisation without the need for expensive infrastructure and installations.

9842-47, Session 9

Factors influencing crime rates: an econometric analysis approach

John M. A. Bothos, Stelios C. A. Thomopoulos, National Ctr. for Scientific Research Demokritos (Greece)

The scope of the present study is to research the dynamics that determine the commission of crimes in the US society. Our study is part of a model we are developing to understand urban crime dynamics and to enhance citizens’ “perception of security” in large urban environments. The main targets of our research are to highlight dependence of crime rates on certain social and economic factors and basic elements of state anticrime policies. In conducting our research, we use as guides previous relevant studies on crime dependence, that were conducted trying to make similar quantitative analyses, regarding the dependence of crime on certain social and economic factors, using statistics and econometric modelling.

Our first approach consists of conceptual state space dynamic cross-sectional econometric models that incorporate a feedback loop that describes crime as a feedback process. In order to define dynamically the

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model variables, we use statistical analysis on crime records and on records about social and economic conditions and policing characteristics (like police force and policing results – crime arrests), to determine the influence of them, as independent variables, on crime, as a dependent variable of the model. The econometric models we apply in this first approach are an exponential log linear model and a logit model. In a second approach, we also try to study the evolution of violent crime through time in the US, independently as an autonomous social phenomenon, using autoregressive and moving average time-series econometric models. Our findings show that there are certain social and economic characteristics that affect the formation of crime rates in the US, either positively or negatively. Furthermore, the results of our time-series econometric modelling show that violent crime, viewed solely and independently as a social phenomenon, correlates with previous years crime rates and depends on the social and economic environment's conditions during previous years.

9842-48, Session 9

Covariance descriptor fusion for target detection

Huseyin Cukur, Hamidullah Binol, Abdullah Bal, Fatih Yavuz, Yildiz Technical Univ. (Turkey)

Target detection is one of the most important issues for military or civilian applications. In order to address such detection tasks, hyperspectral imaging sensors provide useful images data containing both spatial and spectral information. Target detection in the hyperspectral images has various challenging scenarios. To overcome these challenges, covariance descriptor presents many advantages for target detection problems. Detection performance of the conventional covariance descriptor technique can be improved by fusion methods. In this paper, hyperspectral bands are clustered according to inter-bands correlation. These correlation coefficients are used to assign weights to the each cluster. Target detection is then realized by fusion of covariance descriptor results based on weighted clusters. The proposed combination technique is denoted Covariance Descriptor Fusion (CDF). The performance of the CDF is evaluated by applying to hyperspectral imagery to detect man-made objects. The obtained results show that the CDF presents better performance than the conventional covariance descriptor.

9842-49, Session 9

Large-area object search and recovery using sector-based aerial acousto-optic scanning and reflection sensing

Monish R. Chatterjee, Salaheddeen Bugoffa, Univ. of Dayton (United States)

Acousto-optic beam steering has been used over the years for a variety of applications. The ability to steer laser beams at high frequencies (tens of MHz to a few GHz) electronically with high angular resolution (given Bragg angles in the mrad range) makes the Bragg cell an ideal device for angular and spatial steering. In this paper, we describe a simple sector-based angular scanning system intended to cover a large surface area in order to identify and spatially locate relatively small objects scattered over the terrain. The scanning system is modeled as a planar surface on the horizontal (YZ) plane, with an acousto-optic Bragg cell on board an aircraft operating in the XZ plane. The Bragg cell is excited by a chirped RF signal with frequency ramping from low-to-high or high-to-low. As the scanning beam reflects off the horizontal surface, a detector placed strategically at a suitable altitude picks up the reflected wave (shown to be effective over the scan range), and thereby evaluates the refractive index of the material at the location on the basis of the Fresnel coefficient. If the surface, say, is primarily sea water, then the detection is considered “negative” unless a material different from sea water is detected. Following each horizontal scan (about 300 m), the return path is a blank. The Bragg cell, mounted on a stepper motor, is then rotated in the horizontal plane by a small angle,

and the second scan run is carried out from the rotated position. Following this process with only L-to-R or R-to-L active scans and interleaving blanks, a “unit” circular sector is scanned with physical dimensions approximately 300 m x 80 m. Any “positive” refractive index returned by the sensor is stored in the system in terms of the spatial coordinates of the scanned point. The scanning scheme consists of a horizontal row (along Z), following which the aircraft is instructed to reverse direction of flight, and a new row can be carried out in the reverse direction along an incremental change in Y along the horizontal plane. In this manner, a series of horizontal scans covering an arbitrarily large surface area is carried out (technically over a few thousand square km). The scheme is shown in the numerical simulation to yield coordinate locations of any arbitrary distribution of non-sea-water materials distributed over the scanned surface. This scanning system may be useful in search and rescue applications over large surface areas (especially is unreachable directly on the surface itself) using the A-O scanning methodology on board an aircraft at an altitude of approximately 8 km.

9842-50, Session 9

Identical Synchronization of Chaotic Secure Communication Systems with Channel Induced Coherence Resonance

Amir M. Sepantaie, Nader M. Namazi, The Catholic Univ. of America (United States); Amir Sepantaie, Catholic Univ of America (United States)

In the recent years, it has been shown that both chaotic systems and stochastic systems display Stochastic Resonance (SR) behavior, which the system response is enhanced by the virtue of adding noise [1]. Based on the synergistic effect of parameter modulation and multiplicative noise, the identical synchronization of Lorenz chaotic attractor secure communication system is achieved, please see Figure 1. And the transmitted random binary message is retrieved [2]. This paper utilizes Matlab simulation, to present the applicability of SR to chaotic communication system, while retrieving the transmitted random binary message corrupted by the multiplicative noise.

References

- [1] Alexander Neiman, et al, “Synchronization of noisy systems by stochastic signals”, Physical Review E, Vol. 60, No. 1, July 1999.
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Summary

This paper utilizes an identically synchronized Lorenz chaotic drive/response system utilizing stochastic resonance phenomenon, to detect a transmitted random binary message. Using the Lorenz chaotic attractor to obscure the message, the transmission is passed through the channel corrupted by the multiplicative noise where the original binary random data is successfully retrieved. In particular, Chaotic Parameter Modulation is implemented in Matlab.

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9843-1, Session 1

Applying the Hough transform for detecting ground movers in synthetic aperture radar imagery

John Miller, Robert Linnehan, General Atomics Aeronautical Systems, Inc. (United States); Armin W. Doerry, Sandia National Labs. (United States)

This paper describes the impact of ground mover motion on moving targets in Synthetic Aperture Radar (SAR) and video SAR mode imagery. The observations provide an approach for optimizing algorithms that detect moving targets in SAR imagery. The video SAR mode provides a persistent view of a scene centered at the Motion Compensation Point (MCP). A target moving in the along-track direction or accelerating in the cross-track direction generates a ridge of high Radar Cross Section (RCS). The direction of the ridge and its location provide information about the direction of motion and the location of the associated target. Detecting the ridge provides a complementary method to detect the shadow of the target itself. The ridge associated with the moving target is often a linear feature. This paper describes a method of applying the Hough transform, which reliably detects linear features for detecting a ridge of high RCS. The paper presents a method for reducing false alarms by discriminating between a ridge associated with a moving target and a series of co-linear point targets. Co-linear point targets that may cause a false alarm include a series of bushes, trees, boulders, or manmade objects. Synthetic data provides target characteristics for a radar scenario that lend themselves to detect a moving target. The paper presents 2011–2015 flight data collected by General Atomics Aeronautical Systems, Inc. (GA-ASI).

9843-3, Session 1

Multi-static MIMO along track interferometry (ATI)

Chad Knight, Space Dynamics Lab. (United States); Ross W. Deming, Solid State Scientific Corp. (United States)

Along track interferometry (ATI) processing has received extensive attention for its multi-modal capabilities. ATI has the ability to generate high-quality synthetic aperture radar (SAR) images and concurrently detect and estimate the positions of ground moving target indicators (GMTI) with moderate processing resources. This paper focuses on the benefits of a multistatic multiple input multiple output (MIMO) system configuration. The paper specifically analyzes a system configuration that employs two simultaneous transmit phase centers and four receive phase centers. The two transmit phase centers use a ping-pong configuration to provide the multistatic behavior, which improves the minimum detectable velocity (MDV). The transmit phase centers switch back and forth between an up and down linear frequency modulated (LFM) waveform every other pulse. The four receive apertures initially employ diverse (sparse and dense) aperture configurations. The potential pros and cons of such configurations are considered initially from a theoretical perspective and then via simulation. For example, a sparse aperture employing a multistatic approach can generate a dense antenna array, while MIMO can result in improved geo-location estimation. Simulation allows for a more complete understanding of the trade space, particularly when realistic errors are included (channel imbalance, antenna mismatch, etc.). Finally, actual results are collected with the Space Dynamics Laboratory's FlexSAR system in a multistatic MIMO (2 transmit, 4 receive) configuration. The collected FlexSAR data contains controlled targets including vehicles and dismounts so that actual performance metrics can be computed. The FlexSAR results are presented

and analyzed in this paper. Diverse processing considerations are also discussed due to their implications regarding target detectability and geo-location estimation accuracy.

9843-4, Session 1

Signature predictions of surface targets undergoing braking maneuvers in squinted spotlight synthetic aperture radar imagery

David A. Garren, Naval Postgraduate School (United States)

This paper investigates methodologies for predicting the smear signatures in squinted spotlight synthetic aperture radar (SAR) imagery collections due to surface targets that are undergoing braking maneuvers. Previous analysis [1] considered the case of broadside collection geometries. Analytic computation of a power series expansion [1, 2, 3] is used to compute a generic expression for the down-range and cross-range components of the predicted mover signature. In addition, recent analysis [2] presents capabilities for predicting the full signature shape, including the smear width and interference effects. The current investigations focus specifically on the effects of squinted collection geometries upon braking targets signatures.

Studies of moving target signatures in SAR have revealed that the primary component of the smearing lies in the radar cross-range direction. However, there is also a slight component in the radar down-range direction, yielding moving target signatures that frequently have a curved or bowed shape. In fact, the details of the target motion and the radar collection contribute to the resulting location, extent, and shape of the resulting smear. One of the elements of the smear shape is whether the signature is curved upwards like a bowl towards near range or curved downwards like a hill towards far range.

The analytic expressions for the signature contours of braking targets are considered for squinted SAR collections. The braking motion of a surface target introduces additional terms into the signature equations that can induce significant effects upon the resulting smear. Numerous examples are presented to demonstrate that these signature prediction equations yield excellent agreement with simulated SAR smears. These general signature prediction equations can provide an effective tool in predicting the shape, extent, and location of signature smears due to braking surface targets for squinted SAR collection geometries.

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9843-5, Session 1

Analytical SAR-GMTI principles

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This paper provides analytical principles to relate the signature of a moving target to parameters in a SAR system. Our objective is to establish analytical tools that could predict the shift and smearing of a moving target in a subaperture SAR image. Hence, a user could identify the system parameters such as the coherent processing interval for a subaperture that is suitable to localize the signature of a moving target for detection, tracking and geolocating the moving target. The paper begins by outlining two well-known SAR data collection methods to detect moving targets. One uses a scanning beam in the azimuth domain with a relatively high PRF to separate the moving targets and the stationary background (clutter); this is also known as Doppler Beam Sharpening. The other scheme uses two receivers along the track to null the clutter and, thus, provide GMTI. We also present results on implementing our SAR-GMTI analytical principles for the anticipated shift and smearing of a moving target in a simulated code. The code would provide a tool for the user to change the SAR system and moving target parameters, and predict the properties of a moving target signature in a subaperture SAR image for a scene that is composed of both stationary and moving targets. Hence, the SAR simulation and imaging code could be used to demonstrate the validity and accuracy of the above analytical principles to predict the properties of a moving target signature in a subaperture SAR image.

9843-6, Session 1

Performance evaluation of SAR/GMTI algorithms

Wendy L. Garber, Matrix Research Inc. (United States); Uttam Kumar Majumder, Michael J. Minardi, Air Force Research Lab. (United States); William Pierson, Matrix Research Inc. (United States)

No Abstract Available

9843-7, Session 1

Ground moving target processing for tracking selected targets

Howard E. Nichols, BAE Systems (United States); Uttam K. Majumder, Air Force Research Lab. (United States); Gregory J. Owirka, BAE Systems (United States)

BAE Systems has developed a baseline real-time selected targets (ST) tracking capability that successfully tracked multiple civilian vehicles in real-world traffic conditions within challenging semi-urban clutter. Recent enhancements to the baseline capability include a ST track preprocessor, improvements to the system-level design, reverse ST tracking, and a wide-area tracking mode. The advantages of the track preprocessor are two-fold: improved ST tracking performance at intersections and reduced computational burden when compared to traditional MHT algorithms.

9843-8, Session 1

Statistical performance analysis for GMTI using ATI phase distribution

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(United States); Uttam K. Majumder, Michael J. Minardi, Alexander Boytim, Air Force Research Lab. (United States)

Synthetic aperture radar (SAR) imaging is often used to image an area using airborne platforms that generate a large aperture by virtue of the platform motion, and ground moving target indication (GMTI) is a logical extension of that asset to detect movers in the scene and possibly geolocate them. Large apertures generate a large synthetic array providing fine cross-range resolution, and together with wide bandwidth waveforms that provide high range resolution, fine ground resolution images can be generated. SAR algorithms make use of coherent phase compensation from various pulses for focusing and the technique works quite well for scenes containing stationary scattering centers. When moving targets are present, their images are smeared and shifted due to the motion component, and to take advantage of this shift, nearby plates are used to perform multiple SAR images and by employing along track interferometry (ATI), they generate a phase distribution that can be used to detect the presence of moving targets.

This paper examines the distribution of the phase variable used in ATI for zero mean Complex Gaussian clutter/target data, and uses the results to address the target in clutter problem as a hypothesis testing problem to compute the probability of detection vs. false alarm as a function of target to clutter power ratio and target velocity under various terrain conditions. This provides a platform to compare the performance under various conditions for target motion, clutter type and power.

9843-9, Session 1

Agile waveforms for joint SAR-GMTI processing

Steven Jaroszewski, Technology Service Corp. (United States); Uttam K. Majumder, Air Force Research Lab. (United States)

No Abstract Available

9843-10, Session 1

Joint SAR/GMTI waveforms for agile radar systems

Ronald L. Dilsavor, Systems & Technology Research (United States); Uttam K. Majumder, Air Force Research Lab. (United States)

No Abstract Available

9843-11, Session 1

The development of advanced spread spectrum LFM waveforms for enhanced SAR and GMTI

John C. Kirk, Goleta Star, LLC (United States); Uttam K. Majumder, Air Force Research Lab. (United States); Scott Darden, Goleta Star, LLC (United States); Mark R. Bell, Purdue Univ. (United States)

No Abstract Available

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9843-12, Session 1

Ambiguity free joint SAR and GMTI with novel Doppler-quantized wave function

Marcos Mergamo, Intelligent Automation, Inc. (United States); Uttam K. Majumder, Air Force Research Lab. (United States)

No Abstract Available

9843-13, Session 2

Performance of several imaging methodologies in extraction of secondary SAR slow-time signals

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In Synthetic Aperture Radar (SAR) processing the resultant image gives not only the complex reflectivity of image points but also their inter-dependency with respect to time and observation angle. In range or fast-time changes in reflectivity are unexpectedly slight, however, in observation azimuth or slow-time the reflectivity pattern, movement or vibration of strong scatterers is also revealed. These azimuth signals can subsequently reveal pass to pass changes over inter-pass time or observation elevation. Key to extracting the slow-time signals is the imaging method involved. If imaging preserves the phase function across azimuth then the time or aspect phenomenon riding on top of the phase can be extracted. In other cases the phase is distorted or overridden by imaging artifacts. The choice of imaging method is fundamental determining not only image resolution but also the fidelity with which secondary signals along the aperture can be determined. The achievable envelope of secondary signal amplitude, bandwidth and resolution are determined here for several imaging methods including the fraction Fourier transform, deramping, range-doppler, chirp scaling, wave-front and matched filtering methods. Method of extracting these secondary azimuth dependent signals are developed and results are presented for airborne and orbital scenarios. Naturally, sampling speed, pulse spacing and the flight path in slow-time enclose the largest potential envelope of measurable secondary signals while the selection of imaging method restricts the potential measurable signals to a smaller envelope. Sampling restrictions and bounds on range migration curvature for different imaging methods are also investigated.

9843-14, Session 2

Passive imaging of ground moving targets based on sparse and low-rank structures

Eric Mason, Birsen Yazici, Rensselaer Polytechnic Institute (United States)

We present a method for passive imaging of ground moving targets using sparsely distributed stationary receivers that rely on sources of opportunity. Our method performs a scaled correlation between measurements at different receivers.

This correlation process results in the unknown scene reflectivity -and-velocity distribution mapped to a rank-one positive semi-definite operator. Thus, we pose image formation as a low-rank matrix recovery problem, and use the trace operator as convex heuristic.

Furthermore, since a rigid-body target can only move at a fixed velocity, we include a L^1 -norm regulation term to promote sparsity in the velocity space.

We solve the problem by forming the augmented Lagrangian and use the alternating direction of multiplier method.

Our method improves upon existing approaches by being able to image scenes with extended and/or densely distributed moving point targets. Additionally, we recover the target velocity as well as the scene reflectivity. Existing approaches rely on the underlying assumption that the scene of interest includes a single point target.

One such method is developed in [2]. This method forms a stack of images using filtered back projection to form images for different hypothesized velocities.

Another approach is developed in a statistical framework.

This approach poses the problem as a binary hypothesis test and performs image formation using a generalized likelihood ratio test [3,1].

Capitalizing on the low-rank structure induced by correlation of measurements has been used for imaging of stationary targets in [4]. Current work extends [4] to passive imaging of moving targets.

We demonstrate the performance of our proposed method with numerical simulations.

We use for our simulations a signal that is relatively wideband with bandwidth comparable to sources of opportunity such as DVB-T or WiMAX signals.

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9843-15, Session 2

Kronecker PCA-based robust SAR STAP

Kristjan H. Greenewald, Univ. of Michigan (United States); Edmund G. Zelnio, Air Force Research Lab. (United States); Alfred O. Hero III, Univ. of Michigan (United States)

This paper considers a spatio-temporal decomposition for the detection of moving targets in multiantenna synthetic aperture radar (SAR). As a high resolution radar imaging modality, SAR detects and localizes non-moving targets accurately, giving it an advantage over lower resolution GMTI radars. Moving target detection is more challenging due to target smearing and masking by clutter. Space-time adaptive processing (STAP) is often used to remove the stationary clutter and enhance the moving targets, making it possible to detect them more reliably. In this work, it is shown that the performance of STAP can be improved by modeling the clutter covariance as a space vs. time Kronecker product with low rank factors. We propose a low-rank Kronecker product covariance estimation algorithm (LR-Kron) to estimate the clutter covariance and develop an efficient and scalable implementation of it. This proposed covariance estimate is used to form a space-time separable clutter cancellation filter. The proposed method is theoretically guaranteed to provide orders of magnitude reduction in the required number of training samples, enabling training with more relevant and "up to date" samples. Additionally, we demonstrate both theoretically and experimentally the improved robustness of our approach to corruption of the training data, to inhomogeneous clutter, and to changes in clutter distribution. Simulation results and experiments using a GPU implementation of our algorithm on the multichannel Gotcha SAR dataset are presented that confirm the advantages of our approach relative to existing moving target detection techniques in a wide variety of settings.

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9843-29, Session 2

The two-stage bistatic backprojection algorithm

Davis Gilton, Wright State Research Institute (United States); Michael J Minardi, Air Force Research Lab (United States)

No Abstract Available

9843-16, Session 3

ATR performance modeling concepts

Timothy D. Ross, Matrix Research Inc. (United States); Hyatt B. Baker, Air Force Research Lab. (United States); Adam R. Nolan, Etegent Technologies, Ltd. (United States); Ryan E McGinnis, Matrix Research Inc. (United States); Christopher R. Paulson, Air Force Research Lab. (United States)

Performance models are needed for automatic target recognition (ATR) development and use. ATRs consume sensor data and produce decisions about the scene observed. ATR performance models (APMs) on the other hand consume operating conditions (OCs) and produce probabilities about what the ATR will produce. APMs are needed for many modeling roles of many kinds of ATRs (each with different sensing modality and exploitation functionality combinations); moreover, there are different approaches to constructing the APMs. Therefore, although many APMs have been developed, there is rarely one that fits a particular need. Clarified APM concepts may allow us to recognize new uses of existing APMs and identify new APM technologies and components that better support coverage of the needed APMs. The concepts begin with thinking of ATRs as mapping OCs of the real scene (including the sensor data) to reports. An APM is then a mapping from explicit quantized OCs (represented with less resolution than the real OCs) and latent OC distributions to report distributions. The roles of APMs can be distinguished by the explicit OCs they consume. APMs used in simulations consume the true state that the ATR is attempting to report. APMs used online with the exploitation consume the sensor signal and derivatives, such as match scores. APMs used in sensor management consume neither of those, but estimate performance from other OCs. This paper will summarize the major building blocks for APMs, including knowledge sources, OC models, look-up tables, analytical and learned mappings, and tools for signal synthesis and exploitation.

9843-17, Session 3

Vehicle detection in wide-angle SAR

Kerry E. Dungan, Wright State Research Institute (United States)

This study investigates vehicle detection performance for an airborne video SAR over increasingly wide collection angles. Each frame of the video SAR is generated using a single coherent aperture or a non-coherent sum of multiple coherent apertures. The resulting frames may contain information for as little as 3 degrees or as much as 90 degrees of azimuth. The full video SAR accumulates these frames at an azimuth interval in degrees over a 360-degree aspect with respect to the scene under test. If the interval is smaller than the aperture of the frame, then the aspect of each frame overlaps. Using a parameterized video SAR generation, it is possible to see the effects of detection on various frame generation methods and apertures. A cell-averaging CFAR detection algorithm is applied to each frame, searching for vehicles. The resulting detection performance is reported for various frame sizes as well as the accumulation of multiple frames. Furthermore, detection performance is affected by the pose of the vehicles relative to the sensor. Results show that an increase in the azimuth extent

of the video SAR improves detection performance. With some imaging methods, a larger azimuth extent helps to suppress background speckle. Also, a larger azimuth extent improves the chances of imaging a vehicle from a cardinal angle with a larger radar cross section.

9843-18, Session 3

Radio frequency synthetic target signature generation to support deep learning algorithms

John W. Nehrbass, Wright State Research Institute (United States); Uttam K. Majumder, Edmund G. Zelnio, Air Force Research Lab. (United States)

No Abstract Available

9843-19, Session 3

SAR scattering surface orientation estimation

Christopher R. Paulson, Air Force Research Lab. (United States); Bassirou Seck, Wright State Univ. (United States); James Coleman, South Carolina State Univ. (United States); Edmund G. Zelnio, Air Force Research Lab. (United States)

No Abstract Available

9843-20, Session 3

Embedded reconfigurable IP core for the frequency control of synthetic aperture radars

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the development of an embedded reconfigurable IP core for providing sufficient frequency control signals to a large range of modern reconfigurable Synthetic Aperture RADARs operating in various frequency bands. The core can receive data through the available GPS receiver interface for accurate UT time and global position determination. An independent real-time clock scheme with smooth clock auto-recovery is operated internally, in case of loss of GPS synchronization. Analogue master oscillators, phase-locked loops and other hardwired temperature sensitive clocking circuits can safely be replaced. Accurate, low-jitter and low fan-out reference waveforms up to 1 GHz have been tested for oversampling receiver architectures. The system allows connections to array of reconfigurable or reprogrammable receivers for in-situ data time-stamping. Additional programmable GPS-referenced periodic signal processing products are available for SARs, designed to implement a variable integration time scheme. Aperiodic control and interrupt signals are generated using a variety of modes. The core is designed to be reconfigured, programmed and readback by a host PC using either a direct or through a network hub full-duplex fast Ethernet connection or, alternatively, through a USB 2.0 interface.

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9843-21, Session 4

Modeling terrain elevation and reflectivity from digital terrain elevation data and land use/land cover data

Ryan J. Shaver, Michael A. Saville, Wright State Univ. (United States); James Park, Air Force Research Lab. (United States)

An algorithm is presented for synthesizing mathematical models of terrain elevation and reflectivity from digital elevation terrain data (DTED) and land use/land cover data (LUCD). Assuming the DTED and LUCD have spatial intersection, it is straightforward to linearly interpolate each set to a common set of coordinates in the intersection. However, DTED is continuous and LUCD is not typically which results in different and sometimes contrasting sampling requirements of the intersecting region. This study evaluates different similarity measures used to assess the quality of resampling DTED and LUCD data for the purpose of building elevation and reflectivity profiles for physical optics calculation of site-specific radar clutter. Examples of the algorithm are presented for clutter scene generation with the Raider Tracer prediction tool.

9843-22, Session 4

Convolutional neural networks for synthetic aperture radar classification

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For electro-optical object recognition, convolutional neural networks (CNNs) are the state-of-the-art. CNNs are able to learned meaningful features used for classification. However, their application to synthetic aperture radar (SAR) has been limited. In this work we experimented with various CNN architectures on the MSTAR SAR dataset.

As the input to the CNN we considered using only the magnitude (1 channel), and the magnitude and phase (2 channels) of the SAR imagery.

We used the deep learning toolboxes CAFFE and Torch7 depending on the number of input channels, and we run our experiments on the Amazon cloud. Our experiments surpassed the state-of-the-art by 11% in recognition performance.

9843-23, Session 4

Modern approaches in deep learning for SAR ATR

Michael Wilmanski, Christopher Kreucher, Jim Lauer, Integrity Applications, Inc. (United States)

Recent computational and algorithmic advances have brought increased attention to a new class of signal processing algorithms referred to Deep Neural Networks (DNNs). DNNs, as discussed here, are a technique where a set of labeled examples is used to estimate (“learn”) weights corresponding to a classification surface. As such, they have connections to more conventional supervised learning approaches like support vector machines and regression. Deep convolutional neural networks (CNNs) are a type of net that employs convolutional kernels to exploit image-like structure in the input data and have shown to have world-class performance in image recognition and retrieval applications.

A natural application of such networks is to the synthetic aperture radar (SAR) automatic target recognition (ATR) problem. The SAR ATR problem is analogous to the image classification problem, wherein a large database of labeled images exists and the requirement is to label a new unknown sample. The SAR modality has a number of characteristics that distinguish

it from natural imagery, most prominently the fact that the data includes both magnitude and phase, but also the large dynamic range and the fact that object signatures are not rotation invariant. These features may provide additional richness that the network can exploit to its advantage.

The Moving and Stationary Target Acquisition and Recognition (MSTAR) database is a publicly released collection of ten military vehicles taken from a number of aspect angles and provides a standard, common dataset that ATR researchers have used extensively for algorithm development. Most previous approaches to SAR-based ATR in the literature are based on template matching. This approach involves creating a set of templates for each object type, then comparing the correlation between each class template and a test image. While other researchers have proposed using neural networks or SVMs for SAR ATR, Morgan [SPIE DSS, 2015] appears to be the first to publish results of a deep convolutional neural network for this application.

The present work focuses on new approaches to network training drawn from the most modern techniques in deep learning and image processing literature. Training the network is a critical step in applying these techniques – the main goal is to prevent “overfitting”, a pathology where the network simply memorizes the training set and then performs poorly on sequestered data, while achieving a classification surface that ably separates the training set. In this paper, we show that the combination of several modern techniques leads to significant classification performance improvement on the MSTAR dataset. In particular, while Morgan was remarkably able to achieve nearly 93% correct classification on the test set, we show training approaches that achieve nearly 98% correct classification.

9843-24, Session 4

The empirical performance of multinomial pattern matching to ideal point response variations

Matthew S. Horvath, Brian D. Rigling, Wright State Univ. (United States)

Here we investigate the performance of the MPM algorithm for SAR ATR when the IPR is varied. The IPR is equivalent to the image resolution of SAR imagery and is inversely proportional to the sampled K-space extent of a scene. In addition to the mainlobe broadening effects there are also algorithm specific concerns related to the number of images that can be obtained from a scene. The trade-off is in coherently processing an aperture to form a high resolution image versus non-coherently processing it to yield more looks at an albeit lower resolution. Empirical performance results are presented utilizing the AFRL civilian vehicle dataset showing the performance loss incurred when the scene is non-coherently processed to yield multiple look versus coherent processing to form a single high resolution image.

9843-25, Session 4

Multistatic passive polarimetric reconstruction via low-rank tensor recovery

Il-Young Son, Birsan Yazici, Rensselaer Polytechnic Institute (United States)

In this work, we present a novel method for reconstructing, simultaneously, the reflectivity and polarimetric states of stationary targets using measurements obtained from spatially sparse distribution of receivers exhibiting polarimetric diversity and a single source of opportunity. Our method begins by first developing a forward model based on pairwise correlation between receivers. The polarimetric data model is based on dipole model of the targets as developed in [1]. The measurements at each receiver consist of a set of two orthogonally polarized data. The pairwise correlation is then equal to the Kronecker product between two two-dimensional vectors resulting in a four-dimensional vector valued function.

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This leads to a forward operator that operates on an unknown rank 1 integral operator with matrix-valued kernel. After discretization, this unknown integral operator can be modeled as an unknown 4th order tensor. Our objective is to reconstruct this unknown tensor from the set of correlated data. We approach this from an optimization framework, exploiting known structure of the unknown tensor. Namely, we show that the tensor has low n-rank. We adapt recent works on low n-rank tensor recovery technique to solve our problem [2].

This work improves on our previous work in [1] by relaxing the single point target assumption. Hence, this method can reconstruct extended targets and spatially clustered multiple point targets. To the best of our knowledge, no other work has considered polarimetry in passive radar setting.

In the final paper, we will present our theory in detail and a set of numerical simulations to demonstrate the performance of our proposed method in reconstructing both the reflectivity and polarimetric states of the targets.

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9843-26, Session 4

Height reconstruction using differential layover for SAR imagery

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Interferometric synthetic aperture radar (InSAR) is a well-known technology for retrieving ground topography information. Conventional interferometric processing is based on the phase difference between the two data sets collected from different vantage points. We are interested in recovering the ground topography using differential layover information. Layover is a positioning error in SAR images due to incorrect height information. Differential layover refers to the difference in positioning errors due to incorrect height information between two SAR images. We analyze and establish a quantitative relationship between the differential layover and the height of scatterers. We use this relationship to develop a new method for height estimation using differential layover. The differential layover has been discussed in [1] for image registration. The height estimation using differential layover appeared in [2-4] in the context of range-Doppler based imaging. However, these results are for limited monostatic or bistatic [2-4] straight linear SAR geometries and require certain assumptions or approximations, such as the far-field approximation and planar wavefronts and small scene assumptions. Based on a quantitative layover analysis, we provide explicit differential layover expressions between two SAR images acquired from different vantage points. We present an explicit height estimation formula exploiting the differential layover. Our method is applicable to arbitrary imaging geometries and antenna trajectories. In the final paper, we will outline the theory in detail and present numerical simulations to demonstrate our method. While our analysis focuses on the height estimation in conventional SAR imaging, the approach can be applied to other SAR modalities as well.

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9843-30, Session 4

Rapid prediction method

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9844-2, Session 1

Restoration of randomly sampled blurred images

Arthur Forman, Abhijit Mahalanobis, Lockheed Martin Missiles and Fire Control (United States)

We describe a technique for restoring randomly sampled blurred image by minimizing a weighted L2 norm criterion. If the power spectrum of the image (or that of the class to which the image belongs) is known, then this information can be used to weight the spatial frequencies that are expected to be dominant in the solution. However, we observed that weighting the spatial frequencies in a $1/f$ fashion produced very comparable results. The resulting reconstructed face images are visually comparable to those obtained using the exact power spectrum of the image. Thus visually meaningful reconstructions of a randomly sampled image can be obtained under very general conditions by minimizing the L2 norm with $1/f$ weighting.

9844-3, Session 1

A robust close-range photogrammetric target extraction algorithm for size and type variant targets

Kofi Nyarko, Clayton Thomas, Morgan State Univ. (United States); Gilbert Torres, Naval Air Systems Command (United States)

The Photo-G program conducted by Naval Air Systems Command at the Atlantic Test Range in Patuxent River, Maryland, uses photogrammetric analysis of large amounts of real-world imagery to characterize the motion of objects in a 3-D scene. Current approaches involve several independent processes including target acquisition, target identification, 2-D tracking of image features, and 3-D kinematic state estimation. Each process has its own inherent complications and corresponding degrees of both human intervention and computational complexity. One approach being explored for automated target acquisition relies on exploiting the pixel intensity distributions of photogrammetric targets, which tend to be patterns with bimodal intensity distributions. The bimodal distribution partitioning algorithm utilizes this distribution to automatically deconstruct a video frame into regions of interest (ROI) that are merged and expanded to target boundaries, from which ROI centroids are extracted to mark target acquisition points. This process has proved to be scale, position and orientation invariant, as well as fairly insensitive to global uniform intensity disparities.

9844-4, Session 1

A fast automatic target detection method for detecting ships in infrared scenes

Kemal Arda Özertem, Roketsan A.S. (Turkey)

Automatic target detection in infrared scenes is a vital task for many application areas like defence, security and border surveillance. For anti-ship missiles, having a fast and robust ship detection algorithm is crucial for overall system performance. In this paper, a straight forward ship detection method is introduced for infrared scenes. Firstly, morphological grayscale reconstruction is applied to input image and automatic thresholding is done to suppressed image. For the segmentation step, connected component analysis is employed to obtain target candidate regions. At this point, it can be realized that there is a loss of detail especially in vertical direction. To

deal with this drawback, another automatic thresholding is done to original image, but only to target candidate regions. Finally, two detection results are fused to obtain final detection result. For the post-processing stage, two different methods are used. Firstly, noisy detection results are rejected with respect to target size. Secondly, the waterline is detected by using Hough Transform and the detection results, which are located above the waterline with a small margin, are rejected. The performance of overall methodology is tested with real world infrared test data.

9844-5, Session 1

Evaluation of pre-processing, thresholding and post-processing steps for very small target detection in infrared images

Ozan Yardimci, Roketsan Roket Sanayii ve Ticaret A.S. (Turkey); İlkyay Ulusoy Parnas, Middle East Technical Univ. (Turkey)

With the rapid development of digital image acquisition and processing technology, target detection has become applicable to civilian and military fields such as surveillance in public area, guidance in weapon system, automatic control in platforms and border security. Considering the current applications target detection in images is a very popular technology.

Target detection is usually used as a part of a system. After detecting target, it is expected that the procedure will continue with target recognition or target tracking. Target detection can be performed automatically and/or manually depending on the system requirements. In some systems, the operator can choose the target to be tracked or recognized manually. For example, some tracking systems are used to calculate movement of a player in football matches. In this kind of system, manual target detection algorithms are used. Furthermore, identification of criminals is carried out using manual detection algorithms. However, in some systems, the operator cannot interfere with the system. For example, automatic target detection (ATD) algorithms are used in speed control systems. Another important use of ATD is in missile technology. In particular, in long range or high speed missile systems, ATD is required.

There are challenges in ATD which create difficulties in the process. The first problem is the highly cluttered backgrounds which increases the false alarm rate (FAR). If clutter is regarded as noise, a cluttered background decreases the signal-to-noise ratio (SNR). There are several components in the ground, sea and air that constitute background clutter. For the ground clutter, these are forests and buildings etc. For the sea clutter, they are sun glint, sun, clouds and land etc. For the air environment, sun and clouds are types of background clutter. Distinguishing the target from this background clutter is a huge problem and much work has been undertaken to manage this problem. A further problem is the size of the target. For example, in military applications, to gain more time to eliminate the possibility of threat, targets should be detected from long distances. This means detecting the targets when they are very small, even when they have similar characteristics as noise. This is a very challenging problem and the absence of a specific shape or structure of the target makes the job more difficult.

Pre-processing, thresholding and post-processing stages are very important especially for very small target detection from infrared images. The effects of these stages to the final detection performance are measured in this study. Various methods for each stage are compared based on the final detection performance, which is defined by precision and recall values. Among various methods, the best method for each stage is selected and proved. For the pre-processing stage, local block based methods perform the best, nearly for all thresholding methods. The best thresholding method is chosen as the one, which does not need any user defined parameter. Finally, the post processing method, which is suitable for the best performing pre-processing and thresholding methods is selected.

9844-6, Session 2

Uniform smooth filtering approach for fast template matching

Bingcheng Li, Lockheed Martin Systems Integration-Owego (United States)

Template matching, finding matches in images to given templates, has many applications in image processing, computer vision and pattern recognition. In this paper, we propose an image smooth filtering theory to implement SSD (sum of square difference) template matching and show that the proposed method is faster than the known techniques including FFT and two stage techniques.

Many researches have been conducted to develop fast template matching techniques in the last four decades. Template matching techniques are divided into two types: Fast Fourier Transform based techniques and spatial based methods. Our proposed method is a spatial based approach where template matching is operated directly on images. First, we introduce uniform smooth filtering approach for template matching, and prove that the SSD values for uniformly smoothed images and templates are smaller than the truth SSD. Therefore, if the smoothed SSD is over a selected threshold, the truth SSD must be over this threshold. We also show that as the mask size of uniform smooth filtering increases, the SSD at a given point decreases monotonically. This means that we can skip the SSD computation at a point if its smoothed SSD is over the selected threshold. Thus, we can use smoothed SSD to exclude unmatched points and reduce the computational complexity of template matching.

Then we propose hierarchical decomposition of templates in which sizes for top smooth filtering masks are equal to template sizes while sizes for bottoms are 1 (no smoothing). From this hierarchical structure, we propose a multiple stage unmatched point exclusion technique to implement template matching. The first stage applies smooth filtering with a smoothing size equal to the template size. The smoothed SSD can be computed with only one addition and one multiplication for a point in images. If this SSD is larger than a threshold, we move to the next image point. If not, we start the stage 2 SSD computation. In the stage 2, the smooth filtering size is $\frac{1}{2}$ of the stage 1 mask sizes. This process continues until we reach the bottom where no smoothing is applied and the truth SSD is computed. We conduct experiments on the computational cost of the proposed approach and demonstrate that at the top of this hierarchical structure, the SSD computation involves every pixel, however we only need very small number of computations: one addition and one multiplication. On the other hand, at the bottom, the SSD computation cost is very high, however we only need to compute the SSD in very small number of locations in images. This makes the new method be very efficient for template matching.

Next, in order to reduce the computational cost, we introduce the integral approach to implement uniform smooth filtering. We show that after we do integrals (summation), the uniform smooth filtering only needs 3 additions and the computational cost is constant when smooth filtering mask sizes increase. Combining multiple stage based template matching with integral based smooth filtering implementation, we develop a new template matching technique and demonstrate with experimental results that the proposed method is faster than both FFT based methods and traditional spatial template matching approaches

9844-7, Session 2

Survey of data quality metrics from the perspective of detection and classification performance

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Detection and classification of targets is something that we use every day, often without even realizing it; the ability to locate and recognize a face in a crowd, to be able to identify a specific bird by its song, or to know what's for dinner simply by the aroma. Much effort has been spent

in trying to replicate these uncanny abilities of our senses to locate and recognize objects of interest in the world around us. This has been largely accomplished through purpose-built sensors. These sensors can be broadly characterized as non-imaging (e.g. infrared chemical sniffers, biosensors for glucose monitoring, microphones for voice recognition, magnetometers for metal detectors), and imaging, (e.g., photographic for face recognition, thermal imaging for night vision, radar for air-traffic control, sonar for fish finding, x-ray, magnetics and ultrasound for medical imaging). For many of these sensing modalities, Automatic Target Recognition (ATR) algorithms have been developed to automate the process of locating and recognizing the occurrence of a specific state from within the sensed data, whether the presence of a magnetic field or an object within an image. The following is an overview of the metrics used to assess and quantify the quality or 'goodness' of the image or data from the perspective of the ATR. The goal is to provide a high-level view of the challenges and highlight commonalities across the various disciplines.

9844-8, Session 2

Deep transfer learning for automatic target classification: MWIR to LWIR

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Transfer learning tends to be a powerful tool that can mitigate the divergence across different domains (MWIR vs LWIR) through knowledge transfer. Recent research efforts on transfer learning have exploited deep neural network (NN) structures for discriminative feature representation to better tackle cross-domain disparity. Cross-domain disparity can be due to the difference between source and target distributions or different modalities such as going from Midwave IR to Longwave IR. However, few of these techniques are able to jointly learn deep features and train a classifier in a unified transfer learning framework. To this end, we propose a task-driven deep transfer learning framework for automatic target classification, where the deep feature and classifier are obtained simultaneously for optimal classification performance. Therefore, the proposed deep structure can generate more discriminative features by using the classifier performance as a guide. Furthermore, the classifier performance is increased since it is optimized on a more discriminative deep features. The developed supervised formulation is a task-driven scheme, which will provide better learned features for target classification task. By giving pseudo labels for target data, we can transfer knowledge from source (i.e., MWIR) to target (i.e., LWIR) through the deep structures. Experimental results on a real database of MWIR and LWIR targets demonstrate the superiority of the proposed algorithm by comparing with other ones.

9844-9, Session 2

Convolution neural networks for ship type recognition

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Algorithms to automatically recognize ship type from satellite imagery are desired for numerous maritime applications. This task has many challenges. There is high variability within ship classes and lack of consistency in nomenclature. Ship type is determined by functionality rather than physical appearance, and so is difficult to characterize with computer vision approaches. Example imagery accurately labeled with ship type is hard to obtain, especially when there may only be a small handful of a particular ship type present in the world. Convolutional neural networks (CNNs) have shown great promise in image recognition settings, but many of these applications rely on the availability of thousands of example images for training. This work attempts to understand to which types of classification tasks CNNs might be suited by experimenting on a modestly-sized data set of ships and other marine objects in electro-optic satellite imagery.

We report the results of experiments designed to understand the level of classification granularity that can be achieved using CNNs with a small amount of training imagery. We attempt to identify large merchant ship types (e.g., tanker ships, cargo ships, or container ships) given a large set of anomaly detections in a large open-ocean image, including vessels large and small, clouds, white caps, and other objects.

Previous work [1-3] has evaluated algorithms including Support Vector Machines (SVM) with bag-of-visual-words features to discriminate between several large merchant ship classes. The experiments in the current work take a different approach, attempting instead to recognize a specific type of ship among many distractor objects. We consider several popular CNN architectures pre-trained on ordinary images and fine-tuned using our ship data set. We apply our trained classifiers to real-life test cases where a small number of targets are present among many distractors.

A potential use case for this work is the following. A tanker ship has been hijacked and its exact location is unknown. Satellite imagery is collected in the region surrounding the ship's last known location, and the imagery is run through a ship detector which returns hundreds or thousands of results.

These detected objects may be fishing boats, cruise ships, barges, cargo ships, or other false alarms. It's not necessary to determine the exact ship type of every detect, just if each object is a tanker or not. Such a capability may reduce the number of possible locations of the hijacked tanker down to just a small handful. Cross-referencing with AIS posits from the region may narrow the possibilities even further.

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9844-10, Session 3

An improved watershed segmentation algorithm with thermal markers for multispectral image analysis

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The process of image segmentation consists of separating objects of interest in an image or a scene from their background surroundings. This is often a critical first step in many computer and machine vision applications. Segmented images can subsequently be used to perform feature extraction, object detection and recognition, classification, motion estimation and tracking. The subject of image segmentation has been thoroughly studied; however the selection and performance of the algorithms are very specific to the application for which it is being used.

As part of a broader research effort in multispectral image analysis, an improved segmentation algorithm based on the classical Watershed concept was developed. A requirement for this research project was to develop a segmentation algorithm that could effectively extract objects of interest in both the visual and thermal image pairs.

The classic Watershed algorithm can be enhanced with "markers" identifying clusters of pixels belonging to the same object or to the background. There are several ways to create the markers and in this proposed algorithm, the markers are generated from the thermal imagery. The proposed Watershed with Thermal Markers allows the user to extract objects of interest from both visual and/or thermal dataset using an initial seed extracted from the thermal image.

In this report, the performance of the proposed Watershed with Thermal Markers is compared to other classic segmentation algorithms such as the Basic Threshold, K-means, Contours and another variant of the Watershed. These algorithms are applied and compared using a multispectral dataset of commonly found objects in an office environment.

9844-12, Session 3

Building occupant and asset localization and tracking using visible light communication

Christian Emiyah, Kofi Nyarko, Samuel Mbugua, Morgan State Univ. (United States)

LED lighting is becoming more and more ubiquitous within new commercial building constructions and retrofits due to their well documented merits of energy efficiency, environmental friendliness, and reduced cost of operation compared to incandescent and fluorescent lighting. Besides these benefits, LED lighting provides an opportunity for performing visible lighting communication (VLC). This research demonstrates how inexpensive commercial off-the-shelf lighting components and microcontrollers can be used to construct a whole building solution for occupant and asset localization and tracking through VLC. Through the modulation of the emitted light from mesh networked LED luminaires, the location of a "smart" tag can be determined and relayed to a central database. This paper describes the implementation of the VLC enabled LED luminaires, in addition to the customized infrared synchronization protocol, which enabled inexpensive single frequency diodes to be time division multiplexed to avoid packet collisions. Specifically, high lumen LEDs are modulated using differential pulse position modulation to communicate with an asset or occupant tag. The tag senses unique identifiers sent by each module in addition to relative intensity readings from luminaires to determine location. Luminaires use a communication chain approach (token message passing) to regulate packet transmission. This approach also serves as the basis for an IR based mesh networking and distributed computing protocol that is suitable for eliminating any additional building infrastructure besides power. The significance of this research is to demonstrate how new constructions and building retrofits can easily and affordably achieve whole building localization and tracking for intelligent building operations, asset management, occupant safety and building security.

9844-13, Session 3

Automatic seagrass pattern identification on Sonar images

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Natural and human-induced disturbances are resulting in degradation and loss of seagrass. Freshwater flooding, severe meteorological events and invasive species are among the major natural disturbances. Human-induced disturbances are mainly due to boat propeller scars in the shallow seagrass meadows and anchor scars in the deeper areas. Therefore, there is a vital need to map seagrass ecosystems in order to determine worldwide abundance and distribution. Currently there is no established method for mapping the pothole or scars in seagrass. One of the most precise sensors to map the seagrass disturbance is side scan sonar. Here we propose an automatic method which detects seagrass potholes in sonar images. Side scan sonar images are notorious for having speckle noise and uneven illumination across the image. Moreover, disturbance presents complex patterns where most segmentation techniques will fail. In this paper in the first step, the image was enhanced using adaptive thresholding and wavelet denoising techniques. In the next step using mathematical morphology technique the pothole patterns were identified. The proposed method was applied on sonar images taken from Laguna Madre in Texas. Experimental results in comparison with the ground truth show the effectiveness of the proposed method.

9844-14, Session 3

Evaluation schemes for video and image anomaly detection algorithms

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Video anomaly detection is a critical research area in computer vision. It is a natural first step before applying object recognition algorithms. There are many algorithms that detect anomalies (outliers) in videos and images that have been introduced in recent years. However, these algorithms behave and perform differently based on differences in domains and tasks that they are subjected to. In order to better understand the strengths and weaknesses of outlier algorithms and their applicability in a particular domain/task of interest, it is important to measure and quantify their performance using appropriate evaluation metrics. There are many evaluation metrics that have been used in the literature such as precision curves, precision-recall curves, ROC curves etc. In order to construct these different metrics, it is also important to choose an appropriate evaluation scheme that decides when a proposed detection is considered true (or false) detection (or miss) (e.g. Intersection over Union). Choosing the right evaluation metric and the right scheme is very critical since the choice can introduce positive or negative bias in the measuring criterion and may favor (or work against) a particular algorithm or task. In this paper, we review evaluation metrics and popular evaluation schemes that used to measure the performance of anomaly detection algorithms on videos and imagery with one or more anomalies. We analyze the biases introduced by these by measuring the performance of an existing anomaly detection algorithm.

9844-15, Session 3

Universal Fourier domain registration (FDR)

Timothy S. Khuon, National Geospatial-Intelligence Agency (United States)

Accurate data registration between 3-D point cloud datasets is a difficult task to achieve and it frequently can only be accomplished with the use of a manual "tie-point" registration approach. A new approach for automated point cloud registration has been developed by NGA - InnoVision and it is based on an interference phase correlation technique. With this approach, phase compensation can be estimated for basic linear transformations in the Fourier Domain. The three linear transformations currently addressed by this approach are translation, rotation, and scaling. These estimated transformations are applied to a data set to allow alignment with a separate reference data set. Fourier-based approaches to automatically register non-linear warped data are currently under development.

FDR is automatic data registration software which is noise tolerant, multi-modal, multi-dimensional and non-parametric. FDR searches for an optimal registration match between point clouds in the frequency domain, rather than matching geometric features of objects. The algorithm was originally developed to register Lidar Point cloud data and is capable of registering both Linear and Geiger mode Lidar point clouds data and data from different Lidar sensors. Recent tests indicate that FDR is useful for automatically registering a wide range of 2-D and 3_D data including: 2D E/O images, 3D E/O point clouds, 2D SAR images, 3D SAR point clouds, SONAR 2D images, and HSI/MSI with Lidar point clouds.

9844-16, Session 4

Learned filters for object detection in multi-object visual tracking

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(Australia); Mark D. McDonnell, David Kearney, Univ. of South Australia (Australia)

We explore the application of learned convolutional filters in multi-object visual tracking. The filters were learned from image data using artificial neural networks. This work follows recent results in the field of machine learning that demonstrate the use learned filters for enhanced object detection and classification (e.g. [1,2]). Here we employ a track-before-detect approach to multi-object tracking, where tracking guides the detection process. The object detection, in turn, provides trackers with probabilistic input maps, which are calculated by selecting learned features that best discriminate between objects and background. The image features are computed using learned filters, such those trained on the ImageNet database by the OverFeat convolutional neural network [3]. We present a systematic evaluation of our approach using real-world data sets, which highlights its benefits and potential drawbacks.

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9844-17, Session 4

Pedestrian detection from aerial vehicles with object proposals and deep learning

Breton L. Minnehan, Andreas Savakis, Rochester Institute of Technology (United States)

As Unmanned Aerial Systems grow in numbers, pedestrian detection from aerial platforms is becoming a topic of increasing importance. By providing greater contextual information and a reduced potential for occlusion, the aerial vantage point provided by Unmanned Aerial Systems is highly advantageous for many surveillance applications, such as target detection, tracking, and action recognition. However, due to the greater distance between the camera and scene, targets of interest in aerial imagery are generally smaller and have less detail. Deep Convolutional Neural Networks (CNN's) have demonstrated excellent object classification performance and in this paper we adopt them to the problem of pedestrian detection from aerial platforms. We train a CNN with five layers consisting of three convolution-pooling layers and two fully connected layers. We also address the computational inefficiencies of the sliding window method for object detection. In the sliding window configuration, a very large number of candidate patches is generated from each frame, while only a small number of them contains pedestrians. We utilize the Edge Box object proposal generation method to screen candidate patches based on an "objectness" criterion, so that only regions that are likely to contain objects are processed. This method significantly reduces the number of image patches processed by the neural network and makes our classification method very efficient. The resulting two-stage system is a good candidate for real-time implementation onboard modern aerial vehicles. Furthermore, testing on three datasets confirmed that our system offers high detection accuracy for terrestrial pedestrian detection in aerial imagery.

9844-39, Session 4

Tracker-aided adaptive multi-frame recognition of a specific target

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Control (United States)

We consider the problem of recognizing a particular target of interest (i.e. the “correct” target) while rejecting other targets and background clutter. In such instances, the probability of recognizing the correct target (PCT) is a suitable metric for assessing the performance of the target recognition algorithm. We present a definition for PCT and illustrate how it differs from conventional metrics for target recognition by means of an example. It is further shown that an adaptive target recognition algorithm, which relies on track position to obtain multiple looks at the target, can significantly improve PCT while reducing the track uncertainty.

9844-40, Session 4

Target representation and classification using random graphs

Firooz A. Sadjadi, Lockheed Martin Corp. (United States)

In this paper a novel method is described for representation and classification of target by random graphs. A target is represented in terms of set primitives that jointly represent a graph structure. Random graph is a graph structure with randomly varying vertex and arc attribute values. The position of a graph primitive is indicated by a graph node and its adjacencies to the other primitives are represented by the graph arcs. Matching is performed by exploiting the matrix representations of graphs. This method is potentially useful in classifying partially occluded targets.

9844-18, Session 5

Reverberation distributions

Leon Cohen, Hunter College (United States)

The standard current attitude is that the Rayleigh distribution is fundamental and is observed in most cases, but that under some circumstances the observed data does not fit the Rayleigh distribution. Other distributions are then proposed in an ad hoc manner that seemingly fit the data better. These include the K, log-normal, and Weibull distributions, among others. By way of simulation and theory, we have obtained probability distributions for intensity as functions of space and time, and have shown that for certain space-time values, the intensity distribution does become Rayleigh but is often non-Rayleigh. However, these non-Rayleigh distributions are not the K, log-normal, or Weibull distributions, etc. We have developed a new method to approximate probability distributions, where the Edgeworth and Gram-Charlier are special cases. The value of having approximations is not only a question of possible numerical advantage for calculations, but often approximations give insight into the nature of the distribution. We describe a new method of fitting that does not rely on a particular distribution but is self adjustable. Our form encompasses the K, log-normal and other long-tailed distributions, and can be used as a general form for all cases where there are deviations from Rayleigh.

9844-19, Session 5

Wavelets and pulse propagation

Leon Cohen, Hunter College (United States); Patrick J. Loughlin, Univ. of Pittsburgh (United States)

In dispersive pulse propagation, different frequencies travel at different velocities, causing the pulse to change as it propagates. Accordingly, phase space methods, such as the Wigner distribution and spectrogram, have been widely applied to dispersive propagation, leading to insights and simple approximate solutions to linear wave equations. Wavelets have also been applied to pulse propagation. We derive an approximation in terms of the wavelet transform of the propagating pulse.

9844-20, Session 5

Radar target identification using probabilistic classification vector machines

Ismail I. Jouny, Lafayette College (United States)

Radar target identification using probabilistic vector machines is investigated and tested using real radar data collected in a compact range for commercial aircraft models. Probabilistic vector machines (developed by Chen et al in 2009) are potential alternatives to support vector machines in the sense that the number of support vectors and computational complexity does not linearly increase proportional to the dimension of the training data. Furthermore, varying class priors and skewed misclassification costs control the posterior probabilities of class memberships. Unlike relevance vector machines (RVM) that utilize zero Gaussian prior for every weight for both negative and positive classes and are thus vulnerable to questionable vectors, probabilistic vector machines, alternatively, use nonnegative priors for the positive class and vice versa. This leads to sparse estimation of the weight vectors and results in more stable solutions. These machines produce probabilistic outputs for new test vectors and do not require extensive cross-validation grid search. Probabilistic vector machines have yielded promising results in several pattern recognition applications. This paper compares the performance of these machines with other target identification tools, and highlights scenarios where classification via a probabilistic vector machine is more plausible than other conventional radar target classification techniques. The problem addressed in this paper is a M-ary target classification problem and is implemented as a set of pairwise comparisons between all competing hypotheses.

9844-21, Session 5

Multi-class open set recognition for SAR imagery

Matthew Scherreik, Brian Rigling, Wright State Univ. (United States)

Supervised multi-class target recognition algorithms label an input pattern according to the most similar training class.

Typically, the number of training classes is fixed and known a priori.

In practice, however, a classifier may encounter novel targets that were not seen in training and label them incorrectly.

Recent work in open set recognition (OSR) develops classifiers that can identify training targets as well as previously unknown targets.

This results in a reduced number of forced misclassifications by “rejecting” targets that were not present in training.

Several OSR algorithms are based on support vector machines (SVMs), namely, the 1-vs-set machine, W-SVM, and POS-SVM.

The 1-vs-set machine, a linear classifier, forms a “slab” around each training class to discriminate it from the remaining training classes and limit the risk of labeling open space as target space.

The W-SVM uses a novel dual-calibration technique to map the SVM outputs to posterior probabilities, which are then subjected to a pair of user-specified thresholds.

The POS-SVM relies on a single calibration step, but features data-driven posterior probability thresholds that are chosen automatically.

Both the W-SVM and POS-SVM have the capability to use nonlinear SVM kernel functions and perform particularly well with the popular Gaussian RBF kernel.

Past works have shown that these algorithms can be effective for classifying ladar and IR images with a rejection option.

In this paper, we apply these algorithms to the MSTAR SAR dataset and analyze their performance for classifying known targets and rejecting unknown targets in the presence of clutter.

9844-22, Session 5

Multispectral image analysis for object recognition and classification

Claude R. Viau, Pierre Payeur, Univ. of Ottawa (Canada); Ana-Maria Cretu, Université du Québec en Outaouais (Canada)

Computer and machine vision applications are used in numerous fields to analyze static and dynamic imagery in order to assist or automate some form of decision-making process. Advancements in sensor technologies now make it possible to capture and visualize imagery at various wavelengths (or bands) of the electromagnetic spectrum. Multispectral imaging has countless applications in various field including (but limited to) security, defense, space, medical, manufacturing and archeology. The development of advanced algorithms to process and extract salient information from the imagery is a critical component of the overall system performance.

The fundamental objectives of this research were to investigate the benefits of combining imagery from the visual and thermal bands of the electromagnetic spectrum to improve the recognition rate and accuracy of commonly found objects in an office setting. The goal was not to find a new way to “fuse” the visual and thermal images together but rather establish a methodology to extract multispectral descriptors in order improve a machine vision system’s ability to recognize specific classes of objects. A multispectral dataset (visual and thermal) was captured, features from the visual and thermal images were extracted and used to train support vector machine (SVM) classifiers. The SVM models’ class prediction ability was evaluated separately on the visual, thermal and multispectral training datasets. Commonly used performance metrics were applied to assess the sensitivity and accuracy of each classifier.

The research demonstrated that the highest recognition rates were achieved by an expert system (multiple classifiers) that combined the expertise of the visual-only classifier, the thermal-only classifier and the combined visual/thermal classifier.

9844-23, Session 5

Hyperspectral anomaly detection using enhanced global factors

Todd Paciencia, Air Force Studies, Analyses, and Assessments (United States); Kenneth W. Bauer, Air Force Institute of Technology (United States)

Accurate, unsupervised anomaly detection in Hyperspectral Imagery (HSI) is difficult for an arbitrary image and sensor due to several issues: large dimensionality of the data, absorption, sub-pixel materials, collection error, varying complexity and sizes of the scene, as well as differing areas of the spectrum used by the sensor. All of these issues serve to make creating a consistent unsupervised detector difficult. Further, although Receiver Operating Curves are easily constructed, it can be much more difficult to find a single consistent operating point.

This research builds and demonstrates an automated process in order to provide efficient detection regardless of scene or sensor properties. Rotated factors are used both to remove absorption and to create features useful for detection. These global factors are enhanced to provide better detection using a filtering, smoothing, and signal-to-noise strategy. This strategy fuses spectral and local spatial information in order to refine the factor mappings. The enhancement is constructed in such a way so as to adapt to signal-to-noise and scoring properties of the specific image under consideration in an automated fashion, despite being unsupervised, using a parameter branching approach.

The algorithm is optimized to a single operating point using a training set of images, and it is shown that these settings also provide desirable results on additional imagery. Forest, desert, and sea-dominated scenes are included, as well as imagery with a variety of background and anomaly material amalgamations. Comparisons to existing state-of-the-art methods are also given.

9844-24, Session 6

Mobile target tracking system: consecutive use of GHT and NCC methods to increase the matching accuracy

Mustafa Oguzhan Ün, Turkish Naval Academy (Turkey); Hayriye Korkmaz, Marmara Üniv. (Turkey); Mustafa Yagimli, Turkish Naval Academy (Turkey)

In this paper, the shape which gives a fine estimation about what may the object be is handled by Generalized Hough Transform via LabVIEW. To increase the accuracy of matches and make a better estimation of the target, Normalized Cross Correlation Score is also computed between the intensities of the target and the template pixels. In addition, to handle the appearance changes, 12 different angles of view are taken as template pictures. The templates are searched in a video stream from a webcam which has the capability of capturing 30 frames in a second. The matches taking a score over a predefined value are considered as real matches and bounded by a box in the video. The distance between the central point of the image and the central point of the bounding box is computed and converted into an error signal. Using this signal, servomotors are driven to adjust the position of the camera to keep the target at the center. Therefore, the target with a changing background is recognized and tracked in real time.

9844-25, Session 6

Fast tracking based on local histogram of oriented gradient and dual detection

Kai Liu, Xidian Univ. (China); Huan Shi, Xidian Univ (China); Fei Cheng, Wenwen Ding, Baijian Zhang, Xidian Univ. (China)

Visual tracking is an important part in computer vision. At present, although many algorithms of visual tracking have been proposed, there are still many problems which are needed to be solved, such as occlusion and the speed of tracking. To solve these problems, this paper proposes a novel method which based on compressive tracking that have been proposed. In this paper, we use local histogram of oriented gradient (CHOG) instead of Haar-like which is used in compressive tracking, because the computational complexity of local histogram of oriented gradient is easier than the Haar-like. Besides, in order to solve the problem of occlusion, we decide to add dual detection in our algorithm. Firstly, we make sure the occlusion happens if a defined value of the detection result about extracted image features which have been tested by the classifiers is lower than a threshold value which is defined by us. Secondly, we mark the occluded image and extract some features from the occlusion region. In the next frame, we test the current frame by both the classifier and the features of the marked image, which is called dual detection. At last, we pick up some videos from the common dataset, in which occlusion happens frequently. Then we use the videos to test the performance of our algorithm by the benchmark that is proposed by Yi Wu. The result shows that the tracking algorithm in my paper is faster, and the result about handling occlusion is much better than other algorithms, especially compressive tracking.

9844-26, Session 6

Estimation of direction of arrival of a moving target using subspace based approaches

Ripul Ghosh, Utpal Das, Aparna Akula, Satish Kumar, H. K. Sardana, Central Scientific Instruments Organisation (India)

Direction of arrival (DOA) algorithms essentially estimates the azimuth position of a target with respect to a reference point. In this research work, array processing techniques based on subspace decomposition of the signal matrix into two orthogonal subspaces called the noise subspace and signal subspace have been evaluated. Three subspace based approaches – Multiple Signal Classification (MUSIC), Least Square-Estimation of Signal Parameters via Rotation Invariance Techniques (LS-ESPRIT) and Total Least Square- ESPRIT (TLS-ESPRIT) have been evaluated for DOA estimation of wideband acoustic energy sources. These techniques explicitly invoke the Eigen-structure of the covariance matrix and its intrinsic properties are directly used to the underlying estimation problem. Their performances have been compared with the conventional time delay (TD) based approaches such as Generalized Cross Correlation-Phase Transform (GCC-PHAT) and Average Square Difference Function (ASDF).

These algorithms have been tested on static speech data and moving civilian vehicle acoustic data acquired using two uniform linear arrays (ULA) of eight and three element microphones. The signal was acquired using two units DEWE-43 data acquisition system in a synchronised loop with a sampling rate of 10 kHz. Experiments have been performed with different civilian vehicles such as bus, tractor, mini-tractor and truck moving at constant speed in predefined rectangular and square trajectory paths with closest point of approach (CPA) of 5m. The data is pre-processed with mean normalization and spatial smoothing algorithm to remove the coherency. Further, it is segmented into small windows with the assumption that the signal is stationary within that specific duration. We applied Short-time Fourier Transform (STFT) with a 64 point Hamming window to select the frequency bins contributing more power. The subspace based methods are then applied on the selected frequency bins to obtain the average DOA estimation.

Validation is accomplished using experimental data and ground truth (GT) information. The algorithms have been tested on 20 events of speech data generated with a GT of (0°, ±30°, ±45°, ±60°, ±90°) and 61 events of moving vehicles at different distances. The difference between estimated angle and GT, termed here as an error. The mean error and the standard deviation (SD) are calculated over all the runs which are used as performance evaluation metrics. Lower values of mean error and SD confirm the superiority of subspace based approaches over TD based techniques. Amongst the TD and subspace based methods, MUSIC is computationally more expensive and LS-ESPRIT with a mean error±SD of 5.82°±5.65 indicated better performance in DOA estimation for both static and moving wideband acoustic sources. We illustrate the feasibility of using subspace based approaches for estimation of DOA moving target with presenting preliminary results of simulations.

9844-27, Session 6

Outlier and target detection in aerial hyperspectral imagery: a comparison of traditional and percentage occupancy hit or miss transform techniques

Andrew Young, Stephen Marshall, Alison Gray, Univ. of Strathclyde (United Kingdom)

The use of aerial hyperspectral imagery for the purpose of remote sensing is a rapidly growing research area. Currently, targets are generally detected by looking for distinct spectral features of the objects under surveillance. For example, a camouflaged vehicle, deliberately designed to blend into background trees and grass in the visible spectrum, can be revealed using spectral features in the near-infrared spectrum. This project aims to develop an improved target detection method, using a two-stage approach. Firstly by development of a physics-based atmospheric correction algorithm to convert radiance into reflectance hyperspectral image data and secondly by use of improved spectral unmixing techniques. In this work the second stage of the process is discussed. The Percentage Occupancy Hit or Miss Transform is adapted to provide an automated method for target detection in aerial hyperspectral imagery. The results are then compared to more established techniques for target detection, they are Sequential Maximum Angle Convex Cone, Vertex Component Analysis and Mahalanobis Distance.

To compare the methods, a ground truth for the image was created to provide a quantitative value for accuracy of each technique. Each separate algorithm was then run on the image to produce a set of targets. This was then compared with the ground truth and a score based on the number of hits and misses was calculated. Due to the additional variable associated with this new technique, the spread of results is quite varied. However under certain circumstances this new approach provides better results than all the established techniques tested.

9844-29, Session 7

Moving human full body and body parts detection, tracking, and applications on human activity estimation, walking pattern and face recognition

Hai-Wen Chen, Mike McGurr, Booz Allen Hamilton Inc. (United States)

In our recent IEEE workshop paper, we presented a new way for detection and tracking of human full-body and body-parts with color (intensity) patch morphological segmentation and adaptive thresholding for security surveillance cameras (In Performance Evaluation of Tracking and Surveillance (PETS), 2014 IEEE International Workshop, pg. 361-368, Seoul, Korea, 26-29 August, 2014). An adaptive threshold scheme has been developed for dealing with body size changes, illumination condition changes, and cross camera parameter changes. Tests with the PETS 2009 and 2014 datasets show that we can obtain high probability of detection and low probability of false alarm for both full-body and body-parts (arms, legs, torso, and head, etc.). Test results indicate that our human full-body detection method can considerably outperform the current state-of-the-art methods (e.g., HOG, and RFM-HOG) in both detection performance and computational complexity. In this paper, we present further applications on activity recognition. Reliable body-parts (e.g. head) detection allows us to continuously track the individual person even in the case that multiple closely spaced persons are merged. Accordingly, we have developed a new algorithm to split a merged detection blob back to individual detections based on the detected head positions. Detected body-parts also allow us to extract important local constellation features of the body-parts positions and angles related to the full-body. These features are useful for human walking gait pattern recognition and human pose (e.g. standing or falling down) estimation for potential abnormal behavior and accidental event detection, as evidenced with our experimental tests. Furthermore, reliable moving human head detection and tracking allow us to extract out multiple human face segmentations from different time frames of a moving human, and apply a super-resolution algorithm to enhance the face resolution for improved human face recognition performance.

9844-30, Session 7

Ontology-Based Improvement to Human Activity Recognition

David Tahmoush, Claire Bonial, U.S. Army Research Lab. (United States)

Activity and event recognition from video has utilized low-level features over higher-level text-based class attributes and ontologies because they traditionally have been more effective on small datasets. However, by including human knowledge-driven associations between actions and attributes while recognizing the lower-level attributes with their temporal relationships, we can learn a much greater set of activities as well as improve low-level feature-based algorithms by incorporating an expert knowledge ontology.

In an event ontology, events can be broken down into actions, and these can be decomposed further into attributes. For example, throwing events can include throwing of stones or baseballs with the object being relocated from a hand through the air to a location of interest. The throwing can be broken down into the many physical attributes that can be used to describe the motion like BodyPartsUsed = Hands, BodyPartArticulation-Arm = OneArmRaisedOverHead, and many others. Building general attributes from video and merging them into an ontology for recognition allows significant reuse for the development of activity and event classifiers. Each activity or event classifier is composed of interacting attributes the same way sentences are composed of interacting letters to create a complete language.

9844-31, Session 7

Truncated feature representation for automatic target detection using transformed data-based decomposition

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In this work, the data covariance matrix is diagonalized to provide an orthogonal bases set using the eigen vectors of the data. The eigen-vector decomposition of the data is transformed and filtered in the transform domain to truncate the data for robust features related to a specified sets of targets. These truncated eigen features are then combined and reconstructed to utilize in a composite filter and utilized for the automatic target detection of the same class of targets. The results associated with the testing of the current technique are evaluated using the peak-correlation and peak-correlation energy metrics and are presented in this work. The inverse transformed eigen-bases of the current technique may be thought of as an injected sparsity to minimize data in representing the skeletal data structure information associated with the set of targets under consideration.

9844-32, Session 8

Spatial tuning of a RF frequency selective surface through origami *(Invited Paper)*

Kazuko Fuchi, Wright State Research Institute (United States); Philip Buskohl, Giorgio Bazzan, Michael Durstock, James Joo, Gregory Reich, Richard Vaia, Air Force Research Lab. (United States)

Origami devices have the ability to spatially reconfiguration between 2D and 3D states through discrete folding motions. The precise mapping of origami presents a novel method to spatially tune radio frequency RF devices, including such relevant applications as adaptive antennas, sensors, reflectors, and frequency selective surfaces (FSSs). Origami tessellations and FSS are similar in that they both involve periodic patterns (folds for origami

and conductive traces for FSSs) and both derive their intrinsic performance from the patterned structure. However, conventional FSSs are designed based upon a planar distribution of conductive elements, leaving the large design space of the out of plane dimension underutilized. To better capture this design regime, we investigated the resonance tunability of origami FSSs. Dipole and square loop conductive traces were arrayed on three different origami tessellations, a corrugated, Miura, and Waterbomb-Miura pattern. The resonance characteristics of each pattern were computed using COMSOL RF module for various folded configurations. The dipole patterns showed increased resonance shift with decreased separation distances, with the separation in the direction orthogonal to the dipole orientations had a more significant effect. The square loop patterns were less influenced by folding in terms of the resonance shift, however, adjacent elements started to couple to create additional resonances at large fold angles. These results provide a basis of origami FSS designs and motivate the development of computational tools to systematically predict optimal fold patterns for target frequency response and directionality.

9844-33, Session 8

Infrared photodetectors with wavelength extension beyond the spectral limit *(Invited Paper)*

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The cut-off wavelength limit (λ_c) in a photodetector is typically determined by its activation energy (Δ) through a relationship: $\lambda_c = hc/\Delta$. This spectral rule dominates device design and intrinsically limits the long wavelength response of the photodetector due to increased dark currents with decreasing the value of Δ . Modifying the energy distribution of carriers, for example, by introducing hot-cold carrier interactions, can lead to a change in the value of Δ and thus the spectral response. Here, a novel concept utilizing such a hot-carrier effect is achieved in a p-type graded-barrier GaAs/AlGaAs heterojunction. Hot carriers injected into a semiconductor structure interact with cold carriers and excite them to higher energy states. The detector with a designed value of threshold at $3.1 \mu\text{m}$ displays two different extended thresholds at different temperatures. The detector experimental dark current can be fitted by a thermionic emission model using the activation energies according to the designed values. A very-long wavelength infrared response up to $55 \mu\text{m}$ is observed up to 35 K; with increasing temperature, a threshold wavelength of $8.9 \mu\text{m}$ is identified at a temperature up to 90 K. The tunability of the extended response can be accomplished by using an external optical excitation source through varying the degree of hot-hole injection. The advantage of the hot-carrier mechanism is a new detection concept which separates the photoemission threshold from affecting the spectral response, allowing minimizing the detector noise by using a high activation threshold energy. This study shows the possibility of incorporating long-wavelength response in a short-wavelength detector.

9844-34, Session 9

Real life identification of partially occluded weapons in video frames (*Invited Paper*)

Christian F. Hempelmann, Abdullah N. Arslan, Salvatore Attardo, Grady P. Blount, Nikolay M. Sirakov, Texas A&M Univ.-Commerce (United States)

We test the capacity of our improved system based on [1,2 3, 4, 5, 6, 7] to identify not just images of individual guns, but partially occluded weapons and their parts appearing in a video-frame. Our system combines low-level geometrical information gleaned from the visual images and high-level semantic information stored in an ontology enriched with meronymic part-whole relations. The main contributions of this study are in the frames segmentation, matching occluded weapons and a built-out meronymy.

Well-known and commonly deployed in ontologies, actual meronymies need to be engineered and populated with unique solutions. Here this includes adjacency of weapon parts and essentiality of parts to the threat of and the diagnosticity for a weapon. For example, typical magazine shape, essential barrel vs. optional stock, and interchangeability of parts in certain gun platforms needed to be modeled appropriately to increase speed and precision of identification.

In this study we will process the video sequence frame by frame. The extraction method will separate colors and subtract the background. Then another subtraction with the next frame will determine moving targets, before morphological closing will be applied to the current frame in order to clean up noise and fill gaps. Next, the method calculates, for each object, the boundary coordinates and uses them to create a finite numerical sequence as a descriptor. Parts identification is done by cyclic sequence alignment. From the identified parts, the most likely weapon will be determined by using the weapon ontology.

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9844-35, Session 9

Image disparity in cross-spectral face recognition: mitigating camera and atmospheric effects (*Invited Paper*)

Zhicheng Cao, Natalia A. Schmid, Xin Li, West Virginia Univ. (United States)

Matching facial images acquired in different electromagnetic spectral bands remains a challenge problem. An example of this type of comparison is matching active or passive infrared (IR) against a gallery of visible face images. When combined with cross-distance, this problem becomes even more challenging due to deteriorated quality of the IR data. As an example, we consider a scenario where visible light images are acquired at a short standoff distance, while IR images are long range data. To address the difference in image quality due to atmospheric and camera effects – typical degrading factors observed in long range data, we propose two approaches that allow to coordinate image quality of visible and IR face images. The first approach involves Gaussian-based smoothing functions applied to images acquired at a short distance (visible light images in the case we analyze). The second approach involves denoising and enhancement applied to low quality IR face images. A quality measure tool called Adaptive Sharpness Measure is utilized as guidance for the quality parity process, which is an improvement of the famous Tenengrad method. For recognition algorithm, a composite operator combining Gabor filters, Local Binary Patterns (LBP), generalized LBP and Weber Local Descriptor (WLD) is used. The composite operator encodes both the magnitude and phase responses of the Gabor filters. The combining of LBP and WLD utilizes both the orientation and intensity information of edges. Different IR bands – short-wave infrared (SWIR) and near-infrared (NIR), and different long standoff distances are considered. The experimental results show that in all cases the proposed technique of image quality parity (both approaches) benefits the final recognition performance.

9844-36, Session 9

A closed form solution to the one-ball geolocation problem (*Invited Paper*)

Douglas J. Nelson, Jeffrey L. Townsend, National Security Agency (United States)

We address the problem of identifying the source location of an electromagnetic signal from one or more moving receivers. The classical solution to this problem requires at least two moving receivers and is based on a multi-receiver solution of isochrones and isodops representing curves on the earth of constant time difference (TDOA) and frequency difference (FDOA) of arrival computed from a cross-ambiguity surface. We have previously demonstrated that TDOA and FDOA can be estimated from a single received signal observed by a single moving receiver. This "one-ball" geolocation solution follows from the observation that propagation delay from the emitter to the receiver may be obtained from the received frequency by integration. We build on our previous results by demonstrating a closed form (functional representation) of isochrones and isodops, resulting in a system of equations that may be solved for the maximum likelihood solution of the emitter location. There are huge advantages to this solution. The closed form solution requires evaluation of cost functions on a minimal number of lattice points, which do not need to be near the emitter location. In addition, the emitter location is estimated without the need to convolve ellipses.

In addition to solving for the emitter location from a system of isochrones and isodops, we demonstrate other methods for geolocating the emitter. Among these are the solution of a system of equations derived from the cone about the receiver velocity vector containing the emitter and the use of the derivative of the received emitter frequency to generate additional equations.

In processing the received signal, a cross-spectral-based method is used that can estimate and track the received frequency to a fraction of a Hertz,

even for signals, such as the AIS signal whose pulses have duration of only 25 milliseconds. These cross-spectral methods have been developed over the past 30 years and provide superior frequency estimation and tracking.

9844-37, Session 9

A software module for implementing auditory and visual feedback on a video-based eye tracking system

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We describe here the design and implementation of a software module that provides both auditory and visual feedback of the eye position measured by a commercially available eye tracking system. The present audio-visual feedback module (AVFM) serves as an extension to the Arrington Research ViewPoint EyeTracker, but it can be easily modified for use with other similar systems. Two modes of audio feedback and one mode of visual feedback are provided in reference to a circular area-of-interest (AOI). Auditory feedback can be either a click tone emitted when the user's gaze point enters or leaves the AOI, or a sinusoidal waveform with frequency inversely proportional to the distance from the gaze point to the center of the AOI. Visual feedback is in the form of a small circular light patch that is presented whenever the gaze-point is within the AOI. The AVFM processes data that are sent to a dynamic-link library by the EyeTracker. The AVFM's multithreaded implementation also allows real-time data collection (1 kHz sampling rate) and graphics processing that allow display of the current/past gaze-points as well as the AOI. The feedback provided by the AVFM described here has applications in military target acquisition and personnel training, as well as in visual experimentation, clinical research, marketing research, and sports training.

9844-38, Session 9

Content-based vessel image retrieval

Satabdi Mukherjee, Izidor Gertner, The City College of New York (United States)

Content-based image retrieval is an important problem in both medical imaging and surveillance applications. In many cases the archived reference database is not fully structured, thus making content-based image retrieval a challenging problem.

In addition, in surveillance applications, the query image may be affected by weather or/and geometric disturbances.

Our approach of content-based image retrieval consists of two phases. First, we create a structured reference database, then for each new query image we find the closest cluster of images in the structured reference database. Then we add the query image to the closest cluster.

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9845-1, Session 1

Automated target detection from compressive measurements *(Invited Paper)*

Richard Shilling, Robert R. Muise, Lockheed Martin Missiles and Fire Control (United States)

A novel compressive imaging model is proposed that multiplexes segments of the field of view onto an infrared focal plane array. Similar to compound imaging, our model is based on combining pixels from a surface comprising of different parts of the FOV. We formalize this superposition of pixels in a global multiplexing process reducing the number of detectors required of the FPA. We then apply automated target detection algorithms directed on the measurements of this model in a scene. Based on quadratic correlation filters, we extend the target training and detection processes directly using these encoded measurements. Preliminary results are promising.

9845-2, Session 1

Light driven micro-robotics with holographic 3D tracking *(Invited Paper)*

Jesper Glückstad, Technical Univ. of Denmark (Denmark)

We recently pioneered the concept of light-driven micro-robotics including new 3D-printed micro-tools coined Wave-guided Optical Waveguides (WOWs) that can be optically trapped and "remote-controlled" in a volume with six degrees-of-freedom. To be exploring the full potential of this new light-driven micro-robotics approach in challenging microscopic geometries requires a versatile 3D light coupling that can dynamically track a plurality of "micro-robots" to ensure continuous optimal light coupling on the fly. We have integrated computer generated holography to maintain high light throughput for the WOWs, so that we can dynamically control the 3D focus position of the coupling beams. Our results show that we can simultaneously maneuver the WOWs in 3D space while dynamically coupling light through them. The design possibilities offered by 3D-printed WOWs, the augmented holographic light coupling combined with the advanced 3D micromanipulation opens the possibility for performing exciting precision engineered light-matter interaction in the future.

9845-3, Session 1

Challenges and novel solutions in date and visual analysis *(Invited Paper)*

Ashit Talukder, National Institute of Standards and Technology (United States)

No Abstract Available

9845-4, Session 2

Cross-correlation and image alignment for multi-band IR sensors *(Invited Paper)*

Thomas T. Lu, Tien-Hsin Chao, Jet Propulsion Lab. (United States); Frank Chen, Univ. of California, Los Angeles (United States); Andrew Luong, Univ. of California, Irvine (United States); Mallory Dewees, Saddleback College (United States); Xinyi Yan, Univ. of California, Berkeley (United States); Edward T. Chow, Jet Propulsion Lab.

(United States); Gilbert Torres, Naval Air Warfare Ctr. Weapons Div. (United States)

We present the development of a cross-correlation algorithm for correlating objects in the long wave, mid wave and short wave Infrared sensor arrays. The goal is to align the images in the multi-sensor suite by correlating multiple key features in the images. Due to the wavelength differences, the object appears very different in the sensor images even the sensors focus on the same object. In order to perform accurate correlation of the same object in the multi-band images, we perform image processing on the images so that the features of the object become similar to each other. Fourier domain band pass filters are used to enhance the images. Mexican Hat and Gaussian Derivative Wavelets are used to further enhance the features of the object. A Python based QT graphical user interface has been implemented to carry out the process. We show reliable results of the cross-correlation of the objects in multiple band videos.

9845-5, Session 2

Improved maximum average correlation height filter with adaptive log base selection for object recognition

Sara Tehsin, Saad Rehman, Ahmad B. Awan, Kaisar Chaudry, National Univ. of Sciences and Technology (Pakistan); Muhammad Abbas, National Univ. of Sciences and Technology (Pakistan) and National University of Sciences and Technology (Pakistan); Rupert C. D. Young, Univ. of Sussex (United Kingdom); Aafiyah Asif, National Univ. of Sciences and Technology (Pakistan)

Inefficiencies in recognition system are a major concern in pattern recognition and image processing field. A combinational framework of correlation filter and logarithmic transformation has been reported to resolve this issue as well as catering for scale and rotation variances of object in presence of distortion and noise. In this paper, we have extended the work to include the influence of different logarithmic bases on correlation plane. The correlation plane contraction and expansion has been observed under different scenarios. Based on our research, we can now recommend specific log bases to be used under different scenarios and variations. This has been done by testing a range of logarithmic bases for different scenarios and finding optimal link between the logarithmic bases and the type of variations / transformations of the objects. Our results show improved correlation and target detection accuracies.

9845-6, Session 2

Performing target specific band reduction using artificial neural networks and assessment of its efficacy using various target detection algorithms

Deepti Yadav, Manoj K. Arora, Indian Institute of Technology Roorkee (India); Kailash C. Tiwari, Delhi Technological Univ. (India); J. K. Ghosh, Indian Institute of Technology Roorkee (India)

Remote sensing has enabled mapping, monitoring and management of many resources like water, agriculture; forestry etc. Hyperspectral imaging is a powerful tool in the field of remote sensing and has been used for many military applications like detection of landmines, target detection and discrimination about target and decoys etc. The objective of target

detection algorithms is to analyze the image data and detect the targets of interest automatically or with very less human intervention. Major issues in target detection applications are spectral variability, noise, small size of target, complex backgrounds etc. Many of the detection algorithms do not work for difficult targets like small or dim targets, camouflages targets. These issues may result in false alarms. Thus, in many military applications the target / background discrimination is a key issue and therefore analyzing target's behavior in realistic environments is crucial for accurate interpretation of hyperspectral imagery. Use of standard libraries for studying target's spectral behavior suffers from the limitation that targets are measured in different environmental conditions (illumination etc.) than application. This study uses data measured at same time and location as the HSI image. Aim is to analyze spectrums of potential target materials in a way that each target can be spectrally recognized (or distinguished) from a mixture of spectral data. Also, for the purpose of spectral discrimination no standard metric was found in research papers. Hence, this study is an attempt to distinguish them using artificial neural network (ANN) and further verify the efficacy of these ranges in improving target detection. The results of ANN proposes discriminating band range for each target; these ranges were further used to perform target detection using few popular spectral matching target detection algorithm. Moreover, impact of various target related parameters on detection is also studied. Further, the results of algorithms were analyzed using ROC curves to evaluate/verify the effectiveness of the ranges suggested by ANN over other bands of image for target detection of desired targets. In addition, comparative assessment of algorithms is also performed to explore the suitability of these algorithms for these kinds of target.

9845-7, Session 3

Vehicle monitoring under Vehicular Ad-Hoc Networks (VANET) parameters employing illumination invariant correlation filters for Pakistan motorway police (*Invited Paper*)

Akber A. Gardezi, COMSATS Institute of Information Technology (Pakistan); Rupert C. D. Young, Univ. of Sussex (United Kingdom); Tariq Umer, Faisal S. Butt, COMSATS Institute of Information Technology (Pakistan); Christopher R. Chatwin, Univ. of Sussex (United Kingdom)

In the presence of non-uniform brightness frequency domain correlation filters do not give a reliable detection owing to the global energy normalisation. In order to overcome this issue a spatial domain implementation of the Optimal Trade-Off Maximum Average Correlation Height Filter (OT-MACH) domain was proposed which employs local kernel normalisation in order to minimise the effects varying light conditions.

The main concern for using a spatial domain implementation for OT-MACH is its computationally intensive nature. In the past two optimisation techniques were proposed utilising pre-processing by means of low pass filtering and an entropy filter to optimize the OT-MACH filter. This was used to reduce the average detection time of the proposed filter comparable to its frequency domain implementations. In this paper a security application is proposed which uses the spatial domain implementation of OT-MACH (SPOT-MACH) to track a target object over the Pakistan motorway network using a network of cameras linked to a VANET system. The coupling of VANET in the main system enables robust tracking of the vehicle instead of extensive processing of the entire video frame in run time. The use of VANET parameters provides an estimation criterion for the flow of traffic on Pakistan motorway network and would act as a precursor to the training algorithm. The use of VANET parameters like location and speed in this application would contribute towards the computational complexity minimisation of the proposed security application.

9845-8, Session 3

A new clustering algorithm for scanning electron microscope images

Amr H. Yousef, Alexandria Univ. (Egypt) and Univ. of Business and Technology (Saudi Arabia); Prakash Duraisamy, Miami Univ. (United States); Mohammad A. Karim, Univ. of Massachusetts Dartmouth (United States)

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. The most common configuration for an SEM produces a single value per pixel, with the results usually rendered as grayscale images. The captured images may be produced with insufficient brightness, anomalous contrast, jagged edges, poor quality due to low signal-to-noise ratio, grained topography and poor surface details. The segmentation of the SEM images is a tackling problems in the presence of the previously mentioned distortions. In this paper, we are stressing on the clustering of these type of images. In that sense, we evaluate the performance of the well-known unsupervised clustering and classification techniques such as connectivity based clustering (hierarchical clustering), centroid-based clustering, distribution-based clustering and density-based clustering. Furthermore, we propose a new spatial fuzzy clustering technique that works efficiently on this type of images and compare its results against these regular techniques in terms of clustering validation metrics.

9845-9, Session 4

Improving the detection of wind fields from LIDAR aerosol backscatter using feature extraction

Brady R. Bickel, The Pennsylvania State Univ. (United States); Eric R. Rotthoff, Gage Walters, Timothy J. Kane, The Pennsylvania State Univ. (United States); Shane D. Mayor, Univ. of California, Chico (United States)

The tracking of winds and atmospheric features has many applications, from predicting and analyzing weather patterns in the upper and lower atmosphere to monitoring air movement from pig and chicken farms. Doppler LIDAR systems exist to quantify the underlying wind speeds, but the cost of these systems can sometimes be relatively high, and processing limitations exist in these systems. There is also interest in deployment of these systems where Doppler lidar cannot be easily used. The alternative is using an incoherent LIDAR system to analyze aerosol backscatter. Improving the detection and analysis of wind information from aerosol backscatter LIDAR systems will allow for the adoption of these relatively low cost instruments in environments where the size, complexity, and cost of other options are prohibitive. Currently, image correlation techniques are used to calculate wind vectors with LIDAR aerosol backscatter. By using data from a simple aerosol backscatter LIDAR system, we attempt to extend the processing capabilities by calculating wind vectors through image correlation techniques and applying image segmentation techniques to improve the detection of wind features.

9845-10, Session 4

Tracking visual objects using pyramidal rotation invariant features

Sidike Paheding, Almabrok Essa, Evan W. Krieger, Vijayan K. Asari, Univ. of Dayton (United States)

In this paper, we propose a Ringlet based Pyramid Fourier Histogram of Oriented Gradients (R-PFHOG) method for tracking objects from visual videos captured either by a dynamic or stationary camera. In this model, the weighted ringlet and Fourier histogram of oriented gradients are integrated to construct a robust feature that is insensitive to object scale, rotation and occlusion. Columbus Large Image Format (CLIF) and Large Area Image Recorder (LAIR) are used to evaluate effectiveness of the proposed method. Experimental results show that our approach could be a promising candidate for object tracking in wide area surveillance.

9845-11, Session 4

Color DRIFT for robust object tracking in wide area motion imagery

Kevin T. Geary, Evan W. Krieger, Vijayan K. Asari, Univ. of Dayton (United States)

Most state-of-the-art feature tracking methods for object tracking in wide area motion imagery (WAMI) data perform only on grayscale data. However, as color WAMI data becomes more prevalent, color features could be utilized to provide additional information about the object of interest and its surroundings. The additional color features can help increase accuracy and robustness of a feature based tracker. The Directional Ringlet Intensity Feature Transform (DRIFT) object tracker, which utilizes Kirsch kernel filtering for edge features and Gaussian ringlet feature mapping for rotation invariance, is able to yield competitive results compared to state-of-the-art object tracking methods. However, DRIFT, like many other object tracking methods, does not make use of any color data that may be available from the input imagery. It is proposed to create a more robust tracker by integrating a color object tracker into the DRIFT tracking method. The proposed object tracker will obtain DRIFT features from the grayscale converted input imagery. The color tracker makes use of the Y'CbCr color space to extract additional features from the target. The DRIFT and color-based features will be integrated together to determine the target position within each frame of the imagery. By utilizing color data in the object tracking method, the proposed tracker can obtain a better feature set allowing for more accurate identification and tracking. A quantitative evaluation is performed using the proposed method on a color WAMI dataset and the results are compared to state-of-the-art grayscale-only methods. Experimental results show that the proposed approach yields more accurate results.

9845-12, Session 4

Target detection using point (Z-value) and calibrated cameras

Prakash Duraisamy, Miami Univ. (United States); Amr H. Yousef, Univ. of Business and Technology (Saudi Arabia); James Leonard, Miami Univ. (United States); Stephen C. Jackson, Univ. of North Texas (United States)

Target detection using sensor based control is one of the interesting topics in many emerging areas. In this paper, we talk about finding the exact coordinates of the object by fusing single point (Z-value) and calibrated cameras using Quadcopter. In this work, measurement error includes those in object's position and orientation measurements as well as algorithm's search failures such as missed coordinate detections or false coordinate detections. This search does not use any GPS or INS. This is completely demonstrated in indoor environment under real time environment.

9845-13, Session 4

All-automatic swimmer tracking system based on an optimized scaled composite JTC technique

Djamel Benarab, Thibault Napoleon, Ayman Alfalou, ISEN Brest (France); A. Verney, ACTRIS (France); P. Hellard, Fédération Francaise de Natation (France)

In this paper, an all-automatic optimized JTC based swimmer tracking system is proposed and validated on real database of international swimming competitions (FINA world championships Kazan 2015). First, we proposed to calibrate the video using the DLT algorithm (Direct Linear Transformation) which calculates the homography matrix given a sufficient set of point correspondences between pixels and metric coordinates. Then, a special prediction method to localize the potential target region is proposed, (i.e. the region where the target swimmer shows up after the first diving). For that, we take into account the dimensions of the swimming pool and the type of the swim. Once the video is calibrated, we apply our optimized scaled composite JTC. This method consists in creating an adapted input plane that contains the predicted region and the reference image. This latter is generated using a composite filter of n images chosen from the database and its dimension will be scaled according to the ratio between the head's dimension and the width of the swimming corridor. Finally, applying the proposed approach improves the performances of our previous tracking method by adding a detection module in order to achieve an all-automatic swimmer tracking system.

9845-22, Session PSWed

On the security of gyrator transform-based image encryption by chosen-plaintext attack

Jun Sang, Chongqing Univ. (China); Mohammad S. Alam, Univ. of South Alabama (United States); Bin Cai, Chongqing Univ. (China)

For the gyrator transform-based image encryption, in addition to the random operations (such as the random phase encoding), the rotation angles used in the gyrator transforms are also taken as the secret keys, which makes such cryptosystem to be more secure and more difficult to be attacked. To analyze the security of such cryptosystem, one may start from analyzing the security of a single gyrator transform by obtaining the rotation angle with exhaustive search, while the search efficiency may be improved with a computational intelligence-based search. In this paper, the chosen-plaintext attack on the gyrator transform-based image encryption was discussed. By using the impulse functions as the chosen-plaintext, it can be concluded that: (1) For a single gyrator transform, by choosing a plaintext, the rotation angle can be obtained very easily and be much more efficient compared to the exhaustive search and the computational intelligence-based search; (2) For a random phase encoding followed by a single gyrator transform, it is hard to find the rotation angle with a chosen-plaintext attack, while the rotation angle may be obtained with a known-plaintext attack and then the random phase mask can be obtained. However, assuming the value of one of the elements in the random phase mask is known, the rotation angle can be obtained very easily with a chosen-plaintext attack, while the random phase mask can also be recovered. Furthermore, the value of any one of the elements in the random phase mask may be obtained with an exhaustive search, and the rotation angle as well as the random phase mask may be recovered; (3) For a random phase encoding followed by a single gyrator transform, the relationship between the rotation angle and the random phase mask was obtained, which may be useful for further study on the security of the iterative random operations in the gyrator transform domains.

9845-29, Session PSWed

Modeling of scaled and rotated images recognition using different variants of invariant correlation filters

Petr A. Ivanov, Yaroslavl State Technical Univ. (Russian Federation)

The approach of distortion invariant correlation filters usage is one of the popular methods for correlation recognition of images that are under geometrical distortions. One of the benefits of this approach is that correlation function automatically have invariance for shift distortion. But unfortunately such distortions as change of scale and in-plane rotation and it's combination doesn't have such good method of recognition. Usually characteristics of correlation peak are not very good. In this paper the author used different type of mentioned filters for solution of this problem. There were used several correlation filters such as MACE, MINACE, GMACE, DCCF and polynomial filters and it's combinations for two-stage recognition of images from the collected in advance database. There were obtained results of output correlation peaks qualitative and quantitative characteristics. The results provide a possibility for successful usage of implemented algorithms.

9845-30, Session PSWed

Investigation of correlation between vibrometric data and accelerometric data using spectral fringe-adjusted joint transform correlation

Adel A. Sakla, Mohammad S. Alam, Univ. of South Alabama (United States); Vijayan K. Asari, Univ. of Dayton (United States)

Over the last two decades, the 1-D spectral fringe-adjusted joint transform correlation (SFJTC) technique has been proposed as an effective means for performing deterministic target detection in hyperspectral imagery. In addition, different types of sensor data have been proposed in the literature to characterize and detect objects or targets. Some of the recent sensors are accelerometers and laser vibrometers. In this work, we investigate how a laser vibrometer data signature is correlated to any accelerometer based data signature using SFJTC. Toward this end, we applied SFJTC to several data sets of laser velocity vibrometer data and different accelerometer data recorded from a vehicle under different conditions. It was found that all laser vibrometer data correlated equally well with all accelerometer data (regardless of the position of the accelerometer) under all conditions. This result suggests that laser vibrometric data may be used instead of accelerometric data to uniquely characterize vehicles.

9845-14, Session 5

Face recognition using 4-PSK joint transform correlation (*Invited Paper*)

Md Moniruzzaman, Mohammad S. Alam, Univ. of South Alabama (United States)

This paper presents an efficient phase-encoded and 4-phase shift keying (PSK)-based fringe-adjusted joint transform correlation (FJTC) technique for face recognition applications. The proposed technique uses phase encoding and a 4-channel phase shifting method on the reference image which can be pre-calculated without affecting the system processing speed. The 4-channel PSK step eliminates the unwanted zero-order term, autocorrelation among multiple similar input scene objects while yield enhanced crosscorrelation output. For each channel, discrete wavelet decomposition preprocessing has been used to accommodate the impact

of various 3D facial expressions, effects of noise, and illumination variations. The performance of the proposed technique has been tested using various image datasets such as Yale B, extended Yale B, CAS-PEAL and Cohn-Kanade (CK) under different environments such as illumination variation, noise, and 3D changes in facial expressions. The test results show that the proposed technique yields significantly better performance when compared to existing JTC-based face recognition techniques.

9845-15, Session 5

Fourier domain asymmetric cryptosystem for privacy protected multimodal biometric security

Debesh Choudhury, Neotia Institute of Technology Management & Science (India)

Biometrics refer to the physiological human traits such as face, fingerprint, iris, palm prints etc. and the behavioral human traits such as gait, voice, walking style, gesture, typing rhythm etc. Biometric signatures are unique to individuals and hence are reliable for identifying human beings. Biometric identification requires a verifier to search for matches in the entire database of biometric signatures of the whole population. This can open a possible security threat that the verifier can steal the biometric templates from the database. A malicious verifier can acquire the biometric templates and try severe impersonation attacks. Thus privacy protection is very essential in biometric authentication process because the biometric template data may be misused by dishonest verifiers.

We propose an asymmetric cryptosystem based on Fourier domain encryption of multimodal biometric signatures. One modality of biometrics (such as face) is used as the plaintext, which is encrypted by another modality of biometrics (such as fingerprint). A private key is synthesized from the encrypted biometric signature by complex spatial Fourier processing. The encrypted biometric signature is further encrypted by other biometric modalities, and the corresponding private keys are synthesized. The resulting biometric signature is privacy protected since the encryption keys are provided by the human, and hence those are private keys. Moreover, the decryption keys are synthesized using those private encryption keys. The encrypted signatures are decrypted using the synthesized private keys and inverse complex spatial Fourier processing. Computer simulations demonstrate the feasibility of the technique proposed. An optical architecture is also suggested for possible optical implementation.

9845-16, Session 5

New perspectives in face correlation research

Qu Wang, Ayman Alfalou, ISEN Brest (France); Christian Brosseau, Univ. de Bretagne Occidentale (France)

Optical correlation is reviewed as a method to make a decision on the target shape. A broad overview of the main correlation architectures, such as the JTC (Joint Transform Correlator) and the Vander-Lugt correlator (VLC) is first presented. Phase-only filter (POF) and VLC are specifically detailed. Then, we present a novel correlation technique for face recognition applications. Motivated by the robustness of the independent component analysis (ICA) model against the change of image versus rotation, enlighting, background, and scale for a database of independent components, we propose an ICA-based optical correlation technique. The independent components are generated from reference facial images in the learning base by applying the FastICA method. For the purpose of validating the good correlation performances of this technique, we use an adapted peak-to-correlation energy (PCE) criterion. Computer simulations were carried out to illustrate how this algorithm can identify a face with images from the Pointing Head Pose Image Database. Adapted receiver operating characteristic (ROC) plots are calculated to test the decisional performance of the proposed method. Additionnaly, we compare this method with other

face recognition methods, such as all-numerical ICA based techniques, standard composite filter, and asymmetric segmented phase-only filter.

9845-17, Session 5

Efficient face recognition using local derivative pattern and shifted phase-encoded fringe-adjusted joint transform correlation

Bikram K. Biswas, Mohammad S. Alam, Suparna Chowdhury, Univ. of South Alabama (United States)

An improved shifted phase-encoded fringe-adjusted joint transform correlation technique is proposed in this paper for face recognition which can accommodate the detrimental effects of noise, illumination, and other 3D distortions such as expression and rotation variations. This technique utilizes a third order local derivative pattern operator (LDP3) followed by a shifted phase-encoded fringe-adjusted joint transform correlation (SPFJTC) operation. The local derivative pattern operator ensures better facial feature extraction in a variable environment while the SPFJTC helps to eliminate unnecessary correlation signals while yielding robust correlation output for the desired signals. The performance of the proposed method is determined by using the Yale Face Database, Yale Face Database B, and Georgia Institute of Technology Face Database. This technique has been found to yield better face recognition rate compared to alternate JTC based methods.

9845-18, Session 5

Wavelet decomposition-based efficient face liveness detection

Md Moniruzzaman, Mohammad S. Alam, Univ. of South Alabama (United States)

Existing face recognition systems are susceptible to spoofing attacks. So, Face liveness detection is a pivotal part for reliable face recognition, which has recently acknowledged vast attention. In this paper we propose a wavelet decomposition based face liveness recognition system using an energy calculation technique. Live faces contain high energy components compared to fake or printed image. In this paper, we calculate energy components of live face as well as fake face using discrete wavelet decomposition method. We analyze percentage of energy at different levels as well as for different wavelet basis function. We also analyze percentage of energy at different RGB bands and efficient face liveness detection method has been proposed. Discrete wavelet representation has been used to calculate decomposed energy components. Moreover, it provides differentiation of several spatial orientations as well as average and detailed information which are missing in the fake faces. This technique provides excellent discrimination capability when compared to the previously reported works based on the discrete Fourier transform and n-dimensional Fourier transform operations. To verify the proposed approach, we tested the performance using various face antispoofing datasets such as university of south Alabama (USA), MSU and CASIA face antispoofing dataset which incorporates different types of attacks. The test results obtained using the proposed technique shows better performance compared to existing techniques.

9845-19, Session 6

Considerations for the extension of coherent optical processors into the quantum computing regime

Rupert C. D. Young, Philip M. Birch, Christopher R. Chatwin, Univ. of Sussex (United Kingdom)

Previously we have examined the similarities of the quantum Fourier transform to the classical coherent optical implementation of the Fourier transform (R. Young et al, Proc SPIE Vol 87480, 874806-1,11). In this paper, we further consider how superposition states can be generated on coherent optical wave fronts, potentially allowing coherent optical processing hardware architectures to be extended into the quantum computing regime. In particular, we propose placing the pixels of a spatial light modulator individually in a binary superposition state and illuminating them with a coherent wave front from a conventional (but low intensity) laser source in order to make a so-called 'interaction free' measurement. In this way, the quantum object, i.e. the individual pixels of the Spatial Light Modulator in their superposition states, and the illuminating wavefront would become entangled. We show that if this were possible, it would allow the extension of coherent processing architectures into the quantum computing regime and we give an example of such a processor configured to recover one of a known set of images encrypted using the well known coherent optical processing technique of employing a random Fourier plane phase encryption mask which classically requires knowledge of the corresponding phase conjugate key to decrypt the image. A quantum optical computer would allow interrogation of all possible phase in parallel and so immediate decryption.

9845-20, Session 6

Reconstruction of sparse data generated by repeated data-based decomposition

Vahid R. Riasati, Raytheon Space and Airborne Systems (United States)

The l_1 -norm reconstruction techniques have enabled exact data reconstruction with high probability from 'k-sparse' data. This paper presented an added technique to press this reconstruction by truncating the data in its decomposed state. The truncation utilizes a transformation of the eigen-vectors of the covariance matrix and prioritizes the vectors equally without regard to their energy levels associated to the eigen-values of the vectors. This method presents two primary advantages in data representation: first, the data is naturally represented in only a few terms components of each of the vectors, and second, the complete set of features is represented, albeit, the fidelity of the representation may have changed. This investigation provides a means of dealing with issues associated with high-energy fading of small-signal data features. The current technique utilizes injected sparsity to enable repeated data-based decomposition geared towards feature retention and skeletal data structure formation.

9845-21, Session 6

Chip scale broadly tunable laser for laser spectrometer

Tien-Hsin Chao, Thomas LU, Jet Propulsion Lab. (United States); Scott R. Davis, Michael H. Anderson, Vescent Photonics Inc. (United States)

No Abstract Available

9845-23, Session 7

Scene sketch generation using mixture of gradient kernels and adaptive thresholding

Sidike Paheding, Almabrok Essa, Vijayan K. Asari, Univ. of Dayton (United States)

This paper presents a simple but effective algorithm for scene sketch generation from input images. The proposed algorithm combines the edge magnitudes of directional Prewitt differential gradient kernels with Kirsch

kernels at each pixel position, and then encodes them into an eight bit binary code which encompasses local edge and texture information. In this binary encoding step, relative variance is employed to determine the object shape in each local region. Using relative variance enables object sketch extraction totally adaptive to any shape structure. On the other hand, the proposed technique does not require any parameter to adjust output and it is robust to edge density and noise. Two standard databases are used to show the effectiveness of the proposed framework.

9845-24, Session 7

An effective detection algorithm for region duplication forgery in digital images

Fatih Yavuz, Abdullah Bal, Huseyin Cukur, Yildiz Technical Univ. (Turkey)

Powerful image editing tools are very common and easy to use these days. This situation may cause some forgeries by adding or removing some information on the digital images. In order to detect these types of forgeries such as region duplication, we present an effective algorithm based on fixed-size block computation and discrete wavelet transform (DWT). In this approach, the original image is divided into fixed-size blocks, and discrete wavelet transform is applied to each block. Each wavelet transformed block is then represented by circle regions and four features are extracted to reduce the dimension of each block. Finally, the feature vectors are lexicographically sorted, and duplicated image blocks are detected according to comparison metric results. The experimental results show that the proposed algorithm presents computational efficiency due to fixed-size circle block architecture.

9845-25, Session 7

Invisible data matrix detection with smart phone using geometric correction and Hough transform

Halit Sun, Mahir C. Uysalturk, Mahmut Karakaya, Meliksah Univ. (Turkey)

Two-dimensional data matrixes are used in many different areas that provide quick and automatic data entry to the computer system. Their most common usage is to automatically read labeled products (books, medicines, food, etc.) and recognize them. In Turkey, alcohol beverages and tobacco products are labeled and tracked with the invisible data matrixes for public safety and tax purposes. In this application, since data matrixes is printed on a special paper with a pigmented ink, it cannot be seen under daylight. When red color LEDs are used for illumination and reflected light is filtered, invisible data matrixes becomes visible and decoded by special barcode readers. Due to their physical dimensions, price and requirement of special training to use; cheap, small sized and easily carried domestic mobile invisible data matrix reader systems are needed to deliver to every inspectors in the law enforcement units.

In this paper, we first developed an apparatus attached on the smart phone including a red color LED light and a high pass filter. Then, we developed an algorithm to process captured images by smart phones and to decode all information stored in the invisible data matrix images. The proposed algorithm mainly involves four stages. In the first step, data matrix code is processed by Hough transform processing to find "L" shape pattern. In the second step, borders of the Data Matrix are founded by using the convex hull and corner detection methods. Then, distortion of invisible data matrix corrected by geometric correction technique and the size of every module is fixed in rectangular shape. Finally, invisible data matrix is scanned line by line in the horizontal axis to decode it. Based on the results obtained from the real test images of invisible data matrix captured with a smart phone, the proposed algorithm shows high accuracy and low error rate.

9845-26, Session 7

Analytical analysis of adaptive defect detection in amplitude and phase structures using photorefractive four-wave mixing

George T. Nehmetallah, The Catholic Univ. of America (United States); John Donoghue, Solid State Scientific Corp. (United States); Partha P. Banerjee, Univ. of Dayton (United States); Jed Khoury, Air Force Research Lab. (United States); Michiharu Yamamoto, Nitto Denko Technical Corp. (United States); Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

In this paper, extensive theoretical modeling, analysis, and novel numerical verification of a photorefractive polymer based four wave mixing (FWM) based defect detection has been developed. This is an extension to our earlier experimental work in the area to perform defect detection in periodic amplitude and phase objects. Specifically, we develop the theory behind the detection of defects in amplitude and phase patterns, and dislocations in periodic patterns. In accordance with the theory, the results show that this technique successfully detects the slightest defects with no additional enhancement using post image processing techniques. This optical defect detection technique can be applied to the detection of production line defects, e.g., scratch enhancement, defect cluster enhancement, and periodic pattern dislocation enhancement. This technique is very useful in quality control systems, production line defect inspection, and computer vision.

9845-27, Session 7

Real-time holographic heterodyne spatial filtering

Jed Khoury, Lartec, Inc. (United States)

Homodyne and heterodyne detection can be realized with real-time holography. The multiplicative characteristics of interfering beam in a hologram can be utilized for real-time mixing between two modulated signals, and the limited response time can be utilized for temporal filtering. In the proposed scheme, the Fourier transform of an object is spatially temporally modulated by the centrally modulated membrane then followed by heterodyne detection using a real-time hologram. This result in a tunable filter depends on the amplitude of the membrane central modulation. The potential of the proposed scheme is that it can be used in several applications related to non-destructive testing.

9845-28, Session 7

A topological-based spatial data clustering

Hakam W. Alomari, Miami Univ. (United States); Amer F. Al-Badarneh, Jordan Univ. of Science and Technology (Jordan)

An approach is presented that automatically discovers different cluster shapes that are hard to discover by traditional clustering methods (e.g., non-spherical shapes). This allows discover useful knowledge by dividing the datasets into sub clusters; in which each one have similar objects. The approach does not compute the distance between objects but instead the similarity information between objects is computed as needed while using the topological relations as a new similarity measure. An efficient tool was developed to support the approach and is applied to a multiple synthetic and real datasets. The results are evaluated and compared against different clustering methods using different comparison measures such as accuracy, number of parameters, time complexity, and visually inspection. The tool performs better than error-prone distance clustering methods in both the time complexity and the accuracy of the results.

Conference 9846: Long-Range Imaging

Tuesday 19–19 April 2016

Part of Proceedings of SPIE Vol. 9846 Long-Range Imaging

9846-1, Session 1

Impact of atmospheric turbulence and refractivity on the modulation transfer function of incoherent imaging systems

Zhijun Yang, Mikhail A. Vorontsov, Univ. of Dayton (United States)

Using the brightness function imaging approach we analyze impact of the ocean type inverse temperature layer (ITL) on modulation transfer function (MTF) of an incoherent imaging system. It is shown that an ITL located in vicinity of imaging path can result in nonlinear deviation in imaging object spatial spectrum. Periodical (sine) patterns of different spatial frequencies are adopted as objects to show that the presence of ITL leads to formation of images with broadened (finite width) spatial spectrum. The sine pattern image spectrum mean frequency is appeared to be shifted in respect to object frequency. The image spectrum shift and width depend on ITL characteristics and its location in respect to optical wave propagation path. The observed changes in the sine pattern spectral content represent a challenge for analysis of imaging systems performance using conventional MTF based framework. We also analyzed impact of atmospheric turbulence on imaging of periodical (sine) patterns in presence of ITL as well as considered different models for vertical temperature profile resulting from an air-sea temperature difference (ASTD).

9846-2, Session 1

WavePy: A Python package for wave optics

Celina Bekins, Franklin W. Olin College of Engineering (United States); Jeremy P. Bos, Michigan Technological Univ. (United States)

Phase screen-based computer simulations, sometimes referred to wave optics simulations, are a fundamental tool used by researchers studying the effect of atmospheric turbulence on optical wave propagation. However, most if not all wave optics packages are either closed-source and written in a low level language, or dependent on expensive proprietary software packages. In the latter case, MATLAB is the software package of choice. However versatile, MATLAB is both expensive and proprietary. Many researchers have turned to open source tools to avoid onerous licensing fees use restrictions. A number of researchers have found that interactive Python (iPython), including the packages NumPy, SciPy and as supported by Spyder [1] or Python(x,y) [2], is a more than adequate replacement for MATLAB.

In this presentation we will demonstrate a basic wave optics package written in Python. Included in this package are a turbulence phase screen generator based on the MATLAB version described in [3] and a Fresnel propagator for performing split-step propagation simulations. Core to the WavePy package is a basic wave optics data object containing source, target, and propagation path information. After initializing one such data object we will demonstrate setting up and running a simple wave optics simulation, interactively, in just a few steps. We will show that unoptimized WavePy code has a similar execution time to MATLAB code with a similar structure. We expect a fully optimized version of WavePy could potentially outperform MATLAB. Our basic WavePy package will be released on GitHub following the publication of the proceedings.

[1] “Spyder: the Scientific PYthon Development EnviRonment” <https://pythonhosted.org/spyder/overview.html>

[2] “Python(x,y) - the scientific Python distribution.” <https://python-xy.github.io/>

[3] Jeremy P. Bos, Michael C. Roggemann, and V. S. Rao Gudimetla, “Anisotropic non-Kolmogorov turbulence phase screens with variable orientation,” *Appl. Opt.* 54, 2039-2045 (2015)

9846-3, Session 1

Extended scene Shack-Hartmann sensing: analysis of anisoplanatism effect in slant path imaging scenarios

Nima Taherkhani, Jeremy P. Bos, Michael C. Roggemann, Michigan Technological Univ. (United States)

We have developed a long range imaging model that simulates the angular decorrelation effect of a light wave as it propagates through volume turbulence located between an extended object and a Shack-Hartmann wavefront sensor. The extended object is divided into point sources, and ray from each point source traced through layers with properties of Kolmogorov turbulence, over a slant path toward the Shack-Hartmann aperture. The wave front sensor utilizes a Fourier-based algorithm for estimating local tilt by determining relative shift between sub-images in each frame subjected anisoplanatism.

We will explore the Shack-Hartman performance as a function of isoplanatic angle. Results will be compared to analytical expressions such as the one in [1]. We will also examine the effect of different extended objects by varying the image used to create the source intensity distribution. We expect to find some relationship between the spatial content in an object and the performance of the tracking algorithm in the presence of anisoplanatism. We have found that increase in zenith angle lead to decrease in compensating effect of extended scene Shack-Hartmann wavefront sensor.

[1]. Friedrich Wöger and Thomas Rimmele, “Effect of anisoplanatism on the measurement accuracy of an extended-source Hartmann-Shack wavefront sensor,” *Appl. Opt.* 48, A35-A46 (2009)

9846-4, Session 1

Incoherent atmospheric imaging: comparative analysis of numerical simulation techniques

Svetlana L. Lachinova, Optonicus (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States); Daniel A. LeMaster, Matthew E. Trippel, Air Force Research Lab. (United States)

We present comparative analysis of different numerical simulation techniques for imaging of incoherently illuminated extended objects over long-range distances, namely, the conventional wave-optics Monte-Carlo method and a recently developed simulation approach to incoherent imaging in conditions of anisoplanatic turbulence based on the so-called brightness function. The techniques are evaluated in terms of simulation accuracy, limitations, and computational speed. Short-exposure (instantaneous) images obtained for a single atmospheric turbulence realization using both methods are compared side by side and assessed using various image quality metrics characterizing image blur and geometrical distortions (warping). Long-exposure (atmospheric-averaged) simulation results are compared with theoretical estimations based on known analytical solutions. Specifically, for homogeneous media, as well as for the pupil-plane turbulence layer model, the modulation depth of the numerically computed long-exposure images is judged against theoretical expression for the modulation transfer function (MTF). For homogeneously distributed (volume) turbulence, the intensity profiles of obtained images of incoherent Gaussian discs are compared with corresponding theoretical calculations.

9846-5, Session 1

Differential tilt variance effects of turbulence in imagery: comparing simulation with theory

Daniel A. LeMaster, Air Force Research Lab. (United States); Michael Rucci, Barry Karch, Air Force Research Lab. (United States); Russell C. Hardie, Univ. of Dayton (United States); Szymon Gladysz, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (Germany); Matthew Howard, Matthew E. Trippel, Jonathan Power, Air Force Research Lab. (United States)

Differential tilt variance, as recently espoused by Gladysz et al., is a useful metric for interpreting the distorting effects of turbulence in long range imaging systems. In this paper, we compare the theoretical model of differential tilt variance to field measurements and simulations using both the conventional wave optics / Monte Carlo approach and the more recent brightness function approach. This comparison is placed in context of the physical parameters that may be estimated from differential tilt variance, e.g. structure constant, outer scale, et cetera.

9846-6, Session 2

Integrated object tracking framework for range gated camera systems

Mustafa Yagcioglu, Kuthan Yelen, ASELSAN A.S. (Turkey); Alptekin Temizel, ODTÜ (Turkey)

Range-gated imaging systems are active systems which use a high-power pulsed-light source and control the opening and closing times of the camera shutter in conjunction with the light source. By calculating the arrival time of the reflected light from the object, the camera shutter is opened for a short time period to form an image using the returned light. This allows generating high contrast images of the objects in difficult lighting conditions. On the other hand the object distance needs to be known and operators are expected to select the proper shutter timing to keep the object of interest continuously in the view. In order to automate this procedure, a tracking system needs to provide feedback to adjust camera shutter timing by estimating the distance of the object in addition to its horizontal and vertical position. In this paper, we present an object tracking framework integrated to the range-gated camera setup without resorting to an additional laser or radar based range finder unit even the object distance changes during the tracking. Range estimation is solely based on image processing and the distance of the object is estimated by the proposed algorithm with a number of similarity measurement methods. The performances of these methods are compared for various scenarios using the data acquired by the range-gated system setup.

9846-8, Session 2

Integrating turbulence mitigation algorithms with camera systems

Stephen T. Kozacik, Aaron L. Paolini, Eric J. Kelmelis, EM Photonics, Inc. (United States)

Turbulence mitigation techniques can often require the manipulation of multiple parameters to work effectively. These factors fall into three major categories: sensor specific static parameters (e.g. pixel size), dynamic sensor parameters (e.g. focal length), and scene-based parameters (e.g. atmospheric coherence length). Achieving optimal results requires precise control of these variables, which places a significant burden on the operator. This becomes even more important when integrating directly into a camera system since the interface available to the user is generally much more

austere than a computer's. An ideal solution would be to automate the setting and updating of all values. This requires three separate approaches, one for each class of parameters. Static information on the camera can be preloaded based on known sensor configuration. Dynamic camera status can be transmitted directly to the software as it changes. To automate the inclusion of scene-based information requires advanced algorithms to estimate the necessary values from incoming video feeds or obtaining metadata from other sources. By using these three approaches in concert, it is possible to integrate turbulence mitigation techniques directly into sensors without adding additional responsibilities on the operator. In this paper, we will discuss the challenges, both expected and unexpected, of implementing these solutions.

9846-9, Session 3

Application of large-head-box canopy distortion compensation scheme for improved cueing and targeting precision

Mark S. Fischler, Robert Atac, Dan Campbell, Thales Visionix, Inc. (United States)

Thales Visionix, a wholly owned subsidiary of Thales Communications, Inc., has applied a novel method for characterization of and compensation for canopy distortion, allowing for views from any position within a large head box. Canopy distortion occurs when the user is looking through any curved transparency. Any helmet mounted display system must either compensate for this distortion, or incur canopy distortion error in its total error budget. To date, distortions had been characterized under the assumption that the pilot is at or very near the design eye point. However, the measurements we have taken show significant differences in distortion, as the eye moves within a larger allowed head box. We present techniques allowing for compensation of canopy distortion for the entire HMD head-box, implications observed based on applying these techniques for A-10 and F-16 canopies, and an assessment of the cueing precision improvements that can be achieved by this new measurement and compensation scheme.

9846-10, Session 3

Passive long-range imaging with a multi-view telescope system

Kristofor B. Gibson, Space and Naval Warfare Systems Command (United States)

Pristine optical imaging in the Earth's atmosphere is a difficult accomplishment---it not impossible---due mostly to atmospheric scattering, absorption and turbulence. The scattering and absorption is dependent on the type of light in the day, either overcast or cloudless in addition to the type and size of particulates in the air. This scattering and absorption decreases the contrast in the image of an object viewed through the atmosphere. Additionally, the turbulence causes the light to bend randomly as it reaches the camera sensor which causes the image to warp, dance, and appear blurry. All of these factors are amplified with long range imaging since the light propagates along even more atmosphere.

For increasing the contrast of images, many contrast enhancement techniques exist and are effective for long range imaging systems. However, contrast enhancement comes at a cost of also enhancing noise [1]. The SNR stays the same but the noise floor is raised and becomes observable by the human vision system because contrast masking no longer plays a role in hiding the noise [2]. In order to reduce the noise and effectively improve the SNR, our approach is to align and average the multiple images obtained simultaneously from the Multiview Telescope System.

Our approach to mitigating the turbulence is to also utilize the frame aligned images from the multiple imaging systems. This approach, however, is essentially long exposure imaging and thus the scene becomes blurred. In order to reduce the blur, a deconvolution method is used that is parameterized by the atmospheric coherence parameter, r_0 [3]. In our

approach is based on previous work [4] where we present a way to estimate the r_0 parameter using the multiple views of the same scene.

References:

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9846-11, Session 3

Comparison of turbulence mitigation algorithms

Stephen T. Kozacik, EM Photonics, Inc. (United States)

When capturing image data over long distances (0.5 km and above), images are often degraded by atmospheric turbulence, especially when imaging paths are close to the ground or in hot environments. These issues manifest as time-varying scintillation and warping effects that decrease the effective resolution of the sensor and reduce actionable intelligence. In recent years, several image processing approaches to turbulence mitigation have shown promise. Each of these algorithms have different computational requirements, usability demands, and degrees of independence from camera sensors. They also produce different degrees of enhancement when applied to turbulent imagery. Additionally some of these algorithms are applicable to real-time operational scenarios while others may only be suitable for post-processing workflows. EM Photonics has been developing image-processing-based turbulence mitigation technology since 2005 as a part of our ATCOM image processing suite. In this paper we will compare techniques from the literature with our commercially-available real-time GPU accelerated turbulence mitigation software suite, as well as in-house research algorithms. These comparisons will be made using real experimentally obtained data for a variety of different conditions including varying optical hardware, imaging range, subjects, and turbulence conditions. Comparison metrics will include image quality, video latency, computational complexity, and potential for real-time operation.

9846-12, Session 3

Algorithm development, optimization, and simulation framework for a phase-locking fiber laser array

Benjamin Mazur, Casey Campbell, Furkan Cayci, Nick Waite, Fouad E. Kiamilev, Univ. of Delaware (United States); Jony Jiang Liu, U.S. Army Research Lab. (United States)

This research project aims to provide a software framework to test and simulate optimization algorithms for a phase-locking fiber laser array. The adaptive phase-coherent fiber laser array system is a prominent innovation in the areas of optical communications and directed energy projection. In comparison with a monolithic large-aperture system, the phase-locked array exhibits dramatic improvements in cost, size, and energy density at the center of the beam.

The challenge of phase-locking lies in the real-time blind optimization problem due to disruptive factors such as internal noise, heat, and atmospheric turbulence. None of these can be perfectly modeled with a single mathematical function, resulting in a stochastic problem. The central

component of the system is the control algorithm, which, for the laser array we are studying, is currently the Stochastic Parallel Gradient Descent (SPGD) method. SPGD is designed to optimize the phases of beams in the laser array so that they converge quickly, correct for noise, and remain stable to produce a sustained phase-locked beam. Improvements to this algorithm, as well as novel algorithms, are in development; however, it is tedious, time consuming, and complicated to run repeated tests on the hardware system.

In order to arrive at a better algorithm, optimize its parameters, and generate predicted behavior for the hardware, we have developed a testing and simulation framework. The secondary goal is to make the framework as modular as possible so that it can be applied to other problems in optics and imaging. An example of this would be Adaptive Optics systems, many of which also use SPGD. Tools provided by this framework include plots for phase error vs time, parameter heat maps to show optimum parameter values, and Monte Carlo simulations showing the variation in performance of the algorithm across multiple runs.

9846-13, Session 4

Low-cost chirp linearization for long-range ISAL imaging application

Hanying Zhou, Russell Trahan, Bijan Nemati, Michael Shao, Chengxing Zhai, William B. Schulze, Jet Propulsion Lab. (United States); Inseob Hahn, Jet Propulsion Lab (United States)

High quality linear laser frequency chirp over wideband is critical to many laser ranging applications such as inverse synthetic aperture lader (ISAL). In this paper, we describe a relatively low-cost chirp linearization approach for our ISAL imaging testbed, which uses a PZT for external cavity laser frequency tuning. The approach consists of a coarse hardware linearization and then an accurate software linearization steps, both of which relies on a self-heterodyne fiber interferometer (frequency monitor). First, the nominal triangle waveform input to PZT drive is modified through an iterative process prior to ISAL imaging acquisition. Several waveforms with chirp rates between 1 and 4Thz/s have been acquired with greatly improved chirp linearity. This process generally needs to be done only once for a typical COTS PZT that has fairly good repeatability (from chirp to chirp) but poor linearity (within chirp). The modified waveform is then used during ISAL imaging acquisition without active control while the imperfection in transmitted frequency is monitored. The received imaging data is then resampled digitally based on frequency errors calculated from the frequency monitor data, further remove residual static or dynamic nonlinearity in transmitted chirp signal. The measured system impulse response (IPR) from return signal shows near designed range resolution of a few mm, demonstrating the effectiveness of this approach.

9846-14, Session 4

Low-CNR inverse synthetic aperture LADAR imaging demonstration with atmospheric turbulence

Russell Trahan, Bijan Nemati, Hanying Zhou, Michael Shao, Inseob Hahn, William B. Schulze, Jet Propulsion Lab. (United States)

We present results from an inverse synthetic aperture LADAR (ISAL) testbed build at Jet Propulsion Laboratory to explore range-Doppler imaging performance in the low-photon regime and in the presence of atmospheric turbulence. The experiment used open loop control of an external grating laser modulated at 1-4 THz/s, along with post processing algorithms to achieve chirp linearization ex post facto. We also developed techniques to characterize the atmosphere, as well as metrics to determine the appropriate chirp length for a given atmospheric condition. We did photometric studies and estimated the carrier-to-noise ratio (CNR) in the

presence of detector noise. Applying different illumination strengths, we did a series of imaging experiments at different CNR levels. Along with these results, we discuss the application to various ISAL imaging scenarios.

9846-15, Session 4

Optimizing resolution efficiency for long-range EOIR multispectral imaging sensors

Craig Olson, Timothy D. Goodman, Andrew W. Sparks, Craig Wheeler, L-3 Communications (United States)

As airborne EOIR imaging systems look to achieve high-NIIRS full motion video from longer and longer standoff ranges, the challenges behind conceptualizing, designing, and fielding such systems grows significantly. We present a heuristic framework for dissecting the “goodness” of an FMV multispectral sensor and look at the various components behind what makes a high-resolution sensor.

Combining spatial resolution, temporal resolution, spectral resolution, and “signal” resolution with system footprint size/weight/power (SWaP) metrics allows deterministic tradeoffs between optical systems as well as system architectures. Evaluating the full mission performance of distributed small-aperture sensing against a single, large-aperture sensor becomes tractable within the proper framework.

We examine how the combination of fundamental physics, engineering design, and mission system footprint can dictate some of these trade-offs. Spatial resolution can be represented in various ways, but is fundamentally linked to the Lagrange invariant, which dictates aperture size. Temporal resolution may be captured by tracking frame rate or revisit potential of a system, while signal resolution is indicated by the relevant spectral noise floor and/or dynamic range. Normalizing these quantities to system weight and power allows more in-depth comparisons of various types of systems.

We present examples of trade studies of optical architectures in a SWaP-constrained space for long-range imaging, evaluating how many of the system parameters influencing resolution efficiency are intrinsically linked, even for more modern non-traditional systems. We conclude with a mention of how such a framework balances external constraints, such as balancing aperture size against atmospheric limitations for various multispectral bands.

9846-16, Session 4

Atmospheric effects on long stand-off HSI applications

Andre D. Cropper, David C. Mann, Raytheon Space and Airborne Systems (United States)

System performance for all HSI systems is influenced by many factors, including environmental conditions, operational usage, internal system composition and the processing chain. Truly optimizing this performance requires an understanding of the operational conditions under which each system will perform. One of the key factors affecting system performance, especially at long stand-off ranges, is the atmospheric effects. This paper presents analytical results demonstrating the effects of atmospheric conditions on long stand-off airborne HSI systems based on a Raytheon developed performance model for estimating System performance.

This end-to-end System Performance Model is especially designed for long stand-off airborne detection with large off-nadir viewing angles. It takes into account most of the components within the entire imaging chain. The model divides the end-to-end imaging chain into three parts: the environmental component, the Concept of Operations (CONOPS), and the imaging system effects. The environmental component includes solar illumination, scattering, and atmospheric transmittance. The system component includes the effects of system noise and throughput. The CONOPS accounts for the various operating conditions best suited for long stand-off detection. The analytical results presented in this paper provide details on the influence of the atmospheric conditions, including tropical conditions, on NESR and SNR

performance in a Spot Mode CONOPS for a HSI system based on the end-to-end System Performance Model. These results are based on continued work developed from the “Long stand-off Performance Modelling of HSI Airborne Imaging Systems”.

Keywords: Hyperspectral imaging, remote sensing, system performance model, long stand-off sensing, atmospheric effects

9846-19, Session PSTue

A spot detection algorithm for the Shack-Hartmann wavefront sensor

Je-Il Lee, Agency for Defense Development (Korea, Republic of)

Shack-Hartmann(S-H) wavefront sensor has been a very important position in adaptive optics systems for atmosphere turbulence research, high energy laser, optical communication and an ophthalmic medical system etc. S-H sensor has been used to measure and analyze time-varying lights in real-time. According to the spatial and temporal dynamic characteristics of light, various kinds of lenslet array can be adopted in S-H sensor. Spot patterns are determined depending on the lenslet array shapes.

Usually, during adaptive optics experiments, tests and/or according to the system requirement changes, there might be a needs of changes of lenslet array. These shall lead to additional changes of post image processing algorithms, which might give rise to project delay and additional design costs. To reduce these side-effects and give more flexibility of design process, a generalized reference spot detection algorithm was proposed in this paper for an application of infrared S-H wavefront sensor(of course, it can be applied to visible wavelength band S-H sensor). If there is an adoption change of lenslet array, a renewal process of reference spot detection must be performed. All locations of spots and active areas must be determined again before sensing aberrated wavefront of lights.

The proposed algorithm can detect spot patterns independent of geometrical shapes of lenslet array. It consist of four signal processing block, i.e. I) noise measurement & compensation II) segmentation III) coarse detection IV) fine detection. In block I), to enhance the detection accuracy, noise information of 2D detector is measured and compensated. In block II), based on the noise information acquired in ‘block I)’, thresholding and connected-component labeling is performed to segment all spots in individual. In block III), using binary transformed spot image, the locations of spots and active areas are estimated coarsely based on binary mass-centroid method. In block IV), last stage, the fine locations of spots and active areas are re-estimated based on thresholding and gray mass-centroid method using graylevel weighted pixel values. The finding of fine location values for reference spots is the purpose of the proposed algorithm in this paper.

To verify the detection performance of the proposed algorithms, several reference spots which have arbitrary patterns were generated artificially, e.g. rectangular, triangular, sandglass-shaped, X-shaped, center-void rectangular, and tested in software simulation. The proposed algorithms showed that it could detect and separate all reference spots individually in robust. It is expected that the proposed algorithm will give more flexibility of design process which might be in S-H sensor design as intended.

Conference 9847: Anomaly Detection and Imaging with X-Rays (ADIX)

Tuesday - Wednesday 19-20 April 2016

Part of Proceedings of SPIE Vol. 9847 Anomaly Detection and Imaging with X-Rays (ADIX)

9847-1, Session 1

X-ray technologies and the computational checkpoint (*Keynote Presentation*)

Eric J. Houser, U.S. Dept. of Homeland Security (United States)

No Abstract Available

9847-2, Session 1

Aviation security x-ray detection challenges (*Invited Paper*)

Tim Harvey, EMF Corp. (United States)

From single energy to dual energy measurements, the number of sources/detectors with their placement and considerations of emerging signature techniques such as X-ray diffraction spectra that may lead to estimation of atomic number and density as standby measures of “goodness”; a fundamental question can be posed: “what measurements, parameters and metrics should be considered in future system design?” Detection parameters of Pd, Pfa (ROC curves) are well known and often used. Throughput is a key input also. However information theory should be considered to define the task to be performed and determine the fundamental limits of performance. To illustrate, a very different answer may be obtained if the task is: determine the object(s) with some fidelity versus determine just if a threat is present. Detection challenges are complex prior to introducing cost (non-recurring and life-cycle, capitalization as well as only the equipment BOM or equipment procurement) or the diversity and characterization of the non-threats. Many techniques are evolving may offer solutions; information theory based techniques including JEDI--estimation versus detection to ROC curves are some examples. Clearly equipment closest to the gate and the last point of detection in terms of TSA's layered system should be responsive and adaptive in order to fulfill goals of risk-based screening with incorporation of networks (social or others) in the threat detection decision process. Equipment techniques may range from the measurement system type to usage of big data techniques to achieve detection improvements. Feynman said: “There's Plenty of Room at the Bottom” at a lecture given by physicist Richard Feynman at an American Physical Society meeting at Caltech on December 29, 1959. So true, with point-spread-function of medical equipment on the order of a millimeter, there should be lots of room in middle or even before the bottom or nearing bottom. This paper will highlight some technical areas that may assist in establishment of desired detection capability directions and address signature techniques as well as non-signature technology that may improve the detection capability by “seeing better” prior to reaching the Feynman's bottom with information theory as the underpinning to guide the way.

9847-3, Session 2

Detecting liquid threats with x-ray diffraction imaging (XDi) using a hybrid approach to navigate trade-offs between photon count statistics and spatial resolution (*Invited Paper*)

Sondre Skatter, Morpho Detection, Inc. (United States);
Sebastian Fritsch, Morpho Detection Germany GmbH

(Germany); Jens-Peter Schlomka, Morpho Detection Germany, GmbH (Germany) and Morpho Detection, LLC. (United States)

No Abstract Available

9847-4, Session 2

Integration of coherent x-ray scatter imaging with a checkpoint inspection system (*Invited Paper*)

Ed Franco, Rapiscan Systems Labs. (United States)

TBD

9847-5, Session 2

Snapshot 3D material identification via coded aperture x-ray diffraction tomography (*Invited Paper*)

Joel A. Greenberg, Mehadi Hassan, David J. Brady, Duke Univ. (United States)

X-ray diffraction tomography (XRDT) is a well-established technique that makes it possible to identify the material composition of an object throughout its volume. By using coded apertures and compressive sensing algorithms, we have previously shown that one can reduce the scan time relative to traditional techniques (e.g. coherent scatter computed tomography) and realize snapshot imaging. Nevertheless, these systems have traditionally required substantial source-side collimation and image only a lower-dimensional slice of the full object volume (e.g. a pencil or fan beam image only a line or plane, respectively). To create a complete 3D map of the material distribution throughout the object, one must therefore raster scan the object relative to the beam, which takes additional time and moving parts. Furthermore, texturing effects due to the limited transverse beam profile can create challenges in performing material identification.

In this presentation, we demonstrate a new snapshot configuration based on coded aperture XRDT that images an entire volume in a single measurement. By using an incident beam with finite extent in both transverse directions (e.g. a cone beam) and a pixelated, 2D energy-sensitive detector, we capture the XRD spectra at each voxel within a 3D volume within the object. This method is particularly useful for imaging small volumes quickly; for example, we find a 100-1000x reduction in scan time relative to a pencil beam configuration for objects with a transverse diameter of 1-3 cm. This is particularly relevant to tasks such as bottle scanning, tumor imaging, and component inspection. After describing the underlying operational concept, we present results validating the approach for a variety of applications.

9847-6, Session 2

Steep phase gradients and challenges in materials science applications of x-ray phase contrast imaging

Amber L. Dagele, Collin Smith, Edward S. Jimenez, Sandia National Labs. (United States)

**Conference 9847:
Anomaly Detection and Imaging with X-Rays (ADIX)**

X-ray phase contrast imaging (XPCI) is a new imaging modality in the suite of tools used for non-destructive test and evaluation. We are using grating-based XPCI for defect detection in a variety of applications including integrated circuits, micro-fabricated devices, micro-electro-mechanical-system (MEMS) components, additively manufactured parts, and airplane wing laminates. In medical imaging applications, the principal motivators are dose reduction, and contrast in tissues of similar density. Materials science applications benefit from the higher sensitivity of the phase signal and the complementary information extracted from attenuation, phase contrast, and dark-field images. However, there are challenges unique to materials sciences applications. The materials tend to require higher energies for penetration due to a combination of thicker samples and higher atomic numbers. Large differences in atomic number (index of refraction) of neighboring materials are common in these applications. These interfaces translate to steep phase gradients. Significant phase wrapping requires efficient algorithms to recover the phase and complete the image reconstruction. Techniques borrowed from synthetic aperture radar aid the reconstruction. We present the modeling and simulation tools we are developing to determine optimal system parameters for materials science applications and the reconstruction of challenging samples.

9847-7, Session 3

Novel 3D differential phase contrast imaging system (*Invited Paper*)

Lambertus Hesselink, Stanford Univ. (United States)

Making 3-D X-ray measurements of liquids is challenging, as the index of refraction at X-ray wavelengths differs from 1 by an amount of $<10^{-8}$. On the other hand, the short wavelength compared to the dimensions of physical objects ensures that the optical path length can still be sufficiently large to obtain meaningful interferometric data. The challenge is how to measure phase changes in an X-ray beam that traverses a multitude of objects, as in medical and aviation security applications.

About 10 years ago, a significant effort in X-ray interferometry was made at a number of laboratories around the world, with the group from Pfeiffer [1] in Switzerland making pioneering contributions to the field. Differential phase contrast (DPC) imaging was implemented in a three grating set up as described in Reference 1. An incoherent X-ray source transmits a cone of radiation that traverses a square amplitude absorption grating, incident upon a phase grating that splits the beam into two beams at a very small angle (typically about a micro radian or less). The two beams interfere on a second absorption grating producing Moiré fringes on a large size pixelated detector.

DPC imaging since then has been demonstrated in a number of laboratories around the world, including ours for use in medical imaging. The key benefits being improved contrast of phase objects such as fish and soft tissue, and low dose required for relatively high SNR. The drawbacks of the approach are, among others, a small field of view, significant energy dissipation in the absorption gratings (typically almost 10x) and low contrast fringes.

At Stanford we embarked on a different path to create DPC measurements. As the key drawbacks are related to the absorption gratings we decided to build a new X-ray source and detector matched to each other, having a spatial coherence that is suitable for making Talbot Moiré images. We refer to the source as PeXSA for Photo Electron X-ray Source Array, and the detector as PcXDA short for Photonic Channeled X-ray Detector Array.

In the one grating system under development in our lab, the X-ray source emits a striped X-ray pattern akin to the pattern generated by GO. The PeXSA source incorporates a photo emitter that is illuminated by a 405 nm striped laser beam to produce a similar electron striped beam pattern. The electron pattern is imaged onto the Tungsten target thereby generating a striped X-ray pattern, eliminating the need for GO.

In this invited presentation we describe the underlying physics of the Stanford single grating DPC system, and provide data on its operation. In particular we will discuss the performance of the single grating system versus the three grating system, and show recent results on DPC measurements of tens of different liquids. The ultimate goal of the project is

to provide an automated characterization system for identifying liquids in a cluttered environment, such as may occur in aviation security imaging or in 3-D medial imaging of soft tissue.

We gratefully acknowledge the support of the Department of Homeland Security under contract HSHQDC-12-C-00002. The use of the micro-CT facility at Dr. Rebecca Fahrig' lab during the early experiments is gratefully acknowledged.

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9847-8, Session 3

Absorption-phase duality in structured illumination TIE phase imaging

Yunhui Zhu, Massachusetts Institute of Technology (United States)

The propagation of light waves in a material is determined by the complex refractive index n of the material. The imaginary part determines the absorption, and the real part determines the phase delay upon propagation. Transport of intensity equation (TIE) has been a popular and convenient phase imaging method that obtains phase retrieval from the measurements of intensity differentials. Conventional 2-shot uniform illumination TIE can give reliable inversion of the phase but is essentially vulnerable to alignment error and noise corruption in the low frequency region. Here, we demonstrate a phase retrieval method in a microfocus X-ray system using structured illumination TIE (SI-TIE). The method is applied to objects that consist of only light materials obeying the phase -attenuation duality (PAD) relationship, which assumes proportionality between the real and imaginary part of the refractive index of the material. An anti-scattering grid is inserted between the source and the camera to generate illumination patterns with high spatial frequency modulations. By imposing the PAD relationship, we are allowed to reformulate the SI-TIE propagation equation to address both the transmission and diffraction signals using only a single shot of intensity measurement. Compared to previous TIE phase retrieval methods, the low-frequency instability problem is fixed by introducing correlation between the phase and attenuation. The system response to phase variation is also enhanced by the spatial intensity modulation from the structured illumination, resulting in robust phase imaging with enhanced sensitivity. Our simulation results show that substantial improvement of SNR is obtained using the SI-TIE method.

9847-9, Session 3

Multi-view coded aperture coherent scatter tomography

Andrew D. Holmgren, Ikenna Odinaka, Joel A. Greenberg, David J. Brady, Duke Univ. (United States)

We use coded apertures and multiple views to create a compressive coherent scatter computed tomography (CSCT) system. Compared with other CSCT systems, we greatly reduce object dose and scan time. Previous work on coded aperture tomography resulted in a resolution anisotropy that caused poor or unusable momentum transfer spectra when object separation was less than the system resolution. Complimentary and multiple views resolve the resolution issues, while still providing a feasible opportunity for snapshot tomography by adding sources and detectors. Different levels of compression, controlled by the coded aperture and number of views, affect the system performance and are further analyzed in a design study.

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9847-10, Session 3

Information-theoretic analysis of x-ray scatter and phase architectures for anomaly detection

David Coccarelli, Qian Gong, Razvan-Ionut Stoian, Duke Univ. (United States); Joel A Greenberg, Duke University (United States); Michael E. Gehm, Duke Univ. (United States); Yuzhang Lin, Liang-Chih Huang, The Univ. of Arizona (United States); Amit Ashok, College of Optical Sciences, The Univ. of Arizona (United States)

Conventional performance analysis of detection systems confounds the effects of the system architecture (sources, detectors, system geometry, etc.) with the effects of the detection algorithm. Previously, we introduced an information-theoretic approach to this problem by formulating a performance metric, based on Cauchy-Schwartz mutual information, that is analogous to the 'channel capacity' concept from communications engineering. This metric allows direct comparison of the ultimate performance limit of disparate hardware architectures. By informing system design, these analyses give engineers the ability to compare system concepts and therefore allocate development resources efficiently.

In this work, we will discuss our application of this metric to the study of novel screening systems based on X-ray scatter or phase. Using virtual bag ensembles and an X-Ray forward model, we generate simulated measurements. From this data, we calculate limits on system performance. Our results compare photoabsorptive measurement architectures to that of scatter and phase. Moreover, we compare the effects of system geometry and spectral resolution on performance limits. As a baseline system, we used a generalization of a system designed for material classification studied in the Duke CAXSI project [1]. From this baseline we have investigated variations in source fluence, scatter angle geometry, and detector energy resolution. We will report on these results as well as our ongoing investigations of phase-based approaches.

[1] Greenberg, Joel A., Kalyani Krishnamurthy, and David Brady. "Snapshot molecular imaging using coded energy-sensitive detection." *Opt. Express*, 21, 25480-25491 (2013).

9847-11, Session 3

Phase and coherent scatter imaging for improved discrimination of low-density materials

Carolyn A. MacDonald, Sajid Bashir, Laila Hassan, Danielle Hayden, Bushra Kanwal, Sean Starr-Baier, Sajjad Tahir, Mahboob Ur Rehman, Jonathan C. Petrucci, Univ. at Albany (United States)

Security screening with X rays, e.g. baggage screening, typically involves energy-sensitive detection which allows rough categorization by atomic number. However, discriminating between explosives and benign materials with low atomic number can be difficult, leading to a false-positive rate of roughly 20%. Two promising methods for improving screening while retaining high throughput are phase and coherent scatter imaging.

While attenuation is highly dependent on atomic number, phase is highly dependent on electron density, and thus offers an additional discriminant. A major limitation of phase imaging has been the required spatial coherence of the X-ray illumination which typically requires a small (10-50 μ m) source or multiple images captured with precision gratings, both of which present challenges for high throughput image acquisition. An alternative approach, recently proposed for medical imaging by Bennet et. al., uses a single, coarse grid. This significantly relaxes the source spot size requirement, improving acquisition times and allows near-real-time phase extraction using Fourier processing of the acquired images. Geometries to improve resolution as well as reconstruction algorithms to boost SNR

by combining data from multiple harmonics were investigated. A system utilizing a broad scanned slot for high throughput coherent scatter imaging was also demonstrated. Specific angles characteristic of target materials are selected through focused grids and slot apertures, generating a 3D map of the materials of interest. The two techniques can be combined to provide attenuation, phase and material specific diffraction information. Discrimination of materials on the basis of both phase and coherent scatter signatures is demonstrated.

9847-12, Session 4

CT dual-energy decomposition into x-ray signatures Rho-e and Z-e (Invited Paper)

Harry E. Martz, Issac Seetho, Kyle E. Champley, Jerel Smith, Stephen G Azevedo, Lawrence Livermore National Lab. (United States)

In a recent article (IEEE Trans. Nuc. Sci., February 2016), we introduced a novel method that decomposes dual-energy X-ray CT (DECT) data into electron density (ρ_e) and a new effective-atomic-number called (Z_e), which leads to system-independent feature space for characterization of materials. The Z_e of a material, unlike the traditional Z_{eff} , is defined relative to the actual X-ray absorption properties of the constituent atoms in the material, which are based on published X-ray cross sections. Our DECT method, called SIRZ (System-Independent ρ_e/Z_e), uses a set of well-known reference materials and an understanding of the system spectral response to produce accurate and precise estimates of the X-ray-relevant basis variables (ρ_e , Z_e) regardless of scanner or spectra in diagnostic energy ranges (30 to 200 keV). SIRZ can account for and correct spectral changes in a scanner over time and, because the system spectral response is included in the technique, additional beam-hardening correction is not needed. Results show accuracy (<3%) and precision (<2%) values that are much better than prior methods on a wide range of spectra. In this talk, we will describe and present our latest SIRZ results compared to traditional methods using DECT scanners and a set of materials

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9847-13, Session 4

CZT detector architectures for sparse 3D CT transmission and XRD scatter imaging (Invited Paper)

Kris Iniewski, Redlen Technologies (Canada)

CZT Detector Architectures for Sparse 3-D CT transmission and XRD Scatter Imaging

Joel A. Greenberg, Kris Iniewski, and David J. Brady

There are currently two system approaches that can be used to improve baggage scanning at the checkpoint: energy discriminating CT technologies and forward scattering X-ray diffraction (XRD). Duke and Redlen have been working for number of years together on developing suitable detector architectures required by next-generation scanner equipment. The paper discuss various architectural choices that one needs to make to build efficient CT and XRD systems.

To improve material discrimination in baggage scanning better energy resolution detector materials are required. Cadmium-Zinc-Telluride is a unique semiconductor that is comparable in performance with Germanium (Ge) detectors but, unlike Ge, CZT operates at room temperature. In addition, it out-performs existing energy integrating scintillation material traditionally used for transmission imaging in terms of spectral resolution while being able to handle comparable count rates. The unique combination of spectroscopy (energy resolution of 2-3keV) and high count rate capability

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(10-100 Mcps/mm²) at room temperature makes CZT an ideal detector solution for high detection accuracy baggage scanning applications.

While both sparse 3-D CT transmission and scatter imaging both enable material identification, they demand different detector specifications. For example, while typical 3-D transmission signals are on the order of 1-10 Mcps/mm², the scatter signal is often much weaker (typically 2-12 kcps/mm²). CZT is capable of delivering both high count rates and high-resolution spectroscopic performance, although it is challenging to achieve both of these attributes simultaneously. The paper discusses material challenges, detector design trade-offs and ASIC architectures required to build cost-effective CZT based detection systems.

Submitted October 5, 2015. We gratefully acknowledge the financial support from the U.S. Department of Homeland Security, Science and Technology Directorate under contract HSHQDC-11-C-00083. J. Greenberg is with Duke University, Durham, NC, 27708 USA (e-mail: jag27@duke.edu). K. Iniewski is with Redlen Technologies, Saanich, BC V8M 1X6S, Canada (e-mail: kris.iniewski@redlen.com). D. Brady is with Duke University, Durham, NC, 27708 USA (e-mail: dbrady@duke.edu).

9847-14, Session 4

Information-theoretic analysis of x-ray photoabsorption based threat detection system for check-point

Yuzhang Lin, Genevieve G. Allouche, Liang-Chih Huang, The Univ. of Arizona (United States); Amit Ashok, College of Optical Sciences, The Univ. of Arizona (United States); Qian Gong, David Coccarelli, Razvan-Ionut Stoian, Michael E. Gehm, Duke Univ. (United States)

X-ray threat detection systems for bag inspection are designed to generate a 3-d reconstruction or view(s), which are subsequently used for threat detection. Such a design approach expends significant resources (e.g. number of sources/views/detectors) towards the intermediate goal of bag reconstruction that is not necessary for threat detection. This inefficiency in current X-ray threat detection systems motivates questions such as: what is the fundamental limit of current X-ray systems and how does this fundamental limit change with various system parameters (e.g. spatial/spectral detector resolution). In this work, we employ a virtual bag model and physics-based forward model to compute the information-theoretic limits of threat detection using photoabsorption modality. The fundamental limit of system performance is determined using the Cauchy-Schwartz information-theoretic metric as a function of different system parameters in a check-point system. Our simulation studies show that for a baseline check-point system with dual-energy, dual-view geometry, doubling the spectral resolution from dual-energy to quad-energy detectors yields a significant performance improvement, whereas increasing spectral resolution further to eight spectral channels only yields a marginal improvement. Similarly, in such a check-point system increasing the number of views, say from two to three views, only yields marginal performance improvement, while increasing the number of views further (i.e. >3) degrades the system performance for a fixed photon budget. Another interesting outcome of our analysis is that increasing spectral resolution is typically more beneficial than increasing spatial resolution. For example, a 125x125 detector array with 8 spectral channels outperforms a 625x625 detector array with 2 spectral channels in a check-point system geometry.

9847-15, Session 4

High frame-rate real-time x-ray imaging of in situ high-velocity rifle bullets

Lawrence J. D'Aries, U.S. Army Armament Research, Development and Engineering Ctr. (United States); Stuart R. Miller, Rob Robertson, Bipin Singh, Vivek Nagarkar, Radiation Monitoring Devices, Inc. (United States)

High frame-rate imaging is a valuable tool for non-destructive evaluation (NDE) as well as for ballistic impact studies (terminal ballistics), in-flight projectile imaging, studies of exploding ordnance and characterization of other high-speed phenomena. Current imaging systems exist for these studies, however, none have the ability to do in-barrel characterization (in-bore ballistics) to image kinetics of the moving projectile BEFORE it exits the barrel.

The system uses an intensified high-speed CMOS camera coupled to a specially designed scintillator to serve as the x-ray detector. The x-ray source is a sequentially fired portable pulsed unit synchronized with the detector integration window and is able to acquire 2,000 fps (frames per second) with mega-pixel spatial resolution and up to 150,000 fps with reduced resolution. This paper will discuss our results imaging .30 cal bullets moving at over 1,000 mps (meters per second) while still in the barrel. Information on bullet deformation, pitch, yaw and integrity are the main goals of this experimentation. Future goals call for this same technology to be applied to larger projectiles such as medium caliber ammunition.

9847-16, Session 4

Shape threat detection via adaptive computed tomography

Ahmad Masoudi, Ratchaneekorn Thamvichai, Mark Neifeld, The Univ. of Arizona (United States)

X-ray Computed Tomography (CT) is used widely for screening purposes. Conventional x-ray threat detection systems employ image reconstruction and segmentation algorithms prior to making threat/no-threat decisions. We find that in many cases these pre-processing steps can degrade detection performance. Therefore in this work we will investigate methods that operate directly on the CT measurements. We analyze a fixed-gantry system containing 25 x-ray sources and 2200 photon counting detectors. We present two new methods for improving threat detection performance. The first method is a multiplexing strategy that utilizes a combination of sources to illuminate the object under test. We determine the optimal multiplexed measurement using a gradient search on the Chernoff bound on the probability of error (Pe). We find that under a fixed total photon constraint the optimal multiplexed measurement provides a 34.85x reduction in Pe relative to the optimal single source measurement. Our second method is a so-called greedy adaptive algorithm which at each time step uses information from previous measurements to design the next measurement. We utilize sequential hypothesis testing (SHT) in order to derive both the optimal "next measurement" and the stopping criterion to insure a target Pe. We find that selecting the next x-ray source according to such a greedy adaptive algorithm, we can reduce Pe by a factor of 42.4x relative to the conventional measurement sequence employing all 25 sources in sequence.

9847-33, Session PSTue

Data sinogram sparse reconstruction based on steering kernel regression and filtering strategies

Miguel A. Marquez, Edson F. Mojica, Henry Arguello, High Dimensional Signal Processing (Colombia)

Computed tomographic (CT) imaging is a non-invasive, non-destructive technique that allows recovering the internal structure of a 3D object based on a single 2D measurement. CT images have an impact in many applications such as medicine, non-destructive testing, industrial applications such as waste container inspection, security detection, drug detection, quality control on industrial manufacturing, production of composite materials and others. In such applications it is important to reduce the energy radiation during sinogram acquisition. For this purpose, new compressed sensing-based acquisition strategies have been proposed in order to reduce the x-ray radiation dose. In general, these strategies capture fewer measurements than those typically used on the classical

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sampling theory. However, these methods lose critical information of the sinogram which is vital for the reconstruction of the internal object structures. In this paper, a reconstruction method of sparse measurements from a sinogram is proposed. The proposed approach takes advantage of the redundancy of similar patches in the sinogram, and estimates a target pixel using a weighted average of its neighbors. Based on the above considerations, the steering kernel regression and the non-local mean filter are used in the proposed method. Simulation results show that the proposed method provides better reconstructions of the internal structure of an object. In particular, a gain up to 2 dB can be obtained with respect to an l_1 minimization algorithm.

9847-34, Session PSTue

Fractal dimension and lacunarity analysis for breast abnormality prediction using mammograms

Barin Kumar De, Mrinal Kanti Bhowmik, Anindita Roy, Tripura Univ. (India)

Breast Cancer is one of the most life-threatening diseases occurring throughout the world. Detection of breast cancer is effective if it is done in the early stage. Moving towards accurate breast cancer detection, Mammography has been the gold standard in medical imaging for its efficiency in accuracy and reliability. In mammography, X-rays of low energy (usually 30 kVp (Kilo peak Voltage)) is passed through the breast and the breast area is taken out as an image. The image is treated before printing on the film for improved visualization of the size, location and angle of the mass. Abnormalities often encountered in mammogram by the radiologists are masses, calcifications, asymmetry and architectural distortion that the radiologists feel ambiguous to differentiate but they can be of the cancerous form. Due to the presence of abnormalities in breast mammogram difference in texture is observed. In this paper, the effectiveness of fractal features in distinguishing abnormal breast from normal breast has been analyzed by observing the difference in fractal features and asymmetry analysis. On combination of fractal dimension and lacunarity feature applied on a dataset of 75 images of the mini-MIAS database, the accuracy has been found to be 95.94% with specificity and sensitivity of 92.3% and 97.91% respectively. In asymmetry analysis, it has been observed that the value of fractal features is higher in case of breast with asymmetry from the corresponding normal breast. Architectural distortion has been found to have much higher values of fractal features.

9847-17, Session 5

Fast iterative CT image reconstruction for security applications (Invited Paper)

Joseph A. O'Sullivan, Washington Univ. in St. Louis (United States)

No Abstract Available

9847-18, Session 5

Performance analysis of model based iterative reconstruction with dictionary learning in transportation security CT

Eri Haneda, JiaJia Luo, Ali Can, Sathish Ramani, Lin Fu, Bruno De Man, GE Global Research (United States)

In this study, we implement and compare model based iterative reconstruction (MBIR) with dictionary learning (DL) over conventional MBIR with pairwise pixel-difference regularization, in the context of transportation security. DL is a technique of sparse signal representation using an

overcomplete dictionary which has shown success in image processing applications including denoising (Elad and Aharon, 2006), as well as medical CT reconstruction. It has been previously reported that MBIR-DL produces promising results over conventional MBIR in terms of noise reduction and preservation of structural details, especially for low dose and few-view CT acquisitions (Xu et. al. 2012).

A distinguishing feature of transportation security CT is that scanned baggage may contain items with a wide range of material densities. While medical CT typically scans soft tissues, blood with and without contrast agents, and bones, luggage can contain high density materials, which can produce severe distortions such as metal streaking artifacts. Other factors of security CT are the emphasis on scanner throughput for real-time inspection, and the importance of CT number accuracy for target detection. While conventional MBIR has shown exemplary performance in the tradeoff of noise reduction and resolution preservation, we will demonstrate that MBIR-DL may further improve this tradeoff. In this study, we used the KSVD-based DL (Aharon and Elad, 2006) combined with the MBIR cost-minimization framework. We perform a parameter analysis to show the image quality impact by each parameter. We also investigate the few-view CT acquisitions where MBIR-DL can show a stronger advantage over conventional MBIR.

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9847-19, Session 5

Model-based reconstruction for x-ray diffraction imaging

Venkatesh Sridhar, Sherman J. Kisner, Purdue Univ. (United States); Sondre Skatter, Morpho Detection, Inc. (United States); Charles A. Bouman, Purdue Univ. (United States)

X-ray Diffraction (XRD) Tomography is emerging as an important imaging modality for transportation security applications. Unlike Computed Tomography (CT), XRD can even distinguish between materials with similar densities based on their diffraction profiles. However, current XRD system designs face challenges in achieving sufficient spatial resolution and signal-to-noise ratio (SNR) due to the limited number of detected photons. XRD systems can increase the SNR by using geometries that allow for detection of photons scattered at wide angles. However, wide-angle systems also require attenuation correction from an auxiliary CT scan. Alternatively, XRD systems that only detect low-angle scattered photons allow autonomous correction for attenuation, but suffer from lower SNR.

In this paper, we propose a novel 4D model-based iterative reconstruction (MBIR) algorithm for low-angle scatter XRD that can substantially increase the SNR by fully accounting for both the forward model of the scanner and the prior model of the image. Our forward model is based on a Poisson photon counting model that incorporates a spatial point-spread function, detector energy response, and correction for energy-dependent attenuation of the X-ray source spectrum. Our prior model is based on the combination of a Markov random field (MRF) spatial prior together with a reduced non-negative spectral bases set. Using these models, we compute the maximum a posteriori (MAP) estimate to render a 4D reconstruction in space and momentum spectrum. We demonstrate the effectiveness of our method with both simulated and real data sets.

9847-20, Session 5

2.5D dictionary learning based computed tomography reconstruction

Jiajia Luo, Haneda Eri, Ali Can, Sathish Ramani, Lin Fu, Bruno De Man, GE Global Research (United States)

A computationally efficient 2.5D dictionary learning (DL) algorithm has been proposed and implemented in the model-based iterative reconstruction

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(MBIR) framework for low-dose CT reconstruction. MBIR is based on the minimization of a cost function containing data-fitting and regularization terms to control the trade-off between data-fidelity and image noise. Due to the strong denoising performance of DL, there are existing works that incorporate DL as a regularizer in MBIR, and both 2D and 3D DL implementations are possible. Compared to the 2D case, 3D DL keeps more spatial information and generates images with better quality although it requires more computation. In this paper, a novel 2.5D dictionary learning scheme for low-dose CT reconstruction is proposed in the hope to get the high quality reconstruction with much less computational cost. By applying the 2D DL method in three different orthogonal planes and calculating the sparse coefficients accordingly, much of the 3D spatial information can be preserved without the computational penalty of the 3D DL method. In addition, DL for each orthogonal plane can use different parameters, which make 2.5D DL more flexible than conventional DL in both 2D and 3D. For performance evaluation, baggage phantoms with low dose and different number of projection views have been used. Experimental results from both full- and sparse-view acquisition show that the proposed 2.5D DL algorithm outperforms both 2D and 3D DL in terms of both PSNR and SSIM values. In addition, 2.5D DL only requires one third of the computational time of 3D DL.

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9847-21, Session 6

Extraction and classification of 3D objects from volumetric CT data (*Invited Paper*)

Samuel M. Song, TeleSecurity Sciences, Inc. (United States); Junghyun Kwon, Richo Innovations Corporation (United States); Austin Ely, John Enyeart, Chad Johnson, Jongkyu Lee, Namho Kim, Douglas P Boyd, TeleSecurity Sciences, Inc. (United States)

No Abstract Available

9847-22, Session 6

Tackling the x-ray cargo inspection challenge using machine learning

Nicolas Jaccard, Thomas W. Rogers, Univ. College London (United Kingdom); Edward J. Morton, Rapiscan Systems Ltd. (United Kingdom); Lewis D. Griffin, Univ. College London (United Kingdom)

There are over 500 million global container transactions annually. Due the global extent of the network, the vast number of containers involved, the need for different nation states to cooperate, and the need to maintain high container throughput, only a small fraction of the containers are inspected to verify conformity to the shipping manifest and transport regulations. Containers are currently prioritised based on a risk analysis of the shipment manifest and other metadata. Those of highest risk are first inspected non-intrusively using X-ray imaging. The inspection of the X-ray image will determine whether the container should be opened up and physically inspected. However, given new targets set by regulators mandating the inspection of most containers, there is a pressing need to develop methods to automate parts of the inspection workflow, enabling expert operators to focus on a manageable number of images that are most likely to contain threats.

In this contribution, we present a modular framework for automated X-ray cargo image inspection. Two distinct machine learning schemes underpin the framework; i) the classification of images using Random Forest classifiers trained on hand-crafted image intensity and image texture features, and ii) the classification of images using convolutional

neural networks (CNNs), which are often referred to as Deep Learning. CNNs are the state-of-the-art in many machine vision applications, even surpassing human performance in some cases. The framework plays to the strength of these two schemes by using them where most appropriate. Very large numbers of images are usually required to train machine learning algorithms, especially in the case of CNNs. Given that the generation of large X-ray cargo image datasets is a significant time and monetary investment, we propose a method that exploits the multiplicative nature of the transmission image formation process to synthesise a large number of "sufficiently realistic" images. To our knowledge, it is the first time such schemes have been employed for the partial automation of the X-ray cargo image inspection process.

We present results for two main applications: empty container verification and specific threat detection. The role of empty verification is twofold: as a pre-processing step to reduce the number of images to be classified for specific threats downstream, and to detect "false empty" containers where contraband is hidden in containers that were declared as empty. Our framework is able to detect 90% (with fewer than 1-in-600 false alarms) of contraband, with size and density equivalent to a 1.5 kg package of cocaine, placed in an otherwise empty container. Specific threat detection is first demonstrated using cars as a threat model. We achieve 100% detection of cars, whilst raising 1-in-345 false alarms. The framework performs well on cases that are challenging for human operators, e.g. where cars are almost entirely occluded by other goods. Performance for other types of threats are also presented.

We believe that the performance of our framework makes it suitable for deployment in the field and could constitute a significant step towards the partial automation of X-ray cargo image inspection.

9847-23, Session 6

CT reconstruction via denoising approximate message passing

Alessandro Perelli, The Univ. of Edinburgh (United Kingdom); Michael A. Lexa, Ali Can, GE Global Research (United States); Mike Davies, The Univ. of Edinburgh (United Kingdom)

In aviation security, luggage is screened by computed tomography (CT) scanners in order to detect explosives and related materials. Object clutter and the presence of dense materials however complicate image reconstruction and detection. Dense objects cause artifacts (photon starvation) and clutter introduces ambiguity in material density estimation. In this paper, we adapt and apply a compressive reconstruction algorithm and compare its performance to the performance of traditional filtered back projection and to a state-of-the-art model based iterative reconstruction (MBIR) method. Specifically, we propose a variant of the denoising approximate message passing (DAMP) algorithm aiming to extend its applicability from the theoretical domain of i.i.d. random sensing matrices to deterministic ones and from sparse signal models to generically structured ones. DAMP is an iterative algorithm that at each iteration linearly estimates the conditional probability of the image given the measurements and employs a non-linear 'denoising' function which implicitly imposes an image prior. DAMP is well-suited to limited-view acquisitions and can incorporate many different structured signal models. In addition, the ability to use the best denoiser in a given situation (e.g. wavelets, total variation, or even state-of-the-art denoising algorithms such as BM4D) gives DAMP added flexibility not seen in other reconstruction algorithms. We aim to obtain accurate CT reconstruction on real luggage data and characterize convergence performance.

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9847-24, Session 6

Optimizing convergence rates of alternating minimization reconstruction algorithms for real-time explosive detection applications

Carl Bosch, SureScan Corp. (United States); Joseph A. O'Sullivan, David G. Politte, Washington Univ. in St. Louis (United States); Assaf Mesika, Jason Barlow, Soysal Degirmenci, SureScan Corp. (United States)

X-ray computed tomography reconstruction for medical, security and industrial applications has evolved through 40 years of experience with rotating gantry scanners using analytic reconstruction techniques such as filtered back projection (FBP). In parallel, research into statistical iterative reconstruction algorithms has evolved to apply to sparse view scanners in nuclear medicine, low data rate scanners in Positron Emission Technology (PET) and more recently to reduce exposure to ionizing radiation in conventional X-ray CT scanners. Multiple approaches to statistical iterative reconstruction have been developed based primarily on variations of expectation maximization (EM) algorithms. The primary benefit of EM algorithms is the guarantee of convergence that is maintained when iterative corrections are made within the limits of convergent algorithms. The primary disadvantage, however is that strict adherence to correction limits of convergent algorithms extends the number of iterations and ultimate timeline to complete a 3D volumetric reconstruction. Researchers have studied methods to accelerate convergence through more aggressive corrections [ref 1], ordered subsets [ref 2] and spatially variant image updates. In this paper we describe the development of an AM reconstruction algorithm with accelerated convergence for use in a real-time explosive detection application for aviation security. By judiciously applying multiple acceleration techniques and advanced GPU processing architectures, we are able to perform 3D reconstruction of scanned passenger baggage at a rate of 75 slices per second. Analysis of the results on stream of commerce passenger bags demonstrates accelerated convergence by factors of 8 to 15, when comparing images from accelerated and strictly convergent algorithms.

9847-25, Session 6

Rapid GPU-based simulation of x-ray transmission, scatter, and phase measurements for threat detection systems

Qian Gong, David Coccarelli, Razvan-Ionut Stoian, Joel A. Greenberg, Esteban Vera, Michael E. Gehm, Duke Univ. (United States)

Information-theoretic approaches to system analysis are appealing because they represent the ultimate performance limit of the architecture, without the confounding effects of processing algorithms. However, information-theoretic methods require very large amounts of data to properly estimate entropy-related quantities in high-dimensional spaces. To facilitate this approach, we have developed a very high throughput X-ray modeling framework based upon GPU technologies and have created three different versions focusing on transmission, scatter, and phase. All three frameworks allow analysis of arbitrary system configurations. The simulation of transmission imaging is based on a deterministic photoabsorption approach, which models the X-ray transmission through three-dimensional space via ray-tracing techniques and Beer's law. For the scatter framework, we extend the initial transmission approach to include scatter effects that are computed via the Born approximation, while for phase we modify the transmission framework to propagate complex ray amplitudes rather than radiometric quantities. The highly-optimized NVIDIA's OptiX API is used to implement the ray-tracing in all frameworks, greatly speeding up code execution. In addition, we address volumetric modeling of objects

via a hierarchical representation structure of triangle-mesh-based surface descriptions. X-ray transmission and phase images of complex 3D models can be simulated within seconds on a single desktop computer, while scatter images take approximately 30-60 minutes as a result of the significantly greater computational complexity. We will report on the status of all three simulation frameworks and their experimental validations.

9847-26, Session 6

Domain and range decomposition methods for coded aperture x-ray coherent scatter imaging

Ikenna Odinaka, Yan Kaganovsky, Duke Univ. (United States); Joseph A. O'Sullivan, David G. Politte, Washington Univ. in St. Louis (United States); Andrew D Holmgren, Duke University (United States); Joel A. Greenberg, Lawrence Carin, David J. Brady, Duke Univ. (United States)

Coded aperture X-ray coherent scatter imaging is a novel modality for ascertaining the molecular structure of an object. Measurements from different spatial locations and spectral channels in the object are multiplexed through a radiopaque material (coded aperture) onto the detectors. Iterative algorithms for recovering spatially-dependent coherent scatter spectral images break down the optimization problem into smaller and simpler problems. The smaller problems may be solved sequentially or in parallel. Domain decomposition methods break down the optimization problem via the image parameters whereas range decomposition methods break down the problem through the measurements. Examples of domain decomposition methods include majorization-minimization (MM) as used in algorithms such as penalized expectation maximization (EM), and spectrally-grouped edge-preserving reconstruction (SGEPR), fully separable in the image domain. Ordered subsets has been utilized in conjunction with image recovery algorithms to accelerate their convergence. Ordered subsets is a range decomposition method because it uses parts of the measurements, sequentially, to recover the image. Other range decomposition methods include distributed consensus ADMM. Unlike ordered subsets which uses parts of the measurements in a sequential fashion, distributed consensus ADMM uses the measurement parts in parallel. In this paper, we analyze domain and range decomposition methods as they apply to coded aperture X-ray coherent scatter imaging using a spectrally-grouped edge-preserving regularizer and discuss the implications of the abundance of parallel computational architecture on the choice of decomposition methods. We present results of applying the decomposition methods on experimental coded aperture X-ray coherent scatter measurements. We observe that updating different parts of the image or using different parts of the measurements in parallel, decreases the per-iteration rate of convergence, so that more iterations are needed for suitable convergence, whereas using the parts sequentially can accelerate the per-iteration rate of convergence.

9847-27, Session 7

Figures of merit for optimizing imaging systems on joint estimation/detection tasks (Invited Paper)

Eric W. Clarkson, The Univ. of Arizona (United States)

Three figures of merit for system performance on joint estimation/detection tasks in imaging are presented. The first is the EROC curve, which was described in a previous publication. The second is a generalization of Shannon Task Specific Information to the joint task. The third is the Bayesian Risk, which results from a cost analysis of the joint task. The risk-minimizing observer is shown to be the same as the observer that minimizes the area under the EROC curve. These figures of merit are used to show that optimizing for the joint task will decrease performance on the detection component.

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9847-28, Session 7

Information-optimal multiplex illumination design for x-ray threat detection

Liang-Chih Huang, The Univ. of Arizona (United States); Amit Ashok, College of Optical Sciences, The Univ. of Arizona (United States)

We present an information-theoretic design framework for multiplexed X-ray measurement design to detect threat(s) in passenger bags. Current X-ray threat-detection systems rely on a multiple fixed/moving sources to generate view diversity for 3-d bag reconstruction followed by threat detection. We adopt an alternative approach that exploits shape/material statistics of threat/stream-of-commerce items to make threat detection directly on measurements without an intermediate 3-d reconstruction. More specifically, we consider a direct detection method based on the likelihood ratio than enables a more flexible, multiplexed (source) measurement design to improve system resource utilization relative to non-multiplexed, sequential measurements. We employ the Cauchy-Schwartz mutual-information measure as our system design metric, which has a closed-form analytic expression for Poisson mixture class priors. This yields a computational tractable design optimization problem, which is solved using a steepest ascent method with an analytic gradient expression. Simulation studies are performed on synthetic bag ensembles created by a stochastic bag generator which generates bags comprised of randomly placed items with a variety of shapes/materials drawn from object/material libraries. Our simulation results show that the optimal multiplexed design achieves higher probability of detection for given false alarm rate and lower probability of error (i.e. average of type I and type II errors) for different source flux choices, relative to the non-multiplexed design using the same number of measurements. For example, the optimized multiplex design achieves a 99.7% threat detection probability relative to 88% for non-multiplexed design given a 5% false alarm rate.

9847-29, Session 7

Estimation and detection information trade-off for x-ray system optimization

Johnathan B. Cushing, College of Optical Sciences, The Univ. of Arizona (United States); Sagar Mandava, Eric W. Clarkson, Ali Bilgin, The Univ. of Arizona (United States)

Modern X-ray systems perform complex imaging tasks detect and estimate system parameters, such as a baggage system performing threat detection and creating reconstructions. This leads to a desire to optimize both the detection and estimation information of a system, but most metrics only focus on one aspect of system performance. When making design choices there is a need for a concise metric which considers both detection information and estimation information parameters, and then provides the user with the collection possible optimal outcomes.

In this paper a graphical analysis of Estimation and Detection Information Trade-off (EDIT) will be explored. EDIT produces curves which allow for a decision to be made for system optimization based on design constraints and costs associated with estimation and detection. EDIT analyzes the system in the estimation information and detection information space where the user is free to pick their own method of calculating these measures. The user of EDIT can choose any desired figure of merit for detection information and estimation information then the EDIT curves will provide the collection of optimal outcomes.

The paper will first look at two methods of creating EDIT curves. These curves can be calculated using a wide variety of systems and finding the optimal system by maximizing a figure of merit. EDIT could also be found as an upper bound of the information from a collection of system. These two methods allow for the user to choose a method of calculation which best fits the constraints of their actual system.

9847-30, Session 7

Robust x-ray based material identification using multi-energy sinogram decomposition

Yaoshen Yuan, Brian H. Tracey, Eric L. Miller, Tufts Univ. (United States)

There is growing interest in developing X-ray computed tomography (CT) imaging systems with improved ability to discriminate material types, going beyond the attenuation imaging provided by most current systems. Dual-energy CT (DECT) systems can partially address this problem by estimating Compton and photoelectric (PE) coefficients of the materials being imaged, but DECT is greatly degraded by the presence of metal or other materials with high attenuation. Here we explore the advantages of multi-energy CT (MECT) systems based on photon-counting detectors. The utility of MECT has been demonstrated in medical applications where photon-counting detectors allow for the resolution of absorption K-edges. Our primary concern is aviation security applications where K-edges are rare. We simulate phantoms with differing amounts of metal (high, medium and low attenuation), both for switched-source DECT and for MECT systems, and include a realistic model of detector energy resolution. We extend the DECT sinogram decomposition method of Ying et al. to MECT, allowing estimation of separate Compton and photoelectric sinograms. We furthermore introduce a weighting based on a quadratic approximation to the Poisson likelihood function that deemphasizes energy bins with low signal. Simulation results show that the proposed approach succeeds in estimating material properties even in high-attenuation scenarios where the DECT method fails, improving the signal to noise ratio of reconstructions by over 20 dB for the high-attenuation phantom. Our work demonstrates the potential of using photon counting detectors for stably recovering material properties even when high attenuation is present, thus enabling the development of improved scanning systems.

9847-31, Session 7

Investigation of spectral feature variations in x-ray diffraction imaging systems

Scott D. Wolter, Elon Univ. (United States); Joel A. Greenberg, Duke Univ. (United States)

Materials with different atomic or molecular structures give rise to different scatter spectra when measured via X-ray diffraction. The details of these spectra, though, can vary based on both intrinsic (e.g., degree of crystallinity or doping) and extrinsic (e.g., pressure or temperature) conditions. While this sensitivity is useful for detailed characterization of the material properties of a sample, these dependences make it difficult to perform more general classification tasks, such as explosives threat detection in aviation security. A number of challenges therefore currently exist for reliable substance detection including the similarity in spectral features among some categories of materials combined with the spectral feature variations from materials processing and environmental factors. These factors complicate the creation of a material dictionary and the implementation of conventional classification and detection algorithms. In this presentation, we report on two prominent factors that lead to variations in spectral features: crystalline texture and temperature changes. A Bruker D2 Phasor diffractometer was used to obtain reference spectra for over 400 substances. Spectral feature comparisons between materials categories will be described, including solid and liquid oxidizers, flammables, and commercial goods. Among the solid substances, feature variations from processing-induced deformation texturing, strain, and phase transformations may be observed and those substances exhibiting these will be reported. While liquids are largely immune to these effects, they are susceptible to temperature changes that can modify their density or produce phase changes. We will describe in situ temperature-dependent measurement of aqueous-based commercial goods and aqueous organic solvent mixtures in the temperature range of -20°C to 50°C. Finally, we will report on aperture size effects on texturing in common metals and powders.

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9847-32, Session 7

**Impact of detector geometry for
compressive fan beam snapshot coherent
scatter imaging**Mehadi Hassan, Andrew D. Holmgren, Joel A. Greenberg,
Ikenna Odinaka, David J. Brady, Duke Univ. (United States)

Previous realizations of coded-aperture X-ray diffraction tomography (XRDT) techniques based on pencil beams image one line through an object via a single measurement but require raster scanning the object in multiple dimensions. Fan beam approaches are able to image the spatial extent of the object but cannot do material identification at every voxel. Building on these approaches we present our system concept and geometry of combining a fan beam with new energy sensitive detectors and a coded aperture to capture both spatial and material information about the object at each voxel. The system is compressive as we estimate two spatial positions and a momentum transfer spectra at each voxel from a 2D measurement of a photon's energy and one spatial position. We experimentally characterize the system's resolution (1.5 x 15mm spatial and 10% momentum transfer) and also discuss the system dependence on the incident flux.

Using our system we image slices via snapshot measurements and volumes by linearly translating objects through the fan beam to produce 3D and 4D images of the object, respectively, noting that there is a 1D spectral component to each image. The system also captures both spatial and material information at each voxel which is an improvement from previous fan beam designs. Additionally, we study the impact of different detector configurations on image quality and also discuss our findings on the computational resources required for modeling and signal processing.

9847-35, Session 7

**Partially observable Markov decision
processes for risk-based screening**Alex Mrozack, Sondre Skatter, Morpho Detection (United
States); Xuejun Liao, Duke University Department of
Electrical and Computer Engineering (United States);
Lawrence Carin, Duke Univ. (United States)

No Abstract Available

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9848-1, Session 1

The changing paradigm for integrated simulation in support of command and control (C2)

Mark Riecken, Trideum Corp. (United States); Michael R. Hieb, George Mason Univ. (United States)

Modern software and network technologies are on the verge of enabling what has eluded the simulation and operational communities for more than two decades, truly integrating simulation functionality into operational Mission Command or Command and Control (C2) capabilities. This deep integration will benefit multiple stakeholder communities from experimentation and test to training to combat operations by providing predictive and advanced analytics. While it is true that doctrinal and acquisition issues remain to be addressed, nonetheless it is increasingly obvious that few technical barriers persist. How will this change the way in which common simulation and operational data is stored and accessed? As the Services move towards single networks, will there be technical and policy issues associated with sharing those operational networks with simulation data, even if the simulation data is operational in nature (e.g., associated with planning)? How will data models that have traditionally been simulation only be merged in with operational data models? How will the issues of trust be addressed? The Simulation to Mission Command Interoperability Overarching Integrated Product Team (SIMCI OIPT), co-chaired by Program Executive Offices of Simulation Training, and Instrumentation (PEO STRI) and Command, Control, and Communications – Tactical (C3T) has facilitated the development of prototypes in both Course Of Action Analysis (COAA) and Running Estimates (RE). These prototypes have demonstrated to the community and based on this, we provide a practical framework that will further a systematic discussion and a way forward.

9848-2, Session 1

Collaboration between human and nonhuman players in night vision tactical trainer-shadow

Stephen T. Berglie, KINEX (United States)

The Night Vision Tactical Trainer - Shadow (NVTT-S) is a U.S. Army-developed training tool designed to improve critical Manned-Unmanned Teaming (MUMT) communication skills for payload operators in Unmanned Aerial Sensor (UAS) crews. The trainer is composed of several Government Off-The-Shelf (GOTS) simulation components and takes the trainee through a series of escalating engagements using tactically relevant, realistically complex, scenarios involving a variety of manned, unmanned, aerial, and ground-based assets. The trainee is the only human player in the game and he must collaborate, from his web-based mock operating station, with various non-human players via spoken natural language over simulated radio in order to execute the training missions successfully. Non-human players are modeled in two complementary layers -- OneSAF provides basic background behaviors for entities while NVTT provides higher level models that control entity actions based on intent extracted from the trainee's spoken natural dialog with game entities. Dialog structure is modeled based on Army standards for communication and verbal protocols. This paper presents an architecture that integrates the U.S. Army's Night Vision Image Generator (NVIG), One Semi-Automated Forces (OneSAF), a flight dynamics model, as well as Commercial Off The Shelf (COTS) speech recognition and text to speech products to effect an environment with sufficient entity counts and fidelity to enable meaningful teaching and reinforcement of

critical communication skills. It further demonstrates the model dynamics and synchronization mechanisms employed to execute purpose-built training scenarios, and to achieve ad-hoc collaboration on-the-fly between human and non-human players in the simulated environment.

9848-3, Session 1

Reducing acquisition risk through integrated systems of systems engineering

Andrew W. Gross, Brian Hobson, Trideum Corp. (United States); Christina L. Bouwens, MSCI (United States)

In the fall of 2015, the Joint Staff J7 sponsored Bold Quest (BQ) 15.2 event and the Army's Warfighting Assessment (AWA) 16.1 combined a Joint and Multinational capability assessment with components of testing, training, and experimentation. In support of ASA (ALT) SOSE&I, Always On-On Demand (AO-OD) participation helped to mitigate developmental system risk, provided an environment to evaluate new operational concepts and enhanced live and simulation supported pre-deployment training activities during this complex and challenging exercise environment.

AO-OD executed a requirements-based systems engineering process beginning with user needs and objectives from Integrated Air and Missile Defense (IAMD), Patriot Crew Training Support, Coalition ISR (C-ISR), Focused End State 4 (FES4) Mission Command Interoperability with Unified Action Partners (UAP), Mission Partner Environment (MPE) integration (aka MC system) and TTP assessment (in support of a new system under development). The SE process assessed and decomposed the common operational, analytical, and technical requirements so the IEEE Distributed Simulation Engineering and Execution Process (DSEEP) could provide structured accountability for the integration and execution of the AO-OD Live, Virtual, Constructive Development Environment (LVC-DE). As a result, AO-OD successfully planned for, prepared, executed a complex system of systems distributed simulation support environment that satisfied user needs and objectives.

9848-4, Session 1

Decision support for simulation-based operation planning

Johan Schubert, Pontus Hörling, FOI-Swedish Defence Research Agency (Sweden)

In this paper, we develop methods for analyzing large amounts of output data from simulations in a multiple-criteria decision support system focused on answering a commander's specific questions regarding force configuration, outcomes, etc., in military operational planning.

We assume data farming simulations with multiple evaluation criteria have taken place. Before addressing the commander's decision support, we must perform the multiple-criteria analysis and focus the entire data set such that it provides answers to specific questions of importance.

To provide decision support for a commander's specific questions in operation planning, we perform a sequence of process steps at several levels. From a top-level perspective, we first do scenario development, modelling, and simulation, followed by data analysis and decision support in a data farming approach. The final step of decision support goes a step beyond what is traditionally performed in statistical analysis within data farming. We think of this as data farming's decision support mode. In the operation planning problem that we study we have up to ten different measures of effectiveness (MOE). Thus, we need to manage a multiple-

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criteria decision making process. This is handled by preference analysis of the MOEs, followed by a Monte Carlo weight assignment process. With this approach we can avoid the difficult problem of weight assignment by human analysts and decision makers, although final adjustments by analysts may be necessary. With these two processes completed, we can focus on decision support. We further divide decision support into three sub-processes: one the Analyst View process, which is similar to the traditional statistical analysis usually performed in data farming; one the Commander's Overview process, which is focused on the big picture of how to win in military combat; and one the Commander's Specific Questions process, focusing on more specific questions of when we will win in different specific situations. Our focus in this paper is on the Commander's Specific Questions process. All other processes are discussed in other papers.

We give a short overview of the data farming approach used to perform the simulations. The ground warfare scenario under study is described. The main focus of this paper is on developing methods for data analysis and decision support for a commander. We begin with a process overview description that puts the work of this paper into the context of previous work, and then move to the commander's specific questions, which are answered through a series of statistical and visualization methods for specific subsets of all simulation runs.

In conclusion, we presented a process view of data analysis, where we develop and use ranking methods to identify the most advantageous simulation runs and use them to focus the data set such that specific questions regarding topics of interest to a decision maker can be put forward and answered. We think that this approach is a first step towards taking the data farming methodology from its traditional analytical view into an operation planning context and a decision-making mode.

9848-5, Session 2

Enabling power-aware software in embedded systems

James Bonnett, Aaron L. Paolini, EM Photonics, Inc. (United States)

Advances in mobile technology in recent years have enabled a new class of powerful yet inexpensive computing platforms, uniquely suited for use in military embedded systems. Unfortunately, the pace of development has far outstripped that of battery technology, yielding powerful devices with severely limited utility in deployment scenarios. Efforts are underway to develop tools to monitor and control power consumption so as to minimize waste and so offset this deficiency in capability with gains in efficiency. Various controls exist in the Linux kernel which may be used to affect power consumption, but these are fragmented and unstandardized. Rather than enact global system states or policies, we assert that it is more effective for embedded applications to dictate the level of performance required dynamically, as determined by the developer, thus improving temporal granularity of control. Our approach implements an integrated software interface to these system controls to enable power-aware programming, allowing developers to indicate a spectrum of intent with regard to performance/economy tradeoff using intuitive directives, similar in practice to OpenMP. These directives are interpreted by a modified Clang compiler and relayed to a user-space runtime which enacts control over system hardware. This approach allows flexibility in that pre-existing code can be instrumented in a non-invasive manner, and that instrumented code can be executed on other platforms without loss of compatibility.

9848-6, Session 2

The Osseus platform: a prototype for advanced web-based distributed simulation

Derrick Franceschini, Stackframe LLC (United States); Mark Riecken, Trideum Corp. (United States)

Recent technological advances in web-based distributed computing and database technology have made possible a deeper and more transparent integration of some modeling and simulation applications. Despite these advances towards true integration of capabilities, disparate systems, architectures, and protocols will remain in the inventory for some time to come. These disparities present interoperability challenges for distributed modeling and simulation whether the application is training, experimentation, or analysis. Traditional approaches call for building gateways to bridge between disparate protocols and retaining interoperability specialists. Challenges in reconciling data models also persist. These challenges and their traditional mitigation approaches directly contribute to higher costs, schedule delays, and frustration for the end users. Osseus is a prototype software platform originally funded as a research project by the Defense Modeling & Simulation Coordination Office (DMSCO) to examine alternatives using modern, web-based technology and taking inspiration from the commercial sector. Osseus provides tools and services for non-expert users to connect simulations, targeting the time and skill-set needed to successfully connect disparate systems. The Osseus platform presents a web services interface to allow simulation applications to exchange data using modern techniques efficiently over Local or Wide Area Networks. Further, it provides Service Oriented Architecture (SOA) capabilities such that finer granularity components such as individual models can contribute to simulation with minimal effort. We discuss quantitative results from experiments using the prototype platform with OneSAF and a Unity-engine based virtual game engine over commercial networks.

9848-7, Session 2

Many-core graph analytics using accelerated sparse linear algebra routines

Aaron L. Paolini, EM Photonics, Inc. (United States)

Graph analytics is a key component in identifying emerging trends and threats in many real-world applications. Large-scale graph analytics frameworks provide a convenient and intuitive platform for developing algorithms to analyze large datasets. Although conceptually scalable, these techniques exhibit poor performance on modern computational hardware. Another model of graph computation has emerged that promises improved performance and scalability by using abstract linear algebra operations as the basis for graph analysis as laid out by GraphBLAS. By mapping graph problems into sparse linear algebra, existing highly efficient algorithms can be adapted to perform computations on the graph. This approach, however, is often less intuitive to graph analytics experts, who are accustomed to vertex-centric APIs such as Giraph, GraphX, and Tinkerpop. We are developing an implementation of the high-level operations supported by these APIs in terms of linear algebra operations, which will be parallel on each pair of vertices connected by an edge. This implementation is backed by many-core implementations of the fundamental GraphBLAS operations required and offers the advantages of both the intuitive programming model of a vertex-centric API and the performance potential of a sparse linear algebra implementation. This technology can reduce the number of nodes required as well as the run-time for a graph analysis problem, enabling customers to perform more complex analysis with less hardware at lower cost. All of this can be accomplished without the requirement for the customer to make any changes to their analytics code thanks to the compatibility with existing graph APIs.

9848-8, Session 2

Low-tubal-rank Tensor Completion using Alternating Minimization

Xiao-Yang Liu, Columbia Univ. (United States); Shuchin Aeron, Tufts Univ. (United States); Vaneet Aggarwal, Purdue Univ. (United States); Xiaodong Wang, Columbia Univ. (United States)

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The low-tubal-rank tensor is recently proposed as a tool for modeling multi-linear real-world data. In this paper, we present novel algorithms for completion of tensors with low tubal rank using an alternating minimization approach. In the proposed approach, the unknown low-rank tensor is expressed as the product of two much smaller tensors where the low-rank property is automatically incorporated. Its theoretical guarantees are of interest and are poorly understood because this heuristic is iterative and non-convex in nature. We prove that the alternating minimization algorithm guarantees convergence to the global optima at a geometric rate. Second, we derive the required sampling complexity for low error. This approach gives a new method with low complexity to the convex relaxations of the objective, that has been solved using an ADMM approach.

9848-9, Session 2

3D Intel architecture-based reconfigurable SoC for high performance embedded computing

George Dekoulis, Middle East Technical Univ. (Turkey)

This paper describes the development of a new three-dimensional System-on-Chip (SoC) for timing-critical reconfigurable Defense applications. The system implementation is primarily based on the design from scratch of advanced Intel-based Computer Architecture principles using VHDL. The final design is a mixture of various Intel's approaches in handling timing-critical high-performance computing applications. The proposed implementation features a significant improvement in terms of performance over the original Intel specifications. The user selects either a classic 8-bit interface or the new 64-bit interface, which offers direct connectivity to modern 64-bit embedded microprocessors. Both reprogrammable and reconfigurable instructions are supported to fully exploit the capabilities of the new SoC. Various interfaces are being used to provide connectivity to external devices, such as global positioning receivers and existing reconfigurable Defense instruments. The system is ideal for remote applications, scientific campaigns and multiple communications receiver architectures with a geographical displacement between them.

9848-10, Session 3

The expected results method for data verification

Paul Monday, Trideum Corp. (United States)

The credibility of US Army analytical experiments using distributed simulation depends on the quality of the simulation, the pedigree of the input data, and the appropriateness of the simulation system to the problem. The second of these factors is best met by using classified performance data from the Army Materiel Systems Analysis Activity (AMSAA) for essential battlefield models, like sensors, weapon fire, and damage assessment.

Until recently, using classified data has been a time-consuming and expensive endeavor: it requires significant technical expertise to load, and it is difficult to verify that it works correctly. Fortunately, new capabilities, tools, and processes are available that greatly reduce these costs. This paper will discuss these developments, a new method to verify that all of the components are configured and operate properly, and the application to recent Army Capabilities Integration Center (ARCIC) experiments.

Three recent developments have focused improving the process to load the data. OneSAF has redesigned their input data file formats and structures so that they correspond exactly with the Standard File Format (SFF) defined by AMSAA, ARCIC developed a library of supporting configurations that correlate directly to the AMSAA nomenclature, and the Entity Validation Tool was designed to quickly execute the essential models with a test-jig approach to identify problems with the loaded data.

The missing part of the process is provided by the new Expected Results Method. Instead of the usual subjective assessment of quality, e.g., "It looks

about right to me", this new approach compares the performance of a combat model with authoritative expectations to quickly verify that the model, data, and simulation are all working correctly.

Integrated together, these developments now make it possible to use AMSAA classified performance data with minimal time and maximum assurance that the experiment's analytical results will be of the highest quality possible.

9848-11, Session 3

Modeling and simulation of evacuation behavior using fuzzy logic in a goal finding application

Sharad Sharma, Kola Ogunlana, Swetha Sree, Bowie State Univ. (United States)

Modeling and simulation has been widely used as a training and educational tool for depicting different evacuation strategies and damage control decisions during evacuation. However, there are few simulation environments that can include human behavior with low to high levels of fidelity. It is well known that crowd stampede induced by panic leads to fatalities as people are crushed or trampled. Our proposed goal finding application can be used to model situations that are difficult to test in real-life due to safety considerations. It is able to include agent characteristics and behaviors. The findings of this modeling are very encouraging as the agents are able to assume various roles to utilize fuzzy logic on the way to reaching their goals. Fuzzy logic is used to model stress, panic, and the uncertainty of emotions. The fuzzy rules link these parts together while feeding into behavioral rules. The contributions of this paper lies in our approach of utilizing fuzzy logic to show learning and adaptive behavior of agents in a goal finding application. The proposed application will aid in running multiple evacuation drills for what-if scenarios by incorporating human behavioral characteristics that can scale from a room to a building. Our results show that the inclusion of fuzzy attributes made the evacuation time of the agents closer to the real time drills.

9848-12, Session 3

Operational planning using Climatological Observations for Maritime Prediction and Analysis Support Service (COMPASS)

Alison OConnor, Charles River Analytics, Inc. (United States); Ben Kirtman, Univ. of Miami (United States); Scott A. Harrison, Joe Gorman, Charles River Analytics, Inc. (United States)

Current US Navy forecasting systems cannot easily incorporate extended-range forecasts that can improve mission readiness and effectiveness; ensure safety; and reduce cost, labor, and resource requirements. If Navy operational planners had systems that incorporated these forecasts, they could plan missions using more reliable and longer-term weather and climate predictions.

Using extended-range multi-model forecast ensembles, such as those available in the North American Multi-Model Ensemble (NMME), instead of single forecasts would produce higher predictive performance. However, even higher skill predictions can be produced if forecast model ensembles are combined correctly.

Our paper presents an innovative approach that uses machine learning to combine extended-range predictions from multi-model forecast ensembles and generate a probabilistic forecast for any region of the globe up to 12 months in advance. Using 30 years of hindcast predictions, we learn patterns of forecast model successes and failures and assign weights to each environmental condition, 100 km² region, and day given expected

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environmental information. These weights are used to effectively stitch together a single, coherent probabilistic forecast for the region and time period of interest.

Our experimental results demonstrate the benefits of our approach to produce extended-range probabilistic forecasts for mission-specific regions and time periods that are superior, in terms of skill, to individual NMME forecast models and commonly weighted models. As demonstrated by the results of our testing, naval planners and decision-makers would benefit from using our unified extended-range forecast instead of multiple individual forecasts. Other key findings include: weighted combinations of models are strictly better than individual models; machine-learned combinations are especially better; and forecasts produced using our approach have the highest rank probability skill score most often.

9848-13, Session 3

Internet of things: a possible change in the distributed modeling and simulation architecture paradigm

Mark Riecken, Kurt Lessmann, Trideum Corp. (United States); David Schillero, Trideum (United States)

The Data Distribution Service (DDS) was started by the Object Management Group (OMG) in 2004. Currently, DDS is one of the contenders to support the Internet of Things (IOT) and the Industrial IOT (II). DDS has also been used as a distributed simulation architecture. Given the anticipated proliferation of IOT and II devices, along with the explosive growth of sensor technology, can we expect this to have an impact on the broader community of distributed simulation? If it does, what is the impact and which distributed simulation domains will be most affected? DDS shares many of the same goals and characteristics of distributed simulation such as the need to support scale and an emphasis on Quality of Service (QoS) that can be tailored to meet the end user's needs. In addition, DDS has some built-in features such as security that are not present in traditional distributed simulation protocols. If the IOT and II realize their potential application, we predict a large base of technology to be built around this distributed data paradigm, much of which could be directly beneficial to the distributed M&S community. In this paper we compare some of the perceived gaps and shortfalls of current distributed M&S technology to the emerging capabilities of DDS built around the IOT. Although some trial work has been conducted in this area, we propose a more focused examination of the potential of these new technologies and their applicability to current and future problems in distributed M&S.

9848-14, Session 3

On using multiple routing metrics with destination sequenced distance vector protocol for MultiHop wireless ad hoc networks

Miralem Mehic, V?B-Technical Univ. of Ostrava (Czech Republic); Peppino Fazio, Univ. della Calabria (Italy); Miroslav Voznak, V?B-Technical Univ. of Ostrava (Czech Republic); Pavol Partila, Dept. of Telecommunications, VSB-Technical University of Ostrava (Czech Republic); Dan Komosny, Dept. of Telecommunications, Brno University of Technology (Czech Republic); Jaromir Tovarek, Zdenka Chmelikova, Dept. of Telecommunications, VSB-Technical University of Ostrava (Czech Republic)

A mobile ad hoc network is a collection of mobile nodes which communicate without a fixed backbone or centralized infrastructure. Due to the frequent mobility of nodes, routes connecting two distant nodes may change. Therefore, it is not possible to establish a priori fixed paths for message delivery through the network. Because of its importance, routing is the most studied problem in mobile ad hoc networks. In addition, if the Quality of Service (QoS) is demanded, one must guarantee the QoS not only over a single hop but over an entire wireless multi-hop path which may not be a trivial task. In turns, this requires the propagation of QoS information within the network. The key to the support of QoS reporting is QoS routing, which provides path QoS information at each source. To support QoS for real-time traffic one needs to know not only minimum delay on the path to the destination but also the bandwidth available on it. Therefore, throughput, end-to-end delay, and routing overhead are traditional performance metrics used to evaluate the performance of routing protocol. To obtain additional information about the link, most of quality-link metrics are based on calculation of the lost probabilities of links by broadcasting probe packets. In this paper, we address the problem of including multiple routing metrics in existing routing packages that are periodically broadcasted through the network. We evaluate the efficiency of such approach with modified version of DSDV routing protocols in NS3 simulator.

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9849-1, Session 1

Open mission systems: collaborations among collaborations *(Invited Paper)*

Eric Koper, U.S. Air Force (United States)

No Abstract Available

9849-2, Session 1

Sensor Open System Architecture (SOSA) *(Invited Paper)*

Charles Collier, Air Force Research Lab. (United States)

The Sensor Open System Architecture (SOSA) is a technical and economic collaborative effort between the C4ISR community, the Air Force, the Department of Defense (DoD), Industry, and other governmental agencies to maximize C4ISR sub-system, system, and platform affordability, re-configurability, overall performance, and hardware/software/firmware re-use. The SOSA effort will effectively create an operational framework for the integration of disparate payloads into C4ISR systems; with a focus on the development of a functional decomposition for a common multi-purpose backbone architecture for a series of sensor modalities that include: hardware, software, and mechanical/electrical interfaces. The functional decomposition will produce a set of re-useable components, interfaces, and sub-systems that engender re-usable capabilities. This in effect creates a realistic and affordable sense of mission effectiveness through systematic re-use of all available re-composed hardware, software, and electrical/mechanical base components and interfaces.

9849-3, Session 1

Enabling agile manufacturing in ISR through open architecture *(Invited Paper)*

Mark DiPadua, Air Force Research Lab. (United States)

No Abstract Available

9849-4, Session 1

Interoperability in open architecture radar, an MBE/OMS instance *(Invited Paper)*

Neil R. Young, Kenneth S. Reese, General Dynamics Mission Systems (United States)

The Department of Defense has placed a priority on reducing costs and increasing competition in acquisition via Open Architecture systems principles.

Two Open Architecture efforts are the Air Force Rapid Capabilities Office (AFROC) Open Mission Systems (OMS) and the Air Force Research Laboratory (AFRL) Modular Open Systems Approach (MOSA) Back End for RF Systems (MBE-RF) initiatives.

The OMS Open Architecture seeks to "develop and demonstrate a consensus-based, non-proprietary, open architecture for integrating sub-systems and services into airborne platforms." The effort aims "to

reduce acquisition and life-cycle costs as well as the need to reduce the risks associated with development, sustainment, technology refresh, and capability upgrades of mission system architectures on weapon systems."

The MBE Reference Architecture "defines a MOSA design framework for Radio Frequency back end processing systems from which many different MBE system instances can be realized." The purpose of which is to "define and standardize both the basic functional components of an archetype back end processing system and the interactions of those components with each other or with external systems."

However, these OA efforts are not necessarily compatible simply by being "Open". OMS focuses on the airborne platform, an external system to MBE, and the entire MBE "system" addresses the sensor, a subsystem to OMS. This work explores the architecture mapping efforts needed to achieve interoperability between components of an OMS system and an MBE system instance. It also presents a practical demonstration of an OMS-controlled, MBE-based GMTI radar signal processing system.

9849-5, Session 1

Open architecture design for high performance computing *(Invited Paper)*

Ryan K. Hersey, Georgia Tech Research Institute (United States)

No Abstract Available

9849-6, Session 2

The integrated ISR enterprise *(Invited Paper)*

Jeffrey Eggers, U.S. Air Force (United States)

No Abstract Available

9849-7, Session 2

Next Generation Space Interconnect Standard (NGSIS): A modular open standard approach for high performance computing and interconnects in space *(Invited Paper)*

Charles Collier, Air Force Research Lab. (United States)

This paper describes the Next Generation Space Interconnect Standard (NGSIS) effort. This description covers the goals and objectives of the NGSIS effort, the composition of the NGSIS participants, and the approach and roadmap being used for the NGSIS effort and the current status. NGSIS is a Government-Industry collaboration effort to define a set of standards for interconnects between space system components with the goal of cost effectively removing bandwidth as a constraint for future space systems. Initial emphasis is on the standardization of internal connectivity at the electronic chassis level. This includes the needs for high reliability but limited rate data needs typical for spacecraft command and data handling (C&DH) as well as high rate data needs expected for next generation, high performance mission payloads.

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The architectural approach adopted for NGSIS development was to select several appropriate and proven industry standards as “points of departure” and then develop a set of extensions to these standards to address space industry specific needs. The intent of this approach is reduced cost, risk and effort by using proven technologies, while providing a set of common extensions that can be adopted across the space industry to enable interoperability of board level components from different sources and vendors. The NGSIS team selected the VMEbus International Trade Association (VITA) OpenVPX standard family for the physical baseline. VPX supports both 3U and 6U form factors with ruggedized and conduction cooled features suitable for use in extreme environments for chassis and the boards that fit inside of them. So it is evident then that this type of modular (MOSA) solution is at the chassis or box level. It is also evident that the modularity carries across physical chassis boundaries in a manner befitting a distributed modular architecture. A synopsis of this effort describes board and chassis level functions that are essentially flexible building blocks for system design.

The RapidIO (RIO) protocol was selected as the base protocol for the digital data transport. The RIO protocol uses an efficient, high performance packet switching architecture to provide an interconnect capability suitable for chip-to-chip and board-to-board communications. Data rates are scalable per lane up to a current maximum of 6.25 Gbps (gross bit rate) and allow aggregations of lanes into channels with capacities from 40Gbps (8 lanes of traffic) to 80 Gbps (16 lanes of traffic), with a roadmap to higher rates in the future. Current efforts to develop the space specific extensions for improved reliability, robustness and additional features desirable for space systems were worked through the establishment of the “RIO Space Class Device” task group by the RapidIO Trade Association as a collaboration effort with NGSIS participants.

9849-8, Session 2

A REST-ful interpretation for embedded modular systems based on open architecture *(Invited Paper)*

James C. Lyke, Air Force Research Lab. (United States)

No Abstract Available

9849-9, Session 3

Open architecture for rapid deployment of capability *(Invited Paper)*

Jacob Glassman, Naval Sea Systems Command (United States)

Modern warfare has drastically changed from conventional to non-conventional and from fixed threats to dynamic ones over the past several decades. This unprecedented fundamental shift has now made our adversaries and their weapons more nebulous and ever changing. Our current acquisition system however is not suited to develop, test and deploy essential capability to counter these dynamic threats in time to combat them. This environment requires a new infrastructure in our system design to rapidly adopt capabilities that we do not currently plan for or even know about. The key to enabling this rapid implementation is Open Architecture in acquisition.

The DoD has shown it can rapidly prototype capabilities such as unmanned vehicles but has severely struggled in moving from the prototyping to deployment. A major driver of this disconnect is the lack of established infrastructure to employ said capability such as launch and recovery systems and command and control. If we are to be successful in transitioning our rapid capability to the warfighter we must implement established well defined interfaces and enabling technologies to facilitate the rapid adoption of capability so the warfighter has the tools to effectively counter the threat.

9849-11, Session 3

Executable architecture management system *(Invited Paper)*

Jeff W. Monroe, Metron, Inc. (United States)

The Problem – There exists a DoD requirement for all large military programs to document the current state of their program and the expected program end state using DoDAF. This requirement has resulted in the wide use of existing commercial software such as System Architect to create DoDAF views in a manual manner. This approach often has the following issues:

- Costly time and manpower requirements due to need for manual creation of new views and changes to existing views to adjust for architecture changes;
- The lack of existing software optimized for the handling of the visualization, storage, or batch editing of the data involved for a large military program.
- It is time consuming, expensive and error prone for a model to be manually built and executed based on existing architecture documents.

The Solution – ExAMS solves both problems of how to build architectures and how to efficiently assess them by focusing on the representation, storage, and editing of the underlying data as well as the relationships between data elements. ExAMS avoids the standard method of manually creating views as much as possible by automatically generating them from the underlying data. This allows for a change in one part of the architectural data set to automatically propagate into all views constructed from that data. This concept makes it possible to cover the wide range of evolving DoDAF view points as well as easily customizing “Fit For Purpose Views”.

Additionally, the focus on correctly representing the underlying data and relationships allows ExAMS to store and link non-architecture data, which is typically required for simulations to be run. This allows for automatic connection of architectures to a Monte Carlo simulation system with the minimal extra work, allowing the architecture to be loaded into the simulation,

The Value – ExAMS provides significant value across all ACAT programs within the DoD and addresses all of the issues previously mentioned of the current standard. It has the potential of adding a level of automation to the construction and assessment of architecture products for significant programs of records. This would reduce errors, save money, and allow for quicker turnaround of architectures. Additionally the architectures could be executed and evaluated within the context of a warfighting scenario allowing decision makers to evaluate architecture alternatives.

9849-12, Session 3

Reaping the benefits of an open systems approach: getting the commercial approach right *(Invited Paper)*

Gavin Pearson, Defence Science and Technology Lab. (United Kingdom); Anthony Dawe, Peter Stubbs, IBM Corp. (United Kingdom); Olwen Worthington, Defence Science and Technology Lab. (United Kingdom)

Critical to reaping the benefits of an Open System Approach within Defence, or any other sector, is the ability to design the appropriate commercial model (or framework). This paper reports on the development and testing of a commercial model decision support tool. The tool set comprises a number of elements, including a process model, and provides business intelligence insights into likely supplier behaviour. The tool has been developed by subject matter experts and has been tested with a number of UK Defence procurement teams.

The paper will present the commercial model framework, the elements of the toolset and the results of testing.

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9849-13, Session 4

Secure and interoperable communication infrastructures for PPDR organisations
(Invited Paper)

Wilmuth Müller, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany); Hugo Marques, Univ. de Aveiro (Portugal); Frank Brouwer, FIGO B.V. (Netherlands); Bert Bouwers, Rohill Engineering B.V. (Netherlands); Luis Pereira, Instituto de Telecomunicações (Portugal); Jonathan Rodriguez, Instituto de Telecomunicações Aveiro (Portugal); Ilias Politis, Asimakis Lykourgiotis, University of Patras (Greece); Olayinka Adigun, Alexandros Ladas, Kingston University (United Kingdom); David Jelenc, University of Ljubljana (Slovenia)

The growing number of events affecting public safety and security (PS&S) on a regional scale with potential to grow up to large scale cross border disasters puts an increased pressure on agencies and organization responsible for PS&S. In order to respond timely and in an adequate manner to such events Public Protection and Disaster Relief (PPDR) organizations need to cooperate, align their procedures and activities, share the needed information and be interoperable.

Existing PPDR/PMR technologies do not provide broadband capability, which is a major limitation in supporting new services hence new information flows and currently they have no successor. There is also no known standard that addresses interoperability of these technologies.

In this contribution the design of a next generation communication infrastructure for PPDR organizations which fulfills the requirements of secure and seamless end-to-end communication and interoperable information exchange within the deployed communication networks is presented. Based on Enterprise Architecture of PPDR organizations, a next generation PPDR network that is backward compatible with legacy communication technologies is designed and implemented which will provide security, privacy, seamless mobility, QoS and reliability support for mission-critical Private Mobile Radio (PMR) voice and broadband data services.

The designed solution will provide a robust, reliable, and secure mobile broadband communications system for a wide variety of PMR applications and services on PPDR broadband networks, including the ability of inter-system, inter-agency and cross-border operations with emphasis on interoperability between users in PMR and LTE.

9849-14, Session 4

Continuing the march: the past, present, and future of the Internet of Things in the military
(Invited Paper)

Joe Mariani, Deloitte Services LP (United States); Brian T. Williams, Brett Loubert, Deloitte Consulting LLP (United States)

The Internet of Things (IoT) is the generic term for architectures that link data about the physical world to digital tools for analyzing and exploiting that data for use back in the world. While taking the commercial world by storm, the term is rarely heard in connection with military or government uses. As a result, leaders are left without clear insight into whether IoT architectures would be beneficial to them or what changes they may cause to defense or government organizations.

Using the Information Value Loop Framework, this article investigates how the connection of sensors, communication devices, databases, analytics engines, and visualization tools that make up the IoT can produce quantitative benefit for the military. We break down examples into three categories based on the critical need of defense organizations, use the

Information Value Loop to identify critical bottlenecks to the flow of information, and provide specific recommendations for the appropriate actions each category of organization may take.

9849-15, Session 7

Open architecture applied to weapon technologies
(Invited Paper)

Jonathan D. Shaver, Air Force Research Lab. (United States)

No Abstract Available

9849-16, Session 7

Blue guardian update
(Invited Paper)

Donald Barrett, Air Force Research Lab. (United States)

No Abstract Available

9849-17, Session 7

Open systems architectures for Autonomous Underwater Vehicles (AUVs) within the DoD
(Invited Paper)

Mark E. Rothgeb, Applied Research Lab. (United States)

With the rapid increase in the number and capabilities of autonomous vehicles in ground and air regimes, industry is rapidly innovating to satisfy the needs of commercial application spaces across a broad set of industries (e.g. farming, movie-making, sports coverage) and services (e.g. surveying, delivery, hazardous materials handling). Simultaneously, open systems approaches as typified by the Robot Operating System (ROS), Mission Oriented Operating Suite (MOOS), and Gazebo (for simulation) within the larger robotic community are rapidly expanding allowing for leveraging robotic platforms with pre-built services to be employed effectively. Despite these advances, complex systems within the DoD community are often built as vertical applications with vendor lock-in to proprietary API's to the robotic platforms as well as to sensors, mission services, and command and control interfaces. Some efforts to promote an open systems approach and avoid these vertical solutions are occurring within the DoD community including the Naval Sea Systems Command "Advance Explosive Ordnance Disposal Robotic System" (AEODRS) and the DARPA/ONR "Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel" (ACTUV) programs. Each of these struggle with various aspects of their respective open systems approaches. What are the lessons learned from these programs and how should the DoD leverage open source approaches to benefit its unmanned systems, and in particular, the upcoming generation of Autonomous Underwater Vehicles (AUVs)? How can the DoD continue to leverage advancements in platforms, advancements in algorithms, and advancements in cognitive intelligence as innovation rapidly accelerates providing new and useful capabilities? We explore this and discuss approaches to mapping out the roadmap for AUV systems and the implications for other domains.

9849-18, Session 7

Rapid prototype/development of an OA micro-UUV for research and defense
(Invited Paper)

Leonard Baker, Riptide Autonomous Solutions (United States)

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The Riptide Autonomous Solutions Micro-UUV is a development, research, and defense platform that has used OA and today's best rapid development and manufacturing practices to create an undersea vehicle that has gone from paper to in-water testing with a payload in three months. This is a drastic reduction in development time due largely in part to leveraging not only Open Architecture, but open source software and hardware along with state of the art in 3D printing.

The main goals in developing this vehicle were that it uses open source software and hardware, that it is small (less than 36 inches long, less than 20 lbs.), and be cost affordable. Often times the acceleration from development to manufacturing and turnaround time becomes prohibitively expensive either because more effort is needed in parallel or premiums are paid for low lead time of vendor items.

The Micro-UUV kept these costs down by using electrical components that already exist and are heavily used by the open source "maker" industry such as the Beaglebone Black or Arduino series of microcontrollers. The "maker" hardware was then matched up with highly popular open source sensors and software like ROS and MOOS. Given the nature of the "maker" movement, this combination of hardware, sensors, and software took advantage of integration that had been done many times before. This covers everything from Wi-Fi communications, to GPS positioning, to inertial navigation.

Additional time and cost was saved using the latest in 3D printing with smart choices in available 3D print material. Traditional 3D prints can be very porous and not well suited for marine environments. However, using a glass-impregnated nylon 3D print allowed for a 4-day turnaround of major structural components and removed the need of separate brackets, card cages, or other small details since they are part of the 3D print. The end result is a fully fabricated vehicle hull in 4 days that uses a relatively low number of parts. The speed of 3D prints allowed for early validation of fit and performance characteristics of the hull while reducing the size of the vehicle Technical Data Package and thus cost of documenting the overall vehicle. Most importantly, the 3D print and the chosen material are ultimately the final production configuration and do not need to be changed.

The result of a rapidly developed, open source, 3D printed, open architecture vehicle is a development, research, and defense platform that can be configured to add any customer payload that also uses an OA approach in a span of 3 months. It also results in a base vehicle that can be sold at the \$10,000 price point in a market that currently sees \$50,000-\$100,00 for a base vehicle with the same performance. Lastly, the vehicle can be deployed and retrieved by a single person without the need for a crew or machinery, further reducing support costs relative to vehicles in the same class.

Conference 9850: Machine Intelligence and Bio-inspired Computation: Theory and Applications X

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9850-2, Session 1

Design of stochastic feed forward networks with random weights

Dan Christiani, Cory Merkel, Dhireesha Kudithipudi, Rochester Institute of Technology (United States)

Stochastic logic offers significant area efficiency when applied to high-density redundant neural architectures; while noisy chaotic fluctuations associated with stochastic learning systems have been proven to reduce overfitting and escape local minima. Feed forward networks with random weights are uniquely qualified for stochastic logic due to their static abstraction layer. In this research, a single line bipolar stochastic logic is designed for feed forward networks with random weights coupled with an on-line stochastic training algorithm. All the primitive synapse cells are designed using memristors with a semi-empirical trap-assisted tunneling model. A constant random logic hidden layer is realized to produce input abstractions at a cost of one logic gate per additional weight. The output layer is trained using a stochastic least-mean-squares algorithm, where weights are updated probabilistically based on the gradient of the error surface. For functional verification the network is trained to conduct binary signal regeneration.

9850-3, Session 1

The convergence of cyber and electronic warfare

Gustave W. Anderson, Lockheed Martin Corp. (United States)

No Abstract Available

9850-4, Session 2

Function and activity classification in network traffic data using probabilistic attributed graph mining

Georgiy M. Levchuk, John Colonna-Romano, Aptima, Inc. (United States)

The United States increasingly relies on cyber-physical systems to conduct military and commercial operations, such as logistics, transportation, information sharing, energy production and distribution, financial transactions, and infrastructure management. Military cyber-physical systems depend on a wide variety of wired, cellular, and mobile ad-hoc networks, and interconnect via various computing and controlling devices. As rates of cyber-attacks on commercial and government infrastructure increase, cyber-physical operations become more vulnerable. For example, a 2013 Symantec Security Threat Report found an increase of 42% in targeted attacks, 30% in web-based attacks, and 125% in website phishing exploits in the year 2012 compared to 2011, with Symantec blocking 247K web attacks per day. Overwhelmingly, such attacks originate from outside of organizations and involve a variety of complex exploits and multi-phase system penetrations. The analysis of attack trends confirmed that the cyber spaces are increasingly becoming the battlefields between friendly and adversary forces, with normal users caught in the middle (Fanelli and Conti, 2012).

Although protecting federal computer networks and the United States' critical infrastructure remains a high priority and important technological challenge, US Intelligence Agencies are increasingly focused on offensive cyber operations, requiring precise identification and characterization of foreign cyberspace targets and their modes of operation. However, cyber operations are unique because both US warfighters and adversaries often share the same cyberspace infrastructure, which may be operated by governments or non-combatant private entities in the US or friendly countries. Consequently, offensive cyber warfare must have sufficient precision to ensure that effects reach the intended targets while avoiding noncombatants, collateral damage, or disruptions to own operations. Cyber analysts need to develop accurate "cyber battle maps", where the functions, roles, and activities of individual and groups of devices and users are accurately identified.

While a single target may be significant because of its own characteristics, the target's real importance lies in the multiple functions it executes and its relationships with other targets within an operational system (Joint Publication 3-60, Joint Targeting). Moreover, while a single network device and/or user obfuscation methods are effective, they are unable to hide all the interactions that target nodes execute. It has been shown that analyzing the network relationships does in fact achieve the highest discrimination and classification power for detecting anomalous activities of single hosts (Karagiannis, Papagiannaki, and Faloutsos, 2005; Himura et al., 2013; Cheng, and Tang, 2013) and groups of hosts (Iliofotou et al., 2007, 2011; Szabo, 2010).

In this paper, we present the algorithms to detect normal, malicious, and anomalous single-host and multi-host activities. The solutions are based on learning and detecting patterns in the graphs formed from the host-to-host traffic, enriched with the features of traffic volume, density, periodicity, and transport mechanisms. The activity detection methods can help in identifying normal function-based patterns of life in cyber data, detecting coordinated actions such as conducted by normal (e.g., games, managed resources) and abnormal (e.g., botnet) groups of users/devices, and help network analysts to conduct both defensive (e.g., detecting intrusions and attacks) and offensive (e.g., target development, cyber network mapping) operations.

9850-5, Session 2

Critical node analysis (CNA) of electrical infrastructure networks

Venkat Venkateswaran, Rensselaer Polytechnic Institute (United States); Walter Bennette, Air Force Research Lab. (United States)

This work addresses the problem of identifying the set of nodes in a power network critical to system operation. Formally, the CNA problem is the problem of identifying a minimum cardinality set of nodes in a power network which can reduce throughput by a given factor if disabled, despite the ability of the network to reroute flows. We develop here an algorithm to solve this problem. In our approach we model the problem as a bi-level optimization problem where the master problem attempts different attack combinations and the sub-problem responds with the best routing. The optimization problems that result from such a framework are mixed integer programs (MIPs), which we solve using CPLEX, an industry standard optimization software. The algorithm has been tested on numerous benchmark problems and appears to perform well. Extension to handle large networks (upwards of 4000 nodes) and integration within a simulation framework to model cascading failures are discussed.

9850-6, Session 2

Comparison of artificial intelligence classifiers for SIP attack data

Jakub Safarik, V?B-Technical Univ. of Ostrava (Czech Republic); Jiri Slachta, CESNET z.s.p.o. (Czech Republic)

Honeypot application is source of valuable data about attacks on the network. We run several SIP honeypots in various independent networks. Each honeypot runs on public IP address and has typical SIP PBX ports opened. All information gathered via honeypot is periodically sent to the centralized server. The tcpdump packet analyzer also captures all malicious traffic on a node. The result pcap file is trimmed for unwanted fields and periodically sent to the same centralized server. The server then checks, stores and aggregates the data. Then it classifies the aggregated data with neural network algorithm. The paper describes optimizations of neural network classifier, which lower the classification error. The article contains the comparison of two neural network algorithm used for the classification of validation data. The first is the original implementation of the neural network described in recent work; the second neural network uses described optimizations like input normalization or cross-entropy cost function. We also use other typical classification algorithms and test their capabilities on validation data to find the optimal classifier. The article result shows promise for further development of an SIP attack classification engine.

9850-7, Session 2

Optimized Hardware Framework of MLP with Random Hidden Layers

Abdullah Zyarah, Abhishek Ramesh, Cory Merkel, Dhireesha Kudithipudi, Rochester Institute of Technology (United States)

Multilayer Perceptron Networks with random hidden layers are very efficient at automatic feature extraction and offer significant performance improvements in the training process. They essentially employ large collections of fixed, random features, and are expedient for form-factor constrained embedded platforms. In this work, a reconfigurable and scalable architecture for the MLPs is proposed with a customized building block based on CORDIC algorithm. The proposed architecture also exploits fixed point operations for area efficiency. The design is validated for classification on two different datasets. An accuracy of ~90% for MNIST dataset and 72% for gender classification in LFW dataset was observed. The hardware has a four-fold speed-up over the corresponding software realization.

9850-8, Session 2

Evaluating failure states of machine learning algorithms

Misty Blowers, Air Force Research Lab. (United States)

No Abstract Available

9850-9, Session 3

Applying data mining techniques to detect abnormal flight characteristics

Hasan E. Aslaner, Cagri Unal, Turkish Aerospace Industries, Inc. (Turkey); Cem Iyigun, Middle East Technical Univ. (Turkey)

In this paper, it is aimed to explore new types of aviation safety issues

by detecting disregarded cases. This project targets to highlight flight safety issues by applying data mining techniques to recorded flight data and proactively detecting abnormalities in certain flight phases. For this purpose, a result oriented method is offered which facilitates the process of post flight data analysis. First of all, a specific flight phase is defined and critical flight parameters are chosen to be worked on. After that, each flight is represented by these parameters in time series data matrices and for each studied flight, similarities among each other are calculated by taking the Euclidean distances. Finally, hierarchical clustering method is applied to the data matrix which represents similarity levels of the flights to be analyzed in terms of selected parameters. As a result, clusters including the similar flight characteristics are formed. In the final part of the study, flights which have high level of dissimilarity with these clusters are sorted out and classified as suspicious. Therefore, abnormal flight data can be reconsidered for further inspections and flight personnel can be advised against potentially unsafe conditions before subsequent flights.

9850-10, Session 3

Self-organizing map classifier for stressed speech recognition

Pavol Partila, Jaromir Tovarek, Miroslav Voznak, V?B-Technical Univ. of Ostrava (Czech Republic)

This paper presents a method for detecting speech under stress using Self-Organizing Maps. Most people who are exposed to stressful situations can not adequately respond to stimuli. Army, police and fire department occupy the largest part of the environment that are typical of an increased number of stressful situations. The role of men in action are controlled by control center. Control commands should be adapted to the psychological state of a man in action. It is known that the psychological changes of the human body are also reflected physiologically, which consequently means the stress effected speech. Therefore it is clear that the speech stress recognizing system is required in the security forces. One of the possible classifiers, which are popular for its flexibility, is a self-organizing map. It is one type of the artificial neural networks. Flexibility means independence classifier on the character of the input data. This feature is suitable in speech processing. Human Stress can be seen as a kind of emotional state. Mel-frequency cepstral coefficients and fundamental frequency were selected for training and testing the classifier. These coefficients were selected for their sensitivity to emotional changes. The calculation of the parameters was performed on speech recordings, which can be divided into two classes, namely the stress state recordings and normal state recordings. The benefit of the experiment is a method using SOM classifier for stress speech detection. Results shown the advantage of this method, which is input data flexibility.

9850-11, Session 3

One approach to design of speech emotion database

Dominik Uhrin, V?B-Technical Univ. of Ostrava (Czech Republic); Zdenka Chmelikova, Jaromir Tovarek, V?B - Technical University of Ostrava (Czech Republic); Pavol Partila, Miroslav Voznak, V?B-Technical Univ. of Ostrava (Czech Republic)

This article describes a system for evaluating the credibility of recordings with emotional character. Sound recordings form Czech language database for training and testing systems of speech emotion recognition. These systems are designed to detect human emotions in his voice. The emotional state of man is useful in the security forces and emergency call service. Man in action (soldier, police officer and firefighter) is often exposed to stress. Information about the emotional state (his voice) will help dispatching to adapt control commands for procedure intervention. Call agents of emergency call service must recognize the mental state of the caller to

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adjust the mood of the conversation. In this case, the evaluation of the psychological state is the key factor for successful intervention. A quality database of sound recordings is essential for the creation of the mentioned systems. There are quality databases such as Berlin Database of Emotional Speech or Humaine. The actors have created these databases in audio studio. It means that the recordings contain simulated emotions and not real. Our research aims at creating a database of the Czech emotional recordings of real human speech. Collecting sound samples to the database is only one of the tasks. Another one, no less important, is to evaluate the significance of recordings from the perspective of emotional states. The design of methodology for evaluating emotional recordings credibility is described in this article. The results describe the advantages and applicability of the developed method.

sensing. In developing the discussion, I will examine recent developments related to incorporation of losses and spectral properties in such a way as to generalize our simple, continuous-wave (cw) model of essentially lossless operation. I will also discuss on-chip generation and control of entangled photons within the nanophotonic material itself, especially as related to potentially useful applications in information processing.

9850-12, Session 3

Optimization of multilayer neural network parameters for speaker recognition

Jaromir Tovarek, Pavol Partila, Jan Rozhon, Miroslav Voznak, Jan Skapa, Dominik Uhrin, Zdenka Chmelikova, VŠB-Technical Univ. of Ostrava (Czech Republic)

This article discusses the impact of multilayer neural network parameters for speaker identification. The main task of speaker identification is to find a concrete person in the known set of speakers. It means that the voice of an unknown speaker (wanted person) belongs to a group of reference speakers from the voice database. One of the requests was to develop the text-independent system, which means to classify wanted person regardless of content and language. Multilayer neural network has been used for speaker identification in this research. Artificial neural network (ANN) needs to set parameters like activation function of neurons steepness of activation functions, learning rate, the maximum number of iterations, the maximum mean square error ratio and number of neurons in the hidden and output layers. ANN accuracy and training time are directly influenced by the parameter settings. Different roles require different settings. Identification accuracy and ANN training time were evaluated with the same input data but different parameter settings. The goal was to find parameters for the neural network with the highest precision and shortest training time. Input data of neural networks are a Mel-frequency cepstral coefficients (MFCC) and dynamic and acceleration derivatives (delta MFCC and delta-delta MFCC). These parameters describe the properties of the vocal tract. Source of sound recordings was formed by Berlin database of emotional speech [1]. Training and test data were split at a ratio of 3 to 1. The result of the research described in this article is different parameter setting for the multi-layered neural network with a different number of speakers.

9850-13, Session 3

Silicon nanophotonic networks for quantum optical information processing

Edwin E. Hach III, Rochester Institute of Technology (United States)

Silicon nanophotonics show a lot of promise as the basic architecture for quantum information processing devices. This is particularly the case in relation to the scalability of such devices. During this talk I will review our simple theoretical model of a structure that we have identified as a 'fundamental circuit element' for linear optical quantum information processing in silicon nanophotonics. In particular, we have shown that, owing to an effect we call Passive Quantum Optical Feedback (PQOF), the topology of this circuit element allows for certain possible operational advantages, in addition to inherent scalability, not expected in bulk linear optics. I will emphasize the extension of our work to larger networks, including the Knill-Laflamme-Milburn (KLM) Controlled-Not (CNOT) gate and its important constituent, the so-called Nonlinear Sign (NS) shifter. Further, I will discuss our ongoing effort to design and optimize scalable networks that seem to have useful applications in quantum metrology and

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9851-1, Session 1

Proactive human-computer collaboration for information discovery

Phillip DiBona, Nadya Belov, Nick LoFaso, Lockheed Martin Corp. (United States)

In order to form and substantiate hypotheses about the adversary or battlespace, modern analysts benefit from a vast breadth and volume of multi-INT (e.g., imagery, full-motion video, signals and electronic intelligence, human intelligence) data. Additionally, non-traditional data sources such as open source intelligence (OSINT), social media, and gray literature provide analysts with data that is potentially more timely, comprehensive, and closer to emerging situations. Access to this amount of data, however, creates a virtual "information landfill" where finding highly relevant information is prohibitively expensive in terms of time and effort. Additionally, these non-traditional sources, which provide noisy and unstructured data, can prove costly in computational resources and processing time, thus degrading quality of analysis and slowing down the hypothesis generation process.

Seamless Human-Computer Teaming can enhance and scale the human analyst's expertise in gathering, filtering, correlating, and fusing relevant information. However, to be effective, the autonomy and the human must collaborate and have a shared understanding of both the hypotheses as well as the information that forms, supports, or refutes those hypotheses. Lockheed Martin Advanced Technology Laboratories (LM ATL) is researching methods, representations, and processes for human / autonomy collaboration for scaling the analysis and substantiation of hypotheses. This research establishes a machine-readable hypothesis representation that is commonsensical to the human analyst. The representation serves as the unifying context between the human and computer, enabling autonomy, in the form of analytic software, to support the analyst through proactively acquiring, assessing, and organizing high-value information that is needed to inform and substantiate hypotheses.

9851-2, Session 1

Collaborative human-machine analysis to disambiguate entities in unstructured text and structured datasets

Jack H. Davenport, Brian Adams, James Nolan, Decisive Analytics Corp. (United States)

No Abstract Available

9851-3, Session 1

Visual graph query formulation and exploration: a new perspective on information retrieval at the edge

Sue E. Kase, Michelle Vanni, U.S. Army Research Lab. (United States); Joanne Knight, U.S. Army REDCOM CERDEC (United States); Yu Su, Xifeng Yan, Univ. of California, Santa Barbara (United States)

Within operational environments decisions must be made quickly based on the information available. Identifying an appropriate knowledge base and accurately formulating a search query are critical for decision-making effectiveness in dynamic situations. The spreading of graph data

management tools to access large graph databases is a rapidly emerging research area of potential benefit to the intelligence community. A graph representation provides a natural way of modeling data in a wide variety of domains. Graph structures use nodes, edges, and properties to represent and store data. This research investigates the advantages of information search by graph query initiated by the analyst and interactively refined within the contextual dimensions of the answer space toward a solution. The paper introduces SLQ, a user-friendly graph querying system enabling the visual formulation of schemaless and structureless graph queries. SLQ is demonstrated with an intelligence analyst information search scenario focused on identifying individuals responsible for manufacturing a mosquito-hosted deadly virus. The scenario highlights the interactive construction of graph queries without prior training in complex query languages or graph databases, intuitive navigation through the problem space, and visualization of results in graphical format.

9851-4, Session 1

Advanced Human Machine Interaction for an Image Interpretation Workstation

Sebastian Maier, Manuel Martin, Florian van de Camp, Elisabeth Peinsipp-Byma, Jürgen Beyerer, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

In recent years, many new interaction technologies have been developed that enhance the usability of computer systems and allow for novel types of interaction. The areas of application for these technologies have mostly been in gaming and entertainment. However, in professional environments there are especially demanding tasks that would greatly benefit from improved human machine interfaces as well as an overall improved user experience. We therefore envisioned and built an image-interpretation-workstation of the future, a multi-monitor workplace comprised of four screens. Each screen is dedicated to a complex software product such as a geo-information system to provide geographic context, an image annotation tool, software to generate standardized reports and a tool to aid with the identification of objects. Using self-developed systems for hand tracking, pointing gestures and head pose estimation in addition to touchscreens, face identification, and speech recognition systems we created a novel approach to this complex task. For example, head pose information is used to save the position of the mouse cursor on the currently focused screen and to restore it as soon as the same screen is focused again while hand gestures allow for intuitive manipulation of 3d objects in mid-air. While the primary focus is on the task of image interpretation, all of the technologies involved provide generic ways of efficiently interacting with a multi-screen setup and could be utilized in other fields as well. In preliminary experiments, we received promising feedback from users in the military and started to tailor the functionality to their needs.

9851-5, Session 2

Agent Based Modeling in Tactical Wargaming (*Invited Paper*)

Alex James, CUBRC (United States); Timothy P. Hanratty, U.S. Army Research Lab. (United States); Daniel Tuttle, U.S. Army (United States); John B. Coles, CUBRC (United States)

No Abstract Available

9851-6, Session 2

Considering context: reliable entity networks through contextual relationship extraction (*Invited Paper*)

Nichole Hansen, Peter F. David, Timothy Hawes, Decisive Analytics Corp. (United States)

No Abstract Available

9851-7, Session 2

Foundations for context-aware retrieval for proactive decision support (*Invited Paper*)

Ranjeev Mittu, U.S. Naval Research Lab. (United States)

No Abstract Available

9851-8, Session 3

Collaborative data analysis and discovery for cyber security

Diane Staheli, Vincent F. Mancuso, Raul Harnasch, Cody Fulcher, Madeline Chmielinski, Stephen Kelley, MIT Lincoln Lab. (United States)

Cyber has been identified as a key research trajectory for ensuring national security. Researchers have begun to assess the role of humans in cyber, focusing mainly on the analysis process, with limited attention to collaboration, information sharing, and team cognition. Cyber operators face challenges in accessing key information with little collaboration between analysts. Current generation analysts rely on their individual record keeping systems, which hinders their ability to reflect on their own work and transition analytic products to others. Research has demonstrated that online collaboration systems can encourage and facilitate distributed teams in information sharing and group decision-making, however, no such technology exists today for cyber defenders. In pursuit of this, we present the Cyber Analyst Real-Time Integrated Notebook Application (CARINA). CARINA is a collaborative investigation system that aids in decision making by co-locating the analysis environment with centralized cyber data sources, and providing analysts with increased visibility to the work of others.

Using visualization and annotation, CARINA leverages conversation and ad hoc thought to coordinate decisions across an organization. CARINA incorporates features designed to incentivize positive information-sharing behaviors, and provides a framework for incorporating recommendation engines and other analytics to guide analysts in the discovery of related data or analyses. In this paper, we present the user research that informed the development of CARINA, discuss the functionality of the system, and outline potential use cases. We also discuss future research trajectories and implications for cyber researchers and practitioners.

9851-9, Session 3

A knowledge-based approach for task-oriented mission planning

Nadia El Bekri, Yvonne Fischer, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

A key issue in mission planning for aerial reconnaissance is to use the sensor resources in an appropriate way. The mission planning requires knowledge, e.g., about the optimal sensor type (IR/EO) or the necessary flying altitude for a specific task. There are various types of tasks that can be part of the mission, e.g., to detect a vehicle or investigate a bridge. The goal of this

work is to examine knowledge-based approaches like ontologies and the use of them to automatically derive all needed parameters for an optimal sensor mission planning based on the task. The task-oriented mission planning is processed on the tactical level. Based on the task the aerial image analyst defines the specific evaluation conditions. Various parameters are part of the task-oriented mission planning. For example there are the scene, the flight mode, the sensor, the system and the image analysis parameters. We introduce an idea to represent the sensor mission planning task at a relatively high-level knowledge-based approach. We want to create a representation of a useful sensor mission planning where all aspects and its components are considered, what these parts do, how they relate to each other and define the rules and constraints within. The main framework is based on the definitions of target categories and purpose codes (STANAG 3596) and NIIRS level.

9851-10, Session 3

Using machine learning and real-time workload assessment in a high-fidelity UAV simulation environment

Samuel S. Monfort, George Mason Univ. (United States); Ciara M. Sibley, Joseph T. Coyne, U.S. Naval Research Lab. (United States)

Future unmanned vehicle operations will see an inversion of the operator-to-UAV ratio. Current systems typically involve a small team of operators maintaining control over a single aerial platform, but this arrangement results in a suboptimal configuration of operator resources to system demands. Rather than devoting the full-time attention of several operators to a single UAV, the goal should be to distribute the attention of several operators across several UAVs as needed. Under a distributed-responsibility system, operator workload would be continuously monitored and tasks assigned based on system needs and operator capabilities. The current paper sought to identify a set of metrics that could be used to assess workload unobtrusively and in near real-time to inform a dynamic tasking algorithm. To this end, we put 20 participants through a variable-difficulty 40-minute multiple UAV management simulation. We collected and calculated various pupillary and behavioral measures, and from this larger pool identified a subset of candidate metrics using a multiple regression procedure. We then used the most successful regressors as features in an ensemble machine learning algorithm (Random Forest, Support Vector Machines, k-Nearest Neighbors) to predict workload condition in 60-second intervals. This procedure produced an overall classification accuracy of 78%. An automated tasker sensitive to fluctuations in operator workload could be used to efficiently delegate tasks for teams of UAS-operators.

9851-11, Session 3

Leveraging human decision making through the optimal management of centralized resources

Paul Hyden, U.S. Naval Research Lab. (United States); Richard McGrath, United States Naval Academy (United States)

Currently, the assignment of tasks to satellites, an example of a critical centrally managed resource, is largely done manually and serially. The current effort needs to be improved in numerous areas. We propose to use the most advanced integer programming techniques such as the Reformulation Linearization Technique (RLT) on a formulation of the Quadratic Assignment Problem (QAP) to bolster the random search technique where appropriate. The interaction terms included in the QAP is critical to include interaction effects of assigning pairwise combinations of jobs to resources. Cloud computing opportunities coupled with improvements in algorithm development provide great promise for achieving impressive gains in optimization. A critical step is the calculation

of task prioritization. One of the necessary tasks is to create an asset criticality metric. As this is not identified explicitly, factors are identified and a modified TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) algorithm to calculate the asset criticality values is developed. Then, tasks are prioritized based on the asset criticality of the mission they target or affect, the realized impact of an effect on the mission, the probability of the effect, as well as other properties. The results associated with this daily analysis of warfighter needs flows into our subsequent analysis of stochastic demand management.

For an centralized asset like a satellite, maximizing utilization is a natural goal. However, we could always max out utilization by stuffing the schedule. The real goal is to serve customers and missions. Currently, VMOC schedules resources on independent 24-hour windows. In addition, priority is organization based, so tasks requested by the most important organization are assigned to the schedule in the greediest fashion possible. We can improve this delivery of precious satellite resources by getting involved in modeling the requests for effects based on features of our customers. It is important to model the queuing processes that underlie the demand stream for satellite usage. Further enrichments in understanding these customer and mission-associated processes allow for the satellite schedulers to anticipate demand and offload lower priority work opportunistically in pockets of lower demand. Currently, the operators don't have the tools to manage demand in between days. After greedy allocation of the most important jobs, the most number of tasks are wedged on the schedule as possible. So, in principal, a low status job could get bumped day after day without getting scheduled. With improvements to the internal loop of optimizing tasks to the schedule, operators are freed to manage at a higher level of abstraction: users and missions rather than specific effects. We hypothesize that high status users on some platforms may even voluntarily give up some of their untouchable slots if they have an understanding that allowing lower status jobs can give them opportunities on platforms where they have lower priority, producing higher throughput and mutual benefits for all users. Applications of queueing theory include getting waiting time statistics of customers for each priority, preemptive vs. non preemptive priority queueing, queue occupancy distribution, server utilization, and varying the number of servers such as the number of satellites, or parallel satellite resources. This is a much richer set of metrics to describe and manage the demand flow to the satellite and better positions operators to move toward real time management of assets. By using Little's Law, we can start to give forecasted quality of service reports to users. These estimates can then be used to inform the core optimization function and incorporate service quality levels over days, weeks, and months.

New platforms for managing centralized resources break down barriers between warfighters and resource managers, increasing end user capability to manage demand streams and free the warfighter to receive best fit resource assignments.

9851-13, Session 4

Challenges in mapping behaviours to activities using logs from a citizen science project

Alessandra Marli M. Morais, Leandro Guarino de Vasconcelos, Rafael D. Coelho dos Santos, Instituto Nacional de Pesquisas Espaciais (Brazil)

Citizen science projects are those which recruit volunteers to participate as assistants in scientific studies. With the advent of the Internet it becomes possible the creation of Web-based citizen science projects which provided a new way to conduct such collaborations. It enabled such projects to become even more distributed, expand into new and innovative domains, gain popularity and recruit volunteers in any part of the world.

Since citizen science projects depend on volunteer efforts, understanding the motivation that drives a volunteer to collaborate is as important as the technological aspects of the project. For web-based projects, recent studies have been analyzing records of volunteers' activities (logs, or registers of which volunteer did what and when) in attempt to infer information about the volunteers' motivations. Such approach have been used as an alternative

from studies which analyses volunteers' motivation through surveys and interviews. Although the latter can elicit detailed information from volunteers, they are restricted to a subset of participants in citizen science projects, whereas the former can be applied to all registered volunteers.

One natural approach to calculate behavioural features from volunteers in a citizen science project is to extract and map metrics calculated from the records of interactions to features that describe the behaviours. In this work we present some techniques and features that can be used to infer behaviour from logs, along with challenges on calculating those and issues for further research.

Our preliminary findings shows that for a popular web-based citizen science project not all features are meaningful -- visualisation and clustering techniques show that the distribution of some features' values cannot be used for clustering and classification of the volunteers in different profiles.

We also present a technique that could be used for collection of the interaction logs that could enhance classification and separability of different volunteers profiles.

9851-14, Session 4

Cognitive context detection in UAS operators using eye-gaze patterns on computer screens

Pujitha Mannaru, Balakumar Balasingam, Krishna R. Pattipati, Univ. of Connecticut (United States); Ciara M. Sibley, Joseph T. Coyne, Army Research Lab. (United States)

In this paper, we demonstrate the use of eye-gaze metrics of unmanned aerial systems (UAS) operators as effective indices of their cognitive workload. Our analyses are based on an experiment where twenty volunteer UAS operators perform pre-scripted UAS missions of three different difficulty levels by interacting with two custom designed graphical user interfaces (GUI) that are displayed side by side. First, we compute several eye gaze metrics, traditional metrics as well as newly proposed ones, and analyze their effectiveness as cognitive classifiers. Most of the eye gaze metrics are computed by dividing the computer screen into "cells". Then, we perform several analyses in order to select metrics for effective cognitive context classification related to our specific application; the objective of these analyses are to (i) identify appropriate ways to divide the screen into cells; (ii) select appropriate metrics for training and classification of cognitive features; (iii) identify a suitable classification method; and (iv) understand the possibility of online classification. Finally, we develop an approach to improve online classification using hidden Markov models.

9851-16, Session 5

From open source communications to knowledge

Alun D. Preece, Colin Roberts, William Webberley, David Rogers, Martin Innes, Cardiff Univ. (United Kingdom); Dave Braines, IBM United Kingdom Ltd. (United Kingdom)

Rapid processing and exploitation of open source information - including social media sources - in order to shorten decision-making cycles, has emerged as an important issue in intelligence analysis in recent years. Through a series of case studies and natural experiments, focussed primarily upon policing and counter-terrorism scenarios, we have developed an approach to information foraging and framing to inform decision making, drawing upon open source intelligence - in particular Twitter, due to its real-time focus and frequent use as a carrier for links to other media. Our work uses a combination of natural language (NL) and controlled natural language (CNL) processing to support information collection from human sensors, linking and schematising of collected information, and the framing of situational pictures. We illustrate the approach through a

series of vignettes, highlighting (1) how relatively lightweight and reusable knowledge models (schemas) can rapidly be developed to add context to collected social media data, (2) how information from open sources can be combined with reports from trusted observers, for corroboration or to identify conflicting information; and (3) how the approach supports users operating at or near the tactical edge, to rapidly task information collection and inform decision-making. The approach is supported by bespoke software tools for social media analytics and knowledge management.

9851-17, Session 5

A data-stream classification system for the investigation of terrorist threats

Alexia Schulz, Joshua Dettman, Jeffrey Gottschalk, Michael Kotson, Era Vuksani, Tamara Yu, MIT Lincoln Lab. (United States)

Cyber forensics have come to play a more central role in criminal investigations because of the explosion of data that is now collected and available to investigators. Physical forensics has also experienced a data volume and fidelity revolution due to advances in methods for DNA and trace evidence analysis. Key to extracting insight is the ability to correlate across multi-modal data, which depends critically on identifying a touch-point connecting the separate data streams. For example, separate data sources may be connected because they refer to the same individual or entity or because they reveal information about a specific event at a specific time. In this paper we present a data source classification system that is tailored to facilitate the investigation of potential terrorist activity. This ontology is structured to illuminate the defining characteristics of a particular terrorist effort and designed to guide reporting to decision makers that is complete, concise, and evidence-based. The classification system has been validated and empirically utilized in the forensic analysis of a simulated terrorist activity. Next generation analysts can use this schema to label and correlate across existing data streams, assess which critical information may be missing from the data, and identify options for collecting additional data streams to fill information gaps.

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9851-18,

Multi-intelligence analytics for next-generation analysts (MIAGA)

Erik Blasch, Air Force Research Lab. (United States); Edward L. Waltz, Virginia Polytechnic Institute and State Univ. (United States)

Current analysts are inundated with large volumes of data from which extraction, exploitation, and indexing are required. A future need for next-generation analysts is an appropriate balance between automatic analytics from raw data and the ability of the user to interact with information through automation. Many tools and techniques have been postulated which we examine towards matching opportunities with recent technical trends such as big data, access to information, and visualization for the analyst. The concepts and techniques summaries are derived from discussions with real analysts and the trends desired to improve the methods developed for future analysts. For example, qualitative analytics should be matched against physical, cognitive, and contextual quantitative techniques for intelligence analysis. We use the recent publication of "Quantitative Intelligence Analysis: applied Analytic Models, Simulations, and Games" by Ed Waltz in 2014 as a starting point for the discussion.

9851-19,

Enabling task-based information prioritization via semantic web encodings

James Michaelis, U.S. Army Research Lab. (United States)

Modern Soldiers rely upon accurate and actionable information technology to achieve mission objectives. While increasingly rich sensor networks for Areas of Operation (AO) can offer many directions for aiding Soldiers, limitations are imposed by current tactical edge systems on the rate that content can be transmitted. Furthermore, mission tasks will often require very specific sets of information which may easily be drowned out by other content sources.

Prior research on Quality and Value of Information (QoI / VoI) has aimed to define ways to prioritize information objects based on their intrinsic attributes (QoI) and perceived value to a consumer (VoI). As part of this effort, established ranking approaches such as the Analytic Hierarchy Process (AHP) have been considered. However, limited work has been done to formally tie Soldier context – such as descriptions of their mission and tasks – back to intrinsic attributes of information objects.

This work presents a Semantic Web driven framework for defining information object preferences within the context of given mission tasks. Central to this approach is the notion of re-use and repurposing of preference specifications – written by potentially large collections of Subject Matter Experts – toward new mission tasks, as a means of reducing time and effort in QoI/VoI based middleware configuration.

Following a short discussion on related QoI/VoI research, an RDF/OWL data structure is introduced for supporting the following property-driven evaluation of information objects: (I) value restriction, designed to act in a filtering capacity; (II) AHP-based ranking, designed for information object prioritization based on pairwise priorities set between information object properties, as well as between values of individual properties. From here, discussion turns toward a listing of requirements for enabling re-use and repurposing of SME specifications, centered on both inference of similarities between mission tasks and reputation of SME contributors – assessable through provenance of the specifications. The paper concludes with a short summary of proposed future directions.

9851-20, Session PSTue

Transforming a research-oriented dataset for evaluation of tactical information extraction technologies

Heather Roy, Sue E. Kase, U.S. Army Research Lab. (United States); Joanne Knight, U.S. Army REDCOM CERDEC (United States)

The most representative and accurate data for testing and evaluating information extraction technologies is real-world data. Real-world operational data can provide important insights into human and sensor characteristics, interactions, and behavior. However, several challenges limit the feasibility of experimentation with real-world operational data. Real-world data lacks the precise knowledge of a "ground truth," a critical factor for benchmarking progress of developing automated information processing technologies. Additionally, the use of real-world operational data is often limited by classification restrictions due to the methods of collection, procedures for processing, and tactical sensitivities related to the sources, events, or objects of interest. These challenges, along with an increase in the development of automated information extraction technologies, are fueling an emerging demand for operationally-realistic datasets for benchmarking. An approach to meet this demand is to create synthetic datasets, which are operationally-realistic yet unclassified in content, facilitating the sharing of data between military and academic researchers thus increasing coordinated testing efforts. This paper describes the expansion and augmentation of two synthetic text datasets initially developed through academic research collaborations with the Army. Both datasets feature simulated tactical intelligence reports regarding fictitious terrorist activity

occurring within a counter-insurgency (COIN) operation. The datasets were merged to create a single larger dataset containing ground-truth to better exercise developing technologies. The dataset transformation effort and the final dataset and its availability and applicability for research are presented.

9851-21, Session PSTue

Classification of user interfaces for graph-based online-analytical processing

James Michaelis, U.S. Army Research Lab. (United States)

In the domain of business intelligence, user-oriented software for conducting multidimensional analysis via Online-Analytical Processing (OLAP) is now commonplace. In this setting, datasets commonly have well-defined sets of dimensions and measures around which analysis tasks can be conducted. However, many forms of data used in intelligence operations – deriving from social networks, online communications, and text corpora – take the form of graphs with varying types of dimensional structure. Hence, enabling OLAP over such data collections requires explicit definition and extraction of supporting dimensions and measures. Further, as graph-based OLAP remains an emerging technique, limited research has been done on its user interface requirements. Namely, on effective pairing of interface designs to different types of graph-derived dimensions and measures.

This paper presents a novel classification strategy by which interfaces for graph-based OLAP systems can be compared, rooted in Analytic Hierarchy Process (AHP) driven comparisons. Attributes of the classification strategy are defined in an ontology designed to support pairwise comparison of interfaces. Specifically, according to their ability – as perceived by Subject Matter Experts – to support dimensions and measures corresponding to a set of graph-derived attributes. For instance, interfaces may be compared on their ability to support dimension values containing different node quantities and interconnection counts.

To frame this discussion, a survey is provided both on existing variations of graph-based OLAP, as well as existing interface designs previously applied in multidimensional analysis settings. Following this, an ontology of classification attributes for enabling pairwise interface comparison is introduced. A walkthrough of AHP's application via the proposed ontology is then provided. The paper concludes with a short summary of proposed future directions seen as essential for this research area.

9851-22, Session PSTue

Cognitive context detection in UAS operators using pupillary measurements

Pujitha Mannaru, Balakumar Balasingam, Krishna R. Pattipati, Univ. of Connecticut (United States); Ciara M. Sibley, Joseph T. Coyne, U.S. Naval Research Lab. (United States)

In this paper, we demonstrate the use of pupillary measurements as indices of cognitive workload. We analyze the pupillary data of twenty individuals engaged in a simulated Unmanned Aerial System (UAS) operation in order to understand and characterize the behavior of pupil dilation under varying task load (i.e., workload) levels. We present three metrics that can be employed as real-time indices of cognitive workload. In addition, we develop three predictive systems utilizing the pupillary metrics to demonstrate cognitive context detection within simulated supervisory control of UAS. Further, we use pupillary data collected concurrently from the left and right eye and present comparative results of the use of separate vs. combined pupillary data for detecting cognitive context.

9851-23, Session PSTue

On the use of hidden Markov models for eye-gaze pattern modeling and classification

Pujitha Mannaru, Balakumar Balasingam, Krishna R. Pattipati, Univ. of Connecticut (United States); Ciara M. Sibley, Joseph T. Coyne, Army Research Lab. (United States)

We consider the problem of cognitive context detection using eye gaze measurements. Traditional approaches employ eye gaze metrics, such as saccade counts, nearest neighbor index (NNI) and duration of dwells/fixations for context learning. Each of these traditional metrics has drawbacks in modeling behavior of eye gaze patterns. For instance, the saccade based metrics and NNI are insensitive to the area of interest (AOI) of the field of view. The dwell/fixation based metrics are computed by dividing the field of view into AOIs, however, there are many challenges in developing accurate AOI metrics: firstly, there is no clear definition of a particular AOI, in many cases the entire field of view is of interest; secondly, it is possible that the AOI may change adaptively over time. Hence, there is a need to introduce eye-gaze metrics that are aware of the AOI in the field of view; at the same time, the new metrics should be able to automatically select the AOI based on the nature of the gazes.

In this paper, we develop eye gaze metrics based on continuous hidden Markov models (HMM), which model the gazes as 2D Gaussian observations (x-y coordinate of the gaze). The HMM model allows selecting important area of interest through model selection approaches, such as Bayesian information criteria (BIC) or minimum descriptive length (MDL). We demonstrate the use of the proposed approach using an experiment where twenty (volunteer) unmanned aerial system (UAS) operators perform pre-scripted UAS missions of three different difficulty levels by interacting with two custom designed graphical user interfaces (GUI) that are displayed side by side. The HMM modeling is employed to model their eye gaze patterns and the efficacy of the modeling is demonstrated through its ability to classify new gaze data based on its cognitive context.

9851-24, Session PSTue

Mining the SDSS Skyserver SQL queries log

Vitor M. Hirota, Rafael D. Coelho dos Santos, Instituto Nacional de Pesquisas Espaciais (Brazil); M. Jordan Raddick, Ani Thakar, Johns Hopkins Univ. (United States)

SkyServer, the Internet portal for the Sloan Digital Sky Survey (SDSS) astronomic catalog, provides a set of tools that allows data access for astronomers and scientific education. One of SkyServer data access interfaces allows users to enter ad-hoc SQL statements to query the catalog. SkyServer also presents some template queries that can be used as basis for more complex queries. This interface has logged over 280 million queries submitted since 2001.

There are several good reasons to analyze the queries that were submitted to the SQL database servers through SkyServer: investigate usage patterns, identify potential new classes of queries, find similar queries, etc. Several techniques and approaches can be used to shed some light on how users interact with the Sloan Digital Sky Survey data, which could in turn lead to enhancements on the user interfaces and experience in general.

Due to the amount of queries, analysis must be done considering categories or groups of similar queries and not individual ones. In this work we apply text mining techniques to define a methodology to parse, clean and tokenize statements into an intermediate numerical representation for the queries submitted to SkyServer. With this representation we used a Self-Organizing Map to project similar queries in a two-dimensional grid, allowing the identification of queries' and templates' groups.

9851-25, Session PSTue

Network analysis of human trafficking in Pennsylvania

Andrea Forster, The Pennsylvania State Univ. (United States)

Human trafficking is a form of modern slavery categorized as the second most profitable crime behind the drug trade. A research project in Penn State's College of Information Sciences and Technology is examining sex trafficking in an effort to provide actionable intelligence to positively contribute to efforts at combating this phenomenon. The Internet has emerged as a major facilitator for sex trafficking. As a result, the current research is focusing collecting and categorizing data from classified ads posted on Backpage.com, a site heavily used to promote sexual services. The technical means were developed to scrape the information from the classified ads into a database that could be queried and analyzed using key word searches developed through research on sex trafficking including discussions with victim support organizations. In phase two, a blend of traditional analytic methods, data science techniques, and data visualization software is used to identify and categorize relationships among various meta-data elements (e.g., common locations, poster/service profiles, phone numbers, and personal information). Once identified and processed, the relationships are visualized. The resulting social network may then be further analyzed and cross referenced with other information such as news articles to understand indicators of trafficking networks, recognize geographic patterns, and improve overall situational awareness of sex trafficking. The preliminary findings from the research prove that the process is a good starting point for improving the understanding more about sex trafficking and thus contributing to its suppression.

9851-26, Session PSTue

Enhanced visual perception through tone mapping

Andre Harrison, Linda L Mullins, Adrienne Raglin, U.S. Army Research Lab. (United States); Ralph Etienne-Cummings, Johns Hopkins University (United States)

Tone mapping operators compress high dynamic range images to improve the picture quality on a digital display when the dynamic range of the display is lower than that of the image.

However, tone mapping operators have been largely designed and evaluated based on the aesthetic quality of the resulting displayed image or how perceptually similar the compressed image appears relative to the original scene. They also often require per image tuning of parameters depending on the content of the image. In military operations, however the amount of information that can be perceived is more important than aesthetic quality of the image and any parameter adjustment needs to be as automated as possible regardless of the content of the image. We have conducted two studies to evaluate the perceivable detail of a set of tone mapping algorithms and we apply our findings to develop and test an automated tone mapping algorithm that demonstrates a consistent improvement in the amount of perceived detail. An automated and thereby predictable tone mapping method enables a consistent presentation of perceivable features, can reduce the bandwidth required to transmit the imagery, and can improve the accessibility of the data by reducing the needed expertise of the analyst(s) viewing the imagery.

9851-27, Session PSTue

Modeling the impact of value of information (Vol) on situational awareness

John T. Richardson, Mark R. Mittrick, Timothy P. Hanratty, U.S. Army Research Lab. (United States)

Understanding situational awareness in a timely manner is critical to making the correct decisions on the battlefield. It is generally accepted that better decisions are made when a higher situational awareness exists. To demonstrate this we employed a modeling tool that provided an environment to quickly and inexpensively evaluate our intelligence analysis scenario in order to see the impact of the Vol enhanced data on the process. Our results show that Vol enhanced data is superior by providing the analyst with the most situational awareness within the least amount of time.

9851-28, Session PSTue

Dynamic ontology visualization of interconnected concepts in human-vehicle interaction

Mohammad Serkhail Habibi, Amir Shirkhodaie, Tennessee State Univ. (United States)

Ontologies, as sets of concepts and their relationships, represent information more meaningfully for both computers and humans in a specific domain. In object-entity-interaction description of events and activities in machine understandable form, which aids human comprehension provides the mainstay for knowledge discovery. To model a set of interconnected concepts describing certain information, this paper defines a concept generation model (CGM) in smaller time frame and its extension in sequential time frame with minimum spanning tree (MST). The model has a dynamic structure based on relevance and interaction between object and entity and uses semantic feature selection algorithms. The representation of the analyses augments effective ontology visualization for design, management and decision making. An attempt is made here for the visual representation of time-varying ontologies, and provides a discussion from a dynamic graph visualization perspective. The purpose of this paper is to present these techniques and categorize their characteristics and features in order to assist method selection and promote future research in the area of ontology visualization.

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9852-1, Session 1

The early history of the closed loop fiber optic gyro and derivative sensors at McDonnell Douglas, Blue Road Research and Columbia Gorge Research (*Invited Paper*)

Eric Udd, Columbia Gorge Research LLC (United States)

The closed loop fiber gyro was invented at McDonnell Douglas in 1977 and reduced to practice in early 1978. In the course of its development a series of inventions were derived that used the Sagnac interferometer for acoustics, position sensing, strain, distributed sensing and secure fiber optic communication. Work on the Sagnac interferometer continued at Blue Road Research and more recently at Columbia Gorge Research on derivative inventions. This paper provides a historical context to these developments and inventions.

9852-2, Session 1

Potpourri of comments about the fiber optic gyro for its 40th anniversary, and how fascinating it was and it still is! (*Invited Paper*)

Hervé C. Lefèvre, iXBlue SAS (France)

This 40th anniversary is the opportunity to share my fascination for the fiber optic gyro and its potential perfection. The term serendipity was used very early to describe it. The first example was the proper frequency which allows one to get a perfect biasing with imperfect components. Second one on the list, and may be the main one, is the non linear Kerr effect that “vanishes away” with a broadband source. You can add technological serendipity : a proton-exchanged lithium niobate waveguide is a quasi-ideal polarizer, and erbium-doped fiber amplification technology yields a quasi-ideal source. The result is a device that can get a continuously decreasing Allan deviation over many days of integration time, which is absolutely unique compared to all the other kinds of inertial sensors. It makes possible the dream of an inertial navigation system with an accuracy of a nautical mile over a month !

This presentation will be also the opportunity to present a “pot pourri” of comments about various important points which should be outlined : the contribution of Max von Laue to an effect which should be renamed Sagnac-Laue effect ; how amazing is the digital phase ramp simply because “the mean of a difference is the difference of the means” ; how powerful is the test of path-matched white light interferometry which could be renamed channelled spectrum analysis ; and to conclude, some comments about the Shupe effect and the fact that thermal stress in the sensing coil can be simply understood, and in any case, better understood than with the numerous papers using finite element analysis that you can find in the literature.

9852-3, Session 1

Recent developments in laser-driven and hollow-core fiber optic gyroscopes (*Invited Paper*)

Michel J. F. Dignonnet, Stanford Univ. (United States)

This tutorial will discuss two relatively recent research directions aiming at developing Sagnac-based gyroscopes accurate enough for inertial navigation of aircraft: fiber optic gyroscopes (FOGs) interrogated with a laser instead of broadband light to significantly improve the scale-factor stability; and FOGs utilizing a hollow-core fiber (HCF) in the sensing coil to reduce the drift caused by the Shupe effect and Kerr nonlinearity. We will also discuss a number of coupled-resonator optical waveguide gyroscopes proposed to date and explain why they fail to deliver their promise of greatly enhanced Sagnac effect. An experimental laser-driven FOG with near inertial-navigation performance will be reported.

9852-4, Session 1

Fiber optic gyros from research to production (*Invited Paper*)

George A. Pavlath, Northrop Grumman Navigation Systems (United States)

Fiber optic gyros are a great success story for a new inertial measurement technology that successfully transitioned from the laboratory in 1975 to production in 1992. This paper will review its research, development, product development, and production transfer. The focus of the paper will be on this cycle from Stanford University to Northrop Grumman.

9852-5, Session 1

Novel techniques to ensure quality fiber optic gyro coil production (*Invited Paper*)

Steve Yao, Zhihong Li, General Photonics Corp. (United States)

A fiber coil is the most critical, but yet least perfected component affecting the performance of a fiber optic gyro (FOG). Coil winding is generally considered as an art, not a science, requiring technicians with magic skills to produce, mainly due to the lack of testing method and capabilities. Numerous factors affect fiber coils' quality and performance, including the polarization crosstalk, the coil asymmetry, and the properties of potting adhesives. In this talk, we will first discuss all winding induced imperfections and their relationship with respect to the FOG performances. We will then introduce novel testing methods and equipment for measuring the polarization crosstalk, the coil asymmetry, and the Shupe effect. Finally, we demonstrate using Optical Coherence Tomography (OCT) for 3-D coil inspection. With the aid of these test capabilities and associated manufacturing procedures, we show that we are able to consistently produce high quality coils for high precision FOGs. It is comfortable to claim that FOG coil winding is no longer an art, but a science, and can meet the demanding requirements for the mass production and deployment of high precision FOGs for various applications.

9852-6, Session 2

Fiber optic gyroscope development at Honeywell (*Invited Paper*)

Glen A. Sanders, Honeywell Technology (United States)

No Abstract Available

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9852-7, Session 2

Current status of fiber optic gyro efforts for space applications in Japan (*Invited Paper*)

Shinji Mitani, Tadahito Mizutani, Shin-ichiro Sakai, Japan Aerospace Exploration Agency (Japan)

In response to maturation of the Fiber Optic Gyro technologies, FOGs are being used in various applications. Also in Japan, the demand for FOG is high, and is used in some space applications. In this paper, we introduce examples of Japanese products that apply to the space-use. It also describes the some efforts for high-grade navigation use in Japan.

9852-8, Session 2

Compact fiber optic gyroscopes (*Invited Paper*)

Ka Kha Wong, EMCORE Corp. (United States)

The realization of compact fiber optic gyroscopes was made possible by the invention and use of the fiber-optic transceiver (invented by Emcore). Inside the FOG transceiver, the following elements are integrated in a 14-pin butterfly package; namely the SLED, large area photodetector, TIA, TEC, various coupling lenses, a non-reciprocal element, a polarizing beam splitter, and a fiber tail assembly. The optical string of the FOG can be realized by splicing the output of the FOG transceiver to the input fiber of the FOG lithium niobate IOC and the outputs of the IOC spliced to the FOG coil. In higher precision FOGs, direct coupling of the output of the FOG transceiver can be carried out. It is possible to have a spliceless FOG. As a result of the invention of the FOG transceiver, various compact IMU systems have been realized, such as Northfinder modules and mini-navigators. In addition self-containing compact single axis FOG sensors have been realized for systems with challenged space requirements.

9852-9, Session 2

20 years of KVH fiber optic gyro technology (*Invited Paper*)

Jay Napoli, KVH Industries, Inc. (United States)

Precision fiber optic gyroscopes (FOGs) are critical components for a wide range of platforms and applications ranging from navigation and control for unmanned and autonomous systems, to pointing and imaging for georeferencing systems, and stabilization and orientation for payloads and robotics. Significant improvements in the performance of FOGs and FOG-based inertial systems such as IMUs and INs are due, in large part, to advancements in the design and manufacture of optical fiber, and in manufacturing and signal processing. Open loop FOGs, such as those developed and manufactured by KVH Industries, offer tactical-grade performance in a robust, small package. The success of KVH FOGs and FOG-based IMUs is due to innovations in key fields, including the development of proprietary D-shaped fiber with an elliptical core, and the 170 micron diameter ThinFiber. KVH continually improves its FOG manufacturing processes and signal processing, which results in improved accuracies across its FOG product line. KVH acquired its FOG capabilities, including its patented E-Core fiber, when the company purchased Andrew Corporation's Fiber Optic Group in 1997. E-Core fiber is unique in that the light-guiding core - critical to the FOG's performance - is elliptically shaped. The elliptical core fiber has very low loss and high polarization-maintaining ability. In 2010, KVH developed its ThinFiber, a 170 micron diameter fiber that retains the full performance characteristics of E-Core fiber. ThinFiber has enabled the development of very compact, high-performance open-loop FOGs, which are also used in a line of FOG-based inertial measurement units and inertial navigation systems.

9852-10, Session 2

Technological advancements at Al Cielo inertial solutions (*Invited Paper*)

Lisa Koenigsberg, Meir Rosilio, Noam Pasternak, Arnon Arbel, Al Cielo Ltd. (Israel)

Closed Loop Fiber Optic (FOG) gyroscopes are known for their high performance in terms of noise and accuracy. They are also the accurate gyro of choice for long and accurate missions. One of the demands in such missions is a very low error in accumulated angle. A simple PI loop that is commonly implemented as part of a closed loop IFOG can yield errors under certain conditions. Particularly of concern are rate integration errors that appear during angular accelerations. To meet the specifications of a precise application, an advanced PI loop was implemented and tested using a HIL simulation as well as measurement of inertial errors. Errors on the order of several μ Rads are reported.

9852-11, Session 3

Remembering Shaoul Ezekial, one of the early pioneers of fiber optic gyros (*Invited Paper*)

Glen A. Sanders, Honeywell Technology (United States)

No Abstract Available

9852-12, Session 4

Advances in optical fibers for fiber sensors (*Invited Paper*)

Andrew M. Gillooly, Fibercore Ltd. (United Kingdom)

Advances in commercial sensing requirements have been key to the development of advanced optical fibers. Fiber optic gyroscopes (FOGs), medical and industrial pressure sensors, fiber lasers and current sensors have demanded the evolution of optical fibers from simple single mode products to advanced bespoke products. These advanced fibers are explicitly optimized for maximizing sensitivities to the measurand(s) yet isolating from unwanted environmental and parasitic effects.

The drive for smaller sized/higher sensitivity FOGs in aviation and for 3D shape sensing for minimally invasive surgery has created the need for bend insensitive multicore fiber with reduced cladding diameter. 3D shape sensing takes the multicore fiber to the next evolution step by requiring a continuous spin along the length of the fiber, creating a helix shape which enables differentiation between longitudinal strain/compression, bend in the X, Y and Z axes and left/right hand rotation.

The need for in-vivo and downhole pressure sensors has pushed fiber designs towards twin hole or side hole fibers with 80 μ m cladding diameters, elliptical cores and polyimide coatings to enable highly sensitive pressure measurements, easy interrogation and biocompatibility.

The demand for highly sensitive yet highly stable Faraday effect current sensors has pushed the development of highly birefringent, spun, polarization maintaining fibers towards shorter spin pitches and reduced diameters. These fibers allow the maintenance of circular polarization states, isolated from environmental factors yet sensitive to the Faraday effect allowing polarization rotation to measure the electrical current of a conducting cable.

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9852-49, Session 4

Fiber optic gyro development at Fibernetics (*Invited Paper*)

Ralph A. Bergh, Leif Arnesen, Craig Herdman, Fibernetics LLC (United States)

Fiber optic gyroscope based inertial sensors are being used within increasingly severe environments, enabling unmanned systems to sense and navigate in areas where GPS satellite navigation is unavailable or jammed. A need exists for smaller, lighter, lower power inertial sensors for the most demanding land, sea, air, and space applications.

Fibernetics is developing a family of inertial sensor systems based on our closed-loop navigation-grade fiber optic gyroscope (FOG). We are making use of the packaging flexibility of the fiber to create a 3-axis navigation grade inertial measurement unit (IMU) (gyros and accelerometers) that has a volume less than 100 cubic inches. We are also planning a gyrocompass system having roughly the same size. In this paper we provide an update on our progress and describe our novel optical architecture and our modulation scheme for the Sagnac interferometers.

9852-13, Session 5

New technique for fabrication of low loss high temperature stable high reflectivity FBG sensor arrays (*Invited Paper*)

Stephen J. Mihailov, Dan Grobncic, Robert B. Walker, Ping Lu, Huimin Ding, National Research Council Canada (Canada)

Fiber Bragg grating (FBG) arrays in silica based optical fibers are increasingly used in applications involving system monitoring in extreme high temperature environments. Where operational temperatures are > 600 °C, traditional UV-laser inscribed FBGs are not appropriate since the grating's induced Type I index change is erased. Instead, two competing FBG technologies exist: 1) regenerative FBGs resulting from high temperature annealing of a UV-laser written grating in a hydrogen loaded fiber and 2) FBGs written with femtosecond infrared pulse duration radiation (fs-IR), either using the point-by-point method or using the phase mask approach. Regenerative gratings possess low reflectivity and are cumbersome to produce, requiring high temperature processing in an oxygen free environment. Multiple pulse Type II femtosecond IR laser induced gratings made with a phase mask, while having very good thermal stability, also tend to have high insertion loss (- 1dB/grating) limiting the number of gratings that can be concatenated in a sensor array. Recently it has been shown that during multiple pulse type II thermally stable fs-IR FBG production, two competing process occur: an initial induced fs-IR type I FBG followed by a thermally stable high insertion loss type II FBG. In this paper, we show that if only a type I FBG is written using type II intensity conditions but limited numbers of pulses and then annealed above 600 °C, the process results in a type II grating that is stable up to 1000 °C with very low insertion loss ideal for an FBG sensor array.

9852-14, Session 5

Sensing delamination in epoxy encapsulant systems with fiber Bragg gratings

Brad Jones, Garth D. Rohr, Amy K. Kaczmarowski, Sandia National Labs. (United States)

Fiber Bragg gratings (FBGs) are well-suited for embedded sensing of interfacial phenomena in materials systems, due to the sensitivity of their spectral response to locally non-uniform strain fields. Over the last 15

years, FBGs have been successfully employed to sense delamination at interfaces, with a clear emphasis on planar events induced by transverse cracks in fiber-reinforced plastic laminates. We have built upon this work by utilizing FBGs to detect circular delamination events at the interface between epoxy encapsulants and ceramic materials. FBGs are embedded at or near the surface of a ceramic substrate, after which a film of encapsulant is potted around the FBG. Delamination is initiated through indentation at the free surface of the cured encapsulant film. We have characterized the spectral response pre- and post-delamination for both simple and chirped FBGs as a function of delamination size, as well as the position of the FBG relative to the indentation point and the encapsulant-substrate interface. Unsurprisingly, we have found that FBGs are capable of detecting delamination, even when the fiber is positioned outside of the delamination zone. Moreover, we show that chirped FBGs can provide information regarding the location at which delamination was initiated. Our results further highlight the unique capabilities of FBGs as diagnostic tools for sensing delamination in materials systems.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the US Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

9852-15, Session 5

Interrogation and mitigation of polarization effects for standard and birefringent FBGs

Selwan K. Ibrahim, FAZ Technology Ltd. (Ireland); Jan Van Roosbroeck, FBGS International NV (Belgium); John O'Dowd, FAZ Technology Ltd. (Ireland); Bram Van Hoe, FBGS International NV (Belgium); Eric Lindner, FBGS Technologies GmbH (Germany); Johan Vlekken, FBGS International NV (Belgium); Martin Farnan, FAZ Technology Ltd. (Ireland); Devrez M. Karabacak, Fugro (Netherlands); Johannes M Singer, Fugro Technology BV (Netherlands) and FAZ Technology Ltd (Ireland)

Optical sensors based on Fiber Bragg Gratings (FBGs) are used in several applications and industries. Several inscription techniques and type of fibers can be used. The standard FBG inscription process involves stripping/re-coating the fiber and using a UV source and mask allowing the control of the FBG shape and characteristics. Draw tower grating (DTG) enables the inscription of the grating during the fiber drawing process which avoids stripping the coating enabling higher tensile strength for the sensor. Also Femtosecond lasers can be used to inscribe FS-FBGs using point-by-point or line-by-line inscription techniques which enable FBGs to operate at high temperature. However the side effect of the writing process, type of fiber used and the packaging of the sensor highlights a polarization dependency which could be observed with polarized tunable laser based optical interrogators. Here we study the birefringence effect on the fiber/sensor by measuring the polarization dependent frequency shift (PDFS) of the FBG peak for the different FBG types. A PDFS of <1pm up to >20pm was observed across the FBGs. To mitigate and reduce this effect we propose a polarization mitigation technique which relies on a synchronous polarization controller to reduce the effect by a factor greater than 4. In other scenarios the sensor itself is designed to be birefringent (Bi-FBG) to allow pressure and/or simultaneous temperature and strain measurements. Using the same polarization controller we demonstrate how we can interrogate the polarization effects with high accuracy to enable high performance of such sensors to be achievable.

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9852-16, Session 5

High-speed system for FBG-based measurements of vibrations and sound

Devrez M. Karabacak, Fugro (Netherlands); Selwan K. Ibrahim, FAZ Technology Ltd. (Ireland); Yorick Koumans, Promolding BV (Netherlands); Martin Farnan, FAZ Technology Ltd. (Ireland); Rik Knoppers, Promolding BV (Netherlands)

Fiber Bragg Gratings (FBGs) allow for optical detection of localized physical effects without the need to couple the light out and back into a fiber, enabling robust and multiplexed sensor systems. The need of combining wide bandwidth and high resolution for dynamic sensing applications, like acoustics and vibrations, has presented significant challenges for FBG-based solutions. Here, we present a novel FBG-based measurement system enabled by using high-speed and high-precision tunable laser-based optical interrogation scheme. Multiple levels of integrated wavelength referencing coupled with low-noise high-speed electronics allow for spectral feature tracking at a resolution of <20 fm at kHz-frequencies. In combination with fiber accelerometers that employ a unique force transmission mechanism, amplifying strain on the Bragg grating and increasing the resonance frequency of the transducer, resolutions <10 μg (150 Hz bandwidth) to sub-mg resolution in kHz-frequencies is achieved. Similarly, compact wavelength-multiplexed hydrophones with wide range linearity and dynamic range, sub-Pa resolution and flat-sensitivity down to static pressures are demonstrated. The sensors are demonstrated to be customizable to application-specific specifications, and designed to be scalable to large quantity reproducible manufacturing.

In contrast to interferometry-based solutions, the tunable swept-laser detection scheme in combination with strain-based FBG sensors provides a cost-effective system that allows for easy scaling of sensor counts per fiber and fiber counts simultaneously recorded. Finally, the integrated high accuracy triggering and hybrid measurement capabilities present the potential to monitor sounds and vibrations in a wide range of applications from seismic surveys to machine and structural monitoring applications in harsh environments.

9852-17, Session 6

Phase-shifted fiber Bragg gratings and their sensing applications (*Invited Paper*)

Ming Han, Univ. of Nebraska-Lincoln (United States)

Phase-shifted fiber Bragg gratings (PS-FBGs) can be conceptually considered as in-line fiber Fabry-Perot interferometers formed by two regular FBG mirrors. The strong optical resonance resulting from highly reflective FBGs leads to extremely narrow spectral features that can be explored for sensing applications with improved performances over regular FBGs. In this talk, we will discuss the fabrication of PS-FBGs on passive fibers and their sensing applications. More specifically, we will introduce the fabrication and spectral characterization of PS-FBGs directly on germanium-doped single-mode fibers and side-hole fibers without the need of photosensitization using a 193 nm excimer laser and phasemasks. In particular, PS-FBGs on side-hole fibers show two spectral notches corresponding to the two polarization states. Then we will discuss exploring the birefringence of the PS-FBGs on side-hole fiber to achieve temperature-insensitive refractive index sensing and to achieve simultaneous measurement of temperature and hydrostatic pressure. We will also discuss the use of PS-FBGs on regular fibers for highly sensitive ultrasonic detection and show that such sensor system can achieve a ultrasonic detection sensitivity comparable to traditional piezo-electric ultrasonic sensor system. Finally, we will introduce chirped PS-FBGs, a new type PS-FBG sensor platform recently developed in our laboratory, for highly-sensitive and absolute strain measurement and for acoustic emission detection that can adapt to large background strains.

9852-18, Session 6

Field trial of a multi-parameters' monitoring network using FBGs adapted directly in the conventional instruments of dams

Joao B. Rosolem, Claudio A. Hortencio, Claudio Florida, Danilo C. Dini, Rivaél S. Penze, Bruno N. Aires, Fabio R. Bassan, Rodrigo A. Morbach, Eduardo F. da Costa, Felipe C. Salgado, Rodrigo Peres, João Paulo V. Fracarolli, CPqD (Brazil); Marcus Vinícius F. Santana, Augusto Cezar M. Gregatti, Guilherme Muniz, BAESA - Energética Barra Grande S/A (Brazil); Gerson L. Amadeo, Gilson M. Carvalho, Fernando Pertile, Foz do Chapecó Energia S.A. (Brazil); Luis Fernando P. Melegari, Heloisa O. Herreros, Marcelo Y. Kurokawa, CPFL Geração de Energia S.A. (Brazil); Luis F. de Avila, Univ. Estadual de Campinas (Brazil)

The use of fiber optic sensors for dams' monitoring has emerged as a safe and innovative alternative. FBG (Fiber Bragg Grating) technology has the advantages of linear frequency variation with the measured signal intensity, be passive and easy formation of networks of sensors in a single fiber. Some monitoring systems using FBGs have been proposed for dams' applications but in general the sensors installation is done during the dams' construction. In dams already built and in operation the embedding of the FBGs sensors in the physical structures of the dams is not easy and cost-effective. In this case other approach has to be applied.

In this paper, we present the results of a field trial of a multi-parameters' monitoring network using FBGs specially packaged to adapt directly in the conventional instruments of two dams (triorthogonal, shaft extensometer, rockfill flow-through, concrete flow-through, standpipe piezometer, water level gauge and settlement gauge) which are in full operational capability. The FBGs were rigorously specified to adapt in the conventional dams' instruments, taken in account its particular working range. In some cases new FBGs had to be specially developed to adapt to the real conditions of the dams.

We presented the details involved in the design of the sensor's network, such as, the sensors adaptation, the resolution comparison between the conventional instruments and the FBGs, the network topology, the spectral occupancy distribution considering, the number of sensors by fiber and the performance of the FBGs sensors compared with the conventional instruments used in the dams.

9852-19, Session 6

Development and field trial of a FBG-based magnetic sensor for large hydrogenerators

João P. V. Fracarolli, João B. Rosolem, Elias K. Tomiyama, Claudio Florida, Rivaél S. Penze, Rodrigo Peres, Danilo C. Dini, Claudio A. Hortencio, CPqD (Brazil); Paulo I. G. Dilli, Erlon V. da Silva, Marcéu C. dos Santos, Tractebel Energia (Brazil); Fabiano Fruett, Univ. Estadual de Campinas (Brazil)

The monitoring of hydro generators health is of great interest for electrical companies and for industry. Because these machines operate almost uninterruptedly, it is expected that some problems may occur. For example, inter turn short-circuits on the poles windings, caused by failures on the insulation due to the aging process and the harsh environment. These short-circuits sometimes can be observed only when the machine is operating, due to the centrifugal forces that actuates on the poles, pressing

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the turns together. In this work, we propose a passive optical sensor for online magnetic field monitoring in large hydro generators. This sensor uses a FBG (Fiber Bragg Grating) structure attached to a magnetostrictive material composed by the rare-earth alloy Terfenol-D. This material suffers mechanical deformation proportional to the magnetic field applied to it, and then this deformation is transferred to the FBG, resulting in a wavelength displacement of the light reflected by the grating. This device is packaged in a novel rod-shaped enclosure, allowing it to be easily installed on the ventilation ducts of the stator of the machine, so the sensing element faces the poles. When short-circuit occurs, it is expected to be a reduction of the magnetic field generated by the affected pole in comparison to the other poles. Therefore, with the proper signal processing, it is possible to detect shorted turns without having to stop the machine. This sensor was developed and tested in laboratory and it has been evaluated in a field test on a real hydro generator.

9852-20, Session 6

Magnetostriction-based fiber optical current sensors

Suha M. Lasassmeh, Edward Lynch, Chiu-Tai Law, Rani F. El-Hajjar, Univ. of Wisconsin-Milwaukee (United States)

Fiber optical current sensors (FOCSs) utilizing fiber Bragg grating (FBGs) attached to magnetostrictive transducers are investigated. The first generation of FOCS is prototyped by axially attaching two metal rods. A Terfenol-D (T-D) rod with a giant magnetostriction is attached to a Monel-400 rod with adhesive for temperature compensation since both materials have the same linear thermal expansion coefficients. The FBG is mounted across adjoined ends of the two rods along the magnetostrictive expansion axis. Owing to its distinct advantages over conventional current transformers in compactness and immunity of electromagnetic interference for high current detection under high voltage environment, this FOCS can be used for current fault detection in power systems. However, this design has a fragile structure owing to the brittleness of monolithic T-D and uncoated FBG as well as most importantly limited response over a narrow magnetic field intensity (H) range. As a result, we propose new designs of FOCS that address these shortcomings while maintaining the use of simple optical power measurement for H estimation. These new designs require the embedment of an FBG into a) an epoxy block with a designed shape or b) a composite with graded T-D particle size distribution that introduces spectral broadening of the reflected FBG signal proportional to H. In approach a), the originally uniform grating period becomes non-uniform when the epoxy block is stressed by a magnetostrictive plunger with thermal compensation. In approach b), the graded magnetostrictive composites can be fabricated by integrating composite blocks with different T-D volume fractions.

9852-21, Session 6

Simultaneous temperature and tension monitoring of a multi-layer composite film with embedded Hi-Bi optical fiber Bragg gratings

Guanghui Chen, Jianbo Sha, Ming Zhao, Kan Gao, Ping Xue, China Electronics Technology Group Corp. (China); Lianqing Zhu, Beijing Information Science and Technology University (China)

In this paper, we present the experimental results of temperature and tension monitoring of a multi-layer composite film (Tedlar + Dacron +Mylar) with embedded Hi-Bi FBGs. The four Hi-Bi FBGs with different Bragg wavelength were written in a PANDA fiber. The three of them were embedded in the multi-layer composite film and one is used as reference.

Before being embedded, the temperature dependence of the Bragg wavelengths of the Hi-Bi FBGs was studied by placing them in a

temperature-controlled box and gradually raising the temperature from -50? to +100?. The tension dependence was studied by exposing the PANDA fiber with the four Hi-Bi FBGs to static pulling force at room temperature. The two ends of the fiber were fixed on two translation stages respectively and then gradually stretched by moving one translation stage precisely. The reflection spectrum of Hi-Bi FBGs were recorded by an optical sensing interrogator (MOI sm125) with an external PC.

There are four pairs of Bragg wavelengths were found in the reflection spectrum. The two peaks in each pair of Bragg wavelengths are corresponding to the fast-axis mode and slow-axis mode of a Hi-Bi FBG respectively. The difference of the two Bragg wavelengths is about 0.54 nm. When the temperature rose from -50? to +100?, the four pairs of Bragg wavelengths blue-shifted linearly, but the difference of the fast-axis mode Bragg wavelength and the slow-axis mode Bragg wavelength decreased. From the tension experimental data, we found that the four pairs of Bragg wavelengths respectively shift linearly with the change of the pulling force, but the difference of the fast-axis mode Bragg wavelength and the slow-axis mode Bragg wavelength is negligible in the measured range.

We embedded the three of above Hi-Bi FBGs into two pieces of the multi-layer composite film and retained one Hi-Bi FBG out of the films to be used as reference. The temperature and tension experiments of the embedded Hi-Bi FBGs were demonstrated by the same ways mentioned above. The experiment results shown that the Bragg wavelengths of the fast-axis mode and slow-axis mode of the embedded Hi-Bi FBGs shift linearly with the change of temperature and pulling force loaded respectively. Comparing with the reference FBG, the embedded Hi-Bi FBGs were sensitized by the composite film.

9852-22, Session 7

Ultrafast laser inscribed fiber Bragg gratings for sensing applications (*Invited Paper*)

Stephen J. Mihailov, National Research Council Canada (Canada)

No Abstract Available

9852-23, Session 7

Ultrafast fiber grating sensor systems for velocity, position, pressure and temperature measurements (*Invited Paper*)

Eric Udd, Ingrid Udd, Columbia Gorge Research LLC (United States); Jerry J. Benterou, Lawrence Livermore National Lab. (United States); George Rodriguez, Los Alamos National Lab. (United States)

In 2007 early demonstrations were made of a new system based on chirped fiber Bragg gratings capable of measuring the velocity and position of blast waves in energetic material. This was followed by the demonstration of the ability of to measure velocity, position, pressure and temperature during burn, deflagration and detonation of energetic materials. Extensive tests have been conducted by Columbia Gorge Research, ATK, Lawrence Livermore National Lab and Los Alamos National Lab. This paper will review research and test results on this new technology.

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9852-24, Session 8

Distributed temperature measurement using a dual-core fiber with an integrated miniature turn-around

Xiaoguang Sun, Jie Li, Mike Hines, OFS (United States)

Raman based distributed Temperature Sensing (DTS) using optical fiber has found a wide range of applications. A double-ended configuration can greatly improve the accuracy of the temperature measurements by eliminating the temperature error caused by the wavelength dependent loss and allow simple system calibrations. In this configuration, two pieces of parallel fibers are connected at the distal end to create a loop scheme and the backscattered light from both ends of the optic fiber. In confined spaces such as conventional harsh environment fiber packaging, like Fiber-In-Metal-Tube (FIMT), the fiber loop in the distal end is under bending stress and could lead to fiber breakage. Multicore optical fibers (MCFs) can be suited for this application. MCF incorporates several fiber cores inside a single glass cladding structure to minimize the cross-section area and can simplify the cable design. In addition an all-fused-silica-glass turn-around can be integrated into the multicore fiber and no part of the turn-around is bent or under stress thus the reliability of the turn-around device is greatly improved.

We will demonstrate distributed temperature sensing using a dual-core optical fiber and an integrated miniature turn-around to 300°C. The dual core fiber includes two 50µm graded index (GI) cores in a cladding diameter of 200 µm and coated with polyimide. The miniature turnaround measures less than 300 µm in diameter and less than 2mm in length, providing insertion loss of about 0.2 dB in around 1064 nm. The loss of the turn-around at 1060 nm is continued measured at 300C over 24 hours to test the long term stability and reliability. The deviation of the measured fiber temperature from the actual temperature is also estimated.

9852-25, Session 8

Distributed temperature sensing system using a commercial OTDR and a standard EDFA with controlled gain

Fabio R. Bassan, Felipe C. Salgado, Joao B. Rosolem, CPqD (Brazil); Fabiano Fruett, Univ. Estadual de Campinas (Brazil)

Raman based Distributed Temperature Sensors (DTS) have been proposed for different applications such as fire detection, pipeline leakage and overhead temperature monitoring. The optical fiber passivity, non strain dependence and the capacity to distributed sensor are the main reasons to spread this technology.

The temperature measurement of DTS is typically based on optical time domain reflectometer (OTDR) technique, in which high intensity and short optical pulses are sent to sensing fiber and the backscattering Raman anti-Stokes intensity is measured as function of the distance. The main limitation of this technology is associated with the extreme low intensity of Raman anti-stokes backscattering. The necessity of special bit codification, high intensity power laser and high gain with high bandwidth optical receiver increase the complexity of DTS design, increasing its cost.

In this work, we demonstrated for the first time to our knowledge the use of a DTS, which is implemented using two commercial equipment working independently: an OTDR and an erbium doped fiber amplifier (EDFA) with controlled gain. The main idea is to use the OTDR transmitter and receiver features (short pulse width and high gain/bandwidth, respectively) with an EDFA with no slow transient effects which is used to send a high intensity pulse to the fiber sensing generating a improved anti-Stokes backscattering signal to the OTDR receiver. This approach was evaluated in a 30 km of single mode fiber using an OTDR pulse width of 100 ns and an EDFA with 17 dBm of output power.

9852-26, Session 9

Optical frequency domain reflectometry: principles and applications in fiber optic sensing (Invited Paper)

Stephen T. Kreger, Nur Aida Abdul Rahim, Luna Innovations Inc. (United States)

Optical Frequency Domain Reflectometry (OFDR) is the basis of an emerging distributed fiber optic sensing (DFOS) technique that provides an unprecedented combination of resolution and sensitivity. OFDR differs from traditional DFOS techniques in that, rather than providing low resolution (1 m) measurements of strain and/or temperature over long ranges (many kilometers), it provides very high resolution measurements (millimeters) over relatively short ranges (tens of meters up to a few kilometers). OFDR has therefore been associated with the new acronym HD-FOS: High Definition Fiber Optic Sensing.

OFDR employs a swept laser and interferometer to interrogate a fiber optic sensor. Interference fringes are converted to complex reflection amplitudes as a function of sensor length via a Fourier Transform. While the technique can be used with Fiber Bragg Grating (FBG) sensors, OFDR is sensitive enough to measure the Rayleigh scatter inherent to the sensor fiber and thus does not require any specially treated sensors.

We will outline the principles of OFDR and focus on applications that benefit from the sensitivity and resolution of HD-FOS. Specifically, we will look at the impact HD-FOS is having on design and test in industries such as defense, aerospace and automotive that are moving rapidly towards new, lighter weight, stronger and more fuel efficient designs based on composite materials. Examples include earlier defect detection in composite structures; testing, qualification and structural health monitoring of composite parts; and temperature distribution monitoring of battery packs and inverters in hybrid and electric powertrains.

9852-27, Session 9

A rapid demodulation method for optical carrier based microwave interferometer

Zhen Chen, The Univ. of Rhode Island (United States); Gerald Hefferman, The Univ. of Rhode Island (United States) and Warren Alpert Medical School of Brown Univ. (United States); Tao Wei, The Univ. of Rhode Island (United States)

Optical carrier based microwave interferometry for distributed optical sensing, also known as incoherent optical frequency domain reflectometry, has been successfully demonstrated for dynamic distributed sensing applications with decent accuracy. It has a proven advantage over its peer technologies, that the use of broadband light source in the entire sensing system makes it adaptive to multimode optical fibers, including plastic optical fibers, holding the promise to be used under excessive strain loadings. However, one drawback of current state-of-the-art is the necessity of using a vector network analyzer (VNA) to extract the reflections' phase information for distributed sensing. It increases the complexity and cost of the system, especially, at higher frequencies. This paper presents a new approach, introducing a RF modulated broadband optical local oscillator in the system to extract reflectors' phase information. This method significantly reduces the complexity of the previous proposed systems, while maintaining the performances. A working prototype was developed in the laboratory without the use of off-the-shelf precision instruments. The system detection limit of reflectivity is below - 50 dB. High strain resolution (10⁻⁴), high sampling rate (50 Hz), and decent spatial resolution (10 cm) were demonstrated on both single mode and multimode silica fiber. In addition, the high dynamic range (> 1 m²) was demonstrated on a plastic optical fiber. The system is compared with original method with a VNA in use. The limitation of the proposed system is discussed. This proposed technique holds the promise for distributed motion sensing, where large strain is presented.

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9852-28, Session 9

A novel data adaptive detection scheme for distributed fiber optic acoustic sensing

Ibrahim Olcer, TÜBITAK BILGEM (Turkey); Ahmet Oncu, Bogaziçi Univ. (Turkey)

The phase-sensitive OTDR technology with narrow linewidth laser sensitivity poses unique advantages over other sensor technologies and is being widely used in several applications such as health monitoring of civil structures, intrusion detection for perimeter and border security, etc. Conventional signal processing methods rely on averaging of consecutively acquired data frames which inherently reduce the maximum detectable frequency. Wavelet denoising techniques are also of interest to improve the performance of the detection system. Here, we concentrate on a different acoustic vibration detection method which is based on data adaptive processing. Two sets of input data are used: the primary data in which the possibility of signal presence is accepted and the secondary data inputs are assumed to contain only noise (clutter, interference, etc) terms to be used for training the detection system. Our system performs signal processing on real optical backscattered data captured by the high-sampling rate digitizers of the phase-sensitive OTDR system setup in TUBITAK BILGEM premises. The system parameters are reconfigurable so as to test different conditions for performance evaluation. The adaptive signal processor simply gathers M consecutive coherent pulses received from a 22 km long single mode fiber (SMF) that is interrogated by a 100 ns wide laser pulse. Two PZTs are used to introduce acoustic vibrations on the SMF. We show results for the sensitivity and spatial resolution of the system (which can be improved by first training target free assumed data and then using this data to adaptively weight the primary data under test).

9852-29, Session 9

Internal 3D strain field monitoring in concretes during hydraulic fracturing processes

Rongzhang Chen, Mohamed A. S. Zaghloul, Aidong Yan, Shuo Li, Guanyi Lu, Brandon C. Ames, Navid Zolfaghari, Andrew P. Bungler, Univ. of Pittsburgh (United States); Ming-Jun Li, Corning Incorporated (United States); Kevin P. Chen, Univ. of Pittsburgh (United States)

Energy industrial has always been the cornerstone for sustainable development of today's economy, in which gas and oil production certainly play a major role. With increasing level of difficulty in extracting conventional oil/gas resources, the energy industrial has been forced to move to unconventional resources such as shale gas and oil. Hydraulic fracturing was first developed in the early 1950's, evolving since then to include high volume stimulations of horizontal wells for shale gas and oil reservoir. Improved monitoring of the process in the field is necessary to guide efforts for optimization of the process, ensuring it is as effective and sustainable as possible. Additionally, scaled laboratory experiments have an established record for elucidating important mechanisms which can, in turn, be accounted for in field-scale design.

In this paper, we present a distributed fiber optic sensing scheme to image 3D strain fields inside concrete cubes during hydraulic fracturing process. Strain fields in concrete were measured by optical fibers embedded during the concrete fabrication process. The axial strain profile along the optical fiber was interrogated by the in-fiber Rayleigh backscattering with 1-cm spatial resolution using optical frequency domain reflectometry (OFDR). Based on the axial strain profile the 3D strain fields inside the cubes under various hydraulic pressures and fracturing schemes were obtained and used to predict the fracturing locations, size, and prognoses. The fiber optic sensor scheme presented in this paper provides scientists and engineers a unique laboratory tool to understand the hydraulic fracturing processes in both short and long periods of times.

9852-30, Session 10

Fiber optic chemical sensors: current status and future prospects (Invited Paper)

Robert A. Lieberman, Lumoptix, LLC (United States)

Some of the earliest uses of optical fibers were for chemical detection and measurement. The field of fiber optic chemical sensing has grown to include a wide variety of measurement environments, measurands, and measurement techniques. Passive remote spectroscopy, and chemically-augmented active sensing have been used in formats ranging from extrinsic to intrinsic, and at length scales ranging from submicroscopic to multi-kilometer. This talk discusses the relative strengths of the most prevalent fiber optic chemical sensors, both scientific and commercial, and speculates on the future of this burgeoning field.

9852-31, Session 10

Optical fibre gas detections systems (Invited Paper)

Brian Culshaw, Univ. of Strathclyde (United Kingdom)

This tutorial review covers the principles and prospects of fibre optic sensors in gas detection. Many benefits common to fibre sensor technology apply in the context of gas sensing – notably long distance, many km, access to multiple remote measurement points; invariably intrinsic safety; access to numerous important gas species and in many cases uniquely high levels of selectivity and / or sensitivity. The numerous approaches to realisation embrace spectroscopic interrogation techniques, the use of intermediate chemistry to realise colour or changes in dimensions or temperature and the availability of single point, multipoint and distributed sensing architectures. Furthermore the optically based technologies are compatible with demanding regulatory requirements in sectors such as mining and oil and gas.

The interface to the gas species of interest must be addressed using optical wavelengths and power levels compatible with fibre transmission. For direct spectroscopy, this implies near infra-red transmission which still facilitates access to numerous important gas species for direct absorption spectroscopy and many more when Raman can be utilised. Additionally direct spectroscopic absorption can be addressed though both direct optical loss and the consequent photo-thermal changes modifying the optical path delay. Networks up to 300 points are feasible.

Distributed systems imply specially prepared fibres and examples addressing toxic and explosive gases will be described. The performance of the coating technology is especially critical.

An analysis of the challenging routes to final application will follow, alongside a comparative assessment of the numerous fibre based techniques available and their compatibility with typical application sectors.

9852-32, Session 11

A tribute to Professor Annamaria Verga Scheggi (Invited Paper)

Anna G. Mignani, Francesco Baldini, Istituto di Fisica Applicata "Nello Carrara" (Italy)

No Abstract Available

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9852-33, Session 11

Fugitive methane leak detection using mid-infrared hollow-core photonic crystal fiber containing ultrafast laser drilled side-holes (*Invited Paper*)

Jason H. Karp, William A. Challener, Matthias Kasten, Niloy Choudhury, Sabarni Palit, GE Global Research (United States); Gary Pickrell, Daniel Homa, Adam Floyd, Yujie Cheng, Virginia Tech (United States); Fei Yu, Jonathan Knight, Univ. of Bath (United Kingdom)

The increase in domestic natural gas production has brought attention to the environmental impacts of persistent gas leakages. Approaching EPA regulations are likely to limit fugitive gas emission specifically for methane due to its significant greenhouse gas effects. This presents new challenges in detecting and quantifying methane leaks at various portions of the supply chain. A spectroscopic gas sensing solution would ideally combine a long optical path length for high sensitivity and distributed detection over large areas. Specialty microstructured fiber with a hollow core can exhibit a relatively low attenuation at mid-infrared wavelengths where methane has strong absorption lines. Methane diffusion into the hollow core is enabled by machining periodic side-holes along the fiber length through ultrafast laser drilling methods. The complete system provides hundreds of meters of optical path for routing along well pads and pipelines while being interrogated by a single laser and detector. This work will present transmission and methane detection capabilities of mid-infrared photonic crystal fibers. Side-hole drilling techniques for methane diffusion will be highlighted as a means to convert hollow-core fibers into applicable gas sensors.

9852-34, Session 12

Fingerprinting food by means of optical spectroscopy: a photonic tasting (*Invited Paper*)

Anna G. Mignani, Leonardo Ciaccheri, Andrea A. Mencaglia, Istituto di Fisica Applicata "Nello Carrara" (Italy)

The quality and safety of the food we eat attracts a great deal of publicity, and a demand for fresher, better-tasting, safer, healthier and higher quality food is escalating in every country.

In addition to conventional analytical techniques, new instruments and tools are being envisaged that are capable of reducing the costs of quality control and of alerting people of the onset of risks. Also, new instruments for traceability and certification are needed, especially those based on low-cost techniques.

Spectroscopy-based sensors making use of micro-optic and miniaturized components were capable to offer effective and low-cost solutions for many industrial and process control applications. Especially for the food sector, the intrinsic optical and mechanical characteristics of optical fibers, together with the wide availability of bright sources and portable spectrometers, made it possible to implement compact instrumentation applied to quality and safety controls for the food and beverage industry.

Indeed, optical spectroscopy enables a rapid and non-destructive analysis without making use of reagents or chemical treatments, thus avoiding the problem of waste discharge. Since it does not imply environmental side effects, it is an ideal candidate for "green analytics".

Absorption spectroscopy carried out in the visible and near-infrared bands, as well as fluorescence spectroscopy and colorimetry, demonstrated effectiveness in product authentication, fraud detection, and in quantifying nutraceutical and other quality indicators. More recently, Raman spectroscopy has been successfully proposed for rapid quality checks. While absorption, reflection, and fluorescence spectra show broad peaks that result from the

convolution of the many overlapping bands, which are poorly resolved for purposes of multicomponent analysis, Raman spectroscopy shows sharp bands that identify the molecular composition, a true fingerprinting capable of providing a straightforward food assessment.

Given the nature and complexity of the spectroscopic data involved, multivariate and chemometric processing techniques were needed to provide qualitative information for product authentication, or more sophisticated predictive models for quantifying quality and safety indicators. Indeed, smart data processing made optical spectroscopy a promising tool for rapid and non-destructive multicomponent analysis of foodstuffs.

This paper presents examples of absorption, reflection, fluorescence, and Raman spectroscopy, which were used for measuring quality and safety indicators of the most common food such as edible oils, honey, milk, bran, tomatoes, beer, and blueberries.

9852-35, Session 12

Hollow core microstructured fibres: new sensing opportunities (*Invited Paper*)

Marco Petrovich, Univ. of Southampton (United Kingdom)

After over a decade from their first demonstration, Hollow-core Microstructured fibres (HC-MOFs) are the subject of a renewed interest, which is driven by recent fabrication improvements and by a clearer perception of the unique solutions that these fibres may be able to offer to emerging challenges in low latency telecommunications, high power laser delivery and optical fibre sensing. HC-MOFs enable low loss light confinement in an air, rather than glass, which provides them with vastly different properties as compared to conventional fibres. For instance, they can operate at wavelengths exceeding the conventional transparency window of silica (both at short and, more importantly, at long wavelengths); they have approximately three order of magnitude lower optical nonlinearity; substantially lower sensitivity to thermo-optic effects and much increased radiation resistance as compared to standard fibres. In this paper we will review recent progress in the development of HC-PBGFs which is set to pave the way for their application in areas such as chemical sensing in the mid IR, wavelength referencing and sensing applications benefiting from low-thermal sensitivity.

9852-36, Session 12

Femtosecond direct writing for optically integrated optics (*Invited Paper*)

Wolfgang Schade, Technische Univ. Clausthal (Germany)

No Abstract Available

9852-39, Session 14

Nanostructured sapphire optical fiber for gas sensing at high temperature

Hui Chen, Stevens Institute of Technology (United States) and National Energy Technology Lab. (United States); Zsolt Poole, Paul R. Ohodnicki, National Energy Technology Lab. (United States); Henry H. Du, Stevens Institute of Technology (United States)

Single crystal sapphire optical fiber is an excellent candidate for sensing in harsh environment due to its high-temperature structural and chemical stability and good light transmission over a large spectral window. We present an experimental study of nanostructured sapphire optical fiber (NSOF) with nanoporous anodized aluminum oxide (AAO) as its cladding for high temperature gas sensing. Optical properties such as numerical aperture (NA) and power loss of NSOF are examined. We investigate the

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feasibility of entrapping plasmonic nanoparticles (e.g. Pd, Pt, Au, and Ag) in AAO cladding of NSOF to enable hydrogen sensing at temperatures up to 1000°C. Measurements under cyclic temperature and on-off gas flow conditions are also carried out. Parallel sensing experiments using unclad sapphire optical fibers with immobilized plasmonic nanoparticles are conducted for comparison with NSOF. Sensing performance will be discussed with respect to sensitivity and thermal stability of the nanoparticles.

9852-40, Session 14

Numerical analysis of mechanical properties of nanostructured sapphire optical fiber

Kai Liu, Padmalatha Kakanuru, Hui Chen, Fei Tian, Kishore Pochiraju, Henry H. Du, Stevens Institute of Technology (United States)

Single crystal sapphire fiber is an excellent candidate for fiber-optic sensing in harsh environment owing to its superior thermal and chemical stability at elevated temperatures. We have carried out a theoretical and experimental investigation on the mechanical properties of nanostructured sapphire optical fiber (NSOF) cladded with nanoporous anodized aluminum oxide (AAO). Bending behavior of NSOF is simulated using Finite Element Method with porosity and thickness of AAO as parameters. Results from bending tests are compared with the simulation outcome. Numerical and analytical simulations are also conducted to reveal the stress development during coating of metal Al and subsequent conversion to AAO on sapphire fiber. The knowledge established on mechanical properties of NSOF will be of critical significance in its design, production, and utilization for a variety of demanding applications such as sensing for energy generation and energy production systems.

9852-41, Session 14

Temperature-insensitive pressure or strain sensing technology with fiber optic hybrid Sagnac interferometer

Yuanhong Yang, Lin Lu, Shuo Liu, BeiHang Univ. (China); Wei Jin, The Hong Kong Polytechnic University (China); Zonghu Han, Yaohui Cao, Xi'an Flight Automatic Control Research Institute (China)

The fiber optic hybrid Sagnac interferometer which comprise of a broadband source, a fiber optic coupler and special polarization maintaining fiber (PMF) sensing probes has great application potentiality and the drift due to environmental temperature fluctuation is the main obstacle for application field. Based on the interference theoretical model of Sagnac interferometer with multi-segment PMFs, the transmission spectrum characteristic of two-segment PMFs Sagnac was investigated and simulated in detail. The results indicate that there will be two special dip wavelengths in the output spectrum with certain polarization state in loop. The difference between the two dip wavelengths can be stable when the environmental temperature fluctuates, but it will be in proportion to the birefringence change in one of the PMFs. And a temperature-insensitive pressure and strain sensing technology was proposed and designed base on this phenomenon. An experimental hybrid Sagnac interferometer was built and the solid core polarization maintaining photonic crystal fiber (PM-PCF) was taken as the sensing probe. One and two segments of PM-PCFs were inserted in the hybrid fiber loop respectively and the transverse pressure was applied on same PM-PCFs along its main polarization axis. The pressure sensitive coefficients and the temperature drift for the two sensing cases were measured and compared. The experimental results showed that the pressure sensitive coefficients was almost same to -1 nm/N, but the temperature drift in the two-segment fiber loop interferometer was less than 1pm/?. The experimental results agreed well with the theoretical model and the simulation results.

9852-42, Session 14

Polymer foil based optical strain sensor (Invited Paper)

Rozalia Orghici, Technische Univ. Clausthal (Germany); Konrad Bethmann, Fraunhofer Heinrich Hertz Institute (Germany); Michael Köhring, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Elke Pichler, Wolfgang Schade, Technische Univ. Clausthal (Germany)

No Abstract Available

9852-37, Session 15

Long-term stability testing of optical fibre Fabry-Perot temperature sensors

Dimitrios Polyzos, Mathew Jinesh, William N. MacPherson, Robert R. J. Maier, Heriot-Watt Univ. (United Kingdom)

Applications of fibre optic sensors at high temperatures have gained a huge interest recently, as they appeared to be suitable for temperature recording in harsh environments. In this work, we have constructed and tested an intrinsic Fabry-Perot fibre optic sensor consisting of a 125µm diameter single mode fibre (SMF28). The SMF28 fibre was spliced to another fibre of the same type, after a thin chromium layer was deposited on the tip of the fibre through a thin film coating procedure. The result was a low finesse optical SMF-Cr-SMF sensor with cavity lengths varying from 50µm to 100µm. This type of Fabry-Perot sensors were tested in a tube furnace over a temperature range from room temperature up to 1100°C. Following a number of annealing cycles, between the above mentioned temperatures range, very good repeatability of the phase response was achieved. During the cycling process, thermal stress relief takes place which makes the sensors suitable for temperature testing at temperatures just in excess of 1000°C. After initial cycling the sensors are subjected to long term stability tests. The phase response is stable over a period of 5 days at a temperature of 1050°C. The temperature resolution is around 3°C. Further investigation includes embedding applications of these sensors into metallic structures. Additive Manufacturing using Selective Laser Melting (SLM) has been used to achieve this embedding.

9852-38, Session 15

Laser heated pedestal growth system commissioning and fiber processing

Michael P. Buric, Paul R. Ohodnicki, M. J. Yip, Benjamin T. Chorpene, National Energy Technology Lab. (United States)

A new Laser Heated Pedestal Growth system was designed and fabricated using various aspects of effective legacy designs for the growth of single-crystal high-temperature-compatible optical fibers. The system is heated by a 100-watt, DC driven, CO2 laser with PID power control. Fiber diameter measurements are performed using a telecentric video system which identifies the molten zone and utilizes edge detection algorithms to report fiber-diameter. Beam shaping components include a beam telescope; along with gold-coated reflexicon, turning, and parabolic focusing mirrors consistent with similar previous systems. The optical system permits melting of sapphire-feedstock up to 1.5mm in diameter for growth. Details regarding operational characteristics are reviewed and properties of single-crystal sapphire fibers produced by the system are evaluated. Aspects of the control algorithm efficacy will be discussed, along with relevant alternatives. Finally, some new techniques for in-situ processing making use of the laser-heating system are discussed. Ex-situ fiber modification and processing are also examined for improvements in fiber properties.

9852-45, Session 15

Long-period fiber gratings coated with poly zwitterion-based multilayers for salinity measurements

Fan Yang, Fei Tian, Henry H. Du, Stevens Institute of Technology (United States)

We report in this paper the synthesis and utilization of ionic strength-responsive polysulfobetaine methacrylate (PSBMA) and polydiallyldimethylammonium chloride (PDADMAC) for layer-by-layer (LbL) deposition on long period gratings (LPG) inscribed in single mode optical fiber for salinity sensing and measurements. PSBMA swells with increasing water salinity. The resultant change in the density of the PSBMA/PDADMAC multilayers causes alteration of the effective refractive index in the coating on LPG, which can be sensitively monitored by the LPG in form of a shift in the resonance wavelength of the transmitted light. The performance of the PSBMA/PDADMAC coating on LPG for salinity sensing will be presented and discussed.

9852-48, Session 15

Fiber-optic flow sensor based on self-heated temperature sensor array

Guigen Liu, Geraldo Resende Lisboa Piassetta, Univ. of Nebraska-Lincoln (United States); Weilin W. Hou, U.S. Naval Research Lab. (United States); Ming Han, Univ. of Nebraska-Lincoln (United States)

Flow sensors are important for many applications such as process control and turbulence characterization. To date, Doppler effect or time of flight are two common methods investigated for measuring the flow velocity. These two methods rely on the existence of particles entrained in the water flow for wave scattering, leading to the problematic reliability of applications in clean waters where particles are limited. Under this scenario, an alternative fiber-optic velocimeter that doesn't rely on particles has been proposed and demonstrated in this paper. The new velocimeter is constructed using a multibore silica tubing which includes seven bores with one bore in the center and the other six situated outside in a hexagon shape. Each of the seven bores has a diameter of around 130 μm and accommodates a stripped regular single mode fiber (SMF) with a diameter of circa 125 μm . On the cleaved end of each SMF, a silicon pillar has been attached to form a Fabry-Perot (F-P) cavity which pops equally out of the tube endface. By heating the F-P cavity in the center bore, a temperature structure is formed within the seven F-P cavities due to heat transfer. In the presence of water flow, the temperature structure is changed accordingly. Thus, the speed and direction of water stream can be deduced from the temperature (wavelength) readings of the seven F-P cavities. The newly-proposed sensor serves as an alternative to previous sensors requiring presence of particles.

Conference 9853: Polarization: Measurement, Analysis, and Remote Sensing XII

Monday - Tuesday 18-19 April 2016

Part of Proceedings of SPIE Vol. 9853 Polarization: Measurement, Analysis, and Remote Sensing XII

9853-1, Session 1

Physical quantities involved in a Mueller matrix (*Invited Paper*)

Jose J. Gil Perez, Univ. de Zaragoza (Spain)

The polarimetric properties of a material sample are summarized in the sixteen elements of its associated Mueller matrix. The quantities carrying specific information on the significant polarimetric features have to be defined on the basis of the analysis of the mathematical structure of Mueller matrices. It is found that any Mueller matrix can be parameterized through four alternative ways: 1) an angular parameter and fifteen quantities that are invariant under common rotations of the input and output reference frames; 2) two angular parameters and fourteen quantities that are invariant under independent rotations of the input and output reference frames; 3) a retardance vector and thirteen quantities that are invariant under single retarder transformations, and 4) two retardance vectors and ten quantities that are invariant under dual retarder transformations. These parameterizations lead to proper definitions of the retardance and depolarization properties, which together with the diattenuation and polarizance properties, provide complete polarimetric characterization of the sample under consideration.

9853-2, Session 1

A deterministic method for studying depolarization in turbid media

Julia P. Clark, Univ. of California, Merced (United States)

There are a number of interesting experimental and Monte Carlo results regarding the persistence of polarization in turbid media; however, there is not a good theoretical understanding of this phenomenon. These results include circular polarization memory in strongly scattering anisotropic media and the impact of polydisperse scatterers on the depolarization rate.

In this paper, we investigate how the spectrum of the discretized transport equation can be used to predict the depolarization rate. In particular, we compare the depolarization of circularly polarized light to the randomization of the direction of propagation. We discuss the application of this method to imaging in maritime fog.

9853-3, Session 1

Index of refraction estimation from Stokes parameters with diffuse scattering consideration

Hanyu Zhan, David G. Voelz, Sang-Yeon Cho, New Mexico State Univ. (United States)

Remote sensing of the refractive index of a target surface has important applications for detection and classification tasks. Recently, we developed an approach for estimating refractive indices by fitting multiple degree of polarization (DOP) measurements to a model derived from a microfacet polarimetric bidirectional reflectance distribution function (pBRDF). Evaluation of the model indicates that DOP and estimated refractive index values are biased if diffuse scattering is ignored. Although the results obtained with the DOP values are encouraging, Stokes parameters provide a richer set of information than the DOP and are commonly measured by polarimetric systems these days. In addition, conventional microfacet pBRDF models do not capture diffuse scattering contribution and depolarization

phenomena. In this paper, we propose a modified pBRDF with a diffuse scattering consideration and develop a novel method for refractive index estimation from Stokes parameters. The method can also be extended to jointly estimate other parameters associated with the material diffuse scattering component, surface roughness and microfacet normal orientation. Our results show that Stokes parameter-based refractive index estimation is more stable compared to DOP-based estimation and the estimation accuracy improves considerably by including a diffuse component in the scattering model.

9853-5, Session 1

Estimators for overdetermined linear Stokes parameters

John S. Furey, U.S. Army Engineer Research and Development Ctr. (United States)

The forward modeling of polarization is well known in optical theory, but explicit inverse modeling is more useful for data analyses, especially when there are many measurements. The mathematics of estimating overdetermined polarization parameters is worked out within the context of the inverse modeling of linearly polarized light, and as the primary new result the general solution is presented for estimators of the linear Stokes parameters from any number of measurements. The utility of the general solution is explored in several illustrative examples including the canonical case of two orthogonal pairs. In addition to the actual utility of these estimators in Stokes analysis, the discussion provides an excellent illustration of many of the considerations involved in solving the ill-posed problem of overdetermined parameter estimation. Finally, suggestions are made for using a rapidly rotating polarizer for continuously updating polarization estimates.

9853-33, Session 1

A new code SORD for simulation of polarized light scattering in the Earth atmosphere

Sergey V. Korkin, Universities Space Research Association (United States); Alexei I. Lyapustin, NASA Goddard Space Flight Ctr. (United States); Aliaksandr Sinyuk, Sigma Space Corp. (United States) and NASA Goddard Space Flight Ctr. (United States); Brent Holben, NASA Goddard Space Flight Ctr. (United States)

We report a new polarized radiative transfer code, SORD, based on the method of Successive ORDers of scatterings (SO). This method is frequently used for atmospheric applications because of simplicity of coding. The method of SO is superb for relatively thin atmospheres (total optical thickness 1-2) and complicated aerosol height distribution. The code is currently implemented in the AERosol Robotic NETwork (AERONET) retrieval algorithm and meets the AERONET's tough requirements on run time as well as accuracy.

In our code, we assume plane-parallel vertically inhomogeneous atmosphere irradiated by solar beam, and bounded by a reflecting surface (land or ocean). We account for scattering by spherical particles or spheroids mixed with molecular scattering and absorbing gas. Only linear polarization of scattered atmospheric radiation is accounted for, while weak ellipticity is usually ignored. The code is intended to simulate light scattering in the UV, visible, and NIR bands, so thermal radiation is omitted as well.

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In the presentation, we will: (1) provide examples of error analyses for the new code; (2) discuss sensitivity of polarized signal to aerosol optical parameters after multiple scatterings; (3) analyze advantages of joint use of the SO and the discrete ordinates methods (e.g., correction of scattering orders higher than the first one); and finally (4) share our experience with SO method which is rarely discussed in literature (e.g., accuracy of numerical integration over optical thickness).

The code SORD is created in Fortran 90/95. It was tested under Windows and Linux systems and made publicly available via ftp://climate1.gsfc.nasa.gov/skorkin/SORD/

9853-6, Session 2

Pyxis: Uncooled IR imaging polarimeter

David B. Chenault, Polaris Sensor Technologies, Inc.
(United States)

Pyxis is an uncooled infrared imaging polarimeter that produces real time output. The specifications will be described along with representative data.

9853-7, Session 2

FlySPEX: A flexible multi-angle spectropolarimetric sensing system

Frans Snik, Christoph U. Keller, Leiden Observatory (Netherlands); Merijn Wijnen, Hubert Peters, Edwin Smulders, TEGEMA Eindhoven BV (Netherlands)

Accurate multi-angle spectropolarimetry permits the detailed and unambiguous characterization of a wide range of objects. Science cases and commercial applications include atmospheric aerosol studies, biomedical sensing, and food quality control. We introduce the FlySPEX spectropolarimetric fiber-head that constitutes the essential building block of a novel multi-angle sensing system. A combination of miniaturized standard polarization optics inside every fiber-head encodes the full linear polarization information as a spectral modulation of the light that enters two regular optical fibers. By orienting many FlySPEX fiber-heads in any desired set of directions, a fiber bundle contains the complete instantaneous information on polarization as a function of wavelength and as a function of the set of viewing directions. This information is to be recorded by one or several multi-fiber spectrometers. Not only is this system flexible in the amount of viewing directions and their configuration, it also permits multiplexing different wavelength ranges and spectral resolutions by implementing different spectrometers. We present the first prototyping results for a FlySPEX fiber-head design that is optimized for both polarimetric accuracy and commercial series production. We integrate the polarimetric calibration of each FlySPEX fiber-head in the manufacturing process.

9853-8, Session 2

Narrowband emission line imaging spectrometry using Savart plates

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Polarization spatial heterodyne interferometry (PSHI) allows for the development of compact, vibration insensitive, high spectral resolution sensors. Introducing the imaging qualities of a lenslet array extends the advantages of PSHI to imaging interferometers. The use of Savart plates enables a birefringent interferometer that obtains higher spectral resolution with fewer optical aberrations when compared to alternative designs. In this paper, we describe the design, construction, calibration and validation of an imaging polarization heterodyned interferometer (IPHI), based on

Savart plates, along with its associated theoretical model. This sensor is advantageous for spectral imaging in the areas of remote sensing, biomedical imaging and machine vision.

9853-9, Session 2

Acquisition method improvement for Bossa Nova Technologies' full Stokes, passive polarization imaging camera SALSA

Mohamed El Ketara, Sebastien Breugnot, Mathieu Vedel, Bossa Nova Technologies (United States)

Objective and background: We present a new acquisition method for Bossa Nova Technologies' full Stokes, passive polarization imaging camera SALSA. The SALSA camera is a Division of Time Imaging Polarimeter. It uses 4 different images from the same scene and the same point of view to compute the polarimetric information for each pixel of an image. Due to the very technique employed, the user is able to reconstruct the full polarization information without losing any resolution but high-speed measurement can hardly be obtained. We present here a new method used to overcome this limitation by acquiring images at full frame rate and full resolution of the camera. We will then present the effect observed on the acquisition of the Stokes parameters through several experiments.

Results: First, we provide general background of the SALSA camera's technology, its performances and limitations. Then, we demonstrate the necessity of full polarization imaging with high resolution and high speed. Finally, the new acquisition technique is presented through several speed acquisitions and different experiments.

9853-10, Session 3

SkyPASS: Sensor for precision navigation

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By using the polarization pattern in the sky produced by Rayleigh scattering, absolute azimuth can be found in real time and at rates suitable for navigation and surveying. We report on the system and performance data.

9853-11, Session 3

Infrared active polarimetric imaging system controlled by image segmentation algorithms. Application to decamouflage.

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Active polarimetric imaging systems are known to be powerful tools for remote sensing applications since they allow one to reveal contrasts that do not appear in standard intensity images. Various studies have been conducted to optimize the characteristics of those systems, in particular to maximize the contrast between the object of interest and the background in target detection applications. It has been shown that to maximize this contrast, a single polarimetric image has to be acquired with optimized illumination and analysis states. However, these studies rely on a priori knowledge of the scene. To bypass this limitation, a procedure has been proposed which relies on an iterative interplay between an active polarimetric imager with adaptive capabilities and an ultra-fast segmentation technique adapted to noisy polarimetric images allowing to

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recover the shape of the object of interest. The work presented here is an implementation of this procedure on an active polarimetric set-up where the illumination source is a laser at 1.55 μm . We describe the system that presents the unique characteristics of being able to generate and analyze all polarization states in the Poincaré sphere thanks to the use of liquid-crystal variable retarders. We then describe our strategy to optimize the contrast between a target and a background with unknown polarimetric characteristics. Relying on the full flexibility of our design, we show that we can also implement experimentally different polarimetric imaging strategies and compare their performance for decamouflage applications. We successfully demonstrate the interest of our methodology on different target-background examples.

9853-12, Session 3

Leaf volume reflectance is not Lambertian

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Breece and Holmes (1971) – and subsequent researchers – have found the bidirectional reflecting properties of corn and soybean leaves measured in the visible and near infrared wavelength region include a pronounced specular lobe - unlike the leaf bidirectional transmittance, which they found to be nearly Lambertian. We measured in the laboratory the light spectral bidirectional reflecting and transmitting properties of the leaves of nine plant species, including both corn and soybeans, common to the Baltimore, Maryland area. Our results show the leaf spectral reflectances displayed a pronounced specular lobe while leaf spectral transmittances were nearly Lambertian, supporting the conclusions of Breece and Holmes (1971) for corn and soybeans.

We then measured the leaf spectral bidirectional reflectance and transmittance properties through crossed polarizers, vertically polarizing the light incident on the leaf and measuring the reflected light through a horizontal polarizing filter. The spectral transmittance measurements were un-polarized. Our results show that both the leaf spectral reflectance and spectral transmittance for these nine species measured under these conditions is nearly Lambertian.

We conclude that the spectral bidirectional reflectance factors of the leaves of these nine plant species may be represented as the sum of 1) a surface reflectance that is both independent of wavelength and displays a pronounced specular lobe and 2) a non-polarized leaf volume reflectance that displays the effects of light absorption by chlorophyll. The sum of these two reflectance models allows the overall optical bidirectional scattering properties of these leaves to be represented by a quite simple optical model.

9853-13, Session 3

Specular highlight removal by polarization imaging

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The specular highlight reflected by glossy surfaces often plagues some vision applications, such as stereo vision, anomaly detection and commercial photography. Previous work aim to exploit prior or chromaticity to separate highlight, while fail to handle texture-less objects. Specular highlight is strongly polarized compared to the diffuse components, also with higher luminance in intensity-hue-saturation space. In this paper we proposed a novel and efficient polarization-luminance based scheme to guild the specular highlight removal. At first, we utilize the polarization difference between highlight and diffuse components to roughly locate specular reflection area. With the joint polarization features and luminance constraints, the specular reflection area can be efficiently identified and extracted.

Since the specular highlight is highly related the illumination orientation and intensity of light resource, diffuse component depend on the physicochemical properties of object surfaces. It's assumed to be statistically uncorrelated. In this case, inherent statistical analysis of probabilistic independence is applied to separate the highlight and diffuse components from the mixed regions. Note that the captured intensity is a linear sum of diffuse component and highlight.

The proposed method is reliably polarization-based and can obtain high-quality highlight-free images with good texture and boundary preservation, with no need of color segmentation or other pre-processing steps. Experimental results on a variety of targets demonstrate the validity and superiority to remove the highlight components than the state-of-the-art methods, even in dealing with the texture-less objects with large amount of specular highlight.

9853-14, Session 4

Field deployable pushbroom hyperspectral imaging polarimeter system

Mariano Lowenstern, Michael W. Kudenov, North Carolina State Univ. (United States); Julia Craven, Charles F. LaCasse IV, Sandia National Labs. (United States)

Hyperspectral polarimetry is commonly used to measure the spectrum and polarization state of a scene. This information is important to identify material properties for applications such as remote sensing and agricultural monitoring, among others. We report the design and performance of a ruggedized, field deployable Hyperspectral Polarimeter Imaging (HPI) system over the VIS to NIR range (450-800 nm). An entrance slit was used to sample a scene in the pushbroom imaging fashion, sampling over a 110o field of view. Furthermore, athermalized (T = 20-60o) achromatic retarders were implemented to measure the linear Stoke parameters. This paper reports the mechanical and optical layout of the system and its peripherals. We present spectral and polarimetry calibration techniques as well as testing results in field and laboratory environments.

9853-15, Session 4

Overview of division of focal plane color-polarization imagers

Viktor Gruev, Washington Univ. in St. Louis (United States)

We have designed, fabricated, and tested a division-of-focal-plane polarimeter capable of simultaneously imaging both spectral and polarization information at 30 frames per second. The imaging sensor, composed of 1300 by 800 imaging elements, each containing three vertically stacked photodetectors, is covered by pixelated nanowire polarization filters at four different orientations offset by 45°. The polarimeter has a dynamic range of 62 dB and captures intensity, angle, and degree of linear polarization in three visible spectrum bands while consuming 700 mW of power. The imaging sensor has been used for early detection of cancerous tissue as well as underwater imaging and target detection in turbid water conditions. We will summarize the results from these applications.

9853-16, Session 4

Laboratory goniometer approach for spectral polarimetric directionality

John S. Furey, U.S. Army Engineer Research and Development Ctr. (United States); Shellie Zahniser, US Army ERDC (United States); Cliff Morgan, U.S. Army Engineer Research and Development Ctr. (United States)

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A two meter inner diameter goniometer (custom built University of Lethbridge) provided less than 0.1° angular positioning precision for a series of spectral and polarimetric instruments to enable measurements of the directionality of polarized reflectance from soils in the laboratory, at 10° spacings on the goniometer. Instruments mounted on the goniometer, with linear polarizers in rotators (Thorlabs) in front of each instrument, included focal plane array imagers in the Visible (Allied Vision Manta), Near InfraRed (Manta), Short Wave InfraRed (FLIR Tau), and Long Wave InfraRed (Tau 2) spectral bands, as well as a hyperspectral imager in the Vis through NIR (Resonon Pika XC). Additional hyperspectral polarimetric imagers (custom built Army Research Laboratory) in the Vis through NIR, and SWIR, were mounted separately with angles measured by laser on the goniometer frame.

9853-17, Session 5

Revealing the polarization analyzer angles, and the unknown target (*Invited Paper*)

Yoav Yosef Schechner, Technion-Israel Institute of Technology (Israel)

A highly calibrated imaging polarimeter can be complex, slow, or costly. Instead, it is possible to use a simpler system, using only rough angles of a polarization analyzer. Still, the accurate state of the system can then be algorithmically derived. The derivation is based on the observed data, although the Stokes vectors of the analyzed object are unknown a-priori. Such self-calibration requires modest redundancy of measurements and diversity of polarization in the field of view, that can often be met in practice.

9853-18, Session 5

Contrast optimization in broadband polarimetric imaging

Lijo Thomas, Institut d'Optique Graduate School (France); Haofeng Hu, Tianjin Univ. (China); Matthieu Boffety, François Goudail, Institut d'Optique Graduate School (France)

Polarimetric imaging is known to allow one to retrieve information that do not appear in standard intensity images and is a useful tool in such domain as target detection and remote sensing. Since the polarization state of the light is defined only for a specific wavelength, most polarimetric systems work at one given wavelength for the sake of polarimetric accuracy. Therefore, if broad-spectrum sources are used, these systems have to include narrowband filters. However, these filters significantly decrease the light intensity entering the system and thus reduce the signal to noise ratio. For applications where the performance is dictated by the discriminability between two regions of the images (target/background) rather than by the accuracy of the polarimetric measurements, spectral filtering might not be the best option. In this work we investigate the impact of spectral broadening on the discriminability performance of passive and active polarimetric systems. Through simulations, we show that broadening the bandwidth of the illumination can increase the contrast between two regions, as the increase of light flux compensates for the loss of polarimetric precision. Moreover, we show that taking into account the chromatic characteristics of the components of the imaging system can further enhance the contrast. We validate these findings through experiments in passive and active configurations, and demonstrate that the illumination bandwidth can be seen as an additional parameter to optimize polarimetric imaging set-ups. These results can have interesting applications for high-speed imaging and microscopy.

9853-19, Session 5

Variation of linear and circular polarization persistence for changing field of view and collection area in a forward scattering environment

John D. Van der Laan, Jeremy B. Wright, Shanalyn A. Kemme, Sandia National Labs. (United States); Eustace L. Dereniak, The Univ. of Arizona (United States)

We present experimental and simulation results for a laboratory-based forward-scattering environment experiment, where 1 micron diameter polystyrene spheres are suspended in water to model fog. Circular polarization maintains its degree of polarization better than linear polarization as the optical thickness of the scattering environment increases. Both simulation and experiment quantify circular polarization's superior persistence, compared to that of linear polarization, and show that it is much less affected by variations in the field of view and collection area of the optical system. Our experimental environment's lateral extent was physically finite, causing a significant difference between measured and simulated degree of polarization values for incident linearly polarized light, but not for circularly polarized light. Through simulation we demonstrate that circular polarization is less susceptible to the finite environmental extent as well as the collection optic's limiting configuration.

9853-20, Session 5

Polarimetric phenomenology in the reflective regime: a case study using polarized hyper spectral data

Mark C. Gibney, Exelis Geospatial Systems (United States)

Understanding the phenomenology of polarimetric data is necessary if we want to obtain the maximum benefit when we exploit that data. To first order, polarimetric phenomenology is driven by two things; the target material type (specular or diffuse) and the illuminating source (point (sun) or extended (body emission)). In turn, the dominant target material and the illuminating source are determined by the problem addressed with the polarimetric data (eg detecting diffuse targets under trees in VNIR = [diffuse/sun]). In this paper, the polarimetric phenomenology associated with each of these four categories ([specular/sun], [diffuse/sun], [specular/body], [diffuse/body]) will be discussed, tying them to the problems typically associated with each of them.

In addition, a specific case study for the important [diffuse/sun] category will be presented. For the reflective regime (0.3 – 3.0um), the largest polarimetric signal is obtained when the sun illuminates a significant portion of the material BRDF lobe. This naturally points us to problems whose primary target materials are diffuse since the BRDF lobe for specular materials is tiny (low probability of acquiring on the BRDF lobe) & glinty (high probability of saturating the sensor). In the case study mentioned above, we investigated signatures of solar illuminated diffuse paints acquired by a polarimetric hyper spectral sensor. We will discuss the acquisition, reduction and exploitation of that data, and use it to illustrate the primary characteristics of reflective polarimetric phenomenology.

9853-21, Session 5

Estimating Index of Refraction for Material Identification in Comparison to Existing Temperature Emissivity Separation Algorithms

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Polarimetric hyperspectral imaging (P-HSI) combines two of the most common remote sensing modalities. This work leverages the combination of these techniques to improve material classification. Classifying and identifying materials requires parameters which are invariant to changing conditions, most often a material's reflectivity or emissivity is used. These quantities vary with viewing angle relative to the surface normal, however. As drones play an increasingly important role in the Air Force mission, it becomes important to develop material classification techniques robust to different viewing geometries. Utilizing both polarimetric and hyperspectral imaging, index of refraction can be remotely estimated, while simultaneously solving for a handful of parameters, such as object temperature. In general, this is an underdetermined problem but by replicating the spectral variation of the index of refraction using physics-based models the problem can be made overdetermined. Reducing the number of parameters needed to fit index of refraction allows additional parameters to be solved for. A system model has also been developed to test how well this technique is expected to perform under a variety of conditions. Finally, fit results are shown for different materials demonstrating that index of refraction can be retrieved to within approximately .2 rms error at a variety of viewing angles.

9853-22, Session 6

Retrieval of the polarized submarine light field from above surface measurements using polarimetric imaging

Robert Foster, Anna McGilloway, Alexander Gilerson, Carlos Carrizo, Ahmed El-Habashi, Samir Ahmed, The City College of New York (United States)

Knowledge of the underwater light field is fundamental to determining the health of the world's oceans and coastal regions. For decades, traditional remote sensing retrieval methods that rely solely on the spectral intensity of the water-leaving light have provided indicators of marine ecosystem health. As the demand for retrieval accuracy rises, use of the polarized nature of light as an additional remote sensing tool is becoming necessary. In order to observe the underwater polarized light field from above the surface (for ship, shore, or satellite applications), a method of correcting the above water signal for the effects of polarized surface-reflected skylight is needed. For three weeks in July-August 2014, the NASA Ship Aircraft Bio-Optical Research (SABOR) cruise continuously observed the polarized radiance of the ocean and the sky using a HyperSAS-POL system. Additionally, a polarimetric camera was used to acquire images of the sea surface during stations at coincident angles with HyperSAS-POL. In-situ inherent optical properties (IOPs) were continuously acquired using a set of instrument packages modified for underway measurement. Through a combination of vector radiative transfer codes and Monte Carlo simulations, a polarized sky glint correction scheme for a wind-driven ocean surface is developed. The correction is applied to measurements made with HyperSAS-POL and the polarimetric camera. Results of the inter-comparison are presented along with validation of the retrieved submarine light field for both instruments.

9853-23, Session 6

Power spectra trends in imaging polarimetry of outdoor solar illuminated scenes

Meredith K. Kupinski, Russell A. Chipman, College of Optical Sciences, The Univ. of Arizona (United States)

The $1/f^2$ power law (where f is spatial frequency) characterizes the spatial power spectrum of non-polarimetric outdoor scenes when averaged over an appropriately large ensemble. This empirical result has been repeatedly verified in many different imaging applications. In this work we compare the ensemble-averaged power spectrum of radiance and polarized radiance images. Outdoor scenes have been imaged over the past three-years using

JPL's Ground-based Multiangle SpectroPolarimetric Imager (Ground-MSPI) at the University of Arizona (UA). Ground-MSPI is an eight-band spectropolarimetric camera mounted on a rotating gimbal to acquire pushbroom imagery of solar illuminated outdoor landscapes. This Ground-MSPI image library offers a unique opportunity to quantify the statistical trends between polarimetric and non-polarimetric measurements. From power spectrum analysis of 1,975 images in our collection we report that the magnitude of the $1/f$ -exponent is lower for the polarized radiance image than the corresponding radiance image. This result quantifies the contrast mechanism difference for imaging polarimetry, indicates higher spatial frequency content in passive polarimetry of outdoor environments, and supports the assertion that polarimetry offers unique detection capabilities.

9853-24, Session 6

Detection of a poorly resolved airplane using SWIR polarization imaging

Laura M. Dahl, Joseph A. Shaw, Montana State Univ. (United States); David B. Chenault, Polaris Sensor Technologies, Inc. (United States)

Polarization can be used to detect manmade objects on the ground and in the air as it provides additional information beyond intensity and color. Skylight can be strongly polarized, so the detection of airplanes in flight requires careful consideration of the skylight degree and angle of polarization (DoLP, AoP). In this study, we detect poorly resolved airplanes (~4 pixels on target) in flight during daytime partly cloudy and smoky conditions in Bozeman, Montana. We used a Polaris Sensor Technologies SWIR-MWIR rotating polarizer imaging polarimeter to measure the polarization signatures of airplanes and the surrounding skylight from 1.5 to 1.8 μm . An airplane flying in a clear region of partly cloudy sky was found to be 69% polarized at an elevation angle of 13° with respect to the horizon and the surrounding skylight was 4-8% polarized (maximum skylight DoLP was found to be 7-14% at an elevation angle of 51°). As the airplane increased in altitude, the DoLP for both airplane and surrounding sky pixels increased as the airplane neared the band of maximum sky polarization. We observed that an airplane can be less polarized than its surrounding skylight when there is heavy smoke present. In such a case, the airplane was 30-38% polarized at an elevation angle of 17° , while the surrounding skylight was approximately 40% polarized (maximum skylight DoLP was 41-44% at an elevation angle of 34°). In both situations the airplane was most consistently observed in DoLP images rather than SO or AoP images. In this paper, we describe the results in detail and discuss how this phenomenology could result in detection performance of barely resolved aircraft.

9853-25, Session 6

Soil polarization data collected for the global undisturbed/disturbed Earth (GUIDE) program

Thomas E. Berry, Elizabeth Lord, U.S. Army Engineer Research and Development Ctr. (United States)

A key product of the Global Undisturbed/Disturbed Earth (GUIDE) program is the development of a soils database of broadband, hyperspectral, and polarized data. As a part of the GUIDE program, the US Army Engineer Research and Development Center (ERDC) conducted a testing series involving a large variety of instrumentation at several sites at the Yuma Test Center (YTC) in fiscal year 2015 under the auspices of the Joint Improvised Explosive Device Defeat Organization (now the Joint Improvised-Threat Defeat Agency), generating approximately 17 terabytes. Most of this data, available through ERDC, is hyperspectral polarimetric scientific data in the visible, near infrared, shortwave infrared, and longwave infrared bands. As part of this testing series the performance of six handheld devices was characterized. We discuss the process of this data collection at YTC focusing on the polarimetric data, including the two handheld devices

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that relied on polarization for detection. Although some other polarization states discriminate soils better in some other wavelengths, for certain visible and near-infrared bands the Stokes S2 parameter provided the best discrimination.

9853-26, Session 7

Development and validation of P-MODTRAN6 and P-MCScene, 1D and 3D polarimetric radiative transfer models

Alexander Berk, Frederick T. Hawes, Steven C. Richtsmeier, Spectral Sciences, Inc. (United States)

P-MCScene, is being developed by generalizing Spectral Sciences Monte Carlo-based synthetic scene simulation model, MCScene, to include calculation of all 4 Stokes components. P-MCScene polarimetric optical databases will be generated by a new version (MODTRAN7 = P-MODTRAN6) of the government-standard MODTRAN radiative transfer algorithm. The conversion of MODTRAN6 to a polarimetric model is being accomplished by (1) introducing polarimetric atmospheric and surface data, by (2) vectorizing the MODTRAN band model and line-by-line radiation calculations and by (3) integrating the newly revised and validated vector discrete ordinate, VDISORT2, model. Early results demonstrate a clear pathway towards the long-term goal of fully validated polarimetric models.

9853-27, Session 7

Estimation of errors in partial Mueller matrix polarimeter calibration

Andrey S. Alenin, J. Scott Tyo, Israel J. Vaughn, UNSW Canberra (Australia)

While active polarimeters have been shown to be successful at improving discriminability of the targets of interest from their background in a wide range of applications, their use can be problematic for cases with strong bandwidth constraints. In order to limit the number of performed measurements, a number of successive studies have developed the concept of partial Mueller matrix polarimeters (pMMPs) into a competitive solution. Like all systems, pMMPs need to be calibrated to yield accurate results. In this treatment we provide a method by which to select a limited number of reference objects to calibrate a given pMMP design. To demonstrate the efficacy of the approach, we apply the method to a sample system and show that three reference objects may suffice to accurately characterize the errors present within the system.

9853-28, Session 7

Maximum bandwidth snapshot channeled imaging polarimeter with polarization gratings

Charles F. LaCasse IV, Brian J. Redman, Sandia National Labs. (United States); Michael W. Kudenov, North Carolina State Univ. (United States); Julia Craven, Sandia National Labs. (United States)

Compact snapshot imaging polarimeters have been demonstrated in literature to provide Stokes parameter estimations for spatially varying scenes using polarization gratings. However, the demonstrated system does not employ aggressive modulation frequencies to take full advantage of the bandwidth available to the focal plane array. A snapshot imaging Stokes polarimeter is described and demonstrated through simulation results. The simulation studies the challenges of using a maximum bandwidth configuration for a snapshot polarization grating based polarimeter, such

as the fringe contrast attenuation that results from higher modulation frequencies. Similar simulation results are generated and compared for a microgrid polarimeter. Microgrid polarimeters are instruments where pixelated polarizers are superimposed onto a focal plane array, and this is another type of spatially modulated polarimeter, and the most common design uses a 2x2 super pixel of polarizers which maximally uses the available bandwidth of the focal plane array.

9853-29, Session 7

Channeled spectropolarimetry using iterative reconstruction

Dennis J. Lee, Charles F. LaCasse IV, Julia Craven, Sandia National Labs. (United States)

Channeled spectropolarimetry (CSP) enables snapshot measurements of the spectrally dependent state of polarization (SOP) of light. In a CSP system, light passes through two retarders and an analyzer, placed

in series before a spectrometer. This configuration amplitude modulates the Stokes parameters onto a carrier frequency in the spectral domain. The quality of CSP reconstructions can be impacted by a number of factors including environmental perturbations, temperature change, and errors produced by nonuniform sampling of the spectral data. For example, measurements acquired as a function of wavelength will be nonuniformly spaced along wavenumber. A conventional approach is to interpolate the nonuniformly sampled data onto a uniform grid for Fourier transform processing. However, this approach may fail if the data is sparsely sampled, and interpolation discards closely spaced data points that are smaller than the uniform grid. Additionally, the birefringent retarder elements typically used in CSP may be temperature dependent, contributing to sampling and reconstruction error. To address these problems, we present an iterative reconstruction algorithm capable of processing nonuniformly sampled CSP data and of reducing the noise caused by environmental perturbations like temperature fluctuations. Our reconstruction technique is based on developing a mathematical model of the CSP measurements. To reduce noise, our model can incorporate a priori knowledge; for example, we may know that a scene has sparse spectral polarization signatures. In this paper, we will present a description of the algorithm and some simulation and experimental results with a comparison to conventional approaches.

9853-30, Session 7

Bounds on the micropolarizer array channel assumption

Israel J. Vaughn, Andrey S. Alenin, J. Scott Tyo, UNSW Canberra (Australia)

Micropolarizer arrays are occasionally used in partial Stokes, full Stokes, and Mueller matrix polarimeters. When treating modulated polarimeters as linear systems, specific assumptions are made about the Dirac delta functional forms generated in the channel space by micropolarizer arrays. These assumptions are 1) infinitely fine sampling both spatially and temporally and 2) infinite array sizes. When these assumptions are lifted and the physical channel shapes are computed, channel shapes become dependent on both the physical pixel area and shape, as well as the array size. We show that under certain circumstances the Dirac delta function approximation is not valid, and give some bounding terms to compute when the approximation is valid, i.e., which array and pixel sizes must be used for the Dirac delta function approximation to hold. Additionally, we show how the physical channel shape changes as a function of array and pixel size, for a conventional 0°,45°, -45°,90° superpixel micropolarizer array configuration.

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9853-4, Session PTue

New accuracy benchmarks for 1D vector radiative transfer models in aerosol remote sensing, with an intercomparison of eight codes

Anthony B. Davis, Suniti V. Sanghavi, Olga V. Kalashnikova, David J. Diner, Michael J. Garay, Jet Propulsion Lab. (United States); Alexei I. Lyapustin, Sergey V. Korokin, NASA Goddard Space Flight Ctr. (United States); John V. Martonchik, Vijay Natraj, Jet Propulsion Lab. (United States); Vladimir V. Rozanov, Univ. Bremen (Germany); Feng Xu, Jet Propulsion Lab. (United States); Pengwang Zhai, Univ. of Maryland, Baltimore County (United States); Alexander A. Kokhanovsky, EUMETSAT (Germany)

Aerosols have been identified as one of the most resilient sources of uncertainty in global and regional climate modeling, in particular, as to how they interact with clouds. Requirements for the next generation of space-based aerosol (as well as cloud) remote sensing instruments are written to provide the observational capability that will ensure that this roadblock is removed and real progress is enabled. It is widely believed that, to meet this challenge, legacy multi-spectral approaches need to be supplemented with multi-angle and multi-polarization (hence “3M”) measurements and, most likely, retrieval algorithms that exploit the multi-pixel nature of imaging will have to be used as well. Forward models in these inversions will therefore be 1D vector Radiative Transfer (RT) models that are both accurate and efficient, preferably also linearized with respect to all state parameters that matter for aerosol retrievals, and that includes a reasonably good representation of the underlying surface.

It is therefore timely to survey the literature for accuracy benchmarks. Two aspects of the forward signal modeling problem are found wanting: first, vertical variations of the scattering and absorbing aerosol/molecular atmosphere; second, more sophistication is needed in the surface reflection model, including polarization. We will describe two short suites of problems that address these gaps, and proceed to compare the performance of eight different 1D scalar and vector RT models on these scenarios. Interestingly, this collection of models covers the diversity of approaches to solve numerically the 1D RT problem, with or without polarization.

9853-31, Session PTue

Camouflaged target detection based on polarized spectral features

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The polarized hyperspectral images include polarization, spectral, spatial and radiant features, which provide more information about objects and scenes than traditional intensity or spectrum ones. And polarization can suppress the background and highlight the object, leading to the high potential to improve camouflaged object detection. So polarized hyperspectral imaging technique has aroused extensive concern in the last few years. Now, the detection methods are not very mature, most of the algorithms are from the detection of hyperspectral image. And before using these algorithms, Stokes vector is used to process the original four-dimensional polarized hyperspectral data firstly. However, when the data is large and complex, the amount of calculation and error will increase. In this paper, the modified constraint minimum energy method (MCEM) is proposed, which adds the polarization information to construct the polarized spectral filter operator, and tensor decomposition is applied to reconstruct the original four-dimensional data into new three-dimensional data. The MCEM algorithm takes full advantages of spectral and polarization features, and applied to process the original data, which doesn't need to extract the Stokes vector, can reduce the computational cost and error. The experiments conduct on the real polarized hyperspectral images and the

results show that the modified algorithm is more suitable for the detection of camouflaged target in the polarized hyperspectral image.

9853-32, Session PTue

An efficient, FPGA-based, Cluster Detection Algorithm Implementation for a Strip Detector Readout System in a Time Projection Chamber Polarimeter

Kyle J. Gregory, Joanne E. Hill, NASA Goddard Space Flight Ctr. (United States); J. Kevin Black, NASA Goddard Space Flight Ctr. (United States) and Adnet Systems (United States); Wayne H. Baumgartner, NASA Goddard Space Flight Ctr. (United States) and Univ. of Maryland, Baltimore County (United States); Keith M. Jahoda, NASA Goddard Space Flight Ctr. (United States)

A fundamental challenge in a spaceborne application of a gas-based Time Projection Chamber (TPC) for observation of X-ray polarization is handling the large amount of data collected. The TPC polarimeter described uses the APV-25 ASIC to readout a strip detector. Two dimensional photoelectron track images are created with a time projection technique and used to determine the polarization of the incident X-rays. The detector produces a 128x30 pixel image per photon interaction with each pixel registering 12 bits of collected charge. This creates challenging requirements for data storage and downlink bandwidth with only a modest incidence of photons and can have a significant impact on the overall mission cost. An approach is described for locating and isolating the photoelectron track within the detector image, yielding a much smaller data product, typically between 8x8 pixels and 20x20 pixels. This approach is implemented using a Microsemi RT-ProASIC3-3000 FPGA, clocked at 20MHz and utilizing 10.7k logic gates (14% of FPGA), 20 Block RAMs (17% of FPGA), and no external RAM. Results will be presented, demonstrating successful photoelectron track cluster detection with minimal impact to detector dead-time.

9853-34, Session PTue

Automatic oil spill detection on quad polarimetric UAVSAR images

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Oil spill on the water bodies has adverse effects on coastal and marine ecology. Oil spill contingency planning is of utmost importance in order to plan for mitigation and remediation of the oceanic oil spill. Remote sensing technologies are used for monitoring the oil spills on the ocean and coastal region. Airborne and satellite sensors such as optical, infrared, ultraviolet, radar and microwave sensors are available for remote surveillance of the ocean. Synthetic Aperture Radar (SAR) is used most extensively for oil-spill monitoring because of its capability to operate during day/night and cloud-cover condition. The most important part in oil spill detection is the discrimination between oil spill and look-alikes. The natural biogenic film present on sea surface look similar to oil spills on the SAR images. This study detects the possible oil spill regions on fully polarimetric Uninhabited Aerial Vehicle - Synthetic Aperture Radar (UAVSAR) images. The UAVSAR image is decomposed using Cloude-Pottier polarimetric decomposition technique to obtain entropy and alpha parameters. In addition, other polarimetric features such as co-polar correlation and degree of polarization are obtained for the UAVSAR images. These features are used to discriminate oil-spill from look-alikes. The entropy, alpha, co-polar correlation and degree of polarization parameters are used with fuzzy logic based classification to detect oil spill on the SAR images. The experimental results show the effectiveness of the proposed method.

9853-36, Session PTue

Optimum full-Stokes polarimeters with immunity to both Gaussian and Poisson noises

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For a general full-Stokes polarimeter (FSP), there are two types of noises, signal-dependent Poisson shot noise and signal-independent Gaussian additive noise, which will degrade the signal-to-noise ratio (SNR) on the measured Stokes parameters. The relation between the immunity to Gaussian noise and the condition of the measurement matrix has been widely studied in the recent literature. Herein, we present a new merit function and use it to achieve optimal configurations with the immunity to both types of noises. Our studies show that, for the Configuration (I) consisting of a variable retarder followed by a fixed polarizer, the four measurement channels composed of a 102.2° retardance with a pair of azimuths $\pm 71.9^\circ$ and a 142.1° retardance with a pair of azimuths $\pm 34.95^\circ$ are found to be immune to these two noises. For the Configuration (III) consisting of two variable retarders followed by a fixed polarizer, the four measurement channels composed of two quarter-wave-plate (QWP) with four pairs of azimuths ($\pm 70.15^\circ$, $\pm 87.84^\circ$) and ($\pm 42.82^\circ$, $\pm 19.14^\circ$) are found to be one of optimal settings. The tolerances of the retardances or azimuths in the optimized configurations are evaluated for practical manufacture, assembling and alignment. The optimized configurations are reasonable for the performance enhancement of the FSP with four measurement channels. Although it seems that the division-of-time FSP solution using Configuration (I) with two different retardances and with two angular positions for each retardance is not convenient for practical operation, but it is the only way so far to achieve the immunity to both Gaussian and Poisson noise. In contrast, Configuration (I) can be conveniently used to develop the division-of-amplitude, division-of-aperture or division-of-focal-plane single-snapshot FSPs. Since four measurement channels are independent and parallel, there will be no any inconvenient for operation relative to the FSP with the same retardance in each channels. The minimization and equalization of noise variance are evidently important for these three types of snapshot FSPs, because the incident light beam is split into four channels and each channel just gets relatively low illumination.

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9854-1, Session 1

Advanced EO/IR Technologies at DARPA-MTO (*Keynote Presentation*)

Jay Lewis, Defense Advanced Research Projects Agency (United States)

No Abstract Available

9854-2, Session 1

Metasurface spatial light modulators for infrared imaging (*Invited Paper*)

Hou-Tong Chen, Los Alamos National Lab. (United States)

The control of infrared light lies at the core of many modern technologies, while devices built upon naturally occurring materials provide only limited performance, insufficient for emerging infrared technologies with increasingly demanding requirements. Metamaterials and metasurfaces provide excellent opportunities in developing novel optical devices and components for infrared imaging and sensing applications, although significant efforts are still necessary to make such applications fruitful. In this work we present our efforts in developing novel metasurface structures for effective control of optical amplitude, phase, and polarization states, and spatial light modulators based on hybrid metasurfaces for imaging and sensing applications. More specifically, we develop hybrid active/dynamical metasurfaces through integrating functional materials including traditional semiconductors and graphene, where the reflection and/or transmission properties can be efficiently and independently tuned through the application of voltage biases in the pixelized devices serving as infrared spatial light modulators for imaging and sensing.

9854-3, Session 1

Advances in IR APD materials research (*Invited Paper*)

Seth R. Bank, Scott J. Maddox, The Univ. of Texas at Austin (United States); Stephen D. March, The Univ. of Texas at Austin (United States); Wenlu Sun, Min Ren, Joe C. Campbell, Univ. of Virginia (United States)

The alloys of AlInAsSb are an attractive, but underexplored, material family for infrared detector applications, including remote gas sensing, light detection/ranging, and active/passive imaging. For example, InAs possesses nearly ideal material properties for the fabrication of near- and mid-infrared avalanche photodiodes (APDs), which result in extremely low excess noise factors and bandwidth independent of gain. Here, we discuss our recent advances in the growth and fabrication of high gain, low noise InAs APDs. Devices yielded room temperature multiplication gains >300, with much reduced (~10x) lower dark current densities. More broadly however, the AlInAsSb system suffers from a wide miscibility gap, leading to phase segregation over most of the compositional range. We describe our efforts to grow these materials over the full direct-bandgap compositional range. For films lattice-matched to GaSb, we demonstrate direct bandgaps tunable from 0.25 eV to 1.24 eV, corresponding to photon wavelengths from 5000 nm to 1000 nm. This direct-gap tuning range of nearly 1 eV is the largest reported for a III-V alloy lattice-matched to a commercially-available

substrate. The broadly tunable bandgap of this lattice-matched quaternary make it attractive for advanced mid-infrared and near-infrared detectors. This work was supported by the Army Research Office (W911NF-10-1-0391).

9854-4, Session 1

Recent progress in avalanche photodiodes for sensing in the IR spectrum (*Invited Paper*)

Joe C. Campbell, Univ. of Virginia (United States); Seth R. Bank, The Univ. of Texas (United States)

The internal gain of avalanche photodiodes (APDs) can provide higher sensitivity than p-i-n photodiodes, which is beneficial for many sensing applications. However, the origin of the APD gain is impact ionization, a stochastic process that results in excess noise and limits the gain-bandwidth. For the past four decades, reducing the excess noise factor, $F(M)$, has been a focus of APD research and development. One approach has been to identify materials with advantageous impact ionization characteristics such as HgCdTe and Si. Recently, we have shown that InAs exhibits excess noise characteristics that are the same as HgCdTe. Another approach to achieving low noise is through incorporating new materials and impact ionization engineering with appropriately designed heterostructures. One structure that was proposed to achieve very low noise is the staircase APD. Avalanche events occur proximate to a sharp bandgap discontinuities, which function similarly to dynodes in a photomultiplier tube. We have recently demonstrated a staircase structure based on the Al_xIn_{1-x}As_ySb_{1-y} material system, which is grown by molecular beam epitaxy. Record low noise has been achieved and the results are consistent with Monte Carlo simulations. At low bias variations of this structure have also demonstrated high photoconductive gain at very low bias. In addition Al_xIn_{1-x}As_ySb_{1-y} homojunction APDs have achieved excess noise lower than Si at longer wavelengths.

9854-5, Session 1

Broadband antireflection with curved surface nano-pyramids for image sensing devices

Anil Shrestha, Genki Mizuno, Patrcik Oduor, Robert Olah, Achyut Dutta, Banpil Photonics, Inc. (United States); Nibir K. Dhar, Night Vision and Electronic Sensors Directorate (United States)

The reflection loss in imaging devices is one of the major drawbacks, which degrades efficiency resulting in lower responsivity. Since the reflected light is no longer available for conversion into electrons, it is very important to reduce the reflection from the top surface of the device as much as possible. Quarter wavelength and two index antireflection (AR) coatings have been developed to reduce reflection; however, these AR coatings are wavelength dependent and have not performed effectively in a broadband range. Attempts to make AR coating for broadband wavelengths by stacking multiple index AR layer result in thicker and expensive solutions, which still do not provide proper antireflection at all desired wavelengths. Moreover, the usage of AR coatings escalates material and fabrication costs of the device. We propose a novel nanostructure, which matches the refractive index of the device to that of free space to reduce reflection from the top surface, eliminating the use of AR coatings and hence reducing the device

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cost. It is shown via simulation that the proposed nanostructure effectively eliminates the reflection loss over the broadband spectrum of desired wavelengths (e.g. Visible, Mid-wave IR (MWIR), Short-wave IR (SWIR) spectrums) opening various application opportunities.

9854-6, Session 1

Development of nanostructured antireflection coatings for EO/IR applications

Gopal G. Pethuraja, Magnolia Optical Technologies, Inc. (United States); Roger E. Welsler, Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Harry Efstathiadis, Pradeep Halder, SUNY Polytechnic Institute (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

EO/IR systems are being developed for a variety of defense and commercial applications. We are developing nanostructured based high performance AR coatings for various IR spectral bands. The AR coatings enhance the optical transmission through transparent windows by minimizing broadband reflection losses to less than one percent, a substantial improvement over conventional thin-film AR coating technologies.

In this paper we present our recent results to develop AR coatings for various IR spectral bands. The AR coatings are fabricated by depositing nanostructured layers using a self-assembly process. These AR coatings are being developed for short-wavelength IR (SWIR), mid-wavelength IR (MWIR) and long-wavelength IR (LWIR) spectral bands. We will present the theoretical analysis along with experimental results.

9854-7, Session 1

Development of silicon-germanium visible-near infrared arrays on 300mm silicon wafers

John W. Zeller, Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Caitlin Rouse, Harry Efstathiadis, Pradeep Halder, SUNY Polytechnic Institute (United States); Jay S. Lewis, Defense Advanced Research Projects Agency (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

Photodetectors based on silicon-germanium offer a lower-cost alternative to conventional infrared sensors based on material systems such as InGaAs and can provide good near-infrared (NIR) detection performance.

We have fabricated Ge based p-i-n photodetectors on 300 mm diameter Si wafers to take advantage of high throughput, large-area complementary metal-oxide semiconductor (CMOS) technology. The device fabrication process involves low temperature epitaxial deposition of a thin p⁺ (boron) Ge seed/buffer layer, and subsequent higher temperature deposition of a thicker Ge intrinsic layer. This is followed by selective ion implantation of phosphorus of various concentrations to form n⁺ Ge regions, deposition of a passivating oxide cap, and then top copper contacts to complete the p-i-n detector devices.

Various techniques including transmission electron microscopy (TEM) and secondary ion mass spectrometry (SIMS) have been employed to characterize the material and structural properties of the epitaxially grown layers and fabricated detector devices, and these results will be presented.

9854-8, Session 1

High-performance digital read-out integrated circuit (DROIC) for infrared imaging

Genki Mizuno, Robert Olah, Patrick Oduor, Achyut K. Dutta, Banpil Photonics, Inc. (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Banpil Photonics has developed a high-performance Digital Read-Out Integrated Circuit (DROIC) for image sensors and camera systems targeting various military, industrial and commercial Infrared (IR) imaging applications. The on-chip digitization of the pixel output eliminates the necessity for an external analog-to-digital converter (ADC), which not only cuts costs, but also enables miniaturization of the packaging to achieve SWaP-C camera systems. In addition, the DROIC offers new opportunities for greater on-chip processing intelligence that are not possible in conventional analog ROICs prevalent today.

Conventional ROICs, which typically can enhance only one high performance attribute such as frame rate, power consumption, or noise level, fail when simultaneously targeting the most aggressive performance requirements demanded in imaging applications today. Additionally, scaling analog readout circuits to meet such requirements leads to expensive, high-power-consumption with large and complex systems that are untenable in the trend towards SWaP-C.

We present the implementation of a VGA format (640x512 pixel 15µm pitch) capacitive-transimpedance-amplifier (CTIA) DROIC architecture that incorporates a 12-bit ADC at the pixel level. The CTIA pixel input circuitry has two gain modes with programmable full-well-capacity values of 100K e⁻ and 500K e⁻. The DROIC has been developed with a system-on-chip architecture in mind, where all the timing and biasing are generated internally without requiring any critical external inputs. The chip is configurable with many parameters programmable through a serial programmable interface (SPI). It features a global shutter, low power, and frame rates of up to 1000 frames per second in full VGA format are supported through 24 LVDS outputs. This DROIC, suitable for hybridization with focal plane arrays (FPA) is ideal for high-performance uncooled camera applications ranging from near IR (NIR) and shortwave IR (SWIR) to mid-wave IR (MWIR) and long-wave IR (LWIR).

9854-9, Session 1

Overview of detector technology for EO/IR sensing applications (Invited Paper)

Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Yash R. Puri, Magnolia Optical Technologies, Inc. (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Jay S. Lewis, Defense Advanced Research Projects Agency (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

This paper will covers recent advances in nanostructured based detector technology for optical sensing applications. The technologies include a variety of semiconductors, such as GaN/ AlGaN, ZnO, Si/SiGe, CNT and Graphene for optical sensing applications. These technologies are critical for defense and commercial applications that include optoelectronics materials in the UV, Visible and Infrared, using nanostructures, and use of novel materials such as CNT and Graphene. These technologies have opened doors for new approaches to apply device design methodology that are expected to offer enhanced performance and low cost optical sensors in a wide range of applications.

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9854-27, Session PWed

Analysis and implementation of the foveated imaging of the raptor eye

Aaron D. Long, Ram M. Narayanan, Timothy J. Kane, The Pennsylvania State Univ. (United States); Terence F. Rice, Michael J. Tauber, U.S. Army Armament Research, Development and Engineering Ctr. (United States)

The keen vision of birds of prey, or raptors, enables their ability to pick out small objects from far away while maintaining an awareness of their surroundings through wide peripheral vision. This is primarily enabled by the presence of two foveated regions on the retina, which allows for magnified imaging in small portions of the raptor's field-of-view. The ability to combine high resolution and a wide field-of-view is highly desirable for certain imaging applications. A careful study of the raptor eye allows for the implementation of these characteristics in new technology.

An optical model of the raptor eye is prepared and entered into a ray tracing software for analysis. Subsequently, a mathematical description for the optical properties of the eye is developed and interpreted. From these mathematical models, a new optical model is proposed which uses off-the-shelf lenses and aspheric optics to achieve imaging characteristics similar to those of the raptor eye. This lens system is afocal and intended for use by humans as a telescopic system with large magnification in portions of the field-of-view for high resolution and smaller magnification in other regions in order to maintain a wide field-of-view. This afocal lens design is optimized for aberrations, cost, and military use.

9854-28, Session PWed

Characterization of electromechanical actuator implemented to phase-shift system applied to a Michelson interferometer

Antonio Barcelata-Pinzón, Cruz Meneses-Fabian, Benemérita Univ. Autónoma de Puebla (Mexico); Rigoberto Juárez-Salazar, Univ. Tecnológica de la Mixteca (Mexico); Manuel Durán-Sánchez, Ricardo I. Álvarez-Tamayo, Instituto Nacional de Astrofísica Óptica y Electrónica (Mexico); Carlos Ignacio Robledo-Sánchez, Benemérita Univ. Autónoma de Puebla (Mexico); José Federico Casco Vázquez, Instituto Tecnológico de Apizaco (Mexico); José Lorenzo Muñoz-Mata, Universidad Tecnológica de Puebla (Mexico)

Numerical results are presented to show the characterization of an electromechanical actuator capable to achieve equally spaced phase shifts and fraction linearwavelength displacementsaided by an interface and a computational system. This paper is based in the use of inexpensive resourceson stability adverse conditions to achievesimilar results to those obtained with high-grade systems. The actuator is mechanically adapted to a mirror in the Michelson interferometer setup and performs an axial displacement in order to achieve well known and equally spaced pattern phase-shifts, which are observable in a non professional camera connected to computer system to be recorded and processed. Analytic and experimental results are shown.

9854-29, Session PWed

Remote application for spectral collection

Shelli R. Cone, Robert J. Steele, Nigel H. Tzeng, Alexer H. Firpi, Benjamin M. Rodriguez, Johns Hopkins Univ. Applied

Physics Lab., LLC (United States)

In the area of collecting field spectral data using a spectrometer it is common to have the instrument over the material of interest. In certain instances it is beneficial to have the ability to remotely control the spectrometer. While several systems have the ability to use a form of connectivity to capture the measurement it is essential to have the ability to control the settings. Additionally, capturing reference information (metadata) about the setup, system configuration, collection, location, atmospheric conditions, and sample information is necessary for future analysis leading towards material discrimination and identification. This has the potential to lead to cumbersome field collection and a lack of necessary information for post processing and analysis. The method presented in this paper describes a capability to merge all parts of spectral collection from logging reference information to initial analysis as well as importing information into a web-hosted spectral database. This allows the simplification of collecting, processing, analyzing, and storing field spectra for future analysis and comparisons. This concept is developed for field collection of thermal data using the Designs and Prototypes (D&P) Hand Portable FT-IR Spectrometer (Model 102). The remote control of the spectrometer is done with a customized Android application allowing the ability to capture reference information, process the collected data from radiance to emissivity using a temperature emissivity separation algorithm and store the data into a custom web-based service. The presented system of systems allows field collected spectra to be used for various applications by spectral analysts in the future.

9854-31, Session PWed

Characterization of internal geometry / covered surface defects with a visible light sensing system

Jeremy Straub, Univ. of North Dakota (United States)

Previous work has demonstrated the efficacy of using a visible light scanning system to detect and characterize defects in a 3D printed object. While this sensing system assessed both internal and external defects, its efficacy for assessing the internal (and external, but later covered surface) geometry of printed objects was not explicitly considered. Complex objects with these features make in-process defect detection far more important than it would be with an object that can be fully assessed with a post-completion scan, as it is required both for in-process correction (or job termination) as well as for end-product quality assurance. A similar set of techniques is relevant to both exterior surfaces that will later be fully or partially be covered from camera view by later printing as well as structural elements that will be fully contained within the object.

This paper presents work on the use of a multi-camera visible light 3D scanning system to identify defects with printed objects' interior and covered / obscured exterior surfaces. Specifically, this paper discusses how the same techniques discussed in prior work (principally for exterior surface assessment) can be used to detect in-process defects on (later) covered surfaces and internal structural elements, via the use of in-process models. The efficacy of this approach is assessed. Then, focus turns to the changes required for whole-object quality assurance with the presentation and evaluation of a two-step process that uses both in-process and object completion scans to fully validate the quality of a complex printed object.

9854-32, Session PWed

Alignment issues, correlation techniques and their assessment for a visible light imaging-based 3D printer quality control system

Jeremy Straub, Univ. of North Dakota (United States)

Quality control is critical to manufacturing. In many cases, techniques

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are used to define bounds for object conformity, based on historical production data. However, in the case of bespoke or small run jobs (such as those typical of 3D printing) this type of characterization is impossible (as insufficient data is available) or prohibitively expensive. In response to this challenge, as well as the numerous ways that 3D printers can make errors (making specific error condition detection techniques insufficient to detect all quality issues), a visible light imaging approach to quality control has been developed. This approach compares the produced parts to a computer-generated model of what should be produced and flags any discrepancies for analysis (facilitating corrective action or the system pausing or cancelling the job). In addition to its use for small batch production, this approach can also be useful in cases where 100% validation is needed due to the mission or safety critical nature of particular parts.

One issue with the commercialization of this system is minor alignment discrepancies between the generated model and the physical part. These can arise due to printing hardware misalignment issues (that occur over time operating), camera positioning and pointing issues or manufacturing irregularities and other factors. This paper discusses and evaluates a set of techniques for characterizing and correcting alignment issues between the projected and perceived data sets to prevent false positive errors attributable to misalignment. These techniques are compared to a basic pixel difference minimization technique to evaluate their utility.

9854-34, Session PWed

Lithographic VCSEL array multimode and single mode sources for sensing and 3D imaging

Jason Leshin, sdPhotonics, LLC (United States); Mingxin Li, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); James Beadsworth, sdPhotonics, LLC (United States); Xu Yang, Yansong Zhang, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Frank M. Tucker, U.S. Army RDECOM/STTC (United States); Latika K. Eifert, U.S. Army (United States); Dennis G. Deppe, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and sdPhotonics, LLC (United States)

Sensing applications along with free space data links can benefit from advanced laser sources that produce novel radiation patterns and tight spectral control for optical filtering. Vertical-cavity surface-emitting lasers (VCSELs) are one of the laser sources being developed for these applications. While oxide VCSELs are being produced by most companies for these applications, a new type of oxide-free VCSEL is demonstrating many advantages in beam pattern, spectral control, and reliability. These lithographic VCSELs offer increased power density from a given aperture size, and enable dense integration of high efficiency and single mode elements that improve beam pattern.

In this talk we will present device results for lithographic VCSELs and describes its integration into military systems for very low cost pulsed applications, as well as continuous-wave applications in novel sensing applications. The VCSELs are being developed for U.S. Army applications in soldier weapon engagement simulation training to improve beam pattern and spectral control. Wavelengths in the 904 nm and 990 nm ranges are being developed with the spectral control designed to eliminate unwanted water absorption bands from the data links. Multiple beams and radiation patterns based on highly compact packages are being investigated for improved target sensing and transmission fidelity in free space data links. These novel features based on the new VCSEL sources are also expected to find applications in 3-D imaging, proximity sensing and motion control, as well as single mode sensors such as atomic clocks and high speed data transmission.

9854-35, Session PWed

Binary CMOS image sensor with a gate/body-tied MOSFET-type photodetector for high-speed operation

Byoung-Soo Choi, Sung-Hyun Jo, Myunghan Bae, Kyungpook National Univ. (Korea, Republic of); Sang-Hwan Kim, Jang-Kyoo Shin, Kyungpook National University (Korea, Republic of)

A CMOS binary image sensor using a high-sensitivity gate/body-tied (GBT) MOSFET-type photodetector has been proposed. The sensitivity of GBT MOSFET-type photodetector which was fabricated using a CMOS 0.35 μm 2-poly 5-metal standard process is higher than the sensitivity of the p-n junction photodiode, because the output signal of the photodetector is amplified by the MOSFET transistor. Binary image sensor is more efficient using this property. Lower power consumption and higher speed operation is possible compared to conventional image sensor using multi-bit analog to digital converter (ADC). The frame rate of proposed image sensor is over 2000 frames per second (FPS), which is higher than conventional CMOS image sensors.

The output signal of active pixel sensor is applied to the comparator and compared with the reference level. The output 1-bit data of the binary process is determined by this level. To obtain video signal, the output 1-bit data is stored in the memory and is read out by horizontal scanning. The proposed chip is composed of a GBT pixel array (144 X 100), binary process circuit, a vertical scanner, a horizontal scanner, and a readout circuit. The operation mode can be selected between a binary mode and multi-bit mode. This technique can be applied to such areas as texture recognition, bar-coding, and object tracking.

9854-36, Session PWed

Simulation and characterization of SWIR InGaAs focal plane array

Richie S. Nagi, Jaydeep Dutta, Anil Shrestha, Patrick Oduor, Achyut K. Dutta, Banpil Photonics, Inc. (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Banpil Photonics, Inc. has developed novel InGaAs based photodetectors for Short-Wave Infrared (SWIR) imaging, targeting the most demanding security, defense, and machine vision applications. In order to achieve high sensitivity, it is essential to develop photodiodes that provide low dark current at high operating temperatures. This is a prerequisite for reducing the power consumption of the imaging system, as less energy is spent cooling down the focal plane array. Reduction in the sensor cooling requirements also encourages downward trends in the size and weight of the imaging systems, which in turn enables a wider range of applications.

Banpil has simulated, designed and tested focal plane arrays with low dark currents at room temperature. Based on our previous work, the improvements were focused on the device structure and passivation, in order to minimize the contribution of the surface leakage component to the total dark current. The dark current in InGaAs/InP focal plane arrays, with different pixel perimeter to area ratios, was evaluated under various temperatures ranging from 80 K to 400 K. The experimental results are correlated with the simulation results. The effect of the pixel spacing of the focal plane array on the different dark current mechanisms is also explored.

9854-37, Session PWed

A study on optical coherence tomography using high frequency swept source

Xinglin Tong, Lei Ding, Pan Hu, Liang Chen, Cheng Cheng,

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Hongqiao Wen, Jiaguo Xiong, Wuhan Univ. of Technology (China); Hong qiao Wen, Wuhan Univ of Technology (China)

Optical coherence tomography based on ultra high-speed frequency swept technology is used for the assessment of subcutaneous tissue. Using high swept laser technology based on Fourier domain mode locking (FDML), the system operated in the 1300 nm wavelength range with axial scan rate of 150 kHz. Imaging at this wavelength range reduces optical scattering and improves imaging penetration depths in the tissues. The laser consists of a semiconductor amplifier as the gain medium, a tunable Fabry-Perot filter to change the wavelength, and a long fiber ring cavity. The tuning range of laser is 102 nm. A balanced detector is used for spectra collection instead of the expensive CCD. The coherence system is based on a modified Mach-Zehnder interferometer. Circulators and a dual-balanced detector are used to cancel background levels and excess laser noise. The polarization of the reference arm is adjusted by a polarization controller so that it could match with the light from sample arm. Interference fringes generated for recalibration of time to optical frequency is recorded by another Mach-Zehnder interferometer during frequency sweeping period. The echo delay time of the signals reflected from the sample could be measured by a Fourier transform of the corresponding beat frequency signals which are proportional to the path lengths mismatches between sample and reference arm. Optical coherence tomography based on ultra high-speed frequency swept technology provides high imaging speeds, detection sensitivity and large imaging depths. It is a promising technique for the imaging of subcutaneous tissue.

9854-38, Session PWed

Numerical simulations of GeSn extended short-wavelength infrared detectors: material and device modeling

Hanqing Wen, Andreu Glasmann, Enrico Bellotti, Boston Univ. (United States)

Infrared (IR) detectors operating in the short-wavelength infrared (SWIR) spectrum are of great importance in night vision and surveillance due to their ability to work with visible light and under night glow illumination. Recently, significant efforts have been devoted to extend the spectral response of SWIR detectors further to a longer wavelength region where the nightglow is the strongest to enable additional applications such as object identification and environment monitoring. Besides the possible InGaAs solutions, an alternative material working in the extended SWIR (ESWIR) spectrum (1.7 - 2.7 μ m) is GeSn alloys. Unlike other group IV elements or their alloys, it has been shown that GeSn can be converted into direct band gap material with Sn higher than 10%, which will greatly increase the detector's quantum efficiency while maintaining the possibility of monolithically integrated with the silicon read-out circuit.

The purpose of this work is to establish a numerical model of GeSn ESWIR detectors by studying the basic material properties and carrier transport in the devices. Absorption coefficients and minority carrier lifetime due to radiative and Auger recombination are calculated using Green's function theory where both direct and phonon-assisted indirect processes are included. The obtained material parameters are then used in the drift-diffusion model to assess the device performances in terms of quantum efficiency, dark current and detectivity, where devices with different tin compositions will be compared.

9854-39, Session PWed

Enablement of scientific remote sensing missions with in-space 3D printing

Michael P. Hirsch, Thomas McGuire, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

This paper considers the application of in-space 3D printing to scientific remote sensing missions in Earth and other bodies' orbit and deep space. It evaluates the technology's ability to enable new mission paradigms and increase mission resiliency. The technology, which uses thermal energy directed by parabolic mirrors on to a heating chamber to heat the printing material, supports multiple materials including aluminum, other metals and various polymers.

An in-space 3D printer can provide numerous benefits to remote sensing missions. Current spacecraft designs are constrained by available launch vehicle volume which limits both their size and configuration (and, thus, capabilities). Structures produced on Earth must be designed to survive terrestrial gravity and launch forces, leading to over-engineering relative to orbital needs. Orbital structure printing can enable larger and lighter designs (such as massive arrays) facilitating greater separation of imaging system elements and other similar benefits.

In addition to supporting different types of structures, the in-space 3D printing technology facilitates mission design decision deferment. The 3D printing craft, whether traveling to a distant body or Earth orbit, can be loaded with material and electronic components to support the fabrication of multiple prospective spacecraft. The actual way that these materials and components are used can be determined during the mission.

The efficacy of the 3D printing technology for scientific remote sensing missions is evaluated through consideration of several case studies. The paper concludes with a discussion of current work on the technology and the steps required to prepare it for the described uses.

9854-40, Session PWed

Visualization of coke state in hydraulic decoking process

Qian Guo, Wuhan Univ. of Technology (China) and Air Force Early Warning Academy (China); Xinglin Tong, Chengwei Deng, Cui Zhang, Di Huang, Liang Chen, Jiaguo Xiong, Wuhan Univ. of Technology (China)

The state of coke in coke tower is vital to control the hydraulic decoking process. The traditional method is to determine the state of the exposed part of the drill pipe, the state of the carbon water mixture in the coke mouth, and the sound of the water flowing through the human ear. It is too dependent on the weather and the subjective to conducive to the refinement of management and cost control. What's more, it limits the need to have the operator on the tower operation. The relationship model of the sound signal and the coke state can be established through multiple test and comparison of the noise signal and the coke operation. Data acquisition of the sound signal is obtained by means of 5 fiber optic sensors attached to the outer wall of the coke tower. High signal provided by PLC. By collecting data, we summarize the main frequency power fluctuation range of the sound signal in many kinds of state, and extract the nearest 5 decision results for reference. The weighted value of each result according to the update time has gradually increased. On the basis of that, we developed visualization software, real-time reflect out coke coking tower state, providing to the operating personnel decision-making basis, to meet the needs of remote monitoring. MFC is used for interface and animation design, it can be compatible with all Windows operating system. Animation refresh rate is second level, and the vertical height can be accurate to 0.1m, the relative flow of water to the wall of the instantaneous scanning is very small, can meet the needs of the project.

9854-42, Session PWed

Infrared optical and electronic properties in low tellurium doped GaSb substrates for SLS FPA applications

Katy Roodenko, Pok-Kai Liao, Darby Lan, Kevin P Clark, Everett D. Fraser, Kevin W. Vargason, Jenn-Ming Kuo,

**Conference 9854: Image Sensing Technologies:
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Yungchung Kao, Paul R. Pinsukanjana, Intelligent Epitaxy Technology, Inc. (United States)

GaSb substrates become increasingly important in the fabrication of IR photodetectors, lasers and other optoelectronic devices covering IR spectrum in the 2 - 14 μm range. GaSb wafers with low Te doping are of a special interest as substrates for molecular beam epitaxy (MBE) growth of material for IR focal plane arrays that operate under back-side illumination configuration, when the substrate is not completely removed. In this work we examine data from the n-type and p-type Te-doped GaSb samples with doping concentration below $1 \times 10^{18} \text{ cm}^{-3}$ and correlate between the carrier concentration measured by the Hall and the transmission data measured by FTIR spectroscopy. We perform a rigorous analysis of the absorption coefficient based on the free-carrier absorption mechanism that is dominant for the n-type GaSb and the inter-valence band absorption due to the transitions from the light-hole to the heavy-hole band that is the dominant absorption mechanism for the p-type GaSb.

9854-43, Session PWed

New high performance Si for optical devices

Tomohisa Tenma, Matsuzaka Mitsuru, Kazumi Chiba, Kimio Talase, Carlit Holdings Co., Ltd. (Japan)

It is so inexpensive and safe that the Cz-Si is useful for semiconductor. However, its transmittance at $9 \mu\text{m}$ is too low to use it for optical devices because of large amount of oxygen. We greatly reduced the oxygen concentration and improved the transmittance by improving the manufacturing process of the Cz-method. Then we can produce Si has high transmittance with Cz-method, "New Cz-Si". Furthermore, it is inexpensive like Cz-Si.

Now the samples of "New Cz-Si" has been submitted to some customers and they has positive outcomes.

Besides, manufacturing facilities of single-crystal germanium and chalcogenide glasses are held too. We will also start evaluating them with customers in the future and promote an improvement based on the evaluation of the customer.

9854-10, Session 2

Dislocation reduction in HgCdTe grown on CdTe/Si (Invited Paper)

Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

Bulk-grown CdZnTe (Zn = 3%) substrates are the natural choice for HgCdTe epitaxy since it is lattice matched to LW-HgCdTe alloy. However, lack of large area CdZnTe substrates, high production costs, and more importantly, the difference in thermal expansion coefficients between CdZnTe and silicon Read out Integrated Circuits (ROIC) are some of the inherent drawbacks of CdZnTe substrates. Consequently, Hg_{1-x}Cd_xTe detectors fabricated on silicon substrates are an attractive alternative. Recent developments in the MBE buffer layer growth technology on Si substrates has revolutionized the HgCdTe research and offered a new dimension to HgCdTe-based IR technology.

Si substrates provide advantages in terms of relatively large area (3 to 6-inch diameter is easily obtained) compared to CZT substrate materials, durability during processing, and reliability to thermal cycling. Innovations in Si-based composite substrates made it possible to fabricate very large-format IR arrays that offer higher resolution, low-cost arrays and more dies per wafer. Between Si substrates and HgCdTe has large lattice mismatch of 19%.

This leads to dislocation densities of low- 10^7 cm^{-2} for optimal growth of MCT on silicon-based substrates as compared to the mid- 10^4 cm^{-2} dislocation density of HgCdTe grown on CdZnTe.

This presentation shows dislocation reduction by two orders of magnitude reduction of dislocation density using thermal cycle annealing under Hg environment on HgCdTe grown on Si substrates.

9854-11, Session 2

Extended SWIR imaging sensors for hyperspectral imaging applications

Andreas Weber, Matthias Benecke, Joachim C. Wendler, Alexander Sieck, Dominique Hübner, Heinrich Figgemeier, Rainer Breiter, AIM INFRAROT-MODULE GmbH (Germany)

AIM has developed SWIR modules including FPAs based on liquid phase epitaxy (LPE) grown MCT usable in a wide range of hyperspectral imaging applications. Silicon read-out integrated circuits (ROIC) provide various integration and readout modes including specific functions for spectral imaging applications.

An important advantage of MCT based detectors is the tunable band gap. The spectral sensitivity of MCT detectors can be engineered to cover the extended SWIR spectral region up to $2.5 \mu\text{m}$ without compromising in performance.

Currently, AIM is developing the technology to extend the spectral sensitivity of its SWIR modules also into the VIS. This has been successfully demonstrated for $384 \times 288 \text{ } 24 \mu\text{m}$ pitch FPAs. The development of larger format arrays with optimized performance parameters is ongoing and results will be presented in this paper.

The FPAs are integrated into compact dewar cooler configurations using different types of coolers, like rotary coolers, AIM's long life split linear cooler MCC030 or extreme long life SF100 Pulse Tube cooler. The SWIR modules include command and control electronics (CCE) which allow easy interfacing using a digital standard interface.

The development status and performance results of AIM's latest MCT SWIR Modules suitable for hyperspectral systems and applications will be presented.

9854-12, Session 2

Development of graphene based detectors for EO/ IR applications

Isaac N. Lund, Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Harry Efstathiadis, Pradeep Haldar, SUNY Polytechnic Institute (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Jay S. Lewis, Defense Advanced Research Projects Agency (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

Graphene has garnered much attention as a wonder material due to its high carrier mobility having charge carriers act as massless particles allowing for ballistic transport. The addition of graphene to traditional detector material can increase the responsivity, response time, and signal to noise ratio. We focus on the integration of graphene with traditional active detector material to increase performance while reducing the interfacial resistance and dipole trap states between the active material and the graphene. We will discuss the growth mechanism, the graphene's electrical performance, and the results from the transfer technique that allows for the improved detector performance.

**Conference 9854: Image Sensing Technologies:
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9854-13, Session 2

Microcryocoolers for tactical and space IR sensors

Ted C. Nast, Jeff R. Olson, Patrick Champagne, Lockheed Martin Space Systems Co. (United States); Elna Saito, Brendan McCay, Santa Barbara Focalplane (United States); Arthur C. Kenton, DCS Corp. (United States); Christopher L. Dobbins, U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States); Eric W. Roth, Lockheed Martin Space Systems Co. (United States)

Lockheed Martin's advanced technology center has developed a series of microcryocoolers for a range of applications including avionics and space infrared sensors and instruments. These pulse tube coolers are very low weight (approximately 300 gms.) and are based on clearance seal/flexure bearing technology which is extensively employed for long life space missions of 10 years or more. We will discuss the capability of these units, which includes a design specifically developed for fast cool down avionics applications as well as two versions with a range of cooling capabilities. While these units were initially developed for high temperature focal plane applications (150 K) they can provide cooling at temperatures down to 75 K and are capable of power inputs as high as 70 W.

Coolers have been delivered to Santa Barbara Focal plane for integration into a high performance infrared (IR) camera system for AMRDEC as well as to JPL for use on space and planetary instrument systems. The pulse tube system utilizes a moving magnet linear motor and a coaxial cold head. Life test units are ongoing and will be summarized.

9854-14, Session 2

Strategic options towards an affordable high-performance infrared camera

Patrick Oduor, Genki Mizuno, Achyut K. Dutta, Banpil Photonics, Inc. (United States); Jay Lewis, DARPA Microsystems Technology Office (MTO) (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

The CMOS sensor has revolutionized digital imaging devices through low cost that has enabled its ubiquity in consumer products. The promise of infrared (IR) imaging attaining parallel success has been hampered by the inability to achieve cost advantages that are necessary for crossover from military and industrial applications into the consumer and mass-scale commercial realm despite well documented advantages. Banpil Photonics is among a small cadre of IR camera developers adopting new strategies to speed-up the decline of the IR camera cost curve. We present a new IR camera that paves the way towards mass market adoption by not only demonstrating IR capability value add and high-performance demanded by consumer facing application industries such as automotive, medical, and security imaging, but also justifiable price points that are achievable for adoption. Among the strategic options presented include new sensor manufacturing technologies that scale favorably towards automation, wafer-scale approaches, multi-focal plane array compatible readout electronics, and dense or ultra-small pixel pitch devices. In addition, we discuss industry trends that will bridge the gap towards IR camera adoption in the near-term, and its ultimate ubiquity and associated benefits that will be realized.

9854-15, Session 2

Application and market trends for SWIR imaging

Thierry Robin, TEMATYS (France)

The aim of the present work is to analyze the market and to identify the opportunities and challenges in the next years for SWIR imaging detectors and cameras. InGaAs, grown on lattice-matched InP, has been the most practical for imagery in SWIR due to high quantum efficiency and low dark current at room temperature. For wavelengths longer than 1.7 μ m, it is in competition with HgCdTe and InSb. During the last years, some alternatives emerge based on T2SL (Type II SuperLattice).

SWIR imaging covers a large variety of applications in defense and security as well as in industry for NDT (Non Destructive Testing), photovoltaics and semiconductors inspection, and in Biomedical field (in particular for Optical Coherence Tomography). Applications of cameras based on the different types of detectors are discussed, along with a description of the main players and the market evolution and future trends. We will make a presentation our final data and analysis: market application segments and trends in SWIR imaging, analysis of the value chains, main challenges to be addressed both on technology side and application side in the next years.

9854-16, Session 2

Detectors and focal plane modules for weather instruments (*Invited Paper*)

Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States)

Weather satellite instruments require detectors with a variety of wavelengths ranging from the visible to VLWIR. One of the remote sensing applications is the polar orbiting Cross-track infrared Sounder (CrIS) is an interferometric sensor that measures earth radiances at high spectral resolution, using the data to provide pressure, temperature and moisture profiles of the atmosphere. The pressure, temperature and moisture sounding data are used in weather prediction models that track storms, predict levels of precipitation etc. The CrIS instrument contains SWIR (1c - 5 μ m at 98K), MWIR (1c - 9 μ m at 98K) and LWIRs (1c - 15 μ m at 81K) Focal Plane Modules (FPMs). This presentation will cover FPM performance data.

CrIS detectors are 850 μ m diameter detectors. Each FPM consists of nine detectors arranged in a 3 x 3 pattern. SWIR and MWIR FPMs operate at 98 K and the LWIR FPM at 81 K, permitting the use of passive radiators to cool the detectors. D* requirements at peak wavelength are $\geq 5.0E+10$ Jones for LWIR, $\geq 9.3E+10$ Jones for MWIR and $\geq 3.0E+11$ Jones for SWIR. All FPMs exceeded the D* requirements. FPMs have been fabricated and delivered to the CrIS instrument manufacturer meeting instrument flight requirements.

9854-17, Session 3

Terahertz coded aperture imaging with metamaterials (*Invited Paper*)

Willie Padilla, Duke Univ. (United States)

Metamaterial absorbers have been shown to function as efficient spatial light modulators in the millimeter wave, terahertz and infrared bands of the electromagnetic spectrum. All electronic control of metamaterial pixels permits the direct utilization of various measurement matrices including Hadamard, S-matrix and random. Notably, metamaterial spatial light modulators also permit the implementation of more advanced imaging schemes such as orthogonal frequency diverse imaging and quadrature amplitude imaging. In this talk I will present results of advanced coded aperture imaging using only a single pixel in the terahertz range and discuss the future of this exciting field.

9854-18, Session 3

Near-field mapping of terahertz waves on subwavelength surfaces (*Invited Paper*)

Weili Zhang, Tianjin Univ. (China)

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Electromagnetic behaviors of subwavelength geometries in the near field are essential in understanding their interactions with the incident waves. We experimentally demonstrate the near-field mapping of electromagnetic responses of plasmonic metasurfaces using a fiber-coupled near-field scanning terahertz microscopic system recently developed based on a photoconductive-switched time-domain spectrometer.

9854-19, Session 3

Independent component analysis applications on THz sensing and imaging

Soner Balci, The Univ. of Alabama (United States);
Alexander Maleski, Univ of Alabama (United States);
Matheus Mello Nascimento, Univ. de Brasília (Brazil);
Elizabeth Philip, Ju-Hyung Kim, Patrick Kung, Seongsin M. Kim, The Univ. of Alabama (United States)

THz technology has developed and become very promising in sensing and imaging. Researchers have been working on improving the SNR in THz spectroscopies by focusing on the enhancement of THz emitters and detectors which are sometimes hold back due to technological or financial limitations. However, various signal processing methods have been well known tools which can be applied to THz signals as well. By these methods, we can potentially decrease the noise level which would increase the SNR value. One of these methods, ICA, can be applied to THz spectroscopy measurement data with different humidity levels. Then the water spectrum and the actual THz data can be separated which lets us eliminate the water molecules' absorption in THz region by only applying a signal processing method. Same idea is applicable for THz imaging technology. For instance, THz imaging of hidden objects under various material covers is a popular application. The field of biomedical applications of THz imaging will be one of the greatest beneficiaries of this. Since, the human body has high water content, they absorb considerable amount of the THz signal thereby masking the signals absorbed by the matter of interest such as breast tumors studied using breast phantoms. ICA of the signal can overcome this challenge. Moreover, for breast tumors that are present farther in the phantom, beneath several layers of fatty and glandular tissue, the source separation process can give the THz imaging of the tumor greater clarity and boundary definition.

9854-20, Session 3

THz impulse imaging radar: evolution to 1550nm photoconductive switches (Invited Paper)

Elliott R. Brown, Wright State Univ. (United States)

The THz impulse radar was developed several years ago for ex vivo skin-burn imaging, and has since demonstrated the ability to generate clinically relevant contrast from spatially-dependent hydration levels in soft tissue of several types, such as the ocular cornea. One advantage of the impulse radar is its simple, hybrid architecture which combines the high-peak-power of ultrafast photoconductive switches in the transmitter, with the high-responsivity and -bandwidth (RF and video) of Schottky-diode rectifiers in the receiver. Until recently our photoconductive switches were all made from Er-doped GaAs and pumped at 780-nm by frequency-doubled, 1550-nm fiber mode-locked lasers (MLL). Now they are still made from GaAs:Er but designed for pumping by the fundamental, 1550-nm MLL pulse train utilizing a strong extrinsic photoconductivity from Er-bearing nanoparticles. The result is a substantially more affordable, compact, and reliable THz source with output power spectrum spread from ~100 GHz to 600 GHz, and the additional practical benefit of boresight alignment between the THz antenna pattern beam and the residual 1550-nm laser beam. This paper will provide experimental results detailing average transmitter power, receiver signal-to-noise ratio from common hydrated targets, and THz spatial resolution on target. It will also investigate signal-to-clutter ratio from targets of various

surface roughness, and compare the results to those from a radar operating with a coherent, continuous-wave 530-GHz transmitter.

9854-21, Session 4

Perspectives of THz biomedical imaging (Invited Paper)

Seongsin M. Kim, Soner Balci, Elizabeth Philip, The Univ. of Alabama (United States); Matheus Mello Nascimento, Univ. de Brasília (Brazil); Patrick Kung, The Univ. of Alabama (United States)

In recent years, many applications have been recognized for biomedical imaging techniques utilizing terahertz frequency radiation. This is largely due to the capability of unique tissue identification resulting from the nature of the interaction between THz radiation and the molecular structure of the cells. By THz identification methods, tissue changes in tooth enamel, cartilage, and malignant cancer cells have already been demonstrated. Terahertz Time-Domain Spectroscopy (THz-TDS) remains one of the most versatile methods for spectroscopic image acquisition for its ability to simultaneously determine amplitude and phase over a broad spectral range.

In this talk, I will review past and current THz biomedical imaging technologies and will discuss the perspectives of future application of THz imaging in biomedicine.

9854-22, Session 4

Handheld THz security imaging (Invited Paper)

Irl Duling III, Advanced Photonix, Inc. (United States)

Using either a single point or a real time line scan tool for examining areas of the body not covered by the mmW scanner, a pulsed THz sensor can detect sheet explosives, ceramic knives, metal objects, and other anomalies. These anomalies can be classified as metal or dielectric anomalies. At the same time, real time line scan operation can give a visible representation of the cross section of clothing or headgear allowing the visual detection of anomalies.

9854-23, Session 4

The use of terahertz imaging in industry (Invited Paper)

Philip F. Taday, TeraView Ltd. (United Kingdom)

Terahertz pulsed imaging technology has long been seeking problems for which it is the solution. TeraView has been at the forefront of terahertz applications. Recently, we have had significant progress in a number of key market sectors. The first that will be discussed is the application of terahertz pulses to the automotive industry. A number have long discussed the potential of using terahertz technology in the car manufacture industry. TeraView has over the past few years has invested many research hours in investigating this application and now we beginning to work with many key players in deploying the terahertz sensors in monitoring car paint thicknesses on the production line. In order to develop a product not only requires an understanding of terahertz optics but also an understanding of the terahertz properties of film coatings. These issues will be discussed in this paper. The other area that will be discussed briefly is the application of terahertz pulses to failure analysis of advanced semiconductor packaging.

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9854-24, Session 4

THz sensing and imaging with field-effect transistors fabricated in the CMOS, AlGaIn/GaN, graphene and carbon nanotube material systems (*Invited Paper*)

Hartmut G. Roskos, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany); Alvydas Lisauskas, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany) and Vilnius Univ. (Lithuania); Sebastian Boppel, Maris Bauer, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany); Jingshui Zhang, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany) and Beijing Institute of Technology (China); Viktor Krozer, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany) and Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik (Germany)

Antenna-coupled field-effect transistors (sometimes called Tera-FETs) are very useful detectors of THz radiation which can serve as power detectors and heterodyne receivers, implemented as individual detectors and integrated detector arrays. Tera-FETs have been shown to work over a wide frequency range, from the MHz regime up to at least 10 THz. The (Dyakonov-Shur) principle of operation is resistive mixing in the transistor's channel at low frequencies, crossing over to plasmonic mixing at high frequencies. A striking feature is that the mobility of the charge carriers is only of indirect significance for the sensitivity of the devices – mainly via impedance matching issues, but also via the scattering time which determines the cross-over to the plasmonic operation regime. We have implemented and investigated Tera-FETs in four different material systems, silicon CMOS, AlGaIn/GaN, CVD graphene and carbon nanotubes. The most mature, foundry-made 65-nm CMOS Tera-FETs exhibit the best performance with values of the optical noise-equivalent power (NEP) reaching down to the 10-20-pW/Hz^{0.5} range at room temperature, followed by 250-nm AlGaIn/GaN devices with about 40 pW/Hz^{0.5} (all at 0.6-0.7 THz). The carbon devices are still one order of magnitude less powerful. From basic considerations, we expect rather similar performance for the various material systems when the technologies will reach comparable levels of maturity. The CMOS devices gradually link up with Schottky detectors and arguably are already better than those at and above 1 THz. We will show that further optimization of device performance will require to consider and engineer thermoelectric signal contribution.

9854-25, Session 4

Terahertz sensing with waveguides (*Invited Paper*)

Marco Rahm, Marko Gerhard, René Beigang, Technische Univ. Kaiserslautern (Germany)

During the last few years, terahertz (THz) technology has provided an increasing number of powerful measurement systems for non-invasive sensing of substances with spectral fingerprints in the THz frequency domain. Hereby, the main advantage of THz radiation is its ability to penetrate through most dielectrics as e.g. paper, cardboard, plastics, ceramics, textiles etc. However, when only tiny amounts of a substance or strongly diluted mixtures of different constituents are present, the THz technology rapidly reaches its limits due to an insufficient signal-to-noise ratio of the measurement at low power levels.

The signal-to-noise ratio can be significantly increased by use of THz waveguides with high coupling efficiency. Here, we theoretically and experimentally investigate THz waveguides with optimized tapers for efficient coupling of free THz radiation. We also compare THz waveguiding in parallel-plate waveguides and waveguides with ridges. Furthermore, we demonstrate a Mach-Zehnder interferometer for guided THz waves and

evidence its applicability for THz sensing by evaluating constructive and destructive interference in a pure amplitude measurement without the necessity for a direct phase measurement.

9854-26, Session 4

Terahertz imaging with quantum cascade lasers (*Invited Paper*)

Alan W. Lee, Ian A. Zimmerman, Tsung-Yu Kao, LongWave Photonics LLC (United States); Qing Hu, Massachusetts Institute of Technology (United States)

In this work we present results using terahertz quantum cascade lasers operating in the 2 to 5 THz frequency range with milliwatt average power levels used to illuminate images in transmission and reflection mode with single element and multi-element detectors. Multi-element microbolometer arrays allow high pixel acquisition rates on the order of 10⁶ pixels/s with average signal to noise ratios of 25 dB per pixel. 2D images in transmission and reflection mode are obtained. A limitation of this technique in comparison to other terahertz techniques is the lack of depth information. This is overcome by using laser triangulation, which exchanges a spatial dimension for depth information. Single pixel acquisition strategies allow for much higher signal to noise ratios, allowing standoff imaging, as well as confocal imaging sensitive to small changes of dielectric constant in the sample. In the latter we use the high signal to noise ratios for hydration measurement of corneal tissue.

9854-41, Session 4

Metamaterial microwave holographic imaging system (*Invited Paper*)

David R. Smith, Duke Univ. (United States)

We demonstrate a microwave imaging system that combines advances in metamaterial aperture design with emerging computational imaging techniques. The flexibility inherent to guided-wave, complementary metamaterials enables the design of a planar antenna that illuminates a scene with dramatically varying radiation patterns as a function of frequency. As frequency is swept over the K-band (17.5–26.5 GHz), a sequence of pseudorandom radiation patterns interrogates a scene. Measurements of the return signal versus frequency are then acquired and the scene is reconstructed using computational imaging methods. The low-cost, frequency-diverse static aperture allows three-dimensional images to be formed without mechanical scanning or dynamic beam-forming elements. The metamaterial aperture is complementary to a variety of computational imaging schemes, and can be used in conjunction with other sensors to form a multifunctional imaging platform. We illustrate the potential of multisensor fusion by integrating an infrared structured-light and optical image sensor to accelerate the microwave scene reconstruction and to provide a simultaneous visualization of the scene.

Conference 9855: Next-Generation Spectroscopic Technologies IX

Monday - Tuesday 18-19 April 2016

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9855-1, Session 1

Miniaturized NIR scanning grating spectrometer for use in mobile phones (Invited Paper)

Jens Knobbe, Tino Pügner, Heinrich Grüger, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Near infrared (NIR) spectroscopy is a well-established non-destructive technique for the chemical analysis of organic matter. The majority of commercially available instruments is designed for the use in the laboratory, even though some miniaturized (handheld) spectrometers for mobile applications have appeared on the market only recently.

The next step in the evolution of spectrometers for mobile applications is the integration into a mobile phone. A prerequisite for this scenario is the availability of very small, low cost NIR spectrometers with adequate performance for mobile applications. However, such a miniaturization cannot be achieved with standard technology.

Therefore, an extremely miniaturized scanning grating spectrometer at the size of a sugar cube has been developed at Fraunhofer IPMS. To meet the requirements for the integration into a mobile phone a new system approach has been pursued, whereby the Czerny-Turner mount was selected as the basic design form. The key component within the system is a deflectable diffraction grating with an integrated driving mechanism developed at IPMS and manufactured with a proprietary bulk silicon micromachining process (MEMS process). In addition, an appropriate micro assembly strategy suitable for high volume production has been established.

A first sample of the new spectrometer was built and characterized. It was found to have a spectral range from 1000 nm to 1900 nm at a resolution of 10 nm and a signal-to-noise ratio of 650. Some application close measurements were performed. The results show that the performance of the new MEMS spectrometer is in good agreement with the requirements for mobile phone integration.

9855-2, Session 1

How can wireless, mobile data acquisition be used for taking part of the lab to the sample applications and how can it join the internet of things?

Peter Trzcinski, University of Waterloo (Canada); Vassili Karanassios, Univ. of Waterloo (Canada)

Taking part of the lab to the sample is one of the key challenges in analytical chemistry. For such applications, use of a miniaturized chemical analysis instrument with a wireless, data acquisition system are envisaged. Examples include data acquisition using a smartphone or a tablet. Could data acquisition be made a part of the internet of things? Could a smartphone or a tablet be replaced by a wearable computing device? In this presentation, these questions will be critically evaluated for their use in taking part of the lab to the sample types of applications, using examples from the authors' laboratory.

9855-3, Session 1

Built-in hyperspectral camera for smartphone in visible, near-infrared and middle-infrared lights region: Trial products of beans-size Fourier-spectroscopic line-imager and feasibility experimental results of middle infrared spectroscopic imaging

Ichiro Ishimaru, Natsumi Kawashima, Satsuki Hosono, Kagawa Univ. (Japan)

We had already proposed and reported the little-finger size hyperspectral-camera that was able to be applied to visible and near-infrared lights. The proposed method, so called snapshot type, was able to obtain 1 dimensional spectral distribution with one frame imaging data. By merging the scanned line spectroscopic data, we can acquire the 2-dimensional spectral image. The proposed method has been expected to be mounted on smartphones for healthcare sensors, and unmanned air vehicles such as drones for antiterrorism measures or environmental measurements. In this report, we will mention the trial product of the beans size apparatus whose diameter was 5[mm] and length was less than 10[mm]. And also, we will discuss about the feasibility experimental results about middle-infrared spectroscopic imaging.

The proposed Fourier spectroscopic imager is a kind of wavefront-division and common-path phase-shift interferometers. We installed the relative inclined phase-shifter onto optical Fourier transform plane of infinity corrected optical systems. The infinity corrected optical systems was configured with an objective lens and a cylindrical imaging lens. The relative inclined phase-shifter, what was made from a thin glass less than 0.3[mm] thick, had the wedge-prism and cuboid-glass region, because half surface of a thin glass was polished at an oblique angle of around 1[deg.]. The collimated half flux of objective beams derived from single-bright points on objective surface penetrate through the wedge prism and the cuboid glass respectively. These two beams interfere each other and form the interferogram as spatial fringe patterns. In this case, the horizontal axis on 2 dimensional light receiving device is assigned to the amount of phase-shift. And also the vertical axis is assigned to the imaging coordinates on a line view field. Thus, by installing thin phase-shifter onto optical Fourier transform plane, the line spectroscopic imager, what obtains 1 dimensional spectral character distributions, were able to be realized.

9855-4, Session 1

Built-in hyperspectral camera for smartphone in visible, near-infrared and middle-infrared lights region: Sensitivity improvement of Fourier spectroscopic imaging to detect diffuse reflection lights from internal human tissues for healthcare sensors

Natsumi Kawashima, Satsuki Hosono, Ichiro Ishimaru, Kagawa Univ. (Japan)

We proposed the snapshot-type Fourier spectroscopic imaging for smartphone that was mentioned in 1st. report in this conference. For spectroscopic components analysis, such as non-invasive blood glucose

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sensors, the diffuse reflection lights from internal human skins are very weak for conventional hyperspectral cameras, such as AOTF (Acousto-Optic Tunable Filter) type. Furthermore, it is well known that the spectral absorption of mid-infrared lights or Raman spectroscopy especially in long wavelength region is effective to distinguish specific biomedical components quantitatively, such as glucose concentration. But the main issue was that photon energies of middle infrared lights and light intensities of Raman scattering are extremely weak.

For improving sensitivity of our spectroscopic imager, the wide-field-stop & beam-expansion method was proposed.

Our line spectroscopic imager introduced a single slit for field stop on the conjugate objective plane. Obviously to increase detected light intensities, the wider slit width of the field stop makes light intensities higher, regardless of deterioration of spatial resolutions. Because our method is based on wavefront-division interferometry, it becomes problems that the wider width of single slit makes the diffraction angle narrower. This means that the narrower diameter of collimated objective beams deteriorates visibilities of interferograms.

By installing the relative inclined phase-shifter onto optical Fourier transform plane of infinity corrected optical systems, the collimated half flux of objective beams derived from single-bright points on objective surface penetrate through the wedge prism and the cuboid glass respectively. These two beams interfere each other and form the interferogram as spatial fringe patterns.

Thus, we installed concave-cylindrical lens between the wider slit and objective lens as a beam expander. We successfully obtained the spectroscopic characters of hemoglobin from reflected lights from human fingers.

9855-5, Session 1

Built-in hyperspectral camera for smartphone in visible, near-infrared and middle-infrared lights region(3rd. report): Spectroscopic imaging for broad-area and real-time componential analysis system against local unexpected terrorism and disasters

Satsuki Hosono, Natsumi Kawashima, Ichiro Ishimaru, Kagawa Univ. (Japan); Dirk Wollherr, Technical University of Munich (Germany)

The distributed networks for information collection of chemical components with high-mobility objects, such as drones or smartphones, will work effectively for investigations, clarifications and predictions against unexpected local terrorisms and disasters like localized torrential downpours. We proposed and reported the proposed spectroscopic line-imager for smartphones in this conference. In this paper, we will mention the wide-field spectroscopic-image construction by estimating 6 DOF (Degrees Of Freedom: parallel movements= x,y,z and rotational movements= $\theta_x, \theta_y, \theta_z$) from line data to observe and analyze surrounding chemical-environments.

Recently, smartphone movies, what were photographed by peoples happened to be there, had worked effectively to analyze what kinds of phenomenon had happened around there. But when a gas tank suddenly blew up, we did not recognize from visible-light RGB-color cameras what kinds of chemical gas components were polluting surrounding atmospheres. Conventionally Fourier spectroscopy had been well known as chemical components analysis in laboratory usages. But volatile gases should be analyzed promptly at accident sites. And because the humidity absorption in near and middle infrared lights has very high sensitivity, we will be able to detect humidity in the sky from wide field spectroscopic image.

Recently, 6-DOF sensors are easily utilized for estimation of position and attitude for UAV (Unmanned Air Vehicle) or smartphone. But for observing long-distance views, accuracies of angle measurements were not sufficient to merge line data because of leverage theory. Thus, by

searching corresponding pixels between line spectroscopic images, we are trying to estimate 6-DOF in high accuracy. We installed the proposed line spectroscopy for the autonomous moving car and estimated 2 axis of parallel movement from corresponding pixel matching algorithm.

9855-6, Session 1

MEMS FPI-based smartphone hyperspectral imager

Anna Rissanen, VTT Technical Research Ctr of Finland Ltd (Finland); Heikki Saari, VTT Technical Research Ctr. of Finland Ltd. (Finland); Kari Rainio, Ingmar Stuns, Kai Viherkanto, Christer Holmlund, Ismo Näkki, Harri Ojanen, VTT Technical Research Ctr of Finland Ltd (Finland)

Optical MEMS-based Fabry-Perot interferometers (FPIs) enable small, mass producible hyperspectral imagers with potential to enable consumer and mobile applications of hyperspectral imaging. In recent years, Fabry-Perot interferometer technology has been demonstrated in various novel microspectrometer applications ranging from mobile gas sensing to medical- and environmental monitoring applications. In this presentation, we aim to demonstrate a mobile phone- compatible hyperspectral imager based on a configuration of two cascaded FPIs and an RGB colour camera. With this tandem configuration, the overall wavelength tuning range can be extended to cover a larger range than with a single FPI chip. Typically, the tuning range of Fabry-Perot interferometers is limited to $\pm 10\%$ of the mirror optimization wavelength, which in visible wavelengths is less than 200 nm. However, with the cascaded configuration, the operation range can extend up to 400 nm, which increases the application potential of the technology while maintaining the minimized sensor size close to the chip dimension (5 mm² or 7mm²). The built demo set-up uses MEMS FPI chips for visible-range, which consist of atomic layer deposited Al₂O₃/TiO₂-thin film Bragg reflectors, in which the air gap is formed by sacrificial polymer etching in oxygen plasma. Characterization results for the imager set-up with two FPI devices optimized for 500 nm and 650 nm are presented; the imager wavelength operation range is $\approx 450 - 700$ nm with FWHM between 5 - 20 nm, and it is applicable to mobile phone demonstration which is being developed. The potential applications of mobile hyperspectral imagers in the visible range include various health applications and in future, as cell phones are expected to include also lower NIR wavelength range cameras, it is possible to extend the application range even further.

9855-7, Session 2

Fiber spectrometers and fiber sensors to enable process control

Igor Nazarov, Viacheslav Artyushenko, art photonics GmbH (Germany)

There is a variety of fiber spectroscopy methods used for process control: transmission, diffuse reflection, fluorescence, absorption, Raman scattering. They can be used alone or in combinations for more sensitive and precise process control on-line or even in-line. Review of fiber spectrometers will be done to compare research spectroscopy systems with target specification of promising fiber sensors designed for customized applications. Portable, robust, cost-effective fiber sensors may accelerate development of various process-control solutions.

Fiber sensors spectroscopy solutions for process control in industry provide well known advantages:

- 1) Eliminates the need to take samples for lab analysis from a running process as fiber probes can monitor media composition in-line - i.e. in real time and from the critical points.
- 2) remote process-control can be done at long distance - up to 200-300m, - in UV-Vis-NIR range where silica fibers possess by high transmission;
- 3) Robust design of industrial spectral probes enables to operate in analyze

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toxic, aggressive or radioactive, explosive proof environments media and to monitor processes at high pressure, high or low temperature, vibrations, etc.

While silica fibers are limited in transmission till 2.2 μ m, the new Mid IR-fibers enable analysis in 2-17 μ m finger-print range - the most informative for molecular vibration analysis.

Good knowledge of spectral changes specific for distinct chemical process can be extracted using correspondent chemometric model with the spectral fiber systems and used for process-control. Recent advances of multivariate data analysis is an important part of the analytical method development for process monitoring and includes several methodologies: design of experiment (DoE), exploratory factor analysis, multivariate regression algorithms - such as partial least-squares (PLS), - and some others.

Substantial cost reduction of customized fiber sensors may help for a broader and faster PAT methods expansion into industrial applications. This possibility will be presented in review of promising fiber sensors based on LED or Fabry-Perot MEMS filters with the analysis of their key parameters, incorporated chemometric models and results of their experimental tests.

9855-8, Session 2

Parametric models of reflectance spectra for dyed fabrics

Daniel C. Aiken, Scott A. Ramsey, Troy Mayo, Samuel G. Lambrakos, Joseph E. Peak, U.S. Naval Research Lab. (United States)

This study examines parametric modeling of near-infrared (NIR) reflectivity spectra for dyed fabrics, which provides for both their inverse and direct modeling. The dye considered for prototype analysis, triarylamine, exhibits strong absorption across the NIR and shortwave-infrared (SWIR) portions of the spectrum. Triarylamine's unique absorption spectrum coupled with an increasing number of battlefield detection threats in the NIR and SWIR bands has made this dye a viable candidate for a prototype camouflage treatment. The host fabric considered has a multicolor, single camouflage pattern design and is currently used throughout the U.S. armed forces. The results of this study provide validation of the constructed parametric model, within reasonable error tolerances, for the purpose of simulating NIR spectra corresponding to various dye concentrations in host fabrics, and potentially to mixtures of dyes.

9855-9, Session 2

Application of parabolic reflector on Raman analysis of gas samples

Anlan Yu, Duluo Zuo, Xingbing Wang, Jun Gao, Huazhong Univ. of Science and Technology (China)

Studies on the application of a parabolic reflector in spontaneous Raman scattering for low background Raman analysis of gas samples are reported. As an effective signal enhancing technique, photonic bandgap fiber (HC-PBF) and metal-lined capillary normally result in a strong continuous background in spectra caused by the small size of the sample cell and the strong Raman/fluorescence signal from the silica wall and the polymer protective film. In order to obtain enhanced signal with low background, a specially designed sample cell with double-pass and large collecting solid angle constructed by a parabolic reflector and a planar reflector was applied, of which the optical surfaces had been processed by diamond turning and coated by protective film of high-purity alumina. The influences of optical structure, polarization characteristic, collecting solid-angle and collecting efficiency of the sample cell on light propagation and signal enhancement were studied. A Raman spectrum of ambient air with signal to background ratio of 94 was acquired with an exposure time of 1sec by an imaging spectrograph. Besides, the λ detecting limits of 65 ppm for H₂, 135 ppm for CO₂ and 245 ppm for CO were also obtained. The sample cell mainly based on parabolic reflector will be helpful for compact and high-sensitive Raman system.

9855-10, Session 2

3D printing in chemistry: Past, present and future

R. Shatford, Vassili Karanassios, Univ. of Waterloo (Canada)

In the past few years, 3D printing has rapidly progressed from engineering curiosity to mainstream. Now, many local "computer stores" carry 3D printers. In science and technology, 3D printing has found applications ranging from bio-printing of tissue, to fabrication of vessels for chemical reactions, to development of chemistry printers used for synthesis of reactant-molecules, to fabrication of microplasma devices for chemical analysis. In this presentation, 3D technology, materials and chemistry related applications will be reviewed and its application from the authors' laboratory to chemical analysis (in the form of 3D printed microplasma devices) will be discussed.

9855-11, Session 3

Distributed-feedback interband cascade lasers with reduced contact duty cycles
(Invited Paper)

Charles D. Merritt, William W. Bewley, Chadwick L. Canedy, Chul S. Kim, Michael V. Warren, Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States); Mijin Kim, U.S. Naval Research Lab. (United States) and Sotera Defense Solutions, Inc. (United States)

In the absence of well-established epitaxial overgrowth techniques for antimonide materials, the most robust approach to fabricating distributed-feedback (DFB) mid-IR interband cascade lasers (ICLs) is to etch a grating into the top layer of the laser ridge, with subsequent Ti/Pt/Au metallization to create a top electrical contact. The optical mode must overlap the grating layer for sufficient coupling, which significantly increases the loss due to absorption in the metal. In order to mitigate this loss, we demonstrate an approach that covers only a fraction of the ridge's top surface with contact metal, i.e., the contact duty cycle is reduced. This is feasible because the ICL's highly anisotropic electrical conductivity induces far more current spreading than in most diode lasers. A 5-stage ICL wafer was grown on GaSb with a 250-nm-thick InAs top grating layer. Ridges of dimensions 4.5 μ m \times 2 mm were processed with uncoated facets and mounted epi-side-up with Au electroplating. The contact duty cycle was varied from 14 to 100%, with the width of the contacts fixed at 10 μ m. Operation in a single spectral mode at or above room temperature was observed for all duty cycles, with the highest power of 6.8 mW obtained for the DFB with 33% duty cycle. Although there was scatter in the data, the ridges with 25% duty cycle displayed nearly a factor of 2 lower threshold current density than those with 100% duty cycle. The highest slope efficiency was observed for the devices with 33% duty cycle.

9855-12, Session 3

Portable standoff detection system using monolithic QCL arrays with advanced on-board chemometrics: systems and results
(Invited Paper)

Mark F. Witinski, Romain Blanchard, Kalyani Krishnamurthy, Christian J. Pfluegl, Daryoosh Vakhshoori, Pendar Technologies (United States)

Miniaturized and beam combined monolithic Distributed Feedback (DFB) Quantum Cascade Laser (QCL) Arrays customized by Pendar

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Technologies are now tightly integrated with a low-weight, high efficiency, reflective optical system with fast gimbal system steering. The handheld tools under development include advanced on-the-fly data processing and chemometrics to establish reliability and confidence of chemical identification in the presence of chemical clutter. Applications include security, industrial safety, raw materials identification, leak detection, and chemical assays for varied industries such as pharma and chemical.

This presentation will focus on the uniqueness of the QCL source, how it enables fast standoff measurements, key systems drivers for the integrated tools, and how data science and computing advances allow for unprecedented standoff detection.

9855-13, Session 3

Wavelength detection at sub-femtometer resolution using an integrating sphere

Nikolaus Metzger, Univ. of St. Andrews (United Kingdom); Bill Miller, Graeme Malcolm, M Squared Lasers Ltd. (United Kingdom); Kishan Dholakia, Michael Mazilu, Univ. of St. Andrews (United Kingdom)

Laser technology goes hand in hand with precision spectroscopy of atoms and molecules. Coherent, tunable laser light allows us to resolve features in atomic and molecular spectra with an unprecedented resolution and accuracy. Precision spectroscopy is a very active field with a crucial facet being the detection of wavelength and indeed the resolution of individual spectral lines.

Light propagation in a disordered or random media is generally regarded as a randomization process destroying the information contained within the initial beam. Intriguingly however, a coherent beam propagating in a disordered medium yields a unique speckle pattern for a given wavelength. The underlying key principle is that the scattered beam maintains its initial spatial and temporal coherence. The resulting interference is the key for the creation of a distinct speckle pattern dependent on the incident light field and can be used as a fingerprint to identify its characteristics like wavelength of the creating. This fundamental concept can lead to an original approach to realise wavemeters that promise a paradigm shift in their specifications and footprints with respect to grating based devices.

We present a speckle based wavelength detection system that is able to resolve the dither signal of a Rubidium locked laser system with a resolution of better than 0.65 MHz or 1.3 fm. We also study physical key parameters that influence the speckle based wavelength meter and present a theoretical model of the system. Additionally the prospect of active laser stabilization via such a speckle based wavemeter system is investigated.

9855-14, Session 3

Validation and calibration of a TDLAS oxygen sensor for in-line measurement on flow-packed products

Lorenzo Cocola, Massimo Fedel, CNR-IFN UoS Padova (Italy); Helle Allermann, Stanislav Landa, DTI (Denmark); Giuseppe Tondello, LPRO srl (Italy); Alexander Bardenstein, Danish Technological Institute (Denmark); Luca Poletto, CNR-IFN UoS Padova (Italy)

A Tunable Diode Laser Absorption Spectroscopy based device has been developed to allow non invasive evaluation of gaseous oxygen concentration inside packed food containers. This work has been done in the context of the SAFETYPACK European project in order to enable full, automated product testing on a production line.

The chosen samples at the end of the manufacturing process are modified atmosphere bags of processed mozzarella, in which the target oxygen

concentration is required to be below 5%.

The spectrometer allows on-the-fly measurement of moving samples which are passing on a conveyor belt, with an optical layout optimized for bags made of a flexible scattering material, and works by sensing the gas phase enclosed in the headspace at the top of the package.

A field applicable method for the calibration of this device has been identified and validated against traditional, industry standard, invasive measurement techniques. This allows some degrees of freedom for the end-user regarding packaging dimensions and shape.

After deployment and setup of the instrument at the end-user manufacturing site, performance has been evaluated on a different range of samples in order to validate the choice of electro optical and geometrical parameters regarding sample handling and measurement timing at the actual measurement conditions.

9855-15, Session 3

Single-mode interband cascade laser sources for mid-infrared spectroscopic applications

Julian Scheuermann, Michael von Edlinger, nanoplus Nanosystems and Technologies GmbH (Germany); Robert Weih, Julius-Maximilians-Univ. Würzburg (Germany); Steffen Becker, Lars Nähle, Marc Fischer, Johannes Koeth, nanoplus Nanosystems and Technologies GmbH (Germany); Martin Kamp, Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany)

Compared to the near infrared, many technologically and industrially relevant gas species have more than an order of magnitude higher absorption features in the mid-infrared (MIR) wavelength range. These species include for example important hydrocarbons (methane, acetylene), nitrogen oxides and sulfur oxides. Tunable laser absorption spectroscopy (TLAS) has proven to be a versatile tool for gas sensing applications with significant advantages compared to other techniques. These advantages include real time measurement, standoff detection and ruggedness of the sensor.

We present interband cascade lasers (ICLs), which have evolved into important laser sources for the MIR spectral range from 3 to 7 μm . ICLs achieve high efficiency by cascading optically active zones whilst using interband transitions, so they combine common diode laser as well as quantum cascade laser based technologies. Our application grade single-mode distributed feedback devices operate continuous wave at room temperature and are offering several features especially useful for high performance TLAS applications like: side mode suppression ratio of > 30 dB, continuous tuning ranges up to 30 nm, low threshold power densities and low overall power consumption. The devices are typically integrated in a thermoelectrically cooled TO-style package, hermetically sealed using a cap with anti-reflection coated window.

This low power consumption as well as the compact size and ruggedness of the fabricated laser sources makes them perfectly suited for battery powered portable solutions for in field spectroscopy applications.

9855-16, Session 3

Portable low power cavity ring-down spectrometer for precise measurement of carbon dioxide, methane and water vapor

Derek Fleck, Picarro (United States); John Hoffnagle, Sze Tan, Yonggang He, Picarro Inc. (United States)

The necessity for monitoring of changing levels of greenhouse gases (GHGs) is clearly evident now more than ever. This has led to large deployments

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of analytical devices to most remote locations as well as the most densely populated regions around the world. Both large and small scale projects have forced new and old technologies to be pushed to their limits to obtain the highest performing measurements while maintaining a cost effective way to remotely monitor changes in atmospheric concentrations.

In order to accomplish these strict guidelines, we present a low-power cavity ring-down spectrometer that measures Carbon Dioxide, Methane and water vapor which can achieve measurements with precisions lower than 20ppb of CO₂ and 200ppt of CH₄. Comparing to hundreds of watts needed in conventional CRDS design, we demonstrate that the high performance can be achieved with less than 25W. Stability of these measurements has allowed for averaging times of up to 3hr, yielding measurements of methane concentrations with precisions down to 40ppt. This is accomplished utilizing an FSR based frequency scale to determine an absolute frequency scale for these absorption features. Taking advantage of this faster and less costly measurement technique of CRDS, shows future promise with applications spanning scientific and industrial analyses, from isotopes to trace gases.

9855-17, Session 4

Silicon based large area filters: A path way to high resolution, low cost adaptive focal plane arrays *(Invited Paper)*

Dhirendra Kumar Tripathi, K. K. M. B. Dilusha Silva, Jorge Rafel Silva Castillo, Jarek Antoszewski, Mariusz Martyniuk, Lorenzo Faraone, The Univ. of Western Australia (Australia)

Recent Developments in Mercury Cadmium Telluride IR Detector Technology have brought dramatic reduction in the size of pixel and pitch of pixels to just 5 μm in a focal plane array (FPA). These advancements have opened a path way to create small size high resolution focal plane array in MWIR and LWIR wavelength regions. By combining MEMS based optical filters with the high density adaptive focal plane array high resolution low cost adaptive FPA can be obtained. The present work propose a path way to take full advantage of the myriad of available processes to optimize the stress and optical properties that are available exclusively to MEMS technologies, and the many optimization technologies available exclusively for high density FPA fabrication to fabricate such AFPAs.

We have developed an inductive coupled plasma deposited (ICPCVD) silicon thin films based surface micromachined technology which can fabricate MEMS based filters ranging in size from few hundred microns to several millimetre square area. The use of silicon thin films promises possibility of low cost MEMS based filters. These filters are fabricated to operate in the MWIR to LWIR wavelength region. In this work we present the design, fabrication and optical characterization of the filters. The fabrication process is highly effective in producing large area, suspended mirrors with ultra-flat surface profile, which leads to very low wavelength shift across the active optical area of a filter. The devices demonstrated are significantly larger in size compared to our traditional devices, with dimensions ranging from 1mm x 1mm or bigger.

9855-18, Session 4

Issues concerning short-wave infrared signature reduction of dyed fabrics

Scott A. Ramsey, Daniel C. Aiken, Troy Mayo, Samuel G. Lambrakos, Joseph E. Peak, U.S. Naval Research Lab. (United States)

The availability of synthetic materials and dyes having a wide range of spectral properties, as well as methods for analysis of spectral-response characteristics of dyed fabrics, have motivated evaluation of issues concerning the processing of dyed fabrics and their spectral analysis for military and non-military applications. One issue concerns

process parameter optimization for achieving a target SWIR spectrum corresponding to a given set of dyed fabrics and processes for their fabrication. Another issue concerns measurement and modeling of absorption spectra for prediction of dyed-fabric spectral-response characteristics, which are for the design of dyed fabrics with respect to specified environments and target SWIR spectra. This paper presents an overview of efforts and capabilities of the NRL-STO that are for the formulation of advanced dyed fabrics, which can provide for enhanced SWIR signature reduction.

9855-19, Session 4

On-chip spectrometer based on an evanescently coupled multimode spiral waveguide

Brandon Redding, Seng Fatt Liew, Raktim Sarma, Yaron Bromberg, Hui Cao, Yale Univ. (United States)

The development of a high-resolution chip-scale spectrometer is essential to low-cost, portable sensing applications and add functionality to lab-on-a-chip systems. However, the spectral resolution of a spectrometer depends on the spread in the optical pathlengths through a dispersive medium, which is difficult to achieve on-chip where the footprint is inherently limited. Here, we present a novel spectrometer design based on a multimode waveguide patterned in a spiral geometry. Interference between the modes of the waveguide forms a wavelength-dependent speckle pattern which can be used as a fingerprint to identify the input wavelength. The spectral resolution scales with the length of the multimode waveguide but can be improved by introducing evanescent coupling between neighboring waveguide arms. This evanescent coupling increases the spread of optical pathlengths in the spiral, thereby improving the spectral diversity. Experimentally, we show that an evanescently coupled spiral spectrometer with 500μm diameter can resolve two lines separated by 0.01 nm at λ=1520nm. The ability to achieve such high resolution with low loss in a compact footprint could enable applications in low-cost portable sensing or add functionality to lab-on-a-chip systems.

9855-20, Session 4

Low cost long wave infrared spectrometer based on guided mode resonant effect

Mark Mirotznik, Univ. of Delaware (United States); Neelam Gupta, U.S. Army Research Lab. (United States); Victoria Carey, Morgan McElhiney, Univ. of Delaware (United States)

We will describe a low cost spectrometer in the long wave infrared (LWIR) band based on the guided mode resonant filter (GMRF) effect. The device consists of a subwavelength dielectric grating sandwiched between planar layers of contrasting dielectric materials. For these designs we constructed the filters using both germanium (n=4.0) and zinc selenide (n=2.4) as low loss dielectrics with contrasting permittivities. Using rigorous electromagnetic design and analysis method we will demonstrate how a strong narrow band (< 100 nm) reflectance can be induced within the LWIR band. Moreover, the resonant wavelength can be easily tuned over the entire 8-12 micron band by mechanically tilting the device with respect to the optical axis, resulting in a low cost LWIR spectrometer. The principal applications of this device is a hand held chem/bio detector. Simulation and experimental results will be presented demonstrating the effectiveness of the device.

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9855-21, Session 4

Handheld and mobile hyperspectral imaging sensors for wide-area standoff detection of explosives and chemical warfare agents

Nathaniel R. Gomer, Matthew P. Nelson, Charles W. Gardner, Patrick J. Treado, ChemImage Corp. (United States)

Hyperspectral imaging (HSI) is a valuable tool for the investigation and analysis of targets in complex background with a high degree of autonomy. HSI is beneficial for the detection of threat materials on environmental surfaces, where the concentration of the target of interest is often very low and is typically found within complex scenery. Two HSI techniques that have proven to be valuable are Raman and shortwave infrared (SWIR) HSI. Unfortunately, current generation HSI systems have numerous SWaP (spell out) limitations that make their potential integration onto a handheld or field portable platform difficult. The systems that are field-portable do so by sacrificing system performance, typically by providing an inefficient area search rate, requiring close proximity to the target for screening, and/or eliminating the potential to conduct real-time measurements.

To address these shortcomings, ChemImage Sensor Systems (CISS) is developing a variety of wide-field hyperspectral imaging systems. Raman HSI sensors are being developed to overcome two obstacles present in standard Raman detection systems: slow area search rate (due to small laser spot sizes) and lack of eye-safety. SWIR HSI sensors have been integrated into mobile, robot based platforms and handheld variants for the detection of explosives and chemical warfare agents (CWAs). In addition, the fusion of these two technologies into a single system has shown the feasibility of using both techniques concurrently to provide higher probability of detection and lower false alarm rates.

This paper will provide background on Raman and SWIR HSI, discuss the applications for these techniques, and provide an overview of novel CISS HSI sensors focused on sensor design and detection results.

9855-22, Session 4

A novel CMOS-compatible, monolithically integrated line-scan hyperspectral imager covering the VIS-NIR range

Klaas Tack, Pilar Gonzalez, Bert Geelen, Bart Masschelein, Charle Wouter, Bart Vereecke, Andy Lambrechts, IMEC (Belgium)

Imec has developed a process for the monolithic integration of optical filters on top of CMOS image sensors, leading to compact, cost-efficient and faster hyperspectral cameras. Different prototype sensors are available, most notably a 600-1000 nm line-scan imager, and two mosaic sensors: a 4x4 VIS (470-620nm range) and a 5x5 VNIR (600-1000nm). This paper presents the latest addition to imec's family of monolithically-integrated hyperspectral sensors: a line scan sensor covering the range 470-900 nm.

The presented imagers use a set of Fabry-Pérot interferometers, with distributed bragg reflectors as mirrors and varying cavity lengths, post-processed on top of a CMOSIS cmv2k sensor. As for our previous prototypes, only CMOS-compatible processes and materials (in terms of thermal budget and contamination level) can be used. However, to cover the full 470-900 nm range a single material combination is not enough. To overcome this challenge, imec developed a unique process flow that enables:

1. The deposition and patterning on the imager wafer of two filter banks, completely independent from each other, using different material combinations.
2. The integration of rejection filters on top of the two filter banks to block the light outside their respective range.

This new prototype camera can acquire hyperspectral image cubes of 2048 pixels over 192 bands (128 bands for the 600-900 nm range, and 64 bands for the 470-620 nm range) at 340 cubes per second for normal machine vision illumination levels.

9855-23, Session 4

The use of FTIR for the detection of chemical warfare agents and toxic industrial chemicals

Larry McDermott, MKS Instruments (United States); Timothy Stickler, KD Analytical (United States); Sylvie Bosch-Charpenay, Oskar Bosch, Norm Smith, MKS Instruments (United States)

Chemical Warfare Agents (CWAs) and Toxic Industrial Chemicals (TICs) have the potential to result in mass casualties either when used as weapons of mass destruction (WMDs) or if accidentally released. Spectroscopic methods offer many benefits for detecting vapor phase threats including high selectivity and the ability to detect low concentrations (ppb level) of numerous threats continuously and rapidly.

The optimization of an FTIR-based system for early detection of threat agents will be discussed. The system has been thoroughly tested and has demonstrated highly accurate results with a virtually zero false detection rate (less than 2 false alarms per running instrument-year). The high selectivity has been attained by utilizing a high performance FTIR system with a cryogenically cooled detector, a large (10 M) pathlength, a high sample turnover (10 liter per minute sample flow using an integrated pump), a patented continuous real-time background correction scheme and a multi-stage data validation approach. A library containing 375+ CWAs / TICs, commonly encountered chemicals and potential interferents, has been optimized to detect hazardous gases at levels well below the EPA Acute Exposure Guideline levels. In normal use, the system performs an analysis every 9 seconds. This paper discusses the unique analysis approach, the deployment of the instrument and the potential to extend its use beyond critical mission facilities to industrial air monitoring applications.

9855-24, Session PTue

Optical unmixing using programmable spectral source based on DMD

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Traditional spectral unmixing involves a series of signal processing algorithms applied on multispectral or hyperspectral data captured from an imaging device, in order to retrieve the abundances of different endmembers/materials in each pixel. Such algorithms are typically composed of several steps including dimensionality reduction, endmember determination and inversion (estimation of abundances), which are often time-consuming due to the high dimensionality of data, thus limiting the measurement speed.

In this article, a novel method, namely "optical unmixing", is proposed to alleviate the post processing effort by replacing the heavy computation with a spectrally tunable light source. By choosing spectral features of the light

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source intelligently, the abundance map of each material can be retrieved with minimum computation from gray value images captured by a normal camera.

The tunable light source is constructed based on a super continuum laser and a digital micro mirror device (DMD). Combination of a dispersive prism and an orthogonally mounted echelle grating is utilized to generate an echellogram of the super continuum laser, which is projected on to the DMD. Specifically designed patterns are sent to the DMD to generate light with target spectrum.

A complete set of algorithms is developed to fully utilize the flexibility of the programmable light source for blind unmixing with knowledge of a spectrum database. For n unknown endmembers, $3n+1$ measurements are required to retrieve the abundance maps of all endmembers theoretically.

9855-25, Session PTue

Design of thin-film filters for resolution improvements in filter-array based spectrometers using DSP

Woong-Bi Lee, Cheolsun Kim, Gun Wu Ju, Yong Tak Lee, Heung-No Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

Miniature spectrometers have been widely developed in various academic and industrial applications such as bio-medical, chemical and environmental engineering. As a family of spectrometers, optical filter-array based spectrometers fabricated using CMOS or Nano technology provide miniaturization, superior portability and cost effectiveness. In filter array based spectrometers, the resolution which represents the ability how closely resolve two neighboring spectra, depends on the number of filters and the characteristics of the transmission functions (TF) of the filters. In practice, due to the small-size and low-cost fabrication, the number of filters is limited and the shape of the TF of each filter is non-ideal. As a development of modern digital signal processing (DSP), the spectrometers are equipped with DSP algorithms not only to alleviate distortions due to unexpected noise or interferences among filters but also reconstruct the original signal spectrum. For high-resolution spectrum recovery, the TFs of the filters need to be sufficiently uncorrelated with each other. In this paper, we present a design of optical thin-film filters which have the uncorrelated TFs. Each filter consists of multiple layers of high- and low-refractive index materials deposited on a substrate. The proposed design helps the DSP algorithm to improve resolution with a small number of filters. We demonstrate that a resolution of 5 nm within a range from 500 nm to 1100nm can be achieved with only 64 filters.

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9856-5, Session 1

Graphene-based van der Waals heterostructures for emission and detection of terahertz radiation (*Invited Paper*)

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[Invited] This paper reviews recent advances in the research of graphene-based van der Waals heterostructures for emission and detection of terahertz radiation. A gated double-graphene-layer (G-DGL) nano-capacitor is the core shell under consideration, in which a thin tunnel barrier layer is sandwiched by outer graphene layers at both sides. A dc bias voltage between the GLs induces charges (electrons (hole) in the negatively (positively) biased GL), resulting in a bandoffset energy between the GLs. The gate bias voltage can tune the band offset. By applying a pertinent gate bias voltage photon emission or photon absorption, whose energy coincides with the band offset, can assist the inter-GL resonant tunneling. This is called 'Photon-assisted resonant tunneling (PhA-RT).' The PhA-RT gives rise to emission or absorption of THz photons, resulting in a giant THz gain or a giant THz responsivity depending on the polarity of the band offset. Recently we fabricated a G-DGL by using exfoliation and transferring methods for monolayer graphene and a few layers of h-BN. Preliminary experimental results demonstrate the occurrence of THz photon emission and detection in the G-DGL. When the DGL can excite symmetric optical and anti-symmetric acoustic coupled plasmon modes in the GLs. The latter mode can modulate the band-offset between the GL, giving rise to modulation of the inter-GL-layer resonant tunneling. This can dramatically enhance the THz gain or responsivity via plasmon-assisted inter-GL resonant tunneling. When a planar G-DGL active area is prepared one can expect the propagation of the plasmons along the GL, promoting the gain or responsivity enhancement effect. When the G-DGL is configured in a specific areal structure whose dimension gives THz plasmon mode frequencies, one can expect the excitation of resonant plasmon modes. Theoretical study reveals the contribution of those modes to enhancement of the THz gain or responsivity.

9856-33, Session 1

Recent advances in RT-CW, widely tunable semiconductor THz sources (*Keynote Presentation*)

Manijeh Razeghi, Northwestern Univ. (United States)

THz sources based on intracavity difference frequency generation (DFG) in mid-IR QCL have shown considerable progress in the past few years [1]. When a QCL active region is designed with strong coupling between the lower lasing levels and injector levels, which results in a large nonlinear susceptibility $\chi^{(2)}$, THz emission can be generated within the cavity [2]. Thus, this type of THz source is free from the temperature limitation suffered by the THz QCLs based on direct optical transition, and ideally its working temperature is only limited by the mid-IR QCL which can work well even above 100 °C [3], and can be tuned over a broad waveguide range with broadband heterogeneous active region design [4]. It not only shares the common features of the mid-IR QCLs which are mass reproducible, room temperature operation, low cost, compact size, and high efficiency, but also carries the potential of delivering THz emission with high power in a wide frequency range.

With the recent systematic optimizations, including dual-core design based on single phonon resonance structure [4] for high efficiency and broad gain operation, use of a composite distributed-feedback (DFB) grating with dual period component [5] for purifying and tuning the mid-IR as well as the THz spectra, and use of the epi-down $\chi^{(2)}$ resonant phase-matching scheme [6] for high THz outcoupling efficiency, THz sources based on DFG in QCLs with high THz power up to 1.9 mW [1], and wide tuning range of 1-4.6 THz have been demonstrated [4]. Very recently, by utilizing a low-loss buried-ridge waveguide design and highly dissipative epi-down mounting scheme, room temperature continuous wave (RT-CW) operation at 3.6 THz was demonstrated with a continuous power of 3 μ W. [7] While this narrowband THz source is suitable as a local oscillator for heterodyne detections in space observatories, continuous wave, monolithic THz frequency tuning with higher power is always desired for real applications such as chemical sensing and spectroscopy.

Here we present a new strong-coupled strain-balanced quantum cascade laser design for efficient THz generation based intracavity DFG with a epi-down mounting scheme, as shown in Fig. 1(a). A single-core active region made from a composite strain-balanced Al_{0.63}In_{0.37}As/Ga_{0.35}In_{0.65}As/Ga_{0.47}In_{0.53}As material system is designed with broad gain, high efficiency and large nonlinearity. Continuous wave, single mode THz emission with a wide tunable frequency range of 2.06 - 4.35 THz and an output power up to 4.2 μ W is demonstrated at room temperature from two monolithic three-section sampled grating distributed feedback-distributed Bragg reflector lasers, as shown in Fig. 1(b-c).

Higher THz power in a wider tuning range in CW operation at room temperature is achievable by further exploring the active nonlinear region design in the 5-6 μ m wavelength range with a larger coupling strength and higher WPE [8], and a digital concatenated sampled grating can be used for a wider tuning range per device [9].

9856-34, Session 1

Terahertz detectors based on superconducting hot electron bolometers for the imaging application (*Invited Paper*)

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The developments of terahertz (THz) imaging for person-borne concealed weapons at security-check points and non-destructive inspection of defects in materials have burgeoned over the last decade, due to its high spatial resolution comparing with the microwave and atmospheric/obscure penetration comparing with the optics. To demonstrate such advantages, 0.65 THz maybe a quite suitable frequency point, be at enough high frequency for high spatial resolution and can penetrate the atmosphere

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for quite long distance. However, there are not so many sensitive, fast and convenient detectors working at this frequency band. Superconducting tunnel junction (STJ) detectors and transition-edge sensors (TES) have enough sensitivity, but should be working at much lower temperatures, which makes the system more complicate. Superconducting hot electron bolometer (HEB) heterodyne detectors (mixers) are very sensitive at 4.2 K and the frequencies higher than 1 THz. We have fabricated the niobium nitride (NbN) superconducting HEB mixers with the system double sideband (DSB) noise temperature lower than 10 times of the quantum limit: hf/kB (where h is the Planck constant, kB is the Boltzmann constant and f is the operating frequency) at the frequencies higher than 1 THz. Here, we will report the performances of the NbN HEB detectors at 4.2K and 0.65 THz.

The fabricated NbN HEB detectors consist of a complementary logarithmic-spiral antenna made of gold and an NbN film (bridge) connecting across the antenna's inner terminals. For its performance as a mixer, the system DSB noise temperature of about 500 K and the intermediate frequency (IF) gain bandwidth (GBW) of higher than 3.5 GHz have been obtained at 4.2 K and 0.65 THz. For its performance as a direct detector, a microwave-driven scheme has been checked in detail. The noise equivalent power of about 7 pW/Hz0.5 has been obtained at 4.2 K and 0.65 THz.

9856-1, Session 2

Parallel plate waveguide TDS to study THz conductivity of ultrathin materials (*Invited Paper*)

Masayoshi Tonouchi, Manjakavahoaka Razanoelina, Filchito Renee Bagsican, Iwao Kawayama, Osaka Univ. (Japan); Xiang Zhang, Rice university (United States); Lulu Ma, Wiley, VCH (China); Hironaru Murakami, Osaka Univ. (Japan); Robert Vajtai, Pulickel M. Ajayan, Junichiro Kono, Rice university (United States); Daniel M. Mittleman, Brown University (United States)

[Invited] Development of techniques for characterization of extremely thin films is an important challenge in terahertz (THz) science and applications. Spectroscopic measurements of materials on the nanometer scale or of atomic layer thickness (2D materials) require a sufficient terahertz wave-matter interaction length. Waveguide-based THz spectroscopy offers an alternative method to overcome this problem. Here, we investigate a new parallel-plate waveguide (PPWG) technique for measuring dielectric THz properties of ultrathin gold films and graphene, in which we mount the thin-film samples at the center of the waveguide. We discuss a model of THz dielectric parameter extraction based on waveguide theory and analyze the response of thin films for both transverse magnetic (TM) and transverse electric (TE) waveguide modes.

9856-2, Session 2

THz spectroscopic imaging of chemicals through thicker obstacles (*Invited Paper*)

Kodo Kawase, Nagoya Univ. (Japan) and RIKEN (Japan); Mikiya Kato, Nagoya Univ. (Japan); Ryo Yamazaki, Nagoya Univ. (Japan) and Central Customs Lab. (Japan); Kosuke Murate, Nagoya Univ. (Japan)

In 2001, we created an injection-seeded THz-wave parametric generator (is-TPG) with 300mW output based on the parametric processes in a LiNbO3 crystal. In 2003, we demonstrated a non-destructive THz spectroscopic imaging of illicit drugs hidden in envelopes using a widely tunable THz parametric oscillator, though its dynamic range at that time was less than four orders.

Recently, the peak output power of is-TPG approached 50 kW by introducing a microchip YAG laser with shorter pulse width of 420ps. In the

detection section of our system, THz-wave was converted back into near infrared beam by nonlinear optical wavelength conversion. We have realized ten orders of dynamic range using commercially available near infrared photo detector. Now we can detect drugs under much thicker obstacles than before using evolved is-TPG spectroscopic imaging system.

However, the tunability of is-TPG was still limited less than 3 THz due to the strong absorption loss inside the LiNbO3 crystal. In order to suppress this absorption loss, we tilted the LiNbO3 crystal slightly so that the THz waves were generated at the very near-surface of the crystal. The pump beam was totally reflected at the crystal surface where the THz-wave was generated. Thus we have realized much wider tunability up to 5 THz.

Our evolved is-TPG system has potential applications in spectroscopic sensing and imaging of chemicals through obstacles and non-destructive CT imaging of plastic/ceramic products. We have also compared our is-TPG spectrometer and TDS (THz Time Domain Spectroscopy) for the purpose of drug detection through thick envelopes.

9856-3, Session 2

Novel terahertz sensing modalities using ceramics and glasses (*Invited Paper*)

S. K. Sundaram, New York State College of Ceramics at Alfred Univ. (United States)

Three different THz sensing modalities that use ceramics and glasses were identified. Terahertz time-domain spectroscopy (THz-TDS) was used for identification of the sensing modalities in multiphase ceramic waste forms, laser ceramics, and biomedical application.

Single-phase materials of zirconolite (CaZrTi2O7), pyrochlore (Nd2Ti2O7), and hollandite (BaCs0.3Cr2.3Ti5.7O16 and BaCs0.3CrFeAl0.3Ti5.7O16) were characterized. The refractive index and dielectric properties in THz frequencies demonstrate the ability to distinguish between these materials. The temperature dependence of the refractive index and dielectric constant of pyrochlore and zirconolite materials in the range of 25-200°C is found to follow an exponential trend. This can also be used to measure the temperature of the ceramic waste forms on storage over extended geological time scales.

A set of twenty ceramics samples was prepared by solid-state sintering of Y2O3 and Al2O3 powder mixtures with compositions ranging from -0.62 to +0.96% of Y2O3 on each side of the stoichiometric garnet composition. These samples were characterized using THz-TDS between 0.06 and 2.8 THz. Ceramic and single-crystal samples exhibit a similar broad absorption band, which we assign to a 2-phonon difference process, and whose width and intensity depend upon composition.

We also investigated the glass content in hydroxyapatite (HA)- calcium zinc silicate glass composite using THz-TDS. The refractive index and dielectric constant provide a reliable determination of glass content of the composite. Additionally THz-TDS was used to monitor structural changes in HA during simulated body fluid (SBF) incubation. Results show that the THz-TDS can be a promising non-destructive technique for HA research.

9856-4, Session 2

Shedding new light on magnetoelectric coupling in bulk and heterostructured multiferroic oxides (*Invited Paper*)

Pamela Bowlan, Los Alamos National Lab. (United States); Yu-Miin Sheu, National Chiao Tung Univ. (Taiwan); Rolando Valdes Aguilar, The Ohio State Univ. (United States); Stuart A. Trugman, Dmitry A. Yarotski, Antoinette J. Taylor, Rohit P. Prasankumar, Los Alamos National Lab. (United States)

Multiferroic oxides have attracted much attention in recent years due to their potential for controlling magnetism with an electric field and

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ferroelectricity (FE) with a magnetic field. Most multiferroics, however, typically display relatively weak coupling between these parameters and rarely operate near room temperature. This has motivated researchers to design and fabricate layered oxide heterostructures, with the goal of enhancing the magnetoelectric (ME) coupling between individual ferroelectric and magnetic layers while also increasing their operating temperature. However, further progress in this area requires a deeper understanding of the underlying mechanisms and timescales limiting ME coupling in both bulk and heterostructured multiferroics.

In the past few years, we have demonstrated that ultrafast optical and terahertz (THz) spectroscopy is a unique tool for probing the interplay between FE and magnetic ordering in canonical bulk multiferroics such as HoMnO₃ and EuYMnO₃ as well as in multiferroic oxide heterostructures. For example, these studies have revealed a long-lived, photoinduced enhancement of the FE polarization in a FE/ferromagnet (FM) heterostructure, and have also shown that femtosecond optical pulses can induce transient magnetoelectric coupling in a FE/FM heterostructure, with implications for high speed magnetoelectric devices. We have also used THz pulses to directly probe low energy modes in these materials, allowing us to determine the timescales governing energy transfer from electronic to magnetic degrees of freedom. Overall, our studies demonstrate that ultrashort optical pulses can help unravel the mechanisms underlying magnetoelectric coupling in multiferroic oxides, with the potential for all-optical control on femtosecond timescales.

9856-6, Session 3

Low dimensional plasmonic spectroscopy through inversion of the far infrared detection problem (*Invited Paper*)

Gregory C. Dyer, Sandia National Labs. (United States); Gregory R. Aizin, The City Univ. of New York (United States); Albert D. Grine, Don Bethke, Sandia National Labs. (United States); Xiaoyan Shi, The Univ. of Texas at Dallas (United States); Ben V. Olson, John L. Reno, Samuel D. Hawkins, John F. Klem, Wei Pan, Eric A. Shaner, Sandia National Labs. (United States)

Though two dimensional (2D) semiconductor plasmonic systems first emerged several decades ago, a resurgence of interest in this area has occurred largely due to rapid progress in carbon-based materials such as graphene. More mature materials such as III-V semiconductor heterostructures nonetheless remain important 2D plasmonic systems, and should continue to play a role in terahertz (THz) frequency devices such as direct detectors, heterodyne mixers, oscillators and modulators. Despite the apparent maturity of this field, research into fundamental phenomenology including plasmon propagation length and plasmon-plasmon coupling remains relatively less explored. On the other hand, direct THz detection via plasmonic homodyne mixing has reached the point of commercialization.

Here we demonstrate that monolithically integrated direct THz detection provides a means to characterize non-trivial GaAs/AlGaAs-based 2D plasmonic structures. This effectively inverts the spectroscopic problem by using a monochromatic far infrared source to interrogate a complex plasmonic system, rather than aiming to determine an unknown radiation spectrum from a detector's response. By representing a 2D plasmonic system in a transmission line formalism, it is readily apparent that a segment of gated 2D electron gas is a tunable LC resonator. Coupling of multiple, adjacent 2D plasmonic resonators has enabled experimental demonstration of the active control of compound plasmonic cavities, plasmon-plasmon hybridization, plasmonic crystals, localized plasmonic modes, and a plasmonic induced transparency-like effect. Additionally, we will present very recent results from far infrared characterization of an InAs/GaSb-based system where apparent edge transport rather than a plasmonic homodyne mixing signal dominates a photovoltaic response.

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9856-7, Session 3

Terahertz metamaterials: Design, implementation, modeling and applications (*Invited Paper*)

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The ability to design and engineer sub-wavelength metamaterial structures capable of manipulating the propagation of electromagnetic waves and the manner in which they interact with matter is of great fundamental and practical interest. In this paper, we review our recent work on the design, simulation and implementation of metamaterial devices operating at Terahertz frequencies for applications such as optical buffers, delay lines, and ultra-sensitive sensors.

We first present the design, simulation, and realization of THz metamaterials exhibiting plasmon-induced transparency (PIT) through the hybridization of two double split ring resonators on either silicon or flexible polymer substrates. Such structures were able to slow the propagation of THz waves. We have developed a method to quantitatively determine the metamaterial effective thickness, a fundamental parameter characterizing slow light properties of PIT devices. In addition, we have developed an equivalent electrical circuit model that introduces a mutual inductance parameter whose sign is shown to characterize the existence or absence of PIT response from these types of structures.

We have also designed, simulated and realized THz metamaterials perfect absorbers, and developed of a hybrid approach to uniquely determine the constituting elements of their dynamic electrical circuit analogue. Inspired by stereoisomers, another THz metamaterial absorber consists of a stereo-metamaterial engineered by using a spatially different arrangement of meta-atoms. Integrated into an absorber structure, this stereometamaterial exhibits multifunctional specification including broadband absorbing, switching, and polarizing effect dependent upon the polarization of incident light and relative positions of meta-atoms.

9856-8, Session 3

THz components for integrated spectrometer-on-chip applications (*Invited Paper*)

Nezih Pala, Arash Ahmadivand, Mustafa Karabiyik, Raju Sinha, Serkan Kaya, Florida International Univ. (United States); Michael Shur, Rensselaer Polytechnic Institute (United States)

THz frequencies are extremely well-suited for bio-chemical biochemical sensing, detection and identification. Novel compact, tunable, room temperature operable THz components including sources, detectors, and filters will enable integrated spectrometer-on-chip applications.

The proposed THz source is on an insulated SiO₂ substrate consists of a nonlinear optical micro-resonator on top of a THz resonator capable of sustaining the difference THz modes. Optical waveguides are used to couple the input IR beams to the nonlinear resonator. Another pair of Si THz waveguides placed beneath the input optical waveguides couples out the generated THz radiation from the resonator. The effective mode indices of the optical and THz waveguides are optimized in order to satisfy the phase matching condition using the FDTD analysis. On the detector side, the 2DEG based high electron mobility transistors (HEMTs) support gated plasmons. When the gates of the FET are periodically spaced, the grating gate supplies the necessary momentum in order to excite the plasmons by compensating the momentum mismatch between the THz light in free

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space and plasmons. Using FDTD =, we studied the plasmonic dispersion of in the GaN/AlGaIn HEMT device with asymmetric dual-grating gate (ADGG). The branches in the dispersion are completely different than the ones in dispersion of uniform grating devices. ADGG device can support tightly confined /weakly coupled behavior and propagating/strongly coupled plasmonic modes with asymmetrical charge distributions. This non-uniform charge distribution along the channel can result in high responsivity making the ADGG devices a promising candidate for tunable solid-state THz detectors.

9856-9, Session 3

Nonlinear THz quantum dynamics beyond Kohn's theorem (Invited Paper)

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Controlling superpositions of electronic quantum states through nonlinear interactions is a key aspect of quantum computing and ultrafast coherent electronics. In the solid state, the THz frequency range offers a rich spectrum of elementary excitations. Yet, rapid dephasing hinders their exploitation for quantum control. However, Walter Kohn found in 1961 that the cyclotron resonance of Landau-quantized electrons is immune to strong Coulomb interactions, as has been exploited in sophisticated quantum phenomena such as ultrastrong light-matter coupling, superradiance, coherent control, and superfluorescence.

Here, we show how single-cycle THz transients of an amplitude of up to 8.7 kV/cm centered at 1 THz facilitate coherent polarization control of a magnetically biased two-dimensional electron gas (2DEG), driving the cyclotron resonance beyond the limits of Kohn's theorem. Under these strongly non-perturbative excitation conditions, anharmonic Landau ladder climbing up to the 6th rung leads to population inversion, an abruptly increased dephasing rate, and a red-shift of the cyclotron resonance. Most strikingly, strong coherent nonlinearities including four- and six-wave mixing are revealed through two-dimensional THz spectroscopy. While such violations of Kohn's theorem could trivially result from nonparabolic electron dispersion or impurities, a quantitative comparison with our microscopic quantum theory reveals that the nonlinear response is dominated by the Coulomb interaction between electrons and the positively charged ionic background. These many-body dynamics can be used to control internal degrees of freedom of a 2DEG inaccessible to linear optics and may enable efficient exploitation of electronic many-body states for future ultrafast quantum information processing.

9856-10, Session 3

The sensing application of Fano resonances in terahertz metamaterials

Lijuan Xie, Zhejiang Univ. (China)

Terahertz radiation is a special electromagnetic radiation whose frequency lies between the microwave and infrared regions of the spectrum. In this frequency region, many fundamental physical processes could be probed, such as rotational transitions of molecules, large-amplitude vibration motions of organic compounds, lattice vibrations in solids and so on. Recently, terahertz metamaterials had attracted a lot of interest and were used in many fields, such as electrical modulation, compressive imaging and so on. We report on the occurrence of sharp Fano resonances in planar terahertz metamaterials. The sharp resonances were used to realize biochemical sensing and show high sensitivity.

9856-11, Session 3

Cooperative promotion of plasma instabilities for emission of terahertz radiation in an asymmetric dual-grating gate graphene-channel FET

Akira Satou, Yuki Koseki, Takayuki Watanabe, Tohoku Univ. (Japan); Vyacheslav V. Popov, Institute of Radio Engineering and Electronics (Russian Federation); Victor Ryzhii, Taiichi Otsuji, Tohoku Univ. (Japan)

Two-dimensional plasmons in channels of transistors have been investigated for realization of compact, room-temperature operating terahertz (THz) emitters that utilize plasmon instabilities. For mechanisms of plasmon instabilities by the DC current injection, the so-called Dyakonov-Shur (DS) instability and Ryzhii-Satou-Shur (RSS) instability have been proposed theoretically. Graphene can be a solution to the realization of the plasmon instabilities at room temperature. In this paper, we conduct the simulation of the plasmon instabilities in a graphene transistor with a dual-grating-gate structure. We show that the simultaneous occurrence of both the DS and RSS instabilities is possible in this structure and that the growth rate can exceed $5 \times 10^{12} \text{ s}^{-1}$ at room temperature.

We considered the steady-state profile of electron concentration in the graphene channel formed by a gate bias to the gate 1 together with a uniform electron doping of $5 \times 10^{11} \text{ cm}^{-2}$. The uniform DC electric field along the channel direction was then applied to the system in order to induce the plasmon instabilities. We varied the length of the gate 1, L_{g1} . It clearly demonstrates that the growth rate is of the order of 10^{12} s^{-1} and exceeds $5 \times 10^{12} \text{ s}^{-1}$ at maximum, with the frequency above 1 THz. The dependence of the growth rate on L_{g1} shows an oscillation that becomes more rapid as L_{g1} becomes shorter. This behavior is specific to the RSS instability. Besides, it can be seen that this oscillation is superimposed onto monotonic increase in the growth rate with decreasing L_{g1} , except in the region below $L_{g1} = 150 \text{ nm}$. We identify it as the occurrence of the DS instability that exhibits the same behavior. The result obtained strongly suggest that graphene transistor with the dual-grating-gate structure is a potential to realize a compact, room-temperature operating terahertz (THz) emitter.

9856-12, Session 3

Review of terahertz application for characterization, inspection and quality control in near-field and far-field

Kiarash Ahi, Mehdi Anwar, Univ. of Connecticut (United States)

Terahertz (THz) radiation has been widely used for inspection and quality control in near-field and far-field. In far field THz is being used for characterization of materials, inspecting packaged objects, measuring thickness and inspection of different layers of objects. THz resolution is limited because of its large wavelength. Increasing the frequency limits the penetration abilities and thus some efforts are being done to enhance the THz images using soft reconstruction techniques without needing for increasing the frequency. In near-field region, resolutions in the nano-scale were achieved. Near-field THz spectroscopy has been used for mapping the distribution of THz electric field on antennas and metallic surfaces. This method allows spatial resolution to be improved beyond the diffraction limit and offer the only opportunity to investigate nanoscale systems at THz frequencies. In another attempt to increase the resolution, laser beams with frequencies higher than terahertz are used to excite the p-n junctions in semiconductor objects. The excited junctions generate terahertz radiation as a result as long as their contacts are unbroken. In this approach, since the absorption increases exponentially with the frequency, again inspection of the thick packaged semiconductors may not be feasible. In terms of material characterization, since THz pulsed lasers provide pulses with picosecond duration, fast-shallow traps in semiconductors can be localized by THz

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pulsed lasers. This can be done with similar approaches where pulsed lasers were used for photoconductive decay measurements. The growing use of THz in the recent decades has addressed many desired needs in inspection. Because of this fast growing, the need for organizing the achieved objectives, ongoing research and the goals is being sensed. Toward satisfying this need, this paper provides a comprehensive review on the applications of the THz for characterization, inspection and quality control in the both near and far-field regions.

9856-13, Session 3

Detection of small metal particles by a quasi-optical system at sub-millimeter wavelength

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Inspection of alien metal particles in electronic materials such as separators for battery is a critical issue to control quality and to guarantee safety of products. Moreover one of the hardest requirements is detecting particles less than 100 um in diameter mixed in wide dielectric films. However, existing techniques such as electromagnetic induction do not fulfill this requirement. In this paper, we present a new detection technique using sub-millimeter wave frequencies for the requirement. The first advantage of using sub-millimeter wave frequency is that it is easy to distinguish conductive particles from a nonconductive material such as plastic films. The second advantage is that it is more suitable for detection of tiny particles because the wavelength is shorter compared to microwave region. The third advantage is that sub-millimeter wave has a characteristic of straightness propagation similar to light and therefore it enables realization of a detection system at the product line.

A system for demonstration is composed of a Keysight performance network analyzer (N5247A PNA-X) with 170-340 GHz VDI extension modules, transmitting and receiving antennas and focusing optics (dielectric lens). A sub-millimeter-wave output signal is radiated via an antenna and focused onto a metal particle on a film. The scattered wave by the metal particle is detected by an identical antenna through a lens. The presence of metal particle is confirmed by insertion loss between antennas (S21). The present experimental result shows that the minimum size of detectable metal spheres is approximately 300 um in diameter using 170-340 GHz frequencies.

9856-35, Session 3

Near field coupled terahertz metamaterials
(Invited Paper)

Dibakar Roy Chowdhury, Mahindra Ecole Centrale (India)

Active, passive and ultrafast modulations of subwavelength resonances in metamaterials through optical pump terahertz probe (OPTP) spectroscopy will be described in this talk. Particularly, reconfigurable resonance modes in metamaterials were demonstrated through switching from split-ring resonators to closed-ring resonators configurations via selective optical excitation of the split gap of ring resonator constituting the metamaterial unit cell. We observed that both the fundamental and the third-order resonance modes experienced monotonic damping because of increasing conductive losses in the photo-doped split gap region. We have further observed the evolution of the second-order resonance mode by increasing the optical pump at very high value, which is otherwise forbidden in a split-ring resonator for the particular polarization of the incident probe beam. In another experiment we have shown ultrafast modulation of near field coupling between bright and dark resonance modes in metamaterials. Such metamaterial unit cell consists of a pair of orthogonally twisted split ring resonators (bright and dark resonator) tightly bound through the induced

near field electromagnetic lines. We placed ion implanted silicon layer with ultrafast carrier lifetime inside the dark resonator split gap to achieve active control of its resonance modes that determines the near field coupling inside the unit cell. Our experiments reveal ultrafast dynamical transition of near field coupling between bright and dark resonators allowing the metamaterial unit cell to change its state from coupled to decoupled, and eventually back to the coupled state.

9856-14, Session 4

Externally triggered imaging technique for microbolometer-type terahertz imager
(Invited Paper)

Naoki Oda, NEC Corp. (Japan); Takayuki Sudou, Nippon Avionics Co., Ltd. (Japan); Tsutomu Ishi, NEC Corp. (Japan); Syuichi Okubo, Nippon Avionics Co., Ltd. (Japan); Goro Isoyama, Akinori Irizawa, Keigo Kawase, Osaka Univ. (Japan); Ryukou Kato, High Energy Accelerator Research Organization, KEK (Japan)

Both 320x240 and 640x480 terahertz (THz) imagers (pixel pitch of 23.5 um) were developed which have enhanced sensitivity in sub-THz region (ca. 0.5 THz) by a factor of 10. The imagers include functions such as external-trigger imaging, lock-in imaging, beam profiling and so forth. This paper especially describes the function of the external-trigger imaging for the 320x240 imager which was verified in combination with the pulsed THz free electron laser (THz-FEL) developed by Osaka University. The THz-FEL emits THz radiation in a wavelength range of 25 - 150 um and at repetition frequencies of 2.5, 3.3, 5.0 and 10 Hz.

In our experiments, the THz-FEL was tuned at the wavelength of 86 um. The external trigger pulse was generated via pulse generator, using brightening pulse which brightened THz-FEL. A series of pulses from THz-FEL were introduced to both THz imager and Joule meter with a beam splitter, so that the output signal of THz imager was normalized by the output of the Joule meter.

The external-trigger imaging function makes use of slow thermal time constant of microbolometer in THz focal plane array (THz-FPA), which is formed on microbridge structure. The normalized output signals of THz imager were obtained at the repetition frequencies mentioned above and were found consistent with one another. This experimental result shows that the external trigger imaging function operates correctly. The timing-relation of the external trigger pulse to the brightening pulse was varied and the influence of the timing-relation on beam pattern is also discussed.

9856-15, Session 4

Near-field frequency-selective terahertz imaging utilizing graphene and carbon nanotubes
(Invited Paper)

Yukio Kawano, Tokyo Institute of Technology (Japan)

The terahertz (THz) frequency region is located between the electronic and photonic bands, hampering the development of basic components like detectors and sources. The THz wave also has the drawback of low imaging resolution, which results from the two to three order of magnitude longer wavelength than that of visible light. A powerful approach for achieving high spatial resolution of optical imaging is to exploit near-field technique. This method has been well established in visible, near-infrared and microwave regions. However, near-field THz imaging remains to be fully explored. In particular, the development of near-field spectroscopic imaging is one of the important issues. For this purpose, highly sensitive detection of evanescent field alone is necessary. We report new devices for THz near-field spectroscopic imaging in which all components: an aperture, a probe, and a detector are integrated on a single solid-state chip. This technology is based on a nano-carbon THz imager with sub-wavelength resolution and

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frequency-tunable THz spectrometer. Industrial applications to materials and biological research with these devices will be also presented.

9856-16, Session 4

Sensitive THz-wave detection and imaging using nonlinear optical up-conversion
(Invited Paper)

Hiroaki Minamide, RIKEN (Japan)

[Invited] Recently, a remarkable breakthrough related to radiation peak-power over ten kilowatt or broad-band frequency-tunability covering tens of terahertz (THz) frequency were achieved using nonlinear optical wavelength-conversion. Moreover, highly sensitive detection of THz-waves with wide dynamic range using frequency up-conversion at room temperature was obtained. In this paper, we would like to report a extremely sensitive THz-wave detection and a real-time THz-wave imaging using nonlinear optical up-conversion.

In experimental setup, a flash-lamp pumped green laser is used to pump two KTP optical parametric oscillator (OPO) systems. By using three galvanometric scanner, the angles of the KTP crystals are tuned so that lasers with wavelength variable from 1.2 μm to 1.7 μm can be got. The OPO cavity with dual KTP crystals is used to generate near-infrared beam as the pumping of THz difference frequency generation (DFG) in a DAST crystal. The other one is for generation of pumping beam for THz frequency up-conversion in a second DAST crystal. The THz wave is generated in the DAST 1 and collimated by a parabolic mirror. Then it is reflected by three ITO glasses. The object plane is imaged to another DAST where the information on it transfers to the near-infrared signal by frequency up-conversion. The up-converted image is imaged to and recorded by a commercial near-infrared camera (Goodrich SU320KTS-1.7RT/RS170) working at video rate (60 Hz). One of the objects for imaging experiments is a RIKEN logo cut in an aluminum sheet. The resolution is about 900 \times 160 μm , considering the reading error of one pixel.

Sensitive THz-wave detection and real-time THz imaging were obtained by nonlinear optical frequency up-conversion in a DAST crystal, with a high resolution limited by diffraction. This technology is applicable to wider THz application, especially nondestructive inspections.

9856-17, Session 4

GaAs THz photoconductive sources with 1550nm-laser boresight alignment

Elliott R. Brown, Weidong Zhang, Wright State Univ. (United States)

A longstanding problem in the use of THz photoconductive sources is beam alignment. Usually these sources are coupled to free space using a planar antenna mounted on the backside of a low-loss dielectric (e.g., high-resistivity silicon) hyper-hemispherical lens. This often creates a high-directivity (D) THz beam after the lens, typically D \sim 25 dB or higher. The corresponding beam angle of \sim 1 deg or less makes the THz beams difficult to locate, let alone track, in realistic scenarios such as imaging the skin of humans in a clinical setting. With recent advances in GaAs-based "extrinsic" photoconductors driven by 1550-nm lasers, roughly half of the 1550-nm power leaks through GaAs epitaxial layer and then propagates readily through the GaAs substrate and dielectric lens. Given good co-alignment of the antenna boresight with the optical axis of the lens, the THz and 1550-nm beams are nominally coaxial and the THz beam can be located in space by observing the 1550-nm beam using a laser viewing card or more sophisticated techniques. In this work we address the accuracy of this approach vs antenna directivity and lens radius, and consider sources of error such as antenna-lens misalignment. We also address the common need of blocking the 1550-nm radiation after geolocating the THz beam using low-pass filters such as (absorptive) black polyethylene and (reflective) capacitive mesh.

9856-18, Session 4

New algorithm for the passive THz image quality enhancement

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

We propose new approach for THz image quality enhancing using correlation function between the image under consideration and a standard image. This method allows to see the person clothes details that it means multi-times increasing of the passive THz camera temperature resolution.

We discuss a choice of image characteristics for an achievement of correlation function high contrast. Other feature of our approach arises from a possibility of a person image coming to the THz camera by using a computer processing of the image only. It means that we can "decrease" a distance between a person and the passive THz camera.

9856-19, Session 4

Modeling and developing of terahertz imaging equation and enhancement of the resolution of terahertz images using deconvolution

Kiarash Ahi, Mehdi Anwar, Univ. of Connecticut (United States)

This paper introduces a novel reconstruction approach for enhancing the resolution of the terahertz (THz) images. For this purpose the THz imaging equation is derived. According to our best knowledge we are reporting the first THz imaging equation by this paper. This imaging equation is universal for THz far-field imaging systems and can be used for analyzing, describing and modeling of these systems. The geometry and behavior of Gaussian beams in far-field region imply that the FWHM of the THz beams diverge as the frequencies of the beams decrease. Thus, the resolution of the measurement decreases in lower frequencies. On the other hand, the depth of penetration of THz beams decreases as frequency increases. Roughly speaking beams in sub 1.5 THz, are transmitted into integrated circuit (IC) packages and the similar packaged objects. Thus, it is not possible to use the THz pulse in higher frequencies for higher resolution imaging and inspection of the packaged items. In this paper, after developing the 3-D THz point spread function (PSF) of the scanning THz beam and then the THz imaging equation, THz images are enhanced using deconvolution of the THz PSF and THz images. As a result, the resolution has been improved several times beyond the physical limitations of the THz measurement setup in the far-field region and sub-Nyquist images have been achieved. Particularly, MSE and SSIM' have been increased by 27% and 50% respectively. High resolution X-ray images are taken as the ultimate undistorted representations of the objects for calculation of these metrics. Details as small as 0.2 mm were made visible in the THz images which originally reveals no details smaller than 2.2 mm. In other words the resolution of the images has been increased by 10 times. The accuracy of the reconstructed images was proved by high resolution X-ray images.

9856-20, Session 5

Terahertz oscillators using resonant tunneling diodes and their functions for various applications *(Invited Paper)*

Masahiro Asada, Safumi Suzuki, Tokyo Institute of Technology (Japan)

Compact and coherent source is a key component for various applications of the terahertz wave. We report on our recent results of terahertz oscillators using resonant tunneling diodes (RTDs). The RTD is an InGaAs/AlAs double-

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barrier structure on InP substrate, and integrated with a planar slot antenna as a resonator and radiator of oscillation. The output power is obtained from the substrate side through a Si lens. To achieve high-frequency oscillation, the electron delay time in RTD, which degrades the negative differential conductance, was reduced with a narrow quantum well and an optimized collector spacer thickness. The former reduces the electron dwell time in the resonant tunneling region, and the latter simultaneously minimizes the electron transit time and the capacitance at the collector depletion region. The conduction loss of the resonance circuit was also reduced with a wide air-bridge between the RTD and slot antenna. By these structures, fundamental oscillation up to 1.92 THz were obtained at room temperature. For higher frequency, oscillation above 2 THz is theoretically possible by reducing parasitic series resistance in RTD. An oscillator with patch antenna, in which Si lens is unnecessary, was fabricated. In a preliminary experiment, output power of 55 microwatts was obtained in a three-element array. Direct intensity modulation up to 30 GHz and wireless data transmission with quasi-error-free 30 Gbps were demonstrated. By integrating a varactor into the slot antenna, wide frequency tuning of 580-700 GHz in a single device and 580-900 GHz in a 4-element array were also demonstrated.

9856-21, Session 5

Photonic crystal technology for terahertz system integration (Invited Paper)

Masayuki Fujita, Tadao Nagatsuma, Osaka Univ. (Japan)

Developing terahertz integration technologies is essential for practical use of terahertz electromagnetic waves (0.1-10 THz) in various applications including broadband wireless communication, spectroscopic sensing, and nondestructive imaging. However, most existing terahertz application systems are composed of bulky and discrete components, including sources, detectors, hollow waveguides, and lenses. Size reduction of the components and the development of an integration platform are required to make terahertz system integration. The low-loss transmission lines on a thin planar platform should be the most fundamental component to develop it. Metallic transmission lines have been widely studied. However, the propagation loss is as high as -10 dB/cm in the terahertz regions because of high absorption loss.

In this paper, we present our recent challenges for terahertz system integration based on photonic-crystal technologies. Photonic crystals are composed of a dielectric material with a periodic refractive index distribution and allow manipulation of electromagnetic waves by electromagnetic mode design. We particularly focus on photonic-crystal slabs consisting of a two-dimensional lattice of air holes formed in a silicon slab because a strong confinement of the terahertz waves can be achieved in simple planar structures without using metals. We demonstrate ultralow-loss (< 0.1 dB/cm, two or three orders of magnitude smaller than that reported for metallic lines) waveguides at the 0.3-THz band to control the free-carrier absorption using high-resistivity (~20 k Ω) silicon. We also report the prototype of terahertz transceivers based on the waveguide for frequency division wireless communications, which consists of a diplexer, grating coupler, and receiver and transmitter.

9856-22, Session 5

Nonlinear terahertz electromagnetic interactions in energetic materials (Invited Paper)

Mitchell A. Wood, Diego A. R. Dalvit, David S. Moore, Los Alamos National Lab. (United States)

We present results from a molecular dynamics study of the scattering of terahertz electromagnetic waves in energetic materials. Nonlinear light-matter interactions in molecular crystals result in frequency-conversion. Applied electromagnetic fields of moderate intensity can induce these nonlinear effects without triggering chemical decomposition. We use molecular dynamics simulations to compute the two-dimensional inelastic

scattering spectra (e.g., Raman) in the terahertz range for planar slabs of PETN and ammonium nitrate. We discuss third-harmonic generation and polarization-conversion processes in such materials. We argue that the far-field spectral features of the reflected/transmitted light may serve as an alternative tool for stand-off explosive detection.

9856-23, Session 5

Quasioptical devices based on extraordinary transmission at THz (Invited Paper)

Miguel Beruete, Univ. Pública de Navarra (Spain)

The terahertz (THz) range is nowadays under intensive research thanks to the development of efficient sources and detectors. Quasioptical techniques are also contributing to the advance of THz by providing passive components such as lenses, mirrors, polarizers, etc. Moreover, the THz band is the playground where ideas borrowed from optics and microwaves can be applied for rapid development. In this sense, metamaterials and plasmonic concepts extracted from microwaves and optics respectively have given a strong impulse to THz technology. In particular extraordinary transmission through hole arrays has been central both in metamaterials and plasmonics research and has also found application in novel THz devices. In this work, I will cover our latest advances of THz components based on extraordinary transmission and metamaterials concepts. First, a subwavelength hole array operating at THz printed on a flexible substrate will be presented. Then a modified hole array where holes are connected with meandering lines to redshift the peak of extraordinary transmission will be analyzed and discussed. Using similar principles a linear polarizer will be shown. All these concepts will be combined to synthesize a compact quarter-wave plate with dual band operation. Other devices recently developed in our group such as metalenses based on the fishnet metamaterial or epsilon-near-zero concepts, sensing metasurfaces etc., will also be presented.

9856-24, Session 6

Broadband and high-sensitivity terahertz-wave detection using Fermi-level managed barrier diode (Invited Paper)

Hiroshi Ito, Kitasato Univ. (Japan); Tadao Ishibashi, NTT Electronics Corp. (Japan)

We developed a hetero-barrier rectifier named a Fermi-level managed barrier diode (FMB diode) to realize broadband and low noise THz-wave detection. The barrier was formed as an InP/InGaAs hetero-structure, and its barrier height was controlled by the doping in n-type InGaAs. This new design concept enables us to realize a very small barrier height and thus a small differential resistance without using exotic or lattice-mismatched material systems. The small barrier height is important for achieving the impedance matching between the input antenna and the diode to improve the detection efficiency. It is also suitable for realizing a high output current density. The barrier is determined at the stage of epitaxial growth so that it is stable and controllable. The fabricated FMB diode showed a small intrinsic differential resistance of about 40 ohms/ μm^2 with a barrier height of about 70 meV. It was then integrated with a broadband bowtie antenna and assembled in a compact quasi-optical package. The fabricated module could detect signals at frequencies from 200 GHz to 1 THz. Typical zero-biased voltage sensitivity was 1280 V/W at 300 GHz, which was higher than the reported best results for InP-based zero-biased broadband Schottky barrier diodes. The output current density for a 50-ohm load was more than 2000 A/ cm^2 with good linearity. These results indicate that a combination of an FMB diode with a current-input trans-impedance amplifier is a promising solution for a low NEP THz-wave detector.

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9856-25, Session 6

Identification of common explosives using a plasmonic monopole nanoantenna based THz-TDS system (*Invited Paper*)

Ekmel Ozbay, Bilkent Univ. (Turkey)

We present our work on identification of most commonly used explosives (C4, HMX, RDX, PETN, TNT and blackpowder) and some non-explosive samples (Lactose, Sucrose, PABA) using a nano-antenna coupled photo-conductive antenna (PCA) based terahertz time-domain spectroscopy system at 0.1-3.0 THz frequency range. We have designed, fabricated and measured localized surface plasmon resonance (LSPR) based monopole nano-antenna coupled photo-conductive antennas (PCAs) for THz-time domain spectroscopy (TDS) systems. LT-GaAs material was used to fabricate the THz PCAs. The performance of the nano-antenna coupled PCAs was 2x better when compared to the standard PCAs. Time-domain and frequency-domain pre-processings are applied to partly eliminate background noise, rejections, and water absorption lines due to humidity. We demonstrated that false alarm rate is found to be convincingly low using 5 principle components for these samples. We also demonstrated the capability of identifying possible explosive mixtures due to linearity in PC space.

9856-26, Session 6

A terahertz monolithic integrated resonant tunneling diode oscillator and mixer circuit

Sebastian Diebold, Osaka Univ. (Japan); Kazuisao Tsuruda, Jae-Young Kim, Toshikazu Mukai, ROHM Co., Ltd. (Japan); Masayuki Fujita, Tadao Nagatsuma, Osaka Univ. (Japan)

The resonant tunneling diode (RTD) has been demonstrated to provide fundamental oscillation beyond 1.5 THz at room temperature.

While the RTD has been used successfully to detect a signal with a data-rate of 17 Gbit/s, the highest data-rate of an RTD transmitter (Tx) using the same RTD process is only around 2 Gbit/s.

We believe that the maximum data-rate of the RTD Tx is restricted by frequency pulling effects. Circuit simulations, using our newly developed circuit model of the RTD, have shown that even in simulation the maximum data-rate is limited to around 2-3 Gbit/s.

In order to increase the maximum data-rate, a terahertz monolithic integrated RTD oscillator and RTD mixer circuit has been developed. The circuit makes use of two individual RTDs integrated on one carrier substrate. The first RTD operates as a 300 GHz fundamental oscillator. It provides the local oscillator signal for the RTD mixer circuit made of the second RTD.

In simulation, the circuit provides a baseband bandwidth of more than 50 GHz and a radio frequency bandwidth of more than 200 GHz.

The developed circuit should significantly improve the state-of-the-art in RTD-based wireless communications. To the authors' knowledge, this is the first time that a monolithic integration of several terahertz system components using RTDs has been pursued.

9856-27, Session 6

The interaction of intense THz pulses with graphene and the topological insulator Bi₂Se₃ (*Invited Paper*)

Pamela Bowlan, Los Alamos National Lab. (United States) and Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Klaus Reimann, Elias Martinez-Moreno, Thomas Elsässer, Michael Woerner, Max-Born-Institut für Nichtlineare Optik und

Kurzzeitspektroskopie (Germany); Rolando Valdes Aguilar, The Ohio State Univ. (United States); Antionette J. Taylor, Dmitry A. Yarotski, Rohit P. Prasankumar, Los Alamos National Lab. (United States)

Intense ultrashort terahertz (THz) pulses are a powerful tool for controlling and understanding a material's properties on a femtosecond timescale. Their small photon energies make them especially relevant for materials with Dirac cone band structures, like graphene or topological insulators. Such materials offer a lot of potential for practical applications, due to high electron mobilities for example, as well as unique fundamental physics. THz pulses allow for studying carrier dynamics close to the Dirac point, where the THz light-matter interaction is very nonlinear (i.e. for electric fields > 1 kV/cm). These materials also have resonant transitions that we can drive with strong THz pulses. This could be the generation of electron-hole pairs near the Dirac point, or exciting low-energy phonons. Studying these materials with intense THz pulses leads to a better understanding of both resonant and non-resonant effects, as well as their interplay, and can potentially reveal new material properties.

Here we will discuss nonlinear THz measurements on graphene, which reveal a very strong light-matter interaction resulting in hybrid intra/interband electron trajectories that produce harmonics of the incident THz pulse. Our measurements also show that the excited carriers relax back to the ground state in a few picoseconds by radiative coupling and damping, and scattering turns out to play a minor role. In the topological insulator Bi₂Se₃, we coherently pump surface phonons with intense THz pulses. We probe the resulting changes to the surface state using second harmonic generation, shedding light on the influence of phonons on the topological state.

9856-28, Session 7

Temperature dependent terahertz properties of energetic materials (*Invited Paper*)

Abul K. Azad, The Ctr. for Integrated Nanotechnologies (United States); Von H Whitley, Los Alamos National Laboratory (United States); Katie Brown, Towfiq Ahmed, Christian Sorensen, David S. Moore, Los Alamos National Lab. (United States)

Reliable detection of energetic materials is still a challenging problem which requires further investigation. The remote stand-off detection of explosives using molecular fingerprints in the terahertz spectral range has been an evolving research area for the past two decades. Despite many efforts, identification of a particular explosive remains difficult as the spectral fingerprints often shift due to the working conditions of the sample such as temperature, crystal orientation, presence of binders, etc. In this work, we investigate the vibrational spectrum of energetic materials including HMX, RDX, PETN, AN, and 1,3-DNB, as well as some other common materials, diluted in a low loss PTFE host medium using terahertz time domain spectroscopy (THz-TDS) at cryogenic temperatures. The measured absorptions of these materials show temperature dependent spectral shifts of their characteristic peaks while changing their temperature from 300 to 5.5 K. We have developed a theoretical model based on first-principles methods, which is able to identify most of the measured modes in 1, 3-DNB between 0.3 to 2.50 THz. These findings may further improve the security screening of energetic materials.

9856-29, Session 7

Terahertz sources and spectroscopy of topologically protected states (*Invited Paper*)

Dmitry A. Yarotski, Los Alamos National Lab. (United States); Rolando Valdes Aguilar, The Ohio State Univ.

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(United States); Yaomin Dai, Los Alamos National Lab. (United States); Mark Hagmann, The Univ. of Utah (United States); Stuart A. Trugman, Pamela Bowlan, Rohit P. Prasankumar, Antoinette J. Taylor, Los Alamos National Lab. (United States)

Ultrafast optical spectroscopy combines the femtosecond temporal resolution with spectral selectivity and provides unmatched ability to temporally discriminate the dynamics of various degrees of freedom in complex materials. Of particular interest are sub-picosecond pulses in terahertz (THz) range that provide direct access to charge transport phenomena and low-energy excitations (phonons, magnons). Therefore, extensive research effort has been directed towards development of THz sources with smaller dimensions, broader spectral range, and higher output power. Here, we describe nanoscale THz emitters that rely on photomixing of ultrashort optical pulses in the tunneling junction of scanning tunneling microscope, and may produce radiation with an unusually large (up to 100 THz) and tunable bandwidth. We also apply time-resolved THz spectroscopy to reveal the non-equilibrium dynamics of Dirac fermions in topological insulators (TI) and Weyl semi-metals. TIs - a new state of matter where insulating bulk is surrounded by a conducting surface - promise numerous applications in electronic, energy and information technologies. We use THz pulses to separate the bulk from the surface transient response, and directly probe the dynamics of photoexcited carriers protected by time-reversal symmetry in thin films of Bi₂Se₃. Our results indicate that short-lived bulk carriers co-exist with the long-lived surface carriers, which have higher mobility and can be accessed independently below certain film thicknesses. In Weyl semi-metals and topological crystalline insulators Pb_{1-x}Sn_xTe, characterized by a Dirac metallic state on their high-symmetry surfaces, we unveil the evolution of transient material response across the topological phase transition driven by doping and temperature variation.

9856-30, Session 7

Probing charge transfer and hot carrier dynamics in organic solar cells with terahertz spectroscopy (*Invited Paper*)

Paul D. Cunningham, Paul A. Lane, Joseph S. Melinger, U.S. Naval Research Lab. (United States); Okan Esenturk, Middle East Technical Univ. (Turkey); Edwin J. Heilweil, National Institute of Standards and Technology (United States)

Time-resolved terahertz spectroscopy (TRTS) was used to explore charge generation, transfer, and the role of hot carriers in organic solar cell photovoltaic materials. Two model molecular photovoltaic systems were investigated: with Zinc Phthalocyanine (ZnPc) or alpha-Sexathiophene (?-6T) as the electron donors and buckminsterfullerene (C60) as the electron acceptor. TRTS provides charge carrier conductivity dynamics comprised of changes in both population and mobility. By using time-resolved optical spectroscopy in conjunction with TRTS, these two contributions can be disentangled. The sub-picosecond photo-induced conductivity decay dynamics of C60 are revealed to be related to auto-ionization(1): the intrinsic process by which charge is generated in molecular solids. In donor-acceptor blends the long-lived photo-induced conductivity scales with thickness, which permits weight fraction optimization of the constituents. In nanoscale multi-layer films the photo-induced conductivity identifies optimal layer thicknesses. In films of ZnPc/C60, electron transfer from ZnPc yields hot charges that localize and become less mobile as they thermalize. Excitation of high-lying Frank Condon states in C60 followed by hole-transfer to ZnPc similarly produces hot charge carriers that self-localize; charge transfer clearly precedes carrier cooling.(2) This picture is contrasted to charge transfer in ?-6T /C60, where hole transfer takes place from a thermalized state and produces equilibrium carriers that do not show characteristic signs of cooling and self-localization. These results illustrate the value of terahertz spectroscopic methods for probing charge transfer reactions.

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9856-31, Session 7

The terahertz spectroscopic investigation and vibration analysis of triadimefon

Qiang Wang, Xiaohong Gu, Lanyu Li, China Jiliang Univ. (China)

The room-temperature THz spectrum of triadimefon was determined from 0.4 to 2.0 THz. To explain the experimental phenomena and the origin of the absorption peaks, DMol3 package was used to calculate frequency vibrational motions. The computed spectra are based on both isolated molecule as well as solid-state calculations. It is proved that the DFT calculations provide high quality structural and spectral reproductions. Isolated molecule calculations are not capable of reproducing the observed spectral features. The changes in bond lengths and angles of geometry optimizations show similar tendencies, the obvious changes both occur on 1,2,4-triazole group and chlorophenoxy group. The available THz spectra of triadimefon are assigned based the results of BLYP and PW91 density function. The solid-state DFT is an effective way to identify the characteristic spectra of vibrational modes of crystal substances.

9856-32, Session PTue

Simulation of terahertz images from x-ray images: A novel approach for verification of terahertz images and identification of objects with fine details beyond terahertz resolution

Kiarash Ahi, Mehdi Anwar, Univ. of Connecticut (United States)

This paper introduces a novel modeling approach for simulation of the terahertz (THz) images of the objects by solely having their X-ray images. Diffraction effects make fine details of the objects merged together in THz images. Because increasing the frequency of the THz beam decreases its transmission abilities through the materials, this diffraction cannot be mitigated. Thus, it would not be always possible to interpret THz images precisely. Simulation of the THz images from X-ray images can be used as a way for THz image verification and interpretation. The simulated THz images can be compared to the THz images for identifying an object which THz image is unknown. THz imaging systems are less expensive, portable, faster, easier to be used, non-ionizing and don't need costly annual maintenance compared to the X-ray systems. Regardless of the costs, it is also desirable to use THz instead of X-ray to evade damages due to ionizing effects. This approach makes THz imaging systems a sufficient tool for many laboratories and quality control centers to identify objects without the need for using and owning costly-ionizing X-ray systems. In this paper the THz beam is modeled. Then the modeled beam is used to develop the THz point spread function (PSF). An algorithm is also developed to simulate the raster scanning of the PSF of the THz imaging systems over the objects. The result of the simulated raster scanning is used for simulation of the THz images. Optical images are not obtained in transmission manners; they do not include the inside structures of the objects, thus they cannot be given to the raster scanning algorithm for obtaining the simulation of THz images. Consequently, X-ray images are used for this purpose. Simulated images with a great consistency to the real THz images were obtained by using this approach.

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9857-1, Session 1

Theoretical and experimental study of sub-Nyquist FMCW lidar systems

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This paper presents theoretical and experimental results on sub-Nyquist sensing and sparse recovery for intensity modulated laser ranging systems that employ wide-bandwidth linear frequency modulated waveforms (FMCW). The wide bandwidth nature of these systems traditionally requires high speed digitizers and matched filters. To reduce the computational power of such traditional laser radar front ends, we propose to use a sub-Nyquist digitizer for sampling the received signal at rates much lower than Nyquist and perform range detection using a sparse point-source model for the illuminated scene. Such a source model is well-justified for laser-based systems due to the high directivity of the laser beam. The reflected signal is uniformly undersampled, which greatly reduces the total number of measurements collected. Recovery is based on a structured dictionary with columns consisting of circularly shifted versions of the transmitted chirp signal. Using this formulation, we analytically study the coherence of such a sensing system, explicitly highlighting the effects of undersampling, chirp parameters, and the chirp signal's ambiguity function on the performance of the L1 minimization algorithm. Empirical phase transition diagrams are also studied to determine the parameters necessary for exact reconstruction. Our theoretical claims are validated by experiments conducted at Patuxent River Naval Air Station, using a FMCW laser source to illuminate object(s) at various ranges. The reflected signals are detected and sampled at sub-Nyquist rates, and sparse recovery algorithms are used to determine the range and reflectivity of the object(s). Performance will be measured and compared to theoretical/empirical predictions.

9857-2, Session 1

An entropy-driven matrix completion (E-MC) approach to complex network mapping

Ali Koochakzadeh, Piya Pal, Univ. of Maryland, College Park (United States)

Mapping the topology of a complex network in a resource-efficient manner is a challenging problem with applications in internet mapping, social network inference, and so forth. We propose a new entropy driven algorithm leveraging ideas from matrix completion, to map the network using monitors (or sensors) which, when placed on judiciously selected nodes, are capable of discovering their immediate neighbors. The main challenge is to maximize the portion of discovered network using only a limited number of available monitors. To this end, (i) a new measure of entropy or uncertainty is associated with each node, in terms of the currently discovered edges incident on that node, and (ii) a greedy algorithm is developed to select a candidate node for monitor placement based on its entropy. Utilizing the fact that many complex networks of interest (such as social networks), have a low-rank adjacency matrix, a matrix completion algorithm, namely 1-bit matrix completion, is combined with the greedy algorithm to further boost its performance. The low rank property of the network adjacency matrix can be used to extrapolate a portion of missing edges, and consequently

update the node entropies, so as to efficiently guide the network discovery algorithm towards placing monitors on the nodes that can turn out to be more informative. Simulations performed on a variety of real world networks such as social networks and peer networks demonstrate the superior performance of the matrix-completion guided approach in discovering the network topology.

9857-3, Session 1

The effects of compressive sensing on extracted features from tri-axial swallowing accelerometry signals

Ervin Sejdic, Joshua M. Dudik, James L. Coyle, Univ. of Pittsburgh (United States)

Swallowing is a well-defined process of transporting food or liquid from the mouth to the stomach [1]. Patients suffering from dysphagia (swallowing difficulty), usually deviate from this well-defined pattern of healthy swallowing. Dysphagia is a common problem encountered in the rehabilitation of stroke patients, head injured patients, and others with paralyzing neurological diseases [2]. Patients suffering from dysphagia are prone to choking or penetration/aspiration. Aspiration is defined as process when any food or fluids enter into the airway below the true vocal folds [1]. A related phenomenon to aspiration, penetration is defined as the event when material enters the space immediately above the true vocal folds (the supraglottic space) but is not observed to fall below the vocal folds during assessment [2].

In recent years, swallowing accelerometry became a promising non-invasive tool for the assessment of swallowing difficulties, including penetration-aspiration. Swallowing accelerometry refers to the employment of an accelerometer as a sensor modality during cervical auscultation. A recent contribution showed that penetration-aspiration swallows have different time-frequency structures from healthy swallows [3]. In this paper, we propose to examine whether the effects of compressive sensing on extracted features from tri-axial swallowing accelerometry signals. In particular, we will examine the compressive sensing approach based on modulated discrete prolate spheroidal sequences [4].

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9857-4, Session 2

Comparison between various patch wise strategies for reconstruction of ultra-spectral cubes captured with a compressive sensing system

Yaniv Oiknine, Isaac Y. August, Ben-Gurion Univ. of the Negev (Israel); Liat Revah, Ben-Gurion University of the Negev (Israel); Adrian Stern, Ben-Gurion Univ. of the Negev (Israel)

Recently we introduced a Compressive Sensing Miniature Ultra-Spectral Imaging (CS-MUSI) system. The system is based on a single Liquid Crystal cell and a parallel sensor array where the liquid crystal cell performs spectral encoding. Within the framework of compress sensing, the CS-MUSI system is able to reconstruct ultra-spectral cubes captured with only amount -10% samples compared to a conventional system. Despite the compression the techniques is extremely computationally involved because reconstruction of ultra-spectral images requires processing huge data cubes of Gigavoxel size. Fortunately, the computational effort can be alleviated by using separable operation. An additional way to reduce the reconstruction effort is performing the reconstructions on patches. In this work, we compare various patch shapes. We present a comparison between various patch shapes chosen to process the ultra-spectral data captured with CS-MUSI system. The patches may be one dimension (1D) for which the reconstruct is carried spatial pixel wise, or two dimension (2D) such as working on spatial rows/columns of the ultra-spectral cube or three dimension (3D).

9857-5, Session 2

Compressive spectral integral imaging using a microlens array

Weiyi Feng, Nanjing Univ. of Science and Technology (China); Hoover Rueda, Chen Fu, Univ. of Delaware (United States); Qian Chen, Nanjing Univ. of Science and Technology (China); Gonzalo R. Arce, Univ. of Delaware (United States)

In this paper, a compressive spectral integral imaging system using a microlens array is proposed. This system can capture the 4D spectro-volumetric information with a compressive 2D measurement image on the detector plane. In the reconstruction process, the 3D spatial information at different depths and the spectral responses of each spatial volume pixel can be obtained simultaneously. In the experimental setup, sensing of the 3D objects is carried out by optically recording elemental images using a microlens array. With the elemental images, a spectral data cube with different perspectives and depth information can be reconstructed using the TwIST algorithm in the multi-shot compressive spectral imaging framework. Then, the 3D spatial images with one dimensional spectral information at arbitrary depths are computed using the computational integral imaging method by inversely mapping the elemental images according to geometrical optics. A prototype is constructed to test and verify the feasibility of the proposed system. The experimental results show that the 3D volume images and the spectral information of the volume pixels can be successfully reconstructed at the location of the 3D objects. This optical system can capture both 3D volumetric images and spectral information in a video rate, which is valuable in biomedical imaging and chemical analysis.

9857-6, Session 2

Multi-spectral adaptive compressive sensing mathematics based sensor for wide area surveillance

Shubha Kadambe, Raytheon Space and Airborne Systems (United States)

Under the Office of Naval Research Contract, we are developing a multi-spectral adaptive compressive sensing mathematics based sensor for the wide area surveillance application. For this, InView's computer controlled Digital Micro-mirror Device array (DMD) hardware is used. It consists of 1024x768 micro mirror array, total internal reflection (TIR) prism and the electronics associated with controlling the mirrors. We have designed the optics to project a scene on to the DMD array on one side and to collimate the light reflected from the DMD and the TIR prism to the Focal Plane detector Array (FPA) on the other side.

For the surveillance application, this sensor will be used in two modes - coarse sampling and high resolution in the Regions Of Interest (ROI) since our goal is to detect and identify targets with high accuracy. For coarse sampling of the scene, we control the DMD array using the radial Fourier basis function. From these samples measured from the FPA we reconstruct the whole scene by applying the total variation technique iteratively. From the reconstructed scene, we identify the ROIs. We enhance the resolution of ROIs by re-sampling using the Hadamard masks to control the DMD array and by applying the inverse Hadamard matrix to the measured re-samples obtained from the FPA. The coarse sampling is performed once in a while to reduce the computational complexity and the data rate. In the full paper, we will provide a brief description of the optical design and the sensor system, algorithmic details and the results.

9857-7, Session 2

Video background tracking and foreground extraction via L1-subspace updates

Michele Pierantozzi, Sapienza Univ. di Roma (Italy) and Univ. at Buffalo (United States); Ying Liu, Univ. at Buffalo (United States); Stefania Colonnese, Sapienza Univ. di Roma (Italy); Dimitris A. Pados, Univ. at Buffalo (United States)

We consider the problem of on-line foreground extraction from video scenes with non-static background. A technically novel approach is suggested and developed by which the time evolving background is captured by an L1-norm subspace sequence. In contrast to conventional L2-norm subspaces, L1-norm subspaces are seen to offer significant robustness to background variations, disturbances, and rank selection. Subtraction of the L1-subspace tracked background leads, then, to effective foreground/moving objects extraction. Experimental studies included in this paper illustrate and support these theoretical developments.

9857-8, Session 3

Ensemble polarimetric SAR image classification based on contextual sparse representation

Lamei Zhang, Xiao Wang, Bin Zou, Harbin Institute of Technology (China); Zhijun G. Qiao, The Univ. of Texas Rio Grande Valley (United States)

Polarimetric SAR can obtain a comprehensive set of geographic information by a variety polarization combination of multiple channels; therefore, it has

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played an irreplaceable role in the field of seismology, agriculture, forestry and hydrology and geography etc. The proper classification of polarimetric SAR image is a very important application, also the precondition and basis of subsequent polarimetric SAR image interpretation. In recent years, in the field of pattern recognition, sparse representation has become a highly effective and innovative tool. Sparse representation of the data can be considered as the linear combination of most succinct sparse atoms of over-complete dictionary and the non-zero coefficients of atoms reveals that data only has close correlation with a small portion of the basic atoms of over-complete dictionary. The relevant experiments also showed that the sparse representation algorithms can get good results in polarimetric SAR image classification. However, it does not mean that sparse representation algorithm is perfect at different aspects. Like the ordinary classifier, it will also lead to the incomplete consideration because of its non-universality of the atoms selected by only one training sample set. Also, the single classification method under specific factors may have good classification results in some cases, but may not be applicable in the other situations. How to address the effect of a single classifier on polarimetric SAR image becomes one of the most urgent problems to be solved.

In order to solve the issue that single classification cannot fully deal with the problem, ensemble learning was proposed, which makes a plurality of different learners and obtained the more accurate results by integrating the individual results. Ensemble learning can make the weak learners become a stronger one resulting in the improvement of the generalization ability. In order to construct a well-performance ensemble learning system, researchers have proposed a variety of methods, such as Bagging, Boosting, random subspace method, selective ensemble learning and so on. Because the theoretical support of ensemble learning and the significant improvement of the systematic performance, it has become one of the four hot fields of machine learning. In general, an ensemble learning system has two parts: generation of the individual classifiers and the consolidation strategy of the plurality of classifiers.

In order to take full advantage of sparse representation and ensemble learning, this paper proposes a polarimetric SAR image classification method based on the ensemble learning of sparse representation. Firstly, extract the typical features according to the scattering characteristics of the targets; then classify polarimetric SAR image based on the sparse representation of the feature vector and get the preliminary classification result; finally, integrate the classification results to obtain the optimal result according to ensemble learning theory and evaluate the proposed method. The proposed method is validated by the Danish EMISAR L-band fully polarimetric SAR data of Foulum Area (DK) and the preliminary experimental results confirm the performance and potential of the proposed method in PolSAR image interpretation.

9857-9, Session 3

Target detection in GPR data using joint low-rank and sparsity constraints

Abdesselam Bouzerdoum, Fok Hing Chi Tivive, Univ. of Wollongong (Australia); Canicious Abeynayake, Defence Science and Technology Group (Australia)

With the advances in radar technology, ground penetration radars (GPR) have been successfully used in a wide range of applications, including void detection, bridge and tunnel assessment, utility mapping, and mine detection. GPR is a non-intrusive and non-destructive tool for the investigation of the shallow subsurface and the detection of buried targets. However, due to the complexity of the medium composition and the strong (rough) ground surface reflections, target detection and subsurface investigation can be very difficult or, in some case, impossible. Therefore, there is a demand for new methods to remove or, at least, suppress significantly the ground surface reflected signals and the background clutter to improve the target signature. In this paper, a joint low-rank and sparsity-based model is proposed to address the problem of clutter mitigation in GPR data. The proposed model is motivated by two observations that the background clutter and the ground surface reflections span a low-rank subspace and the target component tends to be sparse. A joint low-rank and sparsity constrained optimization problem is formulated to remove

both background clutter and ground surface reflections, where the low rank constraint is applied to the clutter components and the sparsity constraint is used to model the target signals. An iterative soft thresholding technique is developed to estimate a low-rank matrix and a sparse matrix containing the target components. Experimental results based on real GPR data show that the proposed method effectively removes the ground surface reflections and the background clutter and enhances the target signature.

9857-10, Session 3

Sparse representation for the ISAR image reconstruction

Mengqi Hu, John Montalbo, Shuxia Li, Ligang Sun, Zhijun G. Qiao, The Univ. of Texas Rio Grande Valley (United States)

In this paper, a sparse representation for the data from an inverse synthetic aperture radar (ISAR) radar system is derived for two dimensions and three dimensions. The proposed sparse representation motivates the use of a Convex Optimization directly that recovers the image without the loss information of the image with far less samples than that is required by Nyquist-Shannon sampling theorem, which increases the efficiency and decrease the cost of calculation in radar imaging.

9857-11, Session 4

Highly accelerated cardiac cine parallel MRI using low rank matrix completion and partial separability model

Jingyuan Lyu, Leslie Ying, Univ. at Buffalo (United States)

The main goal of the proposed method is to recover the dynamic image sequence from highly under-sampled Fourier measurements. Joint use of partial separability (PS) and spatial-spectral sparsity constraints has shown success in improving the temporal resolution of dynamic magnetic resonance imaging (MRI). However, the PS model fails when the navigation data is not available. This paper presents a new approach to highly accelerated dynamic MRI. In data acquisition, k-space data is moderately randomly undersampled at the center k-space navigator locations, but highly undersampled at the outer k-space for each temporal frame. In image reconstruction, we adopt the PS model which assumes the dynamic image series to be spatial-temporal partially separable, and thus can be represented as the product a temporal basis and spatial basis. Different from conventional PS methods which continuously and fully acquire navigator data at central k-space to estimate the temporal basis, we moderately randomly undersample k-space data at the center k-space navigator locations. Under the assumption that the navigator data in the k-t domain is of locally low rank, estimating the unacquired navigator data becomes a low rank matrix completion problem. Then the temporal basis can be obtained from the few dominant right singular vectors through the singular value decomposition (SVD). We further assume the dynamic image series to be sparse in the spatial and temporal frequency domain to reconstruct the final image series. The proposed method has shown to achieve high quality, artifacts-free reconstructions with reduction factors up to 44, when conventional PS method fails.

9857-12, Session 4

A new sparse Bayesian learning method for inverse synthetic aperture radar imaging via exploiting cluster patterns

Jun Fang, Lizao Zhang, Huiping Duan, Univ. of Electronic Science and Technology of China (China); Lei Huang,

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Shenzhen Univ. (China); Hongbin Li, Stevens Institute of Technology (United States)

The application of sparse representation to SAR/ISAR imaging has attracted much attention over the past few years. This new class of advanced imaging methods present a number of unique advantages over conventional range-Doppler methods, including improved resolvability of point scatterers, reduced speckle, and recoverability from fewer data samples. The basic idea behind these works is to formulate SAR/ISAR imaging as a sparse signal recovery problem. In addition to the sparse structure, real-world SAR/ISAR images often have additional structures that can be utilized. For example, by exploiting the piecewise smoothness and the continuity structure of the target image, an enhanced robustness against speckle noise and a substantial performance improvement can be achieved. Also, in practice, the target of interest usually exhibits block-sparse structures in which nonzero large scatterers occur in clusters. This block-sparse pattern can be considered as a special form of the continuity structure where nonzero scatterers demonstrate continuity in both the range and cross-range domains. This paper aims at leveraging the block-sparse structure of the target image to enhance ISAR imaging performance. We propose a two-dimensional pattern-coupled sparse Bayesian learning method which is a generalization of the conventional sparse Bayesian learning (SBL) method to deal with block-sparse signals. The proposed method is effective and flexible to exploit the underlying block-sparse structures, without requiring the prior knowledge of the block partition. Experimental results demonstrate that the proposed method is able to achieve a substantial performance improvement over existing algorithms, including the conventional SBL method.

9857-13, Session 4

YAMPA: Yet another matching pursuit algorithm for compressive sensing

Muhammad Asad Lodhi, Rutgers, The State Univ. of New Jersey (United States); Sergey Voronin, Univ. of Colorado at Boulder (United States); Waheed U. Bajwa, Rutgers, The State Univ. of New Jersey (United States)

State-of-the-art sparse recovery algorithms often rely on the restricted isometry property for their theoretical guarantees. However, they cannot explicitly incorporate measures such as the restricted isometry constant within their recovery procedures due to the computational intractability of such measures. This paper formulates an iterative thresholding algorithm, termed yet another matching pursuit algorithm (YAMPA), for sparse recovery from compressive measurements. YAMPA differs from other pursuit algorithms in that it adapts to the measurement matrix using a threshold that is explicitly dependent on the worst-case and average coherences of the matrix and it does not require knowledge of the signal sparsity. Performance comparisons of YAMPA against other matching pursuit and message passing algorithms are made for several types of test matrices. These results show that while state-of-the-art approximate message passing algorithms outperform all algorithms (including YAMPA) in the case of well-conditioned matrices, they completely break down in the case of ill-conditioned matrices. On the other hand, YAMPA and comparable pursuit algorithms not only result in reasonable performance for well-conditioned matrices, but their performance also degrades gracefully for ill-conditioned matrices. The paper also shows that YAMPA uniformly outperforms other pursuit algorithms for the case of thresholding constants chosen in a clairvoyant fashion. Further, when combined with a simple and fast technique for selecting thresholding constants in the case of ill-conditioned matrices, YAMPA outperforms other pursuit algorithms in the regime of low undersampling, although straightforward tweaks of some of these algorithms can outperform YAMPA in the regime of high undersampling in this setting.

9857-14, Session 4

Filtered gradient compressive sensing reconstruction algorithm for sparse and structured measurement matrices

Yuri H. Mejia, Henry Arguello, Univ. Industrial de Santander (Colombia)

For the compressive sensing process state-of-the-art proposes random Gaussian, and Bernoulli as measurement matrices. Often the design of the measurement matrix is subject to physical constraints, and therefore it is frequently invalid that the matrix follows a Gaussian or Bernoulli distribution. Examples of these limitations are the structured and sparse matrices of the compressive X-Ray, and compressive spectral imaging systems. A standard algorithm for recovering sparse signals consists in minimizing an objective function that includes a quadratic error term combined with a sparsity-inducing regularization term. This problem can be solved using the iterative algorithms for solving linear inverse problems. This class of methods, which can be viewed as an extension of the classical gradient algorithm, is attractive due to its simplicity. However, current algorithms are slow for getting a high quality image reconstruction because they do not exploit the structured and sparsity characteristics of the compressive measurement matrices. This paper proposes the development of a gradient algorithm for compressive sensing reconstruction by including a filtering step improving quality using less iterations. This algorithm modifies the iterative solution such that it forces converge to a filtered version of the residue ATy , where y is the measurement vector and A is the compressive measurement matrix. We show that the algorithm including the filtering step converges faster than the unfiltered version. We design various filters that are motivated by the high structure of ATy . Extensive simulation results using various sparse and structured matrices highlight the relative performance gain over the existing iterative process.

9857-15, Session 5

Mitigation of sparsely sampled FM jammers through parametric sparse reconstruction

Yimin D. Zhang, Temple Univ. (United States); Ben Wang, Temple Univ. (United States) and Harbin Engineering Univ. (China); Moeness G. Amin, Villanova Univ. (United States)

A Global Navigation Satellite System (GNSS), such as the Global Positioning System (GPS), is vulnerable to jamming signals. As such, anti-jam capability has become essential for reliable satellite navigation. Frequency modulated (FM) waveforms are commonly used as smart jammers which cannot be simply mitigated by windowing or filtering. Time-frequency analysis that leads to accurate estimation of the jammer instantaneous frequencies (IFs) allows effective jammer estimation and suppression.

Traditional anti-jamming GNSS receivers assume the jammed GNSS signals to be uniformly sampled. In real-world operations, however, samples of the jammed GNSS signals may be randomly missing due to, for example, multipath fading, line-of-sight obstructions, removal of narrow interference or impulsive noise. As a result, the observed data may be sparsely sampled. The missing samples generate noise-line artifacts in the TF domain representations, making conventional approaches for anti-jam infeasible.

Recovery and/or IF estimation of FM jammers from sparsely sampled observations falls under the emerging area of compressive sensing and sparse reconstruction. Owing to their instantaneous narrowband characteristics, these jammers exhibit local sparsity when viewed through a short window or when they, in general, are represented in the joint-variable TF domain. The sparsity property invites compressive sensing and sparse reconstruction techniques to play a role in anti-jam GNSS. In this paper, we consider the parametric approach in which the jammer waveforms are constrained to have linear or high-order polynomial phase FM characteristics. Such constraints will lead to an improved accuracy of jammer IF estimation and, subsequently, result in enhanced jammer suppression capabilities.

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9857-16, Session 5

**Dictionary Learning and Sparse Recovery
for Electrodermal Activity Analysis**

Malia Kelsey, Ahmed H. Dallal, Safaa M. Eldeeb, Murat Akcakaya, Univ. of Pittsburgh (United States); Ian Kleckner, Christophe Gerard, Karen S Quigley, Matthew Goodwin, Northeastern Univ. (United States)

Electrodermal Activity (EDA) has been useful to advance research in a wide variety of areas including psychobiology; however, the majority of this research has been restricted to laboratory settings with questionable ecological validity. To overcome the questionable validity many groups are taking advantage of recent advance in wireless biosensors to gather EDA data in more typical settings. While this enhances ecological validity it also introduces analytical challenges that current statistical techniques cannot address. One of these limitations is the limited accuracy of identifying artifacts such as wearer motion, changes in temperature, and electrical interference as true skin conductance responses (SCR). Another challenge is the limited efficiency and automation of analysis techniques. Many groups will either analyze the data by hand going through SCRs individually or use computationally inefficient software that limits the analysis of the large data sets typical of ambulatory recordings. To address these limitations a method to accurately and automatically identify SCRs and artifacts using curve fitting methods was developed. Curve fitting methods have been shown to improve the accuracy of SCR amplitude and location estimations but have not yet been used to distinguish psychological responses from artifacts. Sparse recovery and dictionary learning methods were then combined to improve computational efficiency of analysis. Training data, labeled in Ledalab, was used to learn a dictionary of SCR waveform parameters; then SCRs were searched for within a signal using the dictionary to complete sparse recovery. These methods were compared to gold standard software for speed, accuracy and ease of interpretation.

9857-17, Session 5

**Learning overcomplete representations
from distributed data: A brief review**
(Invited Paper)

Haroon Raja, Waheed U. Bajwa, Rutgers, The State Univ. of New Jersey (United States)

Learning sparse overcomplete representations of data, also referred to as dictionary learning, plays an important role in many signal processing applications. Much of the research on dictionary learning has focused on developing algorithms under the assumption that data is available at a centralized location. But often the data is not available at a centralized location due to practical considerations like data aggregation costs, privacy concerns, etc. This motivates the need for dictionary learning algorithms that consider distributed nature of data as one of the problem variables. In this paper we review several dictionary learning algorithms proposed for distributed data. The variations in the problem setup give rise to the key differences among these algorithms. Most notable distinguishing features are the online versus batch nature of data and the representative versus discriminative nature of the dictionaries. Our proposed algorithm, cloud K-SVD (distributed variant of K-SVD), is one of these algorithms. Just like its centralized variant, cloud K-SVD learns a representative dictionary for batch settings. In particular, we use cloud K-SVD as an example in the paper to show the advantages that can be obtained by utilizing distributed dictionary learning algorithms for real-world distributed datasets.

9857-18, Session 5

**New method for applying manifold
learning into the compressive sensing
scheme**

John Montalbo, Mengqi Hu, Ligang Sun, Zhijun G. Qiao, The Univ. of Texas Rio Grande Valley (United States)

In this paper, we attempt to give an overview and new “novel” method for applying Manifold learning into the compressive sensing scheme. We will give a brief overview of the history of manifold learning (the linear and non-linear) as well as show some of the potential benefits of adapting it as a tool for the imaging scientist and data scientist to use. We will also give a schematic of our own manifold learning process and compare it with the current MLP’s currently in use. Once developed we will attempt to show the limitations of certain classes of manifolds and how computing time. A possible application is on SAR/ISAR radar image reconstruction through using the inverse problem of the Maxwell equations.

9857-19, Session 6

**Sparsity based defect imaging in pipes for
guided-wave structural health monitoring**

Andrew L. Golato, Fauzia Ahmad, Sridhar Santhanam, Moeness G. Amin, Villanova Univ. (United States)

Pipes are used for the transport of fluids and gasses in urban and industrial settings. Buried pipelines have long been used in city environments to transport water, sewage, oil, and other resources. Additionally, extended pipelines are used to transport resources, especially oil and its by-products, over long distances. The nuclear industry also relies on coolant pipes to maintain the stability of power plants. To ensure reliable operation for all of these applications, it is necessary that an inspection system be in place to identify and localize damage/defects in the pipes. Unfortunately, many typical nondestructive evaluation techniques are inadequate due to limited pipe access; often, only the beginning and end sections of the pipe are physically accessible. As such, this problem is well suited to the use of ultrasonic guided-wave based structural health monitoring (SHM). With a limited number of transducers, ultrasonic guided waves can be used to interrogate long lengths of pipes. In this paper, we propose a damage detection and localization scheme that relies upon the inherent sparsity of defects in the pipes. That is, the area subject to damage is typically much smaller than the total surface area of the pipe system. To employ this inspection scheme, a sparse array of transducers is distributed at both accessible ends of a pipe, and utilized in a pitch-catch mode to record signals scattered by defects in the pipe. A Lamb wave based signal model is formulated, which is then inverted via sparse reconstruction. The model accounts for the specificities of Lamb wave propagation through the pipe. Performance validation of the proposed approach is provided using simulated data for an aluminum pipe obtained via finite element modeling.

9857-20, Session 6

Face recognition with L1-norm subspaces

Federica Maritato, Sapienza Univ. di Roma (Italy) and Univ. at Buffalo (United States); Ying Liu, Univ. at Buffalo (United States); Stefania Colonnese, Sapienza Univ. di Roma (Italy); Dimitris A. Pados, Univ. at Buffalo (United States)

We consider the problem of representing individual faces by maximum L1-norm projection subspaces calculated from available face-image ensembles. In contrast to conventional L2-norm subspaces, L1-norm subspaces are seen to offer significant robustness to image variations, disturbances, and rank selection. Face recognition becomes then the problem of associating a new

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unknown face image to the “closest,” in some sense, L1 subspace in the database. Experimental studies included in this paper illustrate and support the theoretical developments.

9857-21, Session 6

Sparsity-based extrapolation for direction-of-arrival estimation using co-prime arrays

Elie Bou Daher, Fauzia Ahmad, Moeness G. Amin, Villanova Univ. (United States)

Non-uniform antenna arrays span large apertures using far fewer elements than dictated by classical array theory, thereby addressing operational constraints on cost and hardware complexity in radar, sonar, and communication applications. Recently, a new structure of non-uniform linear arrays, known as co-prime arrays, has been introduced. A co-prime configuration consists of two undersampled uniformly spaced subarrays with co-prime number of elements and co-prime spatial sampling rates. The difference co-array of the co-prime array contains redundancies and missing elements or ‘holes’. In this paper, we employ a sparsity-based extrapolation technique to fill the holes in the difference coarray corresponding to a co-prime array. Beamforming is then applied to the extrapolated array measurements for enhanced detection of weak targets in the presence of stronger interferers.

9857-22, Session 6

Structure-aware Bayesian compressive sensing for frequency-hopping spectrum estimation

Yimin D. Zhang, Temple Univ. (United States)

Frequency-hopping (FH) communications are a class of spread spectrum communication schemes that finds wide applications in both military and civilian wireless communication systems due to their capability to achieve low probability of intercept and reduced interference. In practice, blind estimation of the instantaneous FH spectrum with an unknown hopping pattern is of significant importance. The main challenge is to robustly parameter estimate in low signal-to-noise (SNR) scenarios. When consider the joint time-frequency domain representations, FH signals exhibit as sparse entries, thus inviting compressive sensing and sparse reconstruction techniques as an effective means to implement FH spectrum estimation. In particular, we use bilinear time-frequency distributions, and their performance is examined by using different interference-reducing time-frequency kernels. Furthermore, it is noticed that FH signals exhibit interesting signal structures, e.g., the piecewise step frequency characteristics, that can be exploited in the reconstruction of their sparse time-frequency representations to yield improved spectrum estimation capability and accuracy, particularly when the input SNR is low. In the paper, the Bayesian compressive sensing (BCS) methods are used and tailored to exploit the structures of the FH signals. BCS methods are known to provide high-resolution signal estimation and are convenient to support various signal structures through proper prior and kernel designs. The effectiveness of the proposed approaches will be verified through extensive simulation results.

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9858-1, Session 1

Quantum-safe cryptography: Will quantum photonics play a role? *(Keynote Presentation)*

Grégoire Ribordy, id Quantique SA (Switzerland)

Progress in the field of quantum computing poses a major challenge to cryptography and information security as a whole. The security of the most commonly used cryptographic schemes relies on the difficulty of solving certain mathematical problems. However, the development of a quantum computer would completely transform this landscape by enabling to efficiently solve them and render these cryptographic schemes insecure. It is consequently essential that we upgrade the cryptographic infrastructure upon which the security of the Internet and other critical services is based to use quantum-safe cryptographic primitives. One such quantum-safe primitive is quantum key distribution. It allows to distribute encryption keys across optical links with security based on the laws of quantum physics and is thus not vulnerable to quantum computing attacks.

In this presentation, we will review the principle of quantum key distribution and discuss state of the art performance. This technology has been commercially available for several years and is used to secure links requiring high-security, for example for datacenter interconnects. So far, widespread use has however been limited and we will discuss the issues that prevent broader adoption. These include technology cost, use case limitation and lack of formal security certification, as well as less tangible factors such as psychological resistance of the conventional cryptography community to physics based approaches.

Quantum key distribution provides a radically new level of security compared to approaches based on mathematics: its security does not depend on how much computing power is available to an adversary. This is an essential characteristic to achieve long-term security. However when, even whether, it will reach widespread use remains an open question.

9858-2, Session 1

Recent progress in quantum communication *(Invited Paper)*

Qiang Zhang, Yang Liu, Univ. of Science and Technology of China (China)

Quantum communication can provide information theoretical security, which can not be achieved by classical communication technology. Here, we review the experimental efforts by our group, including metropolitan area quantum network with untrusted relay, long distance quantum key distribution with measurement device independent security, field test of entanglement swapping and teleportation, daylight free space quantum communication, and etc.

9858-3, Session 1

Photon counting arrays for dim beacon tracking in the near-infrared

William H. Farr, Erik Alerstam, Kenneth Andrews, Meera Srinivasan, Andre Wong, Jet Propulsion Lab. (United States)

A two-dimensional array of single photon detectors (SPD), can acquire and

track an optical beacon with a 10 to 20 dB reduction in centroiding jitter versus a conventional analog sensor array in the near-infrared (900 to 1600 nm) in photon starved applications. We have assembled a laboratory testbed to demonstrate that such a detector array can meet the uplink beacon and downlink beam (for point-ahead confirmation) tracking needs for a deep space optical communications link. After initial validation with a 32x32 silicon SPD array, we have now demonstrated sub-pixel resolution tracking of a 1064 nm beacon with a 32x32 InGaAsP Geiger-mode avalanche photodiode arrays (GmAPD) and less than 50 fW of incident optical power. With the same InGaAsP arrays we have also demonstrated tracking of a 1550 nm downlink beam (beyond the 'cut-off' wavelength) via sub-bandgap absorption with a linear intensity response.

Measured data is compared to model results. Our models include blocking loss due to the finite recovery time of the GmAPD pixels. Finally, we discuss planned integration of a 32x32 GmAPD array into a 22 cm optical transceiver prototype for future system level performance validations

9858-4, Session 2

Quanta image sensor concepts and progress *(Invited Paper)*

Eric R. Fossum, Dartmouth College (United States)

The Quanta Image Sensor (QIS) concept and progress are discussed. Read noise as low as 0.22e- rms has been demonstrated, with a single correlated-double sampling (CDS) readout at room temperature without the use of avalanche gain. The 1.4um pixel pitch devices were fabricated in a commercial 65nm backside illuminated (BSI) CMOS image sensor (CIS) process with minor modification. The new technology will enable photon-counting image sensors operating at over 1000 fields per second with resolution over 32Mpixels. Higher resolution (gigapixel) should be feasible when scaled to more advanced technology nodes. The QIS represents a significant change in image acquisition paradigm.

9858-5, Session 2

Single photon avalanche diode applications for non-line-of-sight imaging *(Invited Paper)*

Jessica Zeman, Univ. of Wisconsin-Madison (United States); Mauro Buttafava, Alberto Tosi, Politecnico di Milano (Italy); Kevin Eliceiri, Andreas Velten, Univ. of Wisconsin-Madison (United States)

Non-line-of-sight imaging allows the imaging of macroscopic scenes without a direct line of sight using time of flight, effectively seeing around corners. It requires the use of fast illumination and detection hardware.

Our method relies on illuminating a visible relay surface in a scene with a picosecond laser pulse and collect the indirect light response from that surface with a fast detection system. Reconstruction algorithms make use of the time of flight information and the location of reflections on the visible relay surface to reconstruct a 3D model of the hidden scene. The computational reconstruction task is similar to the reconstruction of images from collected data in a computed tomography.

Because the method uses weaker indirect light, requirements to time resolution and sensitivity go beyond what is required for most direct time of flight ranging and imaging applications. This calls for the development of new imaging systems. We recently demonstrated an imaging system capable of seeing around corners based on a gated Single Photon

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Avalanche Diode (SPAD) detector. SPAD detectors provide sufficient signal to noise ratio, dynamic range, and time resolution to image room scale scenes at centimeter resolution and have the potential for a compact and low cost commercial system. Gating the SPAD allows us to remove direct light from the scene and image indirect light components with improved dynamic range.

Applications for non-line-of-sight imaging range from the imaging of rooms through a window in disaster response to the imaging of cave structures on the moon from a lunar satellite.

9858-6, Session 2

Single-photon depth imaging for underwater applications (*Invited Paper*)

Gerald S. Buller, Aurora Maccarone, Ximing Ren, Andy M. Wallace, Yvan R. Petillot, Aongus McCarthy, Heriot-Watt Univ. (United Kingdom)

The time-correlated single photon counting approach has been previously applied to depth imaging based on the time-of-flight approach. This approach has been applied to underwater depth imaging, where the detection technique is well-suited to the high levels of optical loss experienced in this environment. This presentation will cover initial laboratory-based investigations of underwater depth imaging and appropriate modelling based on the experimentally determined parameters. The studies have used a monostatic transceiver using a spectrally tunable pulsed source operating at repetition rates of 10's MHz, and silicon single-photon avalanche diode detectors. High-resolution depth imaging has been demonstrated in highly scattering conditions, with up to nine attenuation lengths between the transceiver to target. These measurements have all taken place under eye-safe conditions, at average optical powers of much less than 1mW. The presentation will examine the potential of this approach applied to the underwater depth imaging, and its practicality for future deployment.

9858-7, Session 2

Measurement of Cn2 using a single-photon avalanche diode and a Geiger-mode array

Robert A. Lamb, Selex ES Ltd. (United Kingdom); Agata M. Pawlikowska, SELEX Galileo Ltd. (United Kingdom) and Heriot-Watt Univ. (United Kingdom); Roger M. Pilkington, Peter Sinclair, SELEX Galileo Ltd. (United Kingdom); Gerald S. Buller, Heriot-Watt Univ. (United Kingdom)

Abstract: A single photon counting 3D imaging lidar is used to measure Cn2 over ranges up to 9.5km with a pulse repetition rate of 125kHz and a wavelength of 1550nm. The lidar can be configured to use either a single photon avalanche diode (SPAD) or 32 x 32 pixel Geiger-mode array. The SPAD was used to determine the scintillation index; whereas the array was used to determine both the scintillation index and angle-of-arrival fluctuations. This allows a direct comparison of the two approaches using the Rytov approximation to derive Cn2 for weak to moderate turbulence. Values of Cn2 were obtained at a rate of 4Hz, which is significantly faster than commercial scintillometers. Critical issues in using single photon counting are deriving accurate intensity values from the arrival times of individual photons and the summing of read-out frames from the array to form an image from which image dancing can be analysed. The results show that a 3D imaging lidar using a high-frame rate Geiger-mode array can be used to derive near real-time measurements of turbulence whilst simultaneously imaging targets at long range. This approach provides a means of automatically cueing post-processing techniques to correct image blur due to turbulence.

9858-8, Session 2

Development of low-read-noise high-conversion-gain CMOS image sensor for photon-counting-level imaging

Min-Woong Seo, Shoji Kawahito, Keiichiro Kagawa, Keita Yasutomi, Shizuoka Univ. (Japan)

In this paper, a CMOS image sensor with low read noise and high conversion gain (HCG), implemented by a 0.11- μm Dongbu HiTek (DBH) CIS process, is presented. Its performance is recognized through image outputs from an area image sensor, confirming the capability of photoelectron-counting-level imaging. To achieve high conversion gain, the proposed pixel has two special structures: 1) between the transfer gate (TG) and floating diffusion (FD) node and 2) between the reset gate (RG) and FD node. The first method helps to reduce the parasitic capacitance between the TG and FD node, as placing a fully depleted diode structure between them. The second method perfectly removes the parasitic capacitance between the RG and FD nodes because a reset transistor is not used for HCG pixel. The pixel reset operation is implemented by an implanted n+ layer located close to the FD node. When high voltage is applied to this n+ region, a barrier between the FD node and n+ implant region is lowered by punch-through effect. The FD node is reset by this operation. As a result, the conversion gain is increased due to the minimized FD node capacitance, and the noise performance is also improved by removing two noise sources from power supply.

For the first time, high contrast images from the HCG CMOS image sensor, with less than 0.3 e⁻rms noise level, have been generated at an extremely low light level of a few electrons per pixel. In addition, the photon-counting capability of the developed CMOS imager is demonstrated by a measurement, photoelectron-counting histogram (PCH).

9858-9, Session 3

Silicon technologies for arrays of single photon avalanche diodes (*Invited Paper*)

Angelo Gulinatti, Francesco Ceccarelli, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

Single-Photon Avalanche Diodes (SPADs), either as single-pixel detectors or combined to form arrays of pixels, are regarded today as an enabling technology for applications as diverse as quantum optics, high-throughput single-molecule analysis, frequency-domain or time-domain reconstruction of 3-dimensional scenes, and many others.

Such diverse applications have remarkably different requirements for the single-photon detector in terms of number of pixels, Photon Detection Efficiency (PDE), Dark Count Rate (DCR), temporal resolution, maximum achievable count rate, etc. In particular, the set of device properties needed in order to meet the requirements of a specific application has a strong impact on the choice of the technology adopted for the fabrication of the SPAD array.

In this paper we analyze different technological options for the fabrication of an array of Single Photon Avalanche Diodes and discuss their impact on achievable performance.

9858-10, Session 3

Development of silicon single photon avalanche diode at Voxel-Inc

Vinit H. Dhulla, Drake Miller, Dumitru Mitaru-Berceanu, Voxel, Inc. (United States)

In this paper we present the results of electrical and optical characterization of silicon Single Photon Avalanche Diode (SPAD) development at Voxel-Inc. Measurements are made on a 40X40 SPAD array test chip with column

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readout, in-pixel integrated Active Quenching Circuit (AQC) and pixel enable/disable circuit and ability to control quench time from 35ns to 1.5µs. The pixel pitch is 35µm and includes three different SPADs with active area diameters of 8µm, 10µm and 14µm. The realized SPADs have a breakdown voltage of 23V with a very low variation of 20mV across the entire array. At room temperature, with 10% over-bias the DCR is only 0.32 Hz/µm². The SPADs have a sensitive range of 400-900nm, with a peak PDE of 29% at 510nm and 5% at 800nm. After-pulsing and cross-talk are within the noise fluctuation of the SPAD and non-significant.

9858-11, Session 3

High performance compound semiconductor SPAD arrays *(Invited Paper)*

Eric S. Harmon, Mikhail Naydenkov, LightSpin Technologies, Inc. (United States)

Compound semiconductor SPAD arrays have the opportunity to provide orders of magnitude improvement in dark count rate and radiation hardness compared to silicon SPAD arrays, as well as the ability to detect wavelengths where silicon is blind. Experimental results from GaInP SPAD arrays with 10 -- 25 micron pixel pitches and thousands of SPAD elements per array will be presented.

9858-12, Session 3

Ray-traced spatial modeling of crosstalk in GmAPD cameras

Brian Piccione, Xudong Jiang, Mark Itzler, Princeton Lightwave, Inc. (United States)

Cameras built upon Geiger-mode avalanche photodetector (GmAPD) arrays have recently emerged as a disruptive technology among single-photon imagers, providing shot-noise-limited, solid-state detection with minimal SWAP. However, as applications increasingly demand higher resolutions in photon-starved environments, the need for a fundamental reduction in optical crosstalk becomes apparent. While the phenomenon, in which photons generated via avalanche events are detected by neighboring pixels, is still manageable at current pixel densities, shrinking to smaller pitch arrays only serves to increase nearest-neighbor crosstalk frequency. Hence, crosstalk stands as a fundamental limitation in scaling to larger camera formats.

Here, we model the effects of crosstalk in GmAPD array cameras, ultimately producing spatial crosstalk intensity maps. Using a 3-D ray tracing model, we show that experimental results can be reproduced with high fidelity. With most optical material properties known a priori, we will show how the hitherto unknown physical volume from which crosstalk is emitted can be altered to improve the model fit, providing the first evidence of its true shape. Accurate model in hand, we are also able to identify and isolate various types of crosstalk, ultimately providing the most thorough understanding of the phenomenon to date. Through this understanding, novel device designs built to expressly minimize crosstalk are now feasible.

9858-13, Session 3

Latest technological developments in silicon photomultipliers at FBK *(Invited Paper)*

Claudio Piemonte, Fondazione Bruno Kessler (Italy)

The Silicon Photomultiplier (SiPM) is progressively replacing the classical photomultiplier tubes (PMT) in most applications requiring the detection of faint light and/or precise timing. It features the advantages of a solid-state technology compared to a vacuum-based technology, it is operated at much

lower bias voltage, it is insensitive to magnetic fields and it is not damaged by ambient light. The SiPM building block is the Single-Photon Avalanche Diode (SPAD). Fondazione Bruno Kessler (FBK) in Trento, Italy, started developing this technology in its own foundry in 2005. In this contribution, a description of the Silicon Photomultiplier (SiPM) technology roadmap at FBK will be given. Particular emphasis will be devoted to the description of latest NUV-HD and RGB-UHD technologies. The first is a high-efficiency (about 60%) sensor with peak sensitivity in the near-UV/blue region with a Dark Count Rate (DCR) as low as 100 kHz/mm² at 20 C. The DCR scales very quickly with temperature reaching about 5Hz/mm² at 200 K and 0.01Hz/mm² at 100K. The second is a very high-dynamic range SiPM with peak efficiency in the green/yellow region. The SPADs composing the device have a pitch smaller than 10 microns corresponding to a density of more than 10000 elements/mm². This highly packed structure features 500 nm wide trenches to separate physically neighboring cells. The recovery time of these tiny SPADs is lower than 5 ns. Some applications of these devices will be described to highlight their advantages.

9858-29, Session PWed

Multi-channel high-performance reconfigurable digital pulse processing platform

Vinit H. Dhulla, Sanghub Kim, Voxtel, Inc. (United States)

This paper presents the design of high-performance, compact, general-purpose hardware and an embedded platform that uses a state-of-the-art heterogeneous field-programmable gate array (FPGA) and ARM processor. The compact hardware—a 3.5-inch X 3.5-inch form factor—consists of a three-board stack comprised of the FPGA, processor, and interface boards. To interface with commercial off-the-shelf (COTS) FMC modules—as well as custom-designed boards—the module uses a standard high pin count (HPC) FPGA mezzanine card (FMC) connector and follows the FMC standard. The FMC connector allows for 64 differential LVDS or 128 single-ended input channels. The module operates from a 12V AC-DC converter and interfaces with the PC via gigabit Ethernet (GbE) or camera link. The platform runs a custom Linux operating system and a Node.js webserver running a web application that allows remote access and control of the hardware via a simple web browser. This software architecture eliminates dependency on the operating system, allowing any platform that has a browser to access a uniform user interface. The modular software enables rapid prototyping of new application-specific features and modules. The simple graphical user interface enables control and reconfiguration of the hardware and firmware while keeping users abstracted from the underlying hardware and software. This platform can be used as a general-purpose platform for sensor integration and demonstration and as a platform for prototype camera development in numerous applications. We demonstrate integration of custom 64-element (8 X 8) silicon single-photon avalanche photodiode (SPAD) array with the digital pulse processing platform. The FPGA is configured as a 64-channel pulse counter and time-to-digital converter (TDC) with a timing resolution of 166 ps at a single-shot accuracy of ±5.5 ps.

9858-14, Session 4

On-chip quantum frequency comb source *(Invited Paper)*

Michael Kues, Christian Reimer, Piotr Roztock, Institut National de la Recherche Scientifique (Canada); Lucia caspani, Heriot-Watt Univ. (United Kingdom); Benjamin Wetzler, Institut National de la Recherche Scientifique (Canada); Matteo Clerici, Marcello Ferrera, Heriot-Watt Univ. (United Kingdom); Marco Peccianti, Alessia Pasquazi, Univ. of Sussex (United Kingdom); Brent E. Little, Xi'an Institute of Optics and Precision Mechanics (China); Sai T. Chu, City Univ. of Hong Kong (China); David J. Moss, RMIT

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Univ. (Australia); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada)

Integrated sources of single and entangled photons are currently one of the main research areas in quantum optics, aiming at pushing forward the implementation of e.g. quantum communication and quantum computation schemes in an on-chip format.

Here we report an integrated photon pair source generating multiple correlated photon pairs on different frequencies, simultaneously. This "bi-photon frequency comb" is based on the excitation of spontaneous four-wave mixing within an integrated CMOS-compatible micro-ring resonator. The generated photon pairs cover the full telecommunication bands (S, C and L), confined to frequency modes compatible with standard wavelength-division-multiplexing channels (DWDM, 200 GHz separation) and quantum memories (140 MHz bandwidth). Our source is extremely robust and capable of operating for several weeks without significant fluctuations in performance (<5%) enabled by a self-locked excitation scheme without the need for complex active stabilization. We measured photon coincidences between channels symmetric to the excitation frequency, while no photon coincidences were observed at non-symmetric channels. The coincidence-to-accidental ratio (CAR) on each individual channel pair exceeds 10. Further more the generated photon pairs are nearly single-frequency mode, demonstrated through a signal-signal correlation measurement. The measured heralded correlation dip of 0.14±0.5 affirms the quantum nature of our source and its suitability as a heralded single photon source. Using a bi-chromatic excitation configuration, we further show the direct generation of polarization-diverse photon pairs, demonstrating a new nonlinear process on an integrated platform (type-II spontaneous four-wave mixing). Our demonstrated quantum frequency comb constitutes an important step towards realizing practical integrated quantum optical technologies.

9858-15, Session 4

Diamond nanophotonics structures integrated with superconducting nanowire single photon detectors (Invited Paper)

Haig Atikian, Harvard Univ. (United States); Srujan Meesala, Harvard School of Engineering and Applied Sciences (United States); Alp Sipahigil, Ruffin Evans, Denis Sukachev, Harvard Univ. (United States); Jose Pacheco, Edward Bielejec, Sandia National Labs. (United States); Michael Burek, Adarsh Patri, Johan Israelian, Nigel Clarke, Robert Westervelt, Mikhail Lukin, Harvard Univ. (United States); Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

Diamond nano-photonics devices are rapidly evolving, where non-classical light emitted by diamond defect centers can be generated, manipulated, and detected all on a monolithic platform. Novel fabrication techniques allows us to etch freestanding diamond nanostructures directly from a bulk substrate, enabling one to engineer a myriad of nanostructures to exploit some of diamonds extraordinary material properties. Superconducting nanowire single photon detectors (SNSPDs) are a class of cutting edge photon detectors that outperform other technologies on merits such as detection efficiency, dark counts, timing jitter, and maximum count rates. We developed a fabrication procedure to realize such detectors directly on diamond substrates, and characterize their photon counting performance. Freestanding triangular cross-section diamond waveguides are utilized to guide color center emission to evanescently coupled NbTiN SNSPDs. Silicon Vacancy (SiV) color centers are deterministically placed within these nanostructures with sub 100nm precision, via an aligned silicon focus ion beam (FIB) implantation process. This approach allows for the monolithic and scalable integration of diamond quantum optical circuits based on defect color centers.

9858-16, Session 4

High performance integrated Ge on Si avalanche photodiodes (Invited Paper)

Paul S. Davids, Nicholas Martinez, Hong Cai, Andrew Starbuck, Douglas Trotter, Christopher T. DeRose, Sandia National Labs. (United States)

Selective epitaxially grown Ge on Si is a promising material system for integrated Si photonic high performance photodiodes and single photon detectors for classical and quantum receivers. The intrinsic compressive strain and the compact nature of the devices make them suitable for high speed operations at telecom wavelengths. Here we will present a lateral waveguide coupled Ge on Si avalanche photodiode operating in both linear mode and Geiger mode operation. The device is based on a separate absorption and charge multiplication design. The linear mode gain and the bandwidth for the device will be examined experimentally as a function of the device geometric properties and optimized performance characteristics presented. The Geiger mode performance of the device will also be evaluated using high speed gating and the extension to single photon detection and photon counting applications will be reported.

9858-17, Session 4

3D avalanche multiplication in Si-Ge lateral avalanche photodiodes

Erum Jamil, Majeed M. Hayat, The Univ. of New Mexico (United States); Paul S. Davids, Ryan M. Camacho, Sandia National Labs. (United States)

Si-Ge lateral avalanche photodiodes (Si-Ge LAPDs) are promising devices for single photon detection, but also have technology challenges. They are CMOS compatible and capable of detecting photons near the 1550 nm telecommunications bands. However, the Si-Ge LAPD exhibits a unique avalanche multiplication process in silicon, where the electrons and holes follow curved paths in three-dimensional space. Traditional models for the analysis of the avalanche multiplication process assume one-dimensional paths for the carriers that undergo the chains of impact ionizations; therefore, they are not suitable for analyzing the avalanche properties of Si-Ge LAPDs. In this paper, the statistics of the avalanche process in the Si-Ge LAPD are predicted using an analytical modeling technique that was recently developed by our group for understanding the avalanche multiplication in nanopillar, core-shell avalanche photodiodes, for which the electric field is too non-uniform in magnitude and direction. Specifically, the calculated mean avalanche gain, the excess noise factor and the breakdown probability are presented for the Si-Ge LAPD device. It is also shown that the avalanche characteristics depend upon the specific activated avalanche path, which depends, in turn, on the lateral location where each photon is absorbed in the Ge absorber. This property may be potentially useful for other applications such as spectroscopy. The modeling capability is further utilized to draw conclusions on possible ways to optimize the design of the Si-Ge LAPD for best performance as single-photon detectors, and hence for their use in quantum communications.

9858-18, Session 5

Wide-field time-correlated single photon counting microscopy (Invited Paper)

Klaus Suhling, Liisa Hirvonen, King's College London (United Kingdom)

Time-correlated single photon counting (TCSPC) is a sensitive, robust and precise technique to measure luminescence decays. We employ a photon counting image intensifier in combination with a 1 MHz frame rate CMOS camera, thus combining an ultra-fast frame rate with single

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photon sensitivity. This approach allows mapping the lifetime of europium-containing beads (570 ps), and decays of ruthenium compound Ru(dpp) (a few microseconds) in living HeLa cells. Moreover, the invariant phosphor decay of the image intensifier screen can be used for accurate timing of photon arrival well below the camera exposure time. By taking ratios of the intensity of the photon events in two subsequent frames, decays of ruthenium and iridium-containing compounds with lifetimes of around 1 ps were measured with 18.5 ps frame exposure time (54 kHz camera frame rate), also in living HeLa cells. Fluorescence lifetime imaging (FLIM) microscopy with picosecond time resolution and wide-field detection can be achieved using electronic read-out architectures, and an electron-bombarded CCD-based scheme has also been proposed. These approaches are particularly appropriate for total internal reflection fluorescence (TIRF), super-critical angle fluorescence (SAF) or lightsheet microscopy, and the latest progress in this field will be discussed.

9858-19, Session 5

Zero dead-time, FPGA-only time-correlated single photon counting for fast fluorescence lifetime imaging

Michael Wahl, Tino Roehlicke, Astrid Tannert, Rainer Erdmann, PicoQuant GmbH (Germany)

Time-correlated single photon counting (TCSPC) with sensitive detectors such as SPAD or Hybrid PMTs is the method of choice in fluorescence lifetime imaging (FLIM) when the observed specimen consists of single molecules or sparsely labelled living cells. Even though time-resolved cameras begin to emerge, they often have limitations in spectral sensitivity, fill factor, noise and image size. In situations where these limitations hurt it is often necessary and quite viable to resort to highly sensitive point detectors in combination with image scanning. In this case it is important to perform TCSPC with the highest possible throughput in order to compensate for the relatively slow process of scanning, while still obtaining images of good quality. One key factor to high throughput is eliminating dead-time. However, ultimate time resolution and low differential nonlinearity (DNL) in timing can typically only be obtained with dedicated time-to-digital converters that incur a dead-time on the order of some tens of nanoseconds after each photon detection. On the other hand it is possible to build relatively cheap timing circuits (typically based on FPGA) that allow effectively zero dead-time but compromise on timing resolution and DNL. We have designed a TCSPC board based on FPGA that achieves 40 Mcps throughput, zero dead-time and a resolution of 250 ps without compromising on DNL. Currently it provides two detector channels but the solution is highly scalable. We show some concepts of design and implementation, test results regarding timing accuracy and DNL, as well as application results in fast FLIM.

9858-20, Session 5

Time-correlated photon counting (TCPC) Technique Based on a Photon-Number-Resolving Photodetector

Baicheng Li, Quanlong Miao, Shenyuan Wang, Debin Hui, Tianqi Zhao, Kun Liang, Ru Yang, Dejun Han, Beijing Normal Univ. (China)

Time-Correlated Single Photon Counting (TCSPC) Technique usually employs SPAD (single photon avalanche diode) as the photodetector, it features ultra-high sensitivity and time resolution, and is widely applied in single molecule fluorescence spectroscopy, fluorescence lifetime measurement, fluorescence correlation spectroscopy and laser ranging. In order to guarantee the measuring accuracy and prevent the measurement from pile-up effect, TCSPC requires that the signal intensity has to be carefully weakened to single photon level in one period so that the pulse light contains no more than one photon, leading to a low detection

speed and efficiency. In this study, we proposed an improved technique --Time-Correlated Photon Counting (TCPC) technique and applied it to time-correlated Raman spectroscopy. The main difference between TCPC and the existing TCSPC is that TCPC employs a photon-number-resolving photodetector (SiPM, silicon photomultiplier) and measures exact photon number in one pulse rather than counting single photon by reducing pulse light intensity. Comparing with the TCSPC with SPAD, the TCPC with SiPM has advantages of high measurement speed and efficiency due to excellent photon number resolving capability, large detector area thus matching monochromator for spectroscopy applications, while SiPM's time resolution is comparable to SPAD when detecting multiple photons. A home-made Raman spectrometer has demonstrated an Instrument Response Function (IRF) down to 80ps (FWHM, single photon time resolution) with TCPC and a strip SiPM (1mm \times 0.05mm, containing 500 micro cells), fast and weak Raman signals was separated from slow and strong fluorescence background of bulk trinitrotoluene sample, and the signal-to-noise ratio was significantly enhanced.

9858-21, Session 6

Recent advances in superconducting nanowire single photon detectors for single-photon imaging (Invited Paper)

Varun B. Verma, Michael S. Allman, Martin J. Stevens, Thomas Gerrits, Robert Horansky, Adriana E. Lita, National Institute of Standards and Technology (United States); Francesco Marsili, Andrew D. Beyer, Matthew D. Shaw, Jet Propulsion Lab. (United States); Jeffrey A. Stern, Richard P. Mirin, Sae Woo Nam, National Institute of Standards and Technology (United States)

Arrays of superconducting nanowire single-photon detectors (SNSPDs) have historically been limited to very small sizes due to the low yield of NbN-based SNSPDs. The use of amorphous materials such as WSi and MoSi instead of NbN has significantly improved device yield, enabling for the first time the development of large arrays. In addition to yield, cryogenics and readout of the array are both important considerations in system design. The heat load carried by 64 or 256 coaxial cables to the 1K stage of a cryostat would result in unacceptable hold times. Thus, either a multiplexing scheme or cryogenic readout circuit must be adopted to reduce the number of coaxial cables. We have developed a row-column readout scheme which gives spatial resolution in the array and also reduces the number of cables from N² to 2*N for an NxN array of detectors. We demonstrate single-photon imaging at a wavelength of 1550 nm in real time using a 64-pixel array based on WSi SNSPDs. Future work will extend the wavelength of operation into the mid-IR (2-5 μ m wavelengths).

9858-22, Session 6

Superconducting nanowire single photon detectors based on MgB2

Angel E. Velasco, Daniel Cunnane, Ryan M. Briggs, Andrew D. Beyer, Matthew D. Shaw, Boris Karasik, Jet Propulsion Lab. (United States); Matthaeus Wolak, Narendra Acharya, Xiaoxing Xi, Temple Univ. (United States); Francesco Marsili, Jet Propulsion Lab. (United States)

Tungsten Silicide Superconducting nanowire single photon detectors (WSi SNSPDs) outperform other infrared single photon detector technologies, featuring high detection efficiency (~90%), fast reset times (~50 ns), low jitter (50-100 ps FWHM), and low intrinsic dark count rates (~1 cps) at 1550 nm [1]. However, the application of this technology is limited by the complex, expensive, and large cryogenic systems needed to operate the detectors at sub Kelvin temperatures. Magnesium diboride (MgB2) is a high critical temperature (TC ~ 40 K) superconductor which could potentially

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yield SNSPDs operating at ~ 20 K, where the cryogenics is easy, inexpensive, reliable, and compact. However, MgB₂ also introduces fabrication challenges since it degrades if exposed to air. We have addressed this challenge and fabricated 100 nm wide, 10 nm thick MgB₂ nanowires with the highest TC (~33 K) and current densities (~25 MA/cm²) to date [2,3]. Preliminary results have yielded a device which showed an optical response at 4 K and sub nanosecond relaxation time without latching. The detector responded to the simultaneous absorption of three photons, but not to single photons at 1550 nm. Current work is focused on increasing the sensitivity of the MgB₂ detectors down to the single-photon level by decreasing the thickness of the nanowires below 10 nm [4].

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9858-23, Session 6

Infrared counting and imaging at single-photon frontier with superconducting nanowires *(Invited Paper)*

Alessandro Casaburi, Univ. of Glasgow (United Kingdom)

The superconducting nanowire single-photon detector (SNSPD) [1] offer exquisite sensitivity, low noise and high speed at infrared wavelengths, far outperforming off-the-shelf alternatives such as semiconductor avalanche photodiodes and photomultiplier tubes [2]. The potential of SNSPDs has been demonstrated in a range of important scientific applications, including quantum cryptography [3], remote sensing [4] and laser-based cancer treatment [5]. Our efforts are focussed on the development of next generation SNSPDs employing novel sensor configurations and innovative materials. In this work, we will show our recent results concerning the development and characterization of 2x2 pixel SNSPDs array [6] to scale up the sensitive area of the detector up to 60x60 μm². This Large area sensor with large spectral range sensitivity and short recovery times will enable a range of applications in advanced Imaging, remote sensing and optical communications. We also will give a short overview on our work concerning the development of cryogenically compatible ultra-fast electronics for readout of SNSPDs multi-pixel (> 1000) detector arrays. This is a critical underpinning technology to enable the deployment of single infrared photon camera.

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9858-24, Session 6

Large area arrays of WSi superconducting nanowire single photon detectors

Francesco Marsili, Matthew D. Shaw, Andrew D. Beyer, Ryan M. Briggs, Giovanni Resta, Jeffrey A. Stern, Jet Propulsion Lab. (United States); Prasana Ravindran, Su-Wei Chang, Joseph C. Bardin, Univ. of Massachusetts Amherst (United States); Damon S. Russell, Jet Propulsion Lab. (United States); Varun B. Verma, Richard P. Mirin, Sae Woo Nam, National Institute of Standards and Technology (United States); William H. Farr, Jet Propulsion Lab.

(United States)

Photon counting cameras with sub ns timing resolution are a disruptive technology for many applications in different fields, from as life sciences to astrophysics. While single photon avalanche diode (SPAD) cameras offer excellent performance and large active area at visible wavelengths, semiconducting single photon cameras at near infrared wavelengths (? > 800 nm) are not as mature. Superconducting nanowire single photon detectors (SNSPDs) based on tungsten silicide (WSi) have demonstrated unmatched performance in the near infrared, with ~ 93 % system detection efficiency (SDE) at 1.55 μm wavelength (?), < 1 cps intrinsic dark count rate (DCR), ~ 60 ps FWHM jitter, and reset times of tens of nanoseconds. Here we report on the development of 64 pixel free space coupled arrays of WSi SNSPDs designed for the ground receiver of a deep space optical communication system. By reading out 16 of the 64 pixels, we achieved SDE = 36 % at ? = 1550 nm, BCR ~ 40 kcps, jitter of ~ 150 ps FWHM, and maximum count rate of 38 Mcps. Based on these results, we expect the full 64 pixel array to achieve MCR ~ 200 Mcps, SDE > 50% and BCR < 10 kcps, which would allow us to close a pulse position modulation communication link at 267 Mb/s using three of these arrays coupled to an 11.8 m diameter telescope.

9858-25, Session 7

Characterization of an advanced harmonic subtraction single-photon detection system based on InGaAs/InP avalanche diode *(Invited Paper)*

Joshua C. Bienfang, Alessandro Restelli, National Institute of Standards and Technology (United States)

We discuss the performance of a 1.25 GHz gated single-photon avalanche diode (SPAD) with bias gates of 150 ps FWHM and AC amplitude up to 25 V, a high-efficiency, high-speed SPAD system. This system an interferometric readout technique known as harmonic subtraction, and recent development efforts have enabled the use of up to the 4th harmonic of the gate to discriminate avalanche signals from the gate transient. With an improved design of the RF control system we have been able to demonstrate an ultra-low minimum detectable charge of < 5 fC. We discuss the performance of this system, particularly its afterpulsing performance when counting at rates > 108 s⁻¹. Systems of this type require unique characterization techniques, and we will discuss the methods we have developed for this purpose.

9858-26, Session 7

Advanced active quenching circuits for single-photon avalanche photodiodes *(Invited Paper)*

Mario Stipcevic, Institut Ruder Boskovic (Croatia); Bradley G. Christensen, Paul G. Kwiat, Univ. of Illinois at Urbana-Champaign (United States); Daniel J. Gauthier, Duke Univ. (United States)

Commercial photon counting modules, often based on actively-quenched solid-state avalanche photodiode sensors, are used in wide variety of applications. Manufacturers characterize their detectors by specifying a small set of parameters, such as: detection efficiency, dead time, dark counts rate, afterpulsing probability and single photon arrival time resolution (jitter), but they usually do not specify the conditions under which these parameters are constant or present a sufficient description. In this work, we present an in-depth analysis of the active quenching process and identify intrinsic limitations and engineering challenges. Based on that, we investigate the range of validity of the typical parameters used by several commercial detectors. We identify an additional set of imperfections that must be specified to sufficiently characterize the behavior of single-photon counting detectors in realistic applications. The additional

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imperfections include rate-dependence of the: dead time, jitter, detection delay shift, twilighting, temporal distribution of afterpulsing and artifacts of the electronics. We find that these additional non-ideal behaviors can lead to unexpected effects or strong deterioration of the system performance. Specifically, we discuss implications of these new findings on the security of quantum cryptographic protocols, the quality of single-photon-based random number generators, and a few other applications in which single-photon detectors play a major role. Finally, we describe an example of an optimized avalanche quenching circuit for a high-rate quantum key distribution system based on time-bin entangled photons.

9858-27, Session 7

Femtosecond photon-counting receiver

Michael A. Krainak, NASA Goddard Space Flight Ctr. (United States); Timothy M. Rambo, Northwestern Univ. (United States); Guangning Yang, Wei Lu, Kenji Numata, NASA Goddard Space Flight Ctr. (United States)

An optical correlation receiver is described that provides ultra-precise distance and/or time/pulsewidth measurements even for weak (single photons) and short (femtosecond) optical signals. A new type of optical correlation receiver uses a fourth-order (intensity) interferometer to provide micron distance measurements even for weak (single photons) and short (femtosecond) optical signals. The receiver enables precise distance/time or pulse width measurements using optical signals. The optical correlator is formed with a beamsplitter and two detectors, and a means of delaying one arm of the path between the beamsplitter and a detector. The optical correlator uses a low-noise-integrating detector that can resolve photon number. The correlation (range as a function of path delay) is calculated from the variance of the photon number of the difference of the optical signals on the two detectors. Our preliminary proof-of-principle data (using a short-pulse diode laser transmitter) demonstrates tens of microns precision.

9858-28, Session 7

Low-noise free-running high-rate photon-counting and ranging

Wei Lu, Michael A. Krainak, Guangning Yang, NASA Goddard Space Flight Ctr. (United States); Xiaoli Sun, NASA Goddard Space Flight Ctr (United States); Scott Merritt, NASA Goddard Space Flight Ctr. (United States)

We present a simple method to greatly reduce noise counts to allow high-rate free-running photon-counting receivers. The method is applicable to any photon-counting array technology. We present experimental results and numerical models to validate the method. Using our method with commercial silicon Geiger-mode avalanche photodiode arrays (Sensl Model MicroFM-SMA-10020) we experimentally demonstrated hundreds of Mcps counting rates in a free-running mode with several orders of magnitude reduction of noise counts (dark counts and after-pulsing). We will extend the method to photon-counting devices that operate in the near-infrared.

Conference 9859: Sensors for Next-Generation Robotics III

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9859-15, Session PWed

Piezoresistive pressure sensor for robotic skin

Fahad Mirza, Ritvij R. Sahasrabudhe, Ruoshi Zhang, Joshua R. Baptist, Woo Ho Lee, Dan O. Popa, The Univ. of Texas at Arlington (United States)

Robots are starting to excel from a confined industry space to homes, schools, hospitals, and highly dynamic environments. It is almost impossible to foresee all the probable situations and pre-program to those situations. Humans need to intervene and be present in the control loop in such situations. Among all physical human-robot interactions, haptic communication is an intuitive interaction method. Multi-modal robotic skin with distributed sensors can help robots increase perception capabilities and assist living environments around itself.

We have been investigating Electro-Hydro-Dynamic (EHD) printing as a multi-modal sensor fabrication method because of its direct printing capability onto substrates with non-uniform topographies. We designed interdigitated comb electrodes as a sensing element and fabricated a piezoresistive sensor using customized EHD printable PEDOT:PSS based inks. We formulated three PEDOT:PSS derivative inks: PEDOT:PSS and NMP; PEDOT:PSS, PVP, and NMP; and PEDOT:PSS, PVP, Nafion, and NMP. Bending induced characterization test of prototyped sensors showed high sensitivity, sufficient stability, and linearity.

In this paper, we developed a 4 by 4 skin sensor array integrated with an electronic module SkinCell. SkinCell is a custom electronic module that consists of a microcontroller, Wheatstone bridge with adjustable digital potentiometer, multiplexer, and serial communication unit. SkinCell is used for signal acquisition, conditioning, and networking between sensor modules. Fabricated piezoresistive pressure sensor integrated with SkinCell module was placed on the body surface of KUKA youBot, and basic human robot interaction tasks were successfully performed.

9859-1, Session 1

Results and conclusions: perception sensor study for high speed autonomous operations

Anne R. Schneider, Zachary La Celle, Alberto Lacaze, Karl N. Murphy, Robotic Research LLC (United States); Mark Del Giorno, Del Services LLC (United States); Ryan R. Close, U.S. Army RDECOM CERDEC NVESD (United States)

In previous research, work on sensor requirements, specifications, and testing to evaluate the feasibility of increasing speeds of autonomous vehicle systems was presented. Theoretical background for determining sensor requirements and the basic test setup and evaluation criteria for comparing existing and prototype sensor designs were discussed. This paper will present and discuss the continuation of this work. In particular, the focus of this paper will be analysis of the problem via a real-world comparison of the results of various sensor technologies, as opposed to previous work that utilized more of a theoretical approach. LADAR/LIDAR, radar, visual, and infrared sensors are considered in this research. Results are evaluated against the theoretical desired perception specifications. Conclusions for utilizing a suite of perception sensors to achieve the goal of doubling ground vehicle speeds is discussed.

9859-2, Session 1

Analysis of laser return pulse from multi-layered objects

Jim Hollinger, LSA Autonomy LLC (United States); Alyssa Vessey, LSA Autonomy (United States); Ryan R. Close, Seth Middleton, Kathryn Williams, Ronald R. Rupp, Son Nguyen, U.S. Army RDECOM CERDEC NVESD (United States)

Commercial lidar often focus on reporting the range associated with the strongest laser return pulse, first return pulse, or last return pulse. This technique works well when observing discrete objects separated by a distance greater than the laser pulse length. However, multiple reflections due to more closely layered objects produce overlapping laser return pulses. Resolving the multi-layered object ranges in the resulting complex waveforms is the subject of this paper. A laboratory setup designed to investigate the laser return pulse produced by multi-layered objects is described along with a comparison of a simulated laser return pulse and the corresponding digitized laser return pulse. Variations in the laboratory setup are used to assess different strategies for resolving multi-layered object ranges and how this additional information can be applied to detecting objects partially obscured in vegetation.

9859-3, Session 1

Investigation of human-robot interface performance in household environments

Sven Cremer, Fahad Mirza, Dan O. Popa, The Univ. of Texas at Arlington (United States)

Today, assistive robots are being introduced into human environments at an increasing rate. Human environments are highly cluttered and dynamic, making it difficult to foresee all necessary capabilities and pre-program all desirable future skills of the robot. One approach to increase robot performance is semi-autonomous operation, allowing users to intervene and guide the robot through difficult tasks. To this end, robots need intuitive Human-Machine Interfaces (HMIs) that support fine motion control without overwhelming the operator. In this study we evaluate the performance of several interfaces that balance autonomy and teleoperation for accomplishing several household tasks.

Our proposed HMI framework includes teleoperation devices such as tablets and joysticks, as well as physical interfaces in the form of piezo-resistive force sensors arrays. Mobile manipulation experiments are performed with a sensorized KUKA youBot, an omnidirectional platform with a 5 degrees of freedom (DOF) arm. The tasks involve navigation and manipulation of objects in household environments, requiring the robot to solve problems related to perception, planning, manipulation, error detection, and correction. Performance metrics include time for task completion and accuracy, as well as the operator's comfort and level of control.

9859-4, Session 1

Package analysis of strain gauge based piezo-resistive touch sensors

Sumit Kumar Das, Joshua R. Baptist, Woo Ho Lee, Dan O. Popa, The Univ. of Texas at Arlington (United States)

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Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate or PEDOT:PSS is a flexible polymer which exhibits piezo-resistive properties when subjected to structural deformation. PEDOT:PSS has a high conductivity and thermal stability which makes it an ideal candidate for use as a pressure sensor. There has been several studies and experiments to characterize the polymer's piezoresistive properties. In our study, we explore the idea of modelling the strain gauge based touch sensors which can be printed directly on robots. Using the material properties and piezo-resistive characteristics of PEDOT:PSS, we build a finite element model for a packaged sensor and predict its response given various design choices.

The package with an appropriate response is selected and experimentally tested to validate the FEA model.

9859-5, Session 1

Human-like object tracking and gaze estimation with PKD android

Indika B. Wijayasinghe, Sumit Kumar Das, The Univ. of Texas at Arlington (United States); Haylie Miller, Nicoleta Bugnariu, Univ. of North Texas Health Science Ctr. at Fort Worth (United States); Dan O. Popa, The Univ. of Texas at Arlington (United States)

As the use of robots increase for tasks that require human-robot interactions, it is vital that robots can exhibit and understand human-like cues for effective communications. In this paper we describe the implementation of object tracking capability on Philip K. Dick (PKD) android and a gaze tracking algorithm which serve in furthering the robot capabilities in this direction. Object tracking with human-like head postures of PKD is achieved with visual feedback from Kinect and PKD eye camera. The goal of object tracking with human-like gestures is twofold; to facilitate better human-robot interactions and to enable PKD as a human gaze emulator for future studies. The gaze tracking system employs ETG mobile eye tracking system by SensoMotoric Instruments and Cortex by MotionAnalysis for tracking the head orientations. Virtual reality system CAREN by Motek Medical is used to create objects for tracking. The gaze tracking algorithm converts eye tracking data and head orientations to gaze information facilitating two objectives; to evaluate the performance of the object tracking system for PKD and to use the gaze information to predict the intentions of the user enabling the robot to understand physical cues by humans.

9859-6, Session 1

Assessment of complex exterior geometry for a 3D printed object using visible light scanning

Jeremy Straub, Univ. of North Dakota (United States)

Previous work demonstrated the efficacy of performing defect detection in a 3D printed object using visible light scanning. Both final object and in-process defect detection were demonstrated. However, the objects characterized by this work simple (pyramids) and did not have complex features on their surfaces that would provide additional challenge to the scanning system. This paper considers the efficacy of assessing objects with more complex external surface features as well as objects whose design may impair the whole object comparison techniques used in previous work. Specifically, the paper presents a layer identification system (that separates the layer currently being printed or just printed from prior printing) and a layer-by-layer comparison system that characterizes the quality of each printed layer. Printed layer quality is characterized in terms of completeness and defect instances. This layer-by-layer assessment is not a complete solution, however. In addition to this technique the system also utilizes complete object imagery to assess the continuity of surfaces between layers as well as to detect larger-scale failures (such as the movement of the object on the build platform) that would not necessarily show up in a single

layer assessment.

The efficacy of this multi-mode scanning system is assessed for the characterization of defects on several complex objects. The results are presented and discussed. The paper concludes with a discussion of the future work that is required to bring this visible light based sensing technology from laboratory demonstrations to being a commercial system.

9859-7, Session 1

Electrical design and simulation of kinetic piezoelectric harvester devoted to distributed control cells

Essodong Barcola, Micky Rakotondrabe, Morvan Ouisse, Ausrine Bartasyte, FEMTO-ST (France)

This paper deals with the design, the modeling and the simulation of an electrical circuit devoted to kinetic piezoelectric energy harvesters for powering distributed control cells. Based on a well chosen electrical booster, a diodes based rectifier, an accumulator and an impedance-adaptator with voltage-multiplier, the proposed circuit and its model are deeply analyzed and discussed in term of furnished voltages and power. Simulations are carried out and demonstrate the interest of the different chosen electrical stages.

9859-8, Session 1

Input shaping techniques to control an underactuated robotic flexible link system

Yasser Al Hamidi, FEMTO-ST (France) and Texas A&M Univ. at Qatar (Qatar); Micky Rakotondrabe, FEMTO-ST (France)

This paper compares between three different input shaping feedforward techniques, traditional (TIS), extra insensitive (EI), and modified input shaping (MIS),

to reduce the vibration of a flexible link QUANSER system. The main challenge is that the system under test is an underactuated system: it has one input and two outputs. This makes the application of the input shaping techniques not utilizable directly. We therefore first propose to use a variable change at the output in order to make the process equivalent to a monovariable system without modification of the behavior and of the objective of the control. The experimental tests demonstrate the efficiency of the technique and the different results from the three control techniques are compared and discussed. It comes out that EI shapers are the most efficient in term of robustness.. MIS shaper has a shorter length than that of a corresponding TIS shaper; however both shapers have the same ability of vibration suppression. Also MIS scheme is easier than the traditional scheme because the numerical optimization is unnecessary in the design of the MIS shaper. MIS shaper has an advantage over a TIS corresponding shaper in being capable of suppressing multimode of vibration.

9859-9, Session 1

Design, static modeling and simulation of a 5-DOF precise piezoelectric positioner

Abdenbi Mohand Ousaid, Dominique Gendreau, Patrick Rougeat, Micky Rakotondrabe, FEMTO-ST (France)

This paper presents the design, the static modeling and the performances simulation of a five degrees of freedom precise positioner. Based on piezoelectric stack actuators, the positioner is able to perform high resolution x-y-z linear motions and angular motions about x and about y axes. After presenting the design, the static modeling is carried out in

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order to understand the functioning of the positioner. The simulation of the model is afterwards carried out to estimate the ranges of motions that it can perform. The positioner is very promising in various applications that require dexterity and high resolution displacement such as in images scanning with atomic force microscopes, in micromanipulation or microassembly, ...

9859-20, Session 2

Ultraflexible nanostructures and implications for future nanorobots
(Keynote Presentation)

Robert W. Cohn, Univ. of Louisville (United States); Balaji Panchapakesan, Worcester Polytechnic Institute (United States)

Several high aspect ratio nanostructures have been made by capillary force directed self-assembly including polymeric nanofiber air-bridges, trampoline-like membranes, microsphere-beaded nanofibers, and intermetallic nanoneedles. Arrays of polymer air-bridges form in seconds by simply hand brushing a bead of polymeric liquid over an array of micropillars. The domination of capillary force that is thinning unstable capillary bridges leads to uniform arrays of nanofiber air-bridges. Similarly, arrays of vertically oriented Ag₂Ga nanoneedles have been formed by dipping silver-coated arrays of pyramidal silicon into melted gallium. Force-displacement measurements of these structures are presented. These nanostructures, especially when compressively or torsionally buckled, have extremely low stiffnesses, motion due to thermal fluctuations that is relatively easily detected, and the ability to move great distances for very small changes in applied force. Nanofibers with bead-on-a-string structure, where the beads are micron diameter and loaded with magnetic iron oxide (maghemite), are shown to be simply viewable under optical microscopes, have micro-newton/m stiffness, and have ultralow torsional stiffnesses enabling the bead to be rotated numerous revolutions without breaking. Combination of these high aspect ratio structures with stretched elastomers offer interesting possibilities for robotic actuation and locomotion. Polydimethylsiloxane loaded with nanomaterials, e.g. nanotubes, graphene or MoS₂, can be efficiently heated with directed light. Heating produces considerable force through the thermoelastic effect, and this force can be used for continuous translation or to trigger reversible elastic buckling of the nanostructures. The remote stimulation of motion with light provides a possible mechanism for producing cooperative behavior between swarms of semiautonomous nanorobots.

9859-10, Session 3

A flexible microchannel electrode array for peripheral nerves to interface with neural prosthetics

Ryan Landrith, Caleb Nothnagle, Young-tae Kim, Muthu B. J. Wijesundara, The Univ. of Texas at Arlington (United States)

Neural control of robotic limbs is an active area of research which has been demonstrated through microelectrode arrays in the brain; however, the long term reliability of the interface and invasiveness of the procedure remain in question. Alternatively, peripheral nerve interfaces can be used. In order to control neural prosthetics using peripheral nerves, high density electrode arrays that can be easily implanted on very small peripheral nerves (50µm-500µm) are needed to achieve the required specificity. Interfacing with these small nerves is surgically challenging due to their size and fragile nature. To address this problem, a Flexible MicroChannel Electrode Array (Flex-CEA) for interfacing with small diameter peripheral nerves and nerve fascicles was developed and characterized. The Flex-CEA, fabricated on a thin polyimide substrate, includes a microchannel structure with an array of electrodes for retaining the nerve and interfacing with it, respectively. The design minimizes handling of the nerve when inserting it into the array and

allows for visual confirmation of nerve retention within the channel. The array was fabricated using standard microfabrication techniques to provide greater reproducibility. The development, electrochemical characterization, and in vivo testing of the array are presented. The results demonstrate the array's surgical ease-of-use as well as its suitability for both recording and stimulation of small peripheral nerves.

9859-11, Session 3

Feedforward and output feedback control of a highly oscillating and nonlinear 2-DOF piezoelectric actuator by using input shaping compensator and a linear quadratic regulator

Yasser Al Hamidi, FEMTO-ST (France) and Texas A&M Univ. at Qatar (Qatar); Micky Rakotondrabe, FEMTO-ST (France)

This paper deals with the control of a two degrees (2-dof) of freedom piezoelectric cantilever actuator which is characterized by badly damped oscillations, hysteresis nonlinearity and cross-couplings. First, a feedforward control scheme based on the zero placement technique is introduced to annihilate the oscillations. Then an output feedback scheme is added in order to reduce the cross-couplings effects and to improve the tracking performances. Based on the linear quadratic regulator synthesis, the feedback also adds some robustness face to model uncertainties, such as the nonlinearities approximation, and to eventual external disturbances. Experiments were carried out and confirm the predicted performances.

9859-12, Session 3

Requirement analysis for robotic nursing assistant

Jeongsik Shin, Kris Doelling, Dan O. Popa, The Univ. of Texas at Arlington (United States)

The aim of the paper is to study requirements to design an adaptive robotic nurse assistants (ARNA). An ARNA assistive robot is a mobile manipulator that can navigate cluttered hospital environments and perform chores as a patient sitter, patient walker and many other roles assisting nurses. Equipped with multi-modal skin, force, and 3D RGBD sensors, it can not only understand nurse intent, automate routine tasks, but also keep nurses in the decision loop. It is expected that modular sensor and actuator hardware are deployed in reconfigurable platforms for physical assistance. Furthermore, adaptive human-machine interfaces will play a key role in accomplishing the designed task, as they directly impact the ability of robots to help nurses in a dynamic, unstructured environment. The paper studies requirement as a design guideline to build such a robot system in the aspects of interfacing with human, using hospital equipment and navigating in hospital environment where the robot needs to adapt to.

9859-13, Session 3

Design, modeling and simulation of a three-layers piezoelectric cantilevered actuator with collocated sensor

Patrick Rougeot, Abdenbi Mohand Ousaid, Dominique Gendreau, Micky Rakotondrabe, FEMTO-ST (France)

A new piezoelectric actuator with collocated sensor is designed, modeled and simulated. The structure has three piezoelectric layers where the two external layers serve for the actuation by conveniently applying electrical potentials, and the middle layer serves as the sensor. A model is given for the actuator and sensor and then simulated permitting to evaluate the

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performances. The novel structure are very promising for applications that require control and automation but in the meantime the use of external sensors are unfeasible or difficult.

9859-14, Session 3

Modelling of nonlinear errors for integrated GPS/MEMS-based INS navigation systems

Maged Ismail, Ezz Al-Din Farouk Abd elQawy, Military Technical College (Egypt)

Autonomous Robots need strongly to a navigation system that guarantees smooth maneuvering and safe arrival to objectives. In addition to this accuracy demand, the used navigation system should meet the robotic requirements such as lightness in weight, high reliability, smallness and low cost. Later requirements were achieved, to some extent, by MEMS IMU sensors while the accuracy requirement has been the objective for many researchers in last decade. Integration with GPS was a powerful tool to correct the MEMS-based inertial measurement unit to achieve more robust positioning information. In many GPS/INS integration schemes, the linear errors of MEMS IMU were estimated precisely while the higher order errors were ignored. Some researches were focused on estimating the higher order (non linear) errors by using non linear estimators such as particle filter while the other researchers used non linear autoregressive models, augmented with Kalman filter, to estimate both linear and nonlinear inertial errors and reduce them.

In this paper, we introduce a comparison study, with detailed analysis, of different approaches used for estimating the non linear errors of MEMS IMU. Data collected from a low cost 3D positioning system, provided by GPS integration with MEMS grade inertial sensors, are used.

9859-17, Session 3

Next technology on force sensing: multi-axis resonant sensors

Davinson Castano Can, CEA-LIST (France) and FEMTO-ST (France); Mathieu Grossard, CEA-LIST (France); Arnaud Hubert, FEMTO-ST (France) and Sorbonne Univ. (France)

The aim of this paper is to present the domain of resonant force sensing, which has not been explored yet in the case of multi-axis force sensors. A resonant force sensor is characterized by the use of a frequency output signal to estimate the applied forces, instead of using its amplitude as it is often the case for the other existing technologies used in robotics. The advantages of resonant force sensing for robotics are discussed, especially for the safety requirements in the collaborative field. We extend our analysis to show the main similarities and differences between more classical sensors (based on strain gages for instance) and resonant ones, with a focus on their design. More specifically, we detail the way the design of the sensitive element, which essentially transduces the applied forces into frequencies, plays a major role on its performances.

9859-18, Session 3

Flexible circuits with integrated switches for robotic shape sensing

Cindy K. Harnett, Univ. of Louisville (United States)

Digital switches are commonly used to detect surfaces and limb-position limits in robotics, but they are made from hard materials. Meanwhile, flexible circuits are ubiquitous in robotics because the circuits can bend while carrying signals and power through moving joints. In previous work, an array of surface-mount switches on a flex circuit acted as an all-digital shape

sensor compatible with the power resources of wirelessly-powered systems. However, even the smallest commercially-available surface-mount switches will detach from a flexible circuit after several bending cycles, sometimes violently. This presentation describes a low-cost, conductive-fiber based method to add electromechanical switches to flexible circuits and other soft, bendable materials. Because the switches are digital (on/off), they differ from commercially-available continuous-valued bend/flex sensors. No amplification or analog-to-digital conversion is needed to read the signal, but the tradeoff is that the digital switches only give a threshold value. Boundary conditions on the edges of the flexible circuit are key to setting the threshold curvature value for switching. This presentation will discuss threshold-setting, size scaling of the design, automation for inserting a digital switch into the flexible circuit fabrication process, and methods for reconstructing a shape from an array of digital switch states.

9859-19, Session 3

An extremely lightweight fingernail worn prosthetic interface device

Oguz Yetkin, Joshua R. Baptist, J. Paul Carpenter, The Univ. of Texas at Arlington (United States); Dan O. Popa, Univ. of Texas at Arlington (United States)

In our previous work, we have explored the control of a prosthetic device using a glove worn by an amputee on the uninjured limb to mirror movements as well as a more lightweight system which allows the prosthetic device user to command the device by performing pinch gestures.

In order for any sound-limb worn prosthetic control device to be adopted, it needs to fast, lightweight, and out of the way when not being used.

In this study, we present a prototype fingernail worn device for detecting pinch gestures and communicating with the prosthetic system. The device detects the relative position of fingers to each other by measuring light transmitted via tissue.

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9860-1, Session 1

HELICoiD project: A new use of hyperspectral imaging for brain cancer detection in real-time during neurosurgical operations

Himar Fabelo, Samuel Ortega, Univ. de Las Palmas de Gran Canaria (Spain); Silvester Kabwama, Wessex Neurological Centre - University Hospital Southampton (United Kingdom); Gustavo M. Callicó, Univ. de Las Palmas de Gran Canaria (Spain); Diederik Bulters, Wessex Neurological Centre - University Hospital Southampton (United Kingdom); Adam Szolna, Juan F. Pineiro, Department of Neurosurgery - University Hospital Doctor Negrin (Spain); Roberto Sarmiento, Univ. de Las Palmas de Gran Canaria (Spain)

Hyperspectral images allow obtaining large amounts of information about the surface of the scene that is captured by the sensor. Using this information and a set of complex classification algorithms is possible to determine which material or substance is located in each pixel. The HELICoiD (HypErspectraL Imaging Cancer Detection) project is a European FET project that has the goal to develop a demonstrator capable to discriminate, with high precision, between healthy and tumour tissues, operating in real-time, during neurosurgical operations. This demonstrator could help the neurosurgeons in the process of brain tumour resection, avoiding the excessive extraction of healthy tissue and the accidental leaving of small tumour tissues. The precise delimitation of the tumour boundaries will improve the results of the brain surgeries. The HELICoiD demonstrator is composed by two hyperspectral cameras from HEADWALL manufacturer, the first one in the spectral range from 400 to 1000 nm (visible and near infrared) and the second one in the spectral range from 900 to 1700 nm (near infrared). The demonstrator also includes an illumination system that covers the spectral range from 400 nm to 2200 nm. A data processing unit is in charge of managing all the parts of the demonstrator, and a high performance platform aims to accelerate the hyperspectral image classification process. Each one of these elements is installed in a customized structure specially designed for surgical environments. Preliminary results of the classification algorithms offer high accuracy (over 95%) in the discrimination between healthy and tumour tissues.

9860-2, Session 1

NIR chemical imaging and data aggregation for real-time monitoring of pharmaceutical tablet manufacturing

Patrick R. Wahl, Gregor Hauseder, Daniel Markl, Stephan Sacher, RCPE GmbH (Austria); Matthias Kerschhaggl, EVK DI Kerschhaggl GmbH (Austria); Johannes G. Khinast, Technische Univ. Graz (Austria) and RCPE GmbH (Austria)

Near-infrared chemical imaging (NIR-CI) using high-speed cameras is a strongly evolving technology in food, waste or mineral sorting. Yet, in the pharmaceutical industry it is mainly used in lab settings.

Here we present a NIR-CI system, which is capable of real-time monitoring

of approx. 500.000 tablets per hour and forwarding aggregated data (mean content of the active pharmaceutical ingredient (API), standard deviation (SD) and number of analyzed tablets) to a process control system (PCS). The system consists of a push-broom spectrometer (EVK Helios CLASS G2) and a software for image analysis.

The camera (312 pixels spatial-, 248 pixels spectral resolution, 500 Hz measurement rate) generates 74 MB/s of spectral raw data. To reduce the data chemometric models, developed in Simca 13, are transferred to the spectrometer. They are executed in real-time on the onboard FPGA (Field Programmable Gate Array). The resulting video stream (0.44 MB/s) is further analyzed via openCV, an image processing library. For each detected tablet the mean and SD of API content, predicted via PLS, are calculated and averaged for one second. The results (3?4 byte/s) are written to an OPC-DA server, a standard interface to PCS, enabling a reaction to measured deviations.

9860-3, Session 1

Best practices in hyperspectral system hardware calibrations

Joseph Jablonski, Labsphere, Inc. (United States)

Hyperspectral Imaging is an exciting and rapidly expanding area of instruments and technology. Due to the quickly changing applications the instruments are changing to suit and there is a need for consistent testing, characterization and calibration. This paper seeks to outline a broad prescription and recommendations for basic testing and characterization that must be done on most types of sensors in order to provide calibrated absolute output and performance. We will also make recommendations towards standards and protocols for emerging national laboratory efforts to provide oversight in these areas.

Areas of interest will cover: radiometric evaluation, spectral evaluation, uniformity testing for spatial and spectral, optical parameters for MTF/PSF, sensor SNR and NEP evaluation, keystone, spectral smile, in-band and out-of-band response, stray light, linearity and other critical test parameters for hyperspectral imaging systems.

9860-4, Session 1

Characterization of EO-1 Hyperion surface reflectance estimates in a desert target site

Christopher Neigh, Joel McCorkel, Petya Campbell, Laurence Ong, Vuong Ly, David Landis, Stuart Fry, Elizabeth M. Middleton, NASA Goddard Space Flight Ctr. (United States)

Space borne spectrometers with a similar resolution of earth observing sensors can be a valuable resource for cross calibration. We evaluated EO-1 Hyperion temporal, spectral and spatial stability with time-series analysis and compared surface reflectance from 30-m Hyperion to 2-m resolution WorldView-2 (WV-2) data in the Libya-4 pseudo-invariant calibration site (PICS). Additionally, WV-2 and WV-1 same date imagery were processed as a cross track stereo pair to generate a Digital Terrain Model to evaluate the effects from large (> 70 m) linear dunes. Agreement was moderate to low on dune peaks between WV-2 and Hyperion ($R^2 < 0.4$) but higher in areas of lower elevation and slope ($R^2 > 0.6$). We also found dune slope affected the trend of Hyperion surface reflectance estimates from three atmospheric

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correction approaches from 2004 to 2015. Our results provide temporal, spectral, and spatial estimates of the stability EO-1 Hyperion products over most of the mission that are useful for those who plan to use these data for cross calibration.

9860-5, Session 1

Hyperspectral remote sensing of vegetation: knowledge gain and knowledge gap after 40 years of research

Prasad S. Thenkabail, U.S. Geological Survey (United States)

This presentation summarizes the advances made over 40+ years in understanding, modeling, and mapping terrestrial vegetation as reported in the new book on "Hyperspectral Remote Sensing of Vegetation" (Publisher: Taylor and Francis inc.). The advent of spaceborne hyperspectral sensors or imaging spectroscopy (e.g., NASA's Hyperion, ESA's PROBA, and upcoming Italy's ASI's Prisma, Germany's DLR's EnMAP, Japanese HIUSI, NASA's HypIRI) as well as the advances made in processing when handling large volumes of hyperspectral data have generated tremendous interest in advancing the hyperspectral applications' knowledge base to large areas.

Advances made in using hyperspectral data, relative to broadband data, include: (a) significantly improved characterization and modeling of a wide array of biophysical and biochemical properties of vegetation, (b) ability to discriminate plant species and vegetation types with high degree of accuracy, (c) reducing uncertainties in determining net primary productivity or carbon assessments from terrestrial vegetation, (d) improved crop productivity and water productivity models, (e) ability to assess stress resulting from causes such as management practices, pests and disease, water deficit or water excess, and (f) establishing more sensitive wavebands and indices to study vegetation characteristics.

The presentation will discuss topics such as: (1) hyperspectral sensors and their characteristics, (2) methods of overcoming the Hughes phenomenon, (3) characterizing biophysical and biochemical properties, (4) advances made in using hyperspectral data in modeling evapotranspiration or actual water use by plants, (5) study of phenology, light use efficiency, and gross primary productivity, (5) improved accuracies in species identification and land cover classifications, and (6) applications in precision farming.

9860-6, Session 1

High resolution fluorescence hyperspectral imager

Scott Milligan, Headwall Photonics Inc. (United States)

TITLE High Resolution Fluorescence Hyperspectral Imager

Traditional airborne environmental monitoring has frequently deployed hyperspectral imaging as a leading tool for characterizing and analyzing a scene's critical spectrum-based signatures for applications in agriculture genomics and crop health, vegetation and mineral monitoring and hazardous material detection. As the exploitation of hyperspectral data grows in the airborne community, there has been an increased demand for higher spectral resolution, particularly in the region of 700-800 nanometers. Today, typical 2 to 10nm spectral resolution provide a number valuable indexes to help quantify plant health In order to better quantify the global carbon cycle of vegetation, Headwall Photonics has developed a high spectral resolution VNIR platform with a resolution of 0.1nm.

The following manuscript will provide an overview of a newly-developed hyperspectral imaging platform, the High Resolution Fluorescence Imager. Detailed design architecture and trade studies will be discussed as well as the all reflective, passively athermalized, aberration corrected final design.

9860-7, Session 2

High resolution SWIR hyperspectral imager

Kevin Didona, Headwall Photonics Inc. (United States)

TITLE: High Resolution SWIR Hyperspectral Imager

Traditional airborne environmental monitoring has frequently deployed hyperspectral imaging as a leading tool for characterizing and analyzing a scene's critical spectrum-based signatures for applications in agriculture genomics and crop health, vegetation and mineral monitoring and hazardous material detection. As the exploitation of hyperspectral data grows in the airborne community, there has been an increased demand for higher spectral resolution, particularly in the region of 2200-2500 nanometers. Today, typical 10 nm spectral resolution provides valuable indexes to help quantify plant health as well as geological identification. In order to better quantify target regions of interest for high spectral resolution mapping of more challenging applications such as methane emissions from marine and terrestrial sources, Headwall Photonics has developed a high resolution SWIR platform with a resolution of <1nm.

The following manuscript will provide an overview on a newly-developed hyperspectral imaging platform, the High Resolution SWIR Imager. Detailed design architecture and trade studies will be discussed as well as the all reflective, passively athermalized, aberration corrected final design.

9860-8, Session 2

Development of ultra-high resolution imaging spectrometers for airborne acquisition of solar induced fluorescence (SIF)

Lawrence A. Corp, Bruce Cook, NASA Goddard Space Flight Ctr. (United States); David Bannon, Peter Clemens, Headwall Photonics Inc. (United States); Joel McCorkel, Douglas Morton, Elizabeth M. Middleton, NASA Goddard Space Flight Ctr. (United States)

Remote sensing using imaging spectroscopy offers unique monitoring of the Earth's surface at synoptic time and space scales to provide timely, spatially explicit information regarding the impact of climate change on global gross primary production (GPP). GPP occurs through photosynthesis of organic compounds from carbon dioxide and is a key component of carbon cycle science. To date, large scale monitoring of GPP relies heavily on reflectance-based passive optical observations. Solar Induced Fluorescence (SIF) is an emitted radiant flux that directly relates to the photosynthetic functional state of higher organisms as they harvest sunlight to produce sugars which are the primary energy source for all life on Earth. Recent studies demonstrate the reliability of extracting this emitted signal from the reflected solar continuum and show significant and complex relationships exist between SIF and GPP at ecosystem and global scales. However, further observations are required to unravel this complex relationship before SIF can be fully utilized to constrain estimates of GPP. Scientists in the Biospheric Sciences Laboratory at NASA's Goddard Space Flight Center have undertaken a partnership with Headwall Photonics for the advancement of ultra-high resolution imaging spectrometers. Derivations of the Fraunhofer Line Depth (FLD) principle will be applied to the telluric O2 bands over the red-edge region of the visible spectrum using this enhanced capability to resolve SIF from the reflected solar continuum. We will discuss the underlying science driving the design and resulting system specifications for an ultra-high resolution imaging spectrometer capable of quantifying SIF at airborne observation levels.

9860-9, Session 2

Adaptive uniform grayscale coded aperture design for high dynamic range compressive spectral imaging

Nelson Diaz, Univ. Industrial de Santander (Colombia); Hoover Rueda, Univ. of Delaware (United States); Henry Arguello Fuentes, Univ. Industrial de Santander (Colombia)

Imaging spectroscopy is an important area with many applications in surveillance, agriculture and medicine. The disadvantage of conventional spectroscopy techniques is that they collect the whole datacube. In contrast, compressive spectral imaging systems captures snapshot compressive projections, which are the input of reconstruction algorithms to yield the underlying datacube. Common compressive spectral imagers use coded apertures to perform the coded projections. The coded apertures are the key elements in these imagers due to they define the sensing matrix of the system. The design of the coded aperture entries lead to a good quality in the reconstruction. In addition, the compressive measurements are prone to saturation due to the limited sensor's dynamic range, hence the design of coded aperture must consider saturation. The saturation errors in compressive measurements are unbounded and compressive sensing recovery algorithms only provide solutions for bounded noise or bounded with high probability. This paper proposes the design of adaptive uniform grayscale coded aperture to improve the dynamic range of the estimated spectral images by reducing the saturation levels. The saturation is attenuated between snapshots using an adaptive filter which update the entries of the grayscale coded aperture based on the previous snapshots. The coded apertures are optimized in terms of transmittance and number of grayscale levels. The advantages of the proposed method is the efficiently use of the dynamic range of the image sensor. Extensive simulations show improvements in the image reconstruction of the proposed method compared with random grayscale coded apertures in up to 4 dBs.

9860-10, Session 2

Optical design of MWIR imaging spectrometer

Yueming Wang, Shanghai Institute of Technical Physics (China)

Imaging spectrometer is a promising technology in remote sensing, which plays an important role in earth observing. Up to now, most of the instruments operates in the solar reflective wavelength, 400nm-2500nm. Scientific research showed abundant signature in MWIR and LWIR. But it is very difficult to design and manufacture MWIR and LWIR imaging spectrometer instrument due to complicated optics design, FPA assembly and cryogenics system ,etc.

FTS and grating dispersion is the main solution for MWIR and LWIR imaging spectrometer, such as SYSIPHE(French Aerospace Lab) and AH1(HAWII University). A spherical prism MWIR imaging spectrometer design is presented in this paper. The system operates from 2500nm to 5000nm. The dispersive element is a MgF2 spherical material. The spectrometer consists of slit, collimating mirror, prism, converging mirror and correction lens. To restrain background radiation of the spectrometer, the optics of the spectrometer is not telecentric. The spectrometer have a real exit pupil to match the cold shield of FPA assembly. With a cooled slit, the system is not sensitive to background radiation.

The length of slit is 16mm. Spectral sampling interval is 50nm. F num is 2.5. and good image quality is acquired.

9860-11, Session 2

High resolution hyperspectral imaging with a high throughput virtual slit

Edward A. Gooding, Arsen R. Hajian, Thomas Gunn, Steven D. Bradbury, Hindsight Imaging, Inc. (United States)

Hyperspectral imaging (HSI) device users often require both high spectral resolution, on the order of 1 nm, and high light-gathering power. A wide entrance slit assures reasonable étendue but degrades spectral resolution. Spectrometers built using High Throughput Virtual Slit™ (HTVS) technology optimize both parameters simultaneously. Two remote sensing use cases that require high spectral resolution are discussed. First, detection of atmospheric gases with intrinsically narrow absorption lines, such as hydrocarbon vapors or combustion exhaust gases such as NOx and CO2. Detecting exhaust gas species with high precision has become increasingly important in the light of recent events in the automobile industry. Second, distinguishing reflected daylight from emission spectra in the visible and NIR (VNIR) regions is most easily accomplished using the Fraunhofer absorption lines in solar spectra. While ground reflectance spectral features in the VNIR are generally quite broad, the Fraunhofer lines are narrow and provide a signature of intrinsic vs. extrinsic illumination.

The High Throughput Virtual Slit (HTVS) enables higher spectral resolution than is achievable with conventional spectrometers by manipulating the beam profile in pupil space. By reshaping the instrument pupil with reflective optics, HTVS-equipped instruments create a tall, narrow image profile at the exit focal plane, typically delivering 5X or better the spectral resolution achievable with a conventional design.

9860-12, Session 2

Spectral dynamic scenes reconstruction based in compressive sensing using optical color filters

Kareth M. León, Univ. Industrial de Santander (Colombia); Laura Galvis Carreño, Univ. of Delaware (United States); Henry Arguello Fuentes, Univ. Industrial de Santander (Colombia)

Spectral - temporal compressive imaging is a technique that allows to sense spatio - spectro - temporal information, known as spectral video from a single low - framerate monochrome measurement. Several optical architectures have been recently developed to capture the spectral features of a dynamic scene or spectral video based on the compressive sensing framework. These spectral - temporal compressive architectures are principally composed by four elements: main lens, a coded aperture, a dispersive element and an FPA detector. Traditionally, these acquisition systems use block-unblock coded apertures that either block the light rays in the optical path or allow them to pass through. However, the modulation produced by the block-unblock coded apertures is wavelength independent, thus ignoring the highly correlated structure of the spectral information in a dynamic scene. In this work, the block-unblock coded apertures are replaced by colored coded apertures, whose pixels represent a set of specific optical filters such as low, high or band pass filters that modulate particular wavelengths of the scene. An analysis of the variations in the colored coded aperture pattern that allows to obtain improvements in PSNR compared with the block-unblock coded apertures is presented. Simulation results show an improvement up to 2 dB in the reconstruction quality with respect to the block-unblock coded apertures.

9860-13, Session 2

Hyperspectral sensing based analysis for determining milk adulteration

Sanjay Kimbahune, Syed M. Ghouse, Mithun B.S., Sujit Shinde, Tata Consultancy Services Ltd. (India); Amit Jha, Indian Institute of Technology Madras (India)

This research work was designed to evaluate the suitability and applicability of hyperspectral radiometry technology for robustly detecting contaminants in dairy milk. The most common milk adulterants are (a) soda, (b) urea, (c) water and (d) detergents. The main contribution of this paper is to build a mathematical model to enable quantifying the degree of common contaminants present in milk. Data was collected using a portable spectroradiometer (Eko MS-720) which measures the spectral irradiance in the range from visible to near-infrared irradiance (350 nm - 1050 nm) using samples of milk contaminated with found different contaminants (soda, urea, water and detergent) with known degree of contamination deliberately added in milk. In this study, we used the data in the range of 350 - 1050 nm to identify spectral signatures of different contaminants with different degree of concentration. Data cleansing in the form of pre-processing was followed by machine learning techniques to create a model to capture the contaminant and also the degree of contamination. Linear regression along with wrapper subset eval as attribute evaluator and best first search as search option was found to create the best model. Root Mean Square Error (RMSE) and Squared Correlation Coefficient (SCC) metrics were used to select the best model. The best model for detecting the degree of contamination due to soda, urea, water and detergent in milk was found to have an RMSE of 0.027, 0.0069, 0.0382 and 0.0281 respectively while SCC was 0.9919, 0.9997, 0.9887 and 0.9938 respectively. The preliminary experimental results demonstrate the effective use of spectroradiometer and machine learning technique in reliably detecting contaminants in milk.

9860-15, Session 2

Spatial and spectral calibration of visible and near-infrared imaging spectrometers for remote sensing of chlorophyll fluorescence

James R. Kellner, Katherine C. Cushman, Carlos E. Silva, Sandra M. Wiseman, Xi Yang, Brown Univ. (United States)

Reducing uncertainty in the global carbon budget requires measurements of canopy photosynthesis. However, no existing method can quantify photosynthesis within individual plants at scales larger than a few cm. Portable leaf chambers can determine leaf-level gas exchange, and eddy-covariance instruments infer the net ecosystem-atmosphere carbon flux. These endpoints represent an axis of granularity and extent. Single leaf measurements are finely grained, but necessarily limited in extent, and gas exchange for whole landscapes cannot resolve the performance or contributions of individual plants. This limits the ability of scientists to test mechanistic demographic and physiological hypotheses about the drivers of photosynthesis, and therefore to understand the determinants of carbon fluxes between the land and atmosphere. Here I describe a framework to overcome these challenges using commercial VNIR and SWIR diffraction-grating imaging spectrometers operated from a low-altitude helicopter drone (the Brown Platform for Autonomous Remote Sensing) to quantify solar-induced chlorophyll fluorescence and canopy volumetric water. By conducting frequent, low-altitude flights BPAR can produce imaging spectroscopy time series with measurements separated by minutes to hours at ground sample distances of 1 cm. The talk will focus on instrument characterization and calibration in the context of measurement needs.

9860-16, Session 2

Recent advances in rapid and non-destructive assessment of meat quality using hyperspectral imaging

Michael O. Ngadi, McGill Univ. (Canada)

There is need to evaluate and differentiate meat quality groups in order to meet consumer demands and to adequately cater for increasing market segmentations. A rapid and non-destructive technique is essential for the industry to meet the current need. Meat quality can be assessed in various ways depending on intended use. Typical technological assessment of quality is based on color, texture and chemical attributes such as moisture, fat and protein. Current methods for evaluation of these quality attributes rely on slow, inefficient and sometimes subjective methods. Hyperspectral imaging is an emerging advanced technology that has been applied successfully to measure different meat quality attributes. Early studies that used only spectral responses focused on color and chemical features to differentiate different quality groups without considering texture feature. However, hyperspectral imaging technique allows the use of both spectral and spatial information to obtain objective, high accuracy and real-time assessment of multiple meat quality attributes. It is particularly powerful for prediction of pork marbling, an attribute that is great interest in the pork industry. Hyperspectral imaging systems operating in the ranges from 400 to 1000 nm and from 900 nm to 1700 nm have been used. Selection of appropriate wavebands along with deployment of advanced data analysis are very crucial in developing efficient hyperspectral imaging based solutions. This paper discusses developments in the application of hyperspectral imaging to evaluate meat quality. The potentials and limitations of these techniques are highlighted.

9860-14, Session PWed

Along-track calibration of SWIR push-broom hyperspectral imaging system

Jurij Jemec, Univ. of Ljubljana (Slovenia); Franjo Pernus, Bostjan Likar, Univ. of Ljubljana (Slovenia) and Sensum d.o.o. (Slovenia); Miran Bürmen, Univ. of Ljubljana (Slovenia)

Push-broom hyperspectral imaging systems are increasingly used for various medical, agricultural and military purposes. The acquired images contain spectral information in every pixel of the imaged scene collecting additional information about the imaged scene compared to the classical RGB color imaging. Due to the misalignment and imperfections in the optical components comprising the push-broom hyperspectral imaging system, variable spectral and spatial misalignments and blur are present in the acquired images. To capture these distortions, a spatially and spectrally variant response function must be identified at all spatial and spectral positions. In this study, we propose a procedure to characterize the variant response function of Short-Wavelength Infrared (SWIR) push-broom hyperspectral imaging systems in the along-track direction and remove its effect from the acquired images. A custom laser-machined spatial calibration target is used for the characterization. The spatial and spectral variability of the response function in the along-track direction is modeled by a parametrized basis function and a bivariate spline model. Finally, the characterization results are used to restore the distorted hyperspectral images in the along-track direction by a Richardson-Lucy deconvolution-based algorithm. The proposed calibration method in the along-track direction is thoroughly evaluated on images of targets with well-defined geometric properties. The results suggest that the proposed procedure is well suited for fast and accurate along-track calibration of push-broom hyperspectral imaging systems.

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9861-1, Session 2

In-process thermal imaging of the electron beam freeform fabrication (EBF3) process *(Invited Paper)*

Karen Taminger, Robert A. Hafley, Joseph N. Zalameda, NASA Langley Research Ctr. (United States); Christopher S. Domack, Analytical Mechanics Associates, Inc. (United States); Eric R. Burke, NASA Langley Research Ctr. (United States)

Researchers at NASA Langley Research Center have been developing the Electron Beam Freeform Fabrication (EBF3) metal additive manufacturing process for the past 15 years. In this process, an electron beam is used as a heat source to create a small molten pool on a substrate into which wire is fed. The electron beam and wire feed assembly are translated with respect to the substrate to follow a predetermined tool path. This process is repeated in a layerwise fashion to fabricate metal structural components. In-process imaging has been integrated into the EBF3 system using a near-infrared (NIR) camera. The images are processed to provide thermal and spatial measurements of key processing parameters. These parameters have been incorporated into a closed loop control system enabling automatic, real-time adjustments to maintain consistent thermal conditions throughout the build. Other information in the thermal images is being used to assess quality in real time by detecting flaws in prior layers of the deposit. NIR camera incorporation into the system has improved the consistency of the deposited material and provides the potential for real-time flaw detection which, ultimately, could lead to the manufacture of better, more reliable components fabricated using this additive manufacturing process.

9861-2, Session 2

Four-color imaging pyrometer for mapping temperatures of laser-based metal processes

Daryl J. Dagel, Grant D. Grossetete, Danny MacCallum, Sandia National Labs. (United States)

A 4-color imaging pyrometer was developed to investigate the thermal behavior of laser-based metal processes, specifically laser welding and laser additive manufacturing of stainless steel. The new instrument, coined a 2x pyrometer, consists of four, high-sensitivity silicon CMOS cameras configured as two independent 2-color pyrometers combined in a common hardware assembly. This coupling of pyrometers permitted low and high temperature regions to be targeted within the silicon response curve, thereby broadening the useable temperature range of the instrument. Also, by utilizing the high dynamic range features of the CMOS cameras (sequenced exposure and log mode), the gap between the two wavelength bands was extended and bridged. Together these hardware and software enhancements are predicted to expand the real-time (60fps) temperature response of the 2x pyrometer from 600°C to 3500°C. An industrial blackbody source served as the calibration for the pyrometer, and a correction factor for non-gray behavior of steel was calculated by comparing its response to measurements on a gray surface. Absolute temperatures of laser welds on steel plate were captured in both conduction and keyhole modes. In addition, temperature maps of steel structures were captured during additively manufactured laser powder deposition in an effort to predict the final microstructure and residual stress by tracking the thermal history of each point.

9861-3, Session 2

Multiple sensor detection of process phenomena in laser powder bed fusion

Brandon Lane, National Institute of Standards and Technology (United States); Eric P. Whinton, Dakota Consulting, Inc. (United States); Jarred Heigel, Shawn Moylan, National Institute of Standards and Technology (United States)

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) process in which a high power laser melts layers of metal powder to form complex, three-dimensional shapes. LPBF parts are known to exhibit relatively high residual stresses, anisotropic microstructure, and a variety of defects. To mitigate these issues, in-situ measurements of the melt-pool phenomena may illustrate relationships between part quality and process signatures. However, phenomena such as spatter, plume formation, laser modulation, and melt-pool oscillations may require data acquisition rates exceeding 10 kHz. This hinders use of relatively data-intensive, streaming imaging sensors in a real-time monitoring and feedback control system. Single-point sensors such as photodiodes provide the temporal bandwidth to capture process signatures, while providing little spatial information. Experiments were conducted on a commercial LPBF machine which incorporated synchronized, in-situ acquisition of a thermal camera, high-speed visible camera, photodiode, and laser modulation signal during fabrication of an Inconel 625 AM part with an overhang geometry. Data from the thermal camera provides temperature information, visible camera provides observation of spatter, and photodiode signal provides high temporal bandwidth relative brightness stemming from the melt pool region. In addition, joint-time frequency analysis (JTFA) was performed on the photodiode signal. JTFA results indicate what digital filtering and signal processing is required to highlight particular signatures which may be exploited in monitoring or real time control methods. Image fusion of the synchronized data obtained over multiple build layers allow visual comparison between the photodiode signal and relating phenomena observed in the imaging detectors.

9861-4, Session 2

Decay temperature measurement of ABS + carbon fiber composite during the big area additive manufacturing process

Ralph B. Dinwiddie, Vlastimil Kunc, Brian Post, Lonnie J. Love, John M. Lindahl, Matthew R. Sallas, Oak Ridge National Lab. (United States)

In the fused deposition modeling process, parts are printed layer by layer from the bottom up. As each new hot layer is deposited onto a previously deposited layer, layer adhesion occurs, forming a solid part. However, if the previously deposited layer cools below a critical temperature before the sequential layer is added, the bond is weak, and the layers may delaminate. This paper outlines the measurement technique and results of a substrate layer temperature decay study for Acrylonitrile Butadiene Styrene (ABS) thermoplastic with the addition of chopped carbon fibers.

Two long-wave infra-red cameras have been used to measure various temperature profiles in thermoplastic parts during the printing process. The printer used in this study is the Cincinnati Big Area Additive Manufacturing (BAAM) 3D-printer located at Oak Ridge National Laboratory.

The Cincinnati BAAM prints parts with typical layer thicknesses in the 2.75

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to 4 mm range. A key area of focus is the temperature of the previously deposited layer right before the new hot layer is deposited. The two layers are expected to have a stronger bond if the temperature of the substrate layer is above the ABS glass transition temperature.

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9861-5, Session 2

Assessing the use of an infrared spectrum hyperpixel array hyperspectral imager to measure temperature during additive and subtractive manufacturing

Eric P. Whitenton, Brandon Lane, Shawn Moylan, Jarred Heigel, National Institute of Standards and Technology (United States)

Accurate non-contact temperature measurement is important to optimize manufacturing processes. This applies to both additive (3D printing) and subtractive (material removal by machining) manufacturing. Performing accurate single wavelength thermography suffers numerous challenges. A potential alternative is hyperpixel array hyperspectral imaging. Focusing on metals, this paper discusses issues involved such as unknown or changing emissivity, inaccurate greybody assumptions, motion blur, and size of source effects. The algorithm which converts measured thermal spectra to emissivity and temperature uses a customized multi-step non-linear equation solver to determine the best-fit greybody emission curve. Emissivity dependence on wavelength may be assumed uniform or have a relationship typical for metals. The custom software displays residuals for intensity, temperature, and emissivity to gauge the correctness of the greybody assumption. Initial results are shown from a laser powder-bed fusion additive process, as well as a machining process.

In addition, the effects of motion blur are analyzed, which occurs in both additive and subtractive manufacturing processes. In a laser powder-bed fusion additive process, the scanning laser causes the melt pool to move rapidly, causing a motion blur-like effect. In machining, measuring temperature of the rapidly moving chip is a desirable goal to develop and validate simulations of the cutting process. A moving slit target is imaged to characterize how the measured spectra, and resulting emissivity and temperature values, are affected by motion of a measured target.

9861-6, Session 2

Calibrating IR cameras for in-situ temperature measurement during the electron beam melting process using Inconel 718 and Ti-Al6-V4

Ralph B. Dinwiddie, Ryan R. Dehoff, Michael M. Kirka, Larry E. Lowe, G. S. Marlow, Oak Ridge National Lab. (United States)

The Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL) provides world-leading capabilities in advanced manufacturing (AM) facilities which leverage previous, ongoing government investments in materials science research and characterization. This facility contains systems for producing components with complex geometries using AM techniques (e.g. 3D-Printing). Various metal alloy printers, for example, use an electron beam melting (EBM) system for creating these components which are otherwise extremely difficult, if not impossible, to machine. ORNL has partnered with manufacturers to assist in improving the final part quality of a component and to develop new materials for use in these devices. One method currently being used to study the (AM) processes relies on the advanced imaging capabilities at ORNL. High

performance midwave IR cameras are used for in-situ process monitoring and temperature measurements. However, standard factory calibrations are insufficient due to the very low transmission of the leaded glass window required for X-ray absorption. Two techniques for temperature calibrations will be presented and compared. In-situ measurement of emissivity will also be discussed. Much can be learned from in-situ IR process monitoring of the EBM process. Ultimately, these imaging systems have the potential for routine use for online quality assurance and feedback control. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

9861-7, Session 3

Robotized line scan thermography inspection and advanced signal processing for the evaluation of the state of conservation of mosaics

Clemente Ibarra-Castaneda, Univ. Laval (Canada); Stefano Sfarra, Univ. degli Studi dell'Aquila (Italy); Panagiotis Theodorakeas, National Technical Univ. of Athens (Greece); Fariba Khodayar, Yacine Mokhtari, Univ. Laval (Canada); Nicolas P. Avdelidis, National Technical Univ. of Athens (Greece) and Univ. Laval (Canada); Stefano Perilli, Dario Ambrosini, Univ. degli Studi dell'Aquila (Italy); Maria Kouli, National Technical Univ. of Athens (Greece); Matthieu T. Klein, Adel Ziadi, Visioimage Inc. (Canada); Xavier Maldague, Univ. Laval (Canada)

The nondestructive inspection of mosaics is not a novelty in the thermographic scene. Some interesting works, in particular dedicated to plastered mosaics, can be retrieved in literature. One group of studies proposes the inspection of mosaics containing fabricated defects using the active thermography approach on a static configuration. Some others are centered on in-situ inspections by means of the passive approach. In the present study, a mosaic made by synthetic tesserae with different colors depicting a dove has been inspected by active thermography using a dynamic configuration. In particular, line scan thermography (LST) was employed by reproducing an in-situ inspection: the energy source and camera move along the surface while the mosaic is motionless. The acquired data is then reorganized as a pseudo-static sequence, similar to classic data, in order to perform advanced signal processing. In addition, besides containing artificial defects at several depths and positioned at different locations, some of the defects provide the possibility to monitor thermal variations over time. In particular, the mosaic has: a void into which a quantity of compressed air could be injected, a sponge that could be soaked by a known quantity of water thanks to an external tube, and a sub-superficial recirculation circuit in which flows a stream of cold or hot water. The variability of the nature of these defects, which try to simulate what happens in a real case, is suitable to be modeled by numerical simulation approaches. The latter point has been assessed in this work, as well as a comparison between the LST and the traditional method of thermal stress by static lamps.

9861-8, Session 3

In-situ thermographic inspection for automated fiber placement systems

Peter Juarez, K. Elliott Cramer, NASA Langley Research Ctr. (United States)

One of the advantages of carbon fiber composites is the ease with which they can be tailored to meet specific engineering, aerodynamic, and structural needs. Automated fiber placement systems have enabled fast

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and repeatable construction of large geometrically complex composite structures, and have opened the door to rapid implementation of new composite designs. To research the implementation of automated fiber placement systems, NASA Langley Research Center has recently acquired a multi-axis robotic fiber placement platform known as ISAAC (Integrated Structural Assembly of Advanced Composites). ISAAC can construct complex parts using pre-impregnated carbon fiber (prepreg) tape layup. With these new manufacturing systems come new types of manufacturing defects that need to be detected and mitigated, such as twists, gaps, and folds in the prepreg tape that is deposited on the part. On the ISAAC system, traveling ahead of the tape layup roller is a quartz lamp used to heat the substrate before the tape is applied. This action increases the substrate's tackiness to help adhere the next tape layer, but it can also act as a through-transmission heat source when inspecting the newly deposited layer with a thermal camera. To simulate this scenario before a full implementation, an analogous experiment was set up using a through-transmission heat source to inspect for tape layup defects in an uncured carbon fiber ISAAC built sample. This presentation will cover the design of the experiment, the results of this new technique, and the thermal implications for uncured prepreg. An exploration of full scale implementation requirements will also be discussed.

9861-9, Session 3

Thermal and visible remote sensing for estimation of evapotranspiration of rainfed agrosystems and its impact on groundwater in SE Australia

Rakhshan Roohi, John A. Webb, La Trobe Univ. (Australia)

The rainfed agro-systems are important components of the world's food production system. Depending upon the regional distribution, it accounts for 65 to 95% of the total agriculture. In contrast to the irrigated production system, little attention is paid to understanding the hydrological interactions among the components of rainfed agro-systems and their impact on limited water resources, especially groundwater.

Surface Energy Balance Algorithm for Rainfed Agriculture (SEBARA) has been developed to understand the spatial pattern of evapotranspiration. This model uses satellite images (thermal and visible spectra) to estimate the evapotranspiration of the rainfed agro-systems. The model was applied to two competing landuses; plantations and pastures. Measurements from a flux tower in the pasture catchment and adjusted sapflow measurements in the plantation catchment were used to compare the SEBARA model estimates and an estimation accuracy of 95% was achieved.

Plantation due to higher available net radiation, lower soil heat flux and higher latent heat flux, have a higher water requirement to meet the increased evapotranspirative demand. Generally, plantations have 15-20% higher evapotranspiration than pastures depending upon the age and canopy of the plantations. Contrary to that, the pastures, due to a shallow root system, rely on the soil moisture to meet the water requirements; thus have lower evapotranspiration. However, the evapotranspiration rate of pastures depends upon the pasture species. Comparison of evapotranspiration rate of plantations with groundwater depth indicates that the evapotranspiration declines with groundwater depths of >12m or where shallow groundwater is saline.

9861-10, Session 3

Tomato freshness prediction using step heating and infrared thermography

Jing Xie, Huazhong Agricultural Univ. (China); Sheng-Jen Hsieh, Hongjin Wang, Texas A&M Univ. (United States); Zuojun Tan, Jian Zhang, Huazhong Agricultural Univ. (China)

Tomatoes are the world's 8th most valuable agricultural product, valued

at \$58 billion dollars annually. Non-destructive testing and inspection of tomatoes is challenging and multi-faceted. Optical imaging is used for quality grading and ripeness. Spectral and hyperspectral imaging are used to detect surface defects and cuticle cracks. Infrared thermography has been used to distinguish between different stages of maturity. However, determining the freshness of tomatoes is still an open problem. For this research, infrared thermography was used for freshness prediction. Infrared images were captured at a rate of 1 frame per second during heating (0 to 40 seconds) and cooling (0 to 160 seconds). The absolute temperatures of the acquired images were plotted. Regions with higher temperature differences between fresh and less fresh (rotten within three days) tomatoes of approximately uniform size and shape were used as the input nodes in a three-layer artificial neural network (ANN) model. Two-thirds of the data were used for training and one-third was used for testing. Results suggest that by using infrared imaging data as input to an ANN model, tomato freshness can be predicted with 90% accuracy. T-tests and F-tests were conducted based on absolute temperature over time. The results suggest that there is a mean temperature difference between fresh and less fresh tomatoes ($p = 0.05$). However, there is no statistical difference in terms of temperature variation, which suggests a water concentration difference.

9861-11, Session 4

Development of sonic infrared imaging and its applications on defect detections in materials and structures (Invited Paper)

Xiaoyan Han, Wayne State Univ. (United States)

Although thermal imaging has a long history, it is the recent couple of decades that its usage has increased dramatically with the commercial and industrial applications. Thermal imaging can be classified as passive and active regarding to its heating means. Night vision used in automobile and thermal imaging for evaluating the quality of thermal insulation in buildings are two of the examples of passive thermal imaging. On the other hand, when certain heating mechanism, such as flash lamp, current, is applied, we classify them as active thermal imaging. In this presentation, we like to present our development on Sonic Infrared (IR) Imaging, which is an active thermal imaging technique. Sonic IR Imaging combines pulsed ultrasound excitation and infrared imaging to detect defects in materials. The sound pulse causes rubbing due to non-uniform motion between faces of defects, and infrared sensors image the temperature map over the target to identify defects. The concept of this technology is simple, however, the effectiveness of this technology to detect defects is quite amazing. Defects can be cracks, disbands and/or delamination in metal, metal alloy, and composites. It's a fast, wide area NDE technique. It takes only a fraction of a second or a few seconds, depending on the thermal properties of the target, for one test. We will also present its broad applications through examples in different materials and structures.

9861-12, Session 4

Application of burst vibrothermography to characterize planar vertical cracks

Arantza Mendioroz, Univ. del País Vasco (Spain); Ricardo Celorrio, Univ. de Zaragoza (Spain); Angel S. Cifuentes, Instituto Politécnico Nacional (Mexico); Agustin Salazar, Univ. del País Vasco (Spain); Lander Zatón, University of the Basque Country, UPV/EHU (Spain)

Vibrothermography has proven to be sensitive to detect vertical cracks in a wide variety of materials. In this technique the sample is excited mechanically, with ultrasounds, and at the defects mechanical energy turns into thermal energy mainly because of friction between the defect faces, so the defect turns into a heat source in the presence of ultrasounds. The discontinuity reveals itself as a temperature rise at the surface, which can be detected by an infrared camera. The retrieval of the inner heat source

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distribution responsible for the observed thermograms is an ill-posed inverse problem which needs the application of regularizing techniques. In a previous work we used lock-in vibrothermography to characterize vertical cracks. We combined surface temperature amplitude and phase data obtained at several modulation frequencies and we developed a regularized algorithm to characterize vertical cracks down to 3 mm below the sample surface. The drawback of the technique is that data taking is rather time consuming.

In this work we apply vibrothermography in the burst regime, which is a much faster technique, to characterize vertical cracks. We compute the surface temperature produced by a crack excited by an ultrasound burst and we analyze its sensitivity to the geometry of the crack for different burst durations. We present an improved inversion algorithm to retrieve the geometry of the crack and we test its performance by inverting synthetic data. Finally, inversions of experimental data taken on samples containing calibrated heat sources confirm the validity of the method to characterize vertical cracks.

9861-13, Session 4

Evaluating impact damage in graphite epoxy composite by using low-power vibrothermography

Daria Derusova, Vladimir P. Vavilov, National Research Tomsk State Univ. (Russian Federation); Nikolai Druzhinin, Institute of Strength Physics and Materials Science, Siberian Branch, Russian Academy of Sciences (Russian Federation)

“Classical” IR ultrasonic thermography is based on applying powerful ultrasonic stimulation to test objects. Attempting to expand an inspection area by further increasing ultrasonic power may lead to sample damage, particularly, in a stimulation point. The recently proposed low-power resonant ultrasonic vibrothermography method involves an individual approach to the inspection of materials by performing a detailed analysis of vibrations on the sample surface in a wide range of acoustic frequencies. The determination of defect resonant frequencies enables efficient transfer of acoustic wave energy into a defect area and further transformation of this energy into heat due to intensive plastic deformations and internal friction. This paper contains the results of applying low-power ultrasonic IR thermography to detecting impact damage in graphite epoxy composite by using techniques of laser vibrometry and IR thermography.

9861-14, Session 4

Combining passive thermography and acoustic emission for large area fatigue damage growth assessment of a composite structure

Joseph N. Zalameda, Eric R. Burke, NASA Langley Research Ctr. (United States); Michael R. Horne, National Institute of Aerospace (United States); Eric I. Madaras, NASA Langley Research Ctr. (United States)

Passive thermography and acoustic emission data were obtained for improved real time damage detection during fatigue loading. A strong positive correlation was shown between acoustic energy event location and thermal heating, especially if the structure under load was nearing ultimate failure. An image processing routine was developed to map the acoustic emission data onto the thermal imagery. This required removing optical barrel distortion and angular rotation from the thermal data. The acoustic emission data were then mapped onto thermal data, revealing the cluster of acoustic emission event locations around the thermal signatures of interest. By combining both techniques, progression of damage growth is confirmed

and areas of failure are identified. This technology is being used for fatigue testing of advanced composite structures to both validate structural designs and damage progression models.

9861-15, Session 4

Infrared thermography for CFRP inspection: computational model and experimental results

Henrique C. Fernandes, Univ. de São Paulo (Brazil); Hai Zhang, Univ. Laval (Canada); Karen S Morioka, University of São Paulo (Brazil); Clemente Ibarra-Castanedo, Fernando Lopez, Xavier Maldague, Univ. Laval (Canada); José R. Tarpani, Univ. de São Paulo (Brazil)

Infrared Thermography (IRT) is a well-known Non-destructive Testing (NDT) technique. In the last decades, it has been widely applied in several fields including inspection of composite materials (CM), specially the fiber-reinforced polymer matrix ones. Consequently, it is important to develop and improve efficient NDT techniques to inspect and assess the quality of CM parts in order to warranty airworthiness and, at the same time, reduce costs of airline companies. In this paper, active IRT is used to inspect carbon fiber-reinforced polymer (CFRP) flat laminate with artificial inserts (built-in sample) placed on different layers prior to the manufacture. The laminate layout is [02/902]6. Inserts are made of Kapton® (polyimide resin) film and have three different sizes: 4 x 4 mm2, 3 x 3 mm2 and 2 x 2 mm2. Two optical active IRT are used. The first is pulsed thermography (PT) which is the most widely utilized IRT technique. The second is a line-scan thermography (LST) technique: a dynamic technique, which can be employed for the inspection of materials by heating a component, line-by-line, while acquiring a series of thermograms with an infrared camera. It is especially suitable for inspection of large parts as well as complex shaped parts. A computational model developed using COMSOL Multiphysics® was used in order to simulate the inspections. Sequences obtained from PT and LST were processed using principal component thermography (PCT) for comparison. Results showed that it is possible to detect insertions of different sizes at different depths using both PT and LST IRT techniques.

9861-16, Session 5

Active thermal NDT: problems and solutions

Vladimir P. Vavilov, Tomsk Polytechnic Univ. (Russian Federation)

A process of active thermal/infrared nondestructive testing (T/I NDT) combines physical phenomena of heat conduction and infrared thermography. Respectively, both advantages and disadvantages of this technique are related to the corresponding phenomena. The heating technique also contributes to the process by involving other specific features. For example, the diffusion character of heat conduction allows inspection of all solid materials but may smash temperature indications in space and slow them down in time. Infrared technology assures fast and non-contact imaging but causes specific noise due to the physics of radiation. Optical stimulation is non-contact and easily controllable but can be uneven and inefficient in the case of reflective surfaces. Eddy current excitation is strongly dependent on test object geometry and significantly increases temperature in sound areas. Powerful ultrasonic stimulation may work perfectly on ‘kissing’ disbonds which are barely detectable by other NDT techniques but this method may not be fully nondestructive. All the above-mentioned peculiarities of active T/I NDT are known and have been explored by many researchers. This paper summarizes the most common problems of thermal NDT and their possible solutions. Typical problems and solutions related to active T/I NDT are illustrated with plentiful experimental results to facilitate optimization of inspection procedures in various application areas.

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9861-17, Session 5

IR thermography for the assessment of the thermal conductivity of thermoelectric modules at intermediate temperature

Paolo Bison, Consiglio Nazionale delle Ricerche (Italy); Stefano Boldrini, Alberto Ferrario, Francesco Montagner, Alvisio Miozzo, Monica Fabrizio, CNR-IENI (Italy)

The correct measure of the performances of thermoelectric (TE) modules for energy conversion is a mandatory task both for laboratory research and for industries engaged in TE modules development or in their integration into thermoelectric generators. The efficiency of a TE module can be characterized by its figure of merit ZT depending on the electrical conductivity, the Seebeck coefficient, the temperature and the thermal conductivity of the thermoelectric material. The research and optimization of the performance of TE materials is focused towards the maximization of the power factor (electrical conductivity times the square of Seebeck) and the minimization of the thermal conductivity. In order to achieve high ZT values, ceramic semiconductor materials with low thermal conductivity are used.

A testing device oriented to the maximum flexibility, based on the heat flow meter at the cold side of the module has been developed. It can test TE modules (single or in cascade) with a footprint up to 60x60 mm², from room temperature up to intermediate temperature, under vacuum or inert atmosphere. Specifically, the flow meter is made of a block of material, with known thermal conductivity. The heat flow is finally determined by means of the measurements of the temperature profile along the heat flow path by IR thermography. IR thermography is also utilized to evaluate the contact resistance, as a function of the contact pressure, between the active thermoelectric elements, the thermoelectric module ceramic plates and the metallic layer working as a heat diffuser. Some FE thermal analysis of the system performed for its design are presented.

9861-18, Session 5

Fracture behavior of reinforced aluminum alloy matrix composites using thermal imaging tools

Nicolas P. Avdelidis, National Technical Univ. of Athens (Greece) and Univ. Laval (Canada); Dimitris Exarhos, University of Ioannina (Greece); Patricia Vazquez, Universite de Reims Champagne - Ardenne (France); Clemente Ibarra-Castanedo, Univ. Laval (Canada); Stefano Sferra, Univ. degli Studi dell'Aquila (Italy); Xavier Maldague, Univ. Laval (Canada); Theodore Matikas, University of Ioannina (Greece)

In this work the influence of the microstructure at the vicinity of the interface on the fracture behavior of particulate-reinforced aluminum alloy matrix composites (Al/SiCp composites) is studied by using thermographic tools. In particular, infrared thermography was used to monitor the plane crack propagation behavior of the materials. The deformation of solid materials is almost always accompanied by heat release. When the material becomes deformed or is damaged and fractured, a part of the energy necessary to initiate and propagate the damage is transformed in an irreversible way into heat. The thermal camera detects the heat wave, generated by the thermo-mechanical coupling and the intrinsic dissipated energy during mechanical loading of the sample. By using an adapted detector, thermography records the two dimensional "temperature" field as it results from the infrared radiation emitted by the object. The principal advantage of infrared thermography is its noncontact, non-destructive character. This methodology is being applied to characterise the fracture behavior of the particulate composites. Infrared thermography is being used to monitor the plane crack propagation behavior of such materials.

Furthermore, an innovative approach to use microscopic measurements using the 1x and 4x IR microscopic lenses was attempted, in order to enable smaller features (in the micro scale) to be imaged and measured with accuracy and assurance.

9861-19, Session 5

Superimpose signal processing method for micro-scale thermal imaging of solar salt at high temperature

Junko Morikawa, Yukitaka Kato, Massimiliano Zamengo, Tokyo Institute of Technology (Japan)

The mobile type apparatus for a quantitative micro-scale thermography using a micro-bolometer is originally proposed based on our original techniques such as an achromatic lens design to capture a micro-scale image in the long-wave infrared, a video signal superimposing for the real time emissivity correction, a pseudo acceleration of a timeframe, and a micro-scale flying spot method.

In this study, we newly propose a mobile type instrumentation of micro-scale infrared thermal imaging system, which is applicable to high-temperature measurements up to 700 degC or higher, in order to observe a micro-scale heat transfer and heat exchange in solar salts. Superimpose system is just set up adjusted to the signal processing in high temperature to realize the quantitative thermal imaging.

The video signal synthesizer enables to record a direct digital signal of monitoring temperature data. The encoded digital signal data is embedded in each image once and is read out in the analysis. The protocol of encode/decode the measured data is originally defined. The mixed signals of IR camera and the imposed data are applied to the pixel by pixel emissivity corrections and the pseudo-acceleration of the periodical thermal phenomena. By using this superimposed technique; the direct temperature image of the molten state of solar salt in high temperature was captured for the first time. The structure formation process during the phase change was also visualized by this thermal imaging method in high temperature.

9861-20, Session 5

Optimizing components and evaluating technical performance of IR thermographic NDT systems

Arsenii Chulkov, Vladimir P. Vavilov, Sachin S. Pawar, Tomsk Polytechnic Univ. (Russian Federation)

A typical infrared (IR) thermographic system intended for active thermal/IR nondestructive testing (NDT) includes a heat source, an IR imager and a computer. The software ensures acquisition and processing of IR image sequences to result with a binary map of defects or any other image which is to be interpreted by a thermographer in order to meet inspection requirements. Typically, system developers supply a certain set of technical parameters of an inspection system, such as heater power, imager temperature resolution, acquisition rate and a set of available data processing algorithms. However, end-users prefer to know minimum detectable defects in each particular test case. A peculiarity of thermal/IR NDT is that a technical performance of this method cannot be expressed only with few parameters, such as defect thickness (in percent of material thickness) in the X ray method, defect depth (eddy current penetration depth) in the eddy current method, surface crack opening in the method using liquid penetrants, etc. In fact, in thermal/IR NDT, one is to specify a set of many parameters which provide temperature signals in defective sites at the level of accompanying noise and thus determine a detection limit. That is why, reference samples of different types are often used in thermal/IR NDT. In this paper, the approach for determining thermal NDT limits is discussed in two test cases: detecting corrosion in steel and detecting delaminations in graphite epoxy composite. The suggested approach allows optimization of inspection parameters if thermal and optical parameters of a

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tested material are known. A portable active thermal NDT unit developed at Tomsk Polytechnic University for aviation applications, as well as validation of its technical characteristics, are described in details.

9861-21, Session 6

Simulation of thermographic responses of delaminations in composites with quadrupole method (*Invited Paper*)

William P. Winfree, Joseph N. Zalameda, Patricia A. Howell, K. Elliott Cramer, NASA Langley Research Ctr. (United States)

The application of the quadrupole method for simulating thermal responses of delaminations in carbon fiber reinforced epoxy composites materials is presented. The method solves for the flux at the interface containing the delamination. From the interface flux, the temperature at the surface is calculated. While the method presented is for single surface, flash heating, expansion of the technique to arbitrary temporal flux heating is discussed. The quadrupole method is shown to have two distinct advantages relative to finite element or finite difference techniques. First, it is straight forward to incorporate arbitrary shape delaminations into the simulation. Second, the quadrupole method enables calculation of the thermal response at only the times of interest. This, combined with a significant reduction in the number of degrees of freedom for the same simulation quality, results in a reduction of the computation time by a couple of orders of magnitude. Therefore, it is a more viable technique for model based inversion of thermographic data. Results for simulations of delaminations in composites are presented and compared to measurements.

9861-22, Session 6

Regression analysis of non-contact acousto-thermal signature data

Amanda K. Criner, Air Force Research Lab. (United States); Norm Schehl, Univ. of Dayton Research Institute (United States)

The non-contact acousto-thermal signature (NCATS) is a nondestructive evaluation technique with potential to detect fatigue in materials such as noisy titanium and polymer matrix composites. The determination of underlying physical mechanisms and properties may be determined by parameter estimation via nonlinear regression. The nonlinear regression analysis formulation, including the underlying models, is discussed. Several models and associated data analyses are given along with the assumptions implicit in the underlying model. The results are anomalous. These anomalous results are evaluated with respect to the accuracy of the implicit assumptions.

9861-23, Session 6

Comparison of time and frequency behavior in TSR and PPT evaluation

Beata Oswald-Tranta, Montan Univ. Leoben (Austria)

Subsurface defects can be detected by flash thermography by evaluating the temperature response at the surface. Many techniques have been developed in the past to localize a defect and also to estimate its depth and size. Two of the most established methods are TSR and PPT, whereby TSR analyzes the data in the time domain, and PPT evaluates the signal in the frequency domain. In order to get the data in the frequency domain, Fourier transformation, especially FFT is used to calculate the phase shifting for the different frequencies. The usage of FFT assumes a periodical signal or a temporal signal which is limited in the time. As this is not the case for the

temperature signal after a short pulse heating, the transformation to the frequency domain generates some errors. Therefore parameters as sampling frequency and evaluation duration have to be selected carefully. Even if many publications have been already dealt with this topic, in this paper a new approach is attempted by comparing the temporal behavior as it is handled by the TSR technique with the frequency behavior calculated by PPT. The results are interpreted with the help of simulation models of flat bottom hole samples and measurement results.

9861-24, Session 6

Interpretation and modeling of thermographic NDT based on thermographic signal reconstruction (TSR)

Steven M. Shepard, Maria Frenberg Beemer, Thermal Wave Imaging, Inc. (United States)

Active thermography is widely used for detection of subsurface flaws. In its simplest form, transient heating is applied to the sample and a localized hot spot (compared to the surrounding background) appears in the resulting IR image sequence. Enhanced detection of subsurface flaws is accomplished by several signal processing methods that operate on the entire time history of each pixel, e.g. pulse phase, principal component analysis and Thermographic Signal Reconstruction (TSR), which is unique in that it does not require flaw-background contrast, so that information can be extracted from a single pixel time history. Quantitative analysis or modeling of the contrast between the flaw and background is typically performed numerically, using finite difference or inverse Laplace transform (quadrupole) methods, or to a lesser degree, using analytical Green's function or eigenvalue methods. Although the TSR method is widely used for signal enhancement, it also serves as a useful platform for modeling of thermographic response for multilayer samples, and can be extended to include discrete flaws that normally require 2 or 3 dimensional treatment. By viewing the active thermography process over its entire "lifetime" as a transition between stationary diffusion states, one observes that the presence of an interface or flaw causes a transition between these states to occur in a predictable way. We will demonstrate that a wide range of material, flaw and boundary condition configurations can be modeled by scaling this transition and the stationary states appropriately.

9861-25, Session 6

Tracking composite material damage evolution using Bayesian filtering and flash thermography data.

Elizabeth D. Gregory, Stephen D. Holland, Iowa State Univ. of Science and Technology (United States)

It is common practice in the aerospace industry to use the most recent nondestructive evaluation (NDE) data for a part as the current state estimate for that part. In this paper we propose a method for tracking the condition of a composite part using Bayesian filtering of NDE data over the service lifetime of the part. The Bayesian filtering process uses all the NDE data available for the current and past states of the part to provide the best estimate of the current state and predict the future state of the part using any knowledge available about service loads. We provide simulation results for the algorithm that demonstrate the prediction and update steps of the Bayesian filter. We also present the results of the filter as it is applied to experimental data from composite panels that have been impacted to create damage and then the area of damage was grown incrementally by additional loading to simulate a real-world damage evolution situation. Flash thermography data was collected after each incremental growth in damage. In order to compare the quality of the state estimate computed tomography (CT) data was also collected at each increment to be the 'truth' for comparison. The Bayesian filter process yielded a state estimate that better resembled the CT 'truth' as compared with the most recent flash thermography NDE alone.

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9861-26, Session 6

Thermography and k-means clustering methods for inspection of scratch and bubble defects in anti-reflective coating film

Xunfei Zhou, Hongjin Wang, Sheng-Jen Hsieh, Texas A&M Univ. (United States)

Anti-reflective (AR) film is widely used on telescopes, eyewear, and screens to enhance the transmission of light. However, defects such as bubbles or scratches reduce the usability and functionality of optical film. Optical cameras are typically used for inspection, but the accuracy of optical imaging is limited by factors such as the illumination source, camera viewing angles, and defect location. This paper describes an inspection method based on active thermography that can potentially overcome these limitations. Eighteen scratch and bubble defects with dimensions ranging from 0.03mm to 4.4 mm were introduced on AR film. An infrared camera was used to capture thermal images of the defects over 65 seconds of heating. After the images were acquired, a de-trend process was utilized to highlight the defective areas, and k-means clustering was used to identify the edges of the defects. Results suggest active thermography can detect scratch defects with a width of 0.08mm to 4.40 mm and bubble defects with diameters ranging from 0.2 to 4 mm. The developed algorithm can estimate the size of defects with dimensions larger than 1 mm with less than 10% bias. However, for defects with dimensions less than 1mm, the algorithm estimation error ranges from 59.5% to 140% due to camera resolution limitations. However the developed algorithm can detect a scratch defect with a width less than one pixel. The results also suggest that active thermography can be used to detect scratch and bubble defects regardless of the location of the illumination source(s).

9861-27, Session 7

Classification of electrical problems detected by infrared thermography using a risk assessment process

Gregory B. McIntosh, Teasdale Consultants Ltd. (Canada); Roy Huff, The Snell Group (United States)

For more than 40 years thermography has been used for electrical problem detection. In addition, since radiometric infrared cameras can establish surface temperature of the problem, a classification system is often utilized based upon a problem's surface temperature, or temperature rise above normal operating temperature or ambient air temperature. This however can be an extremely unreliable classification method for a number of reasons including: emissivity and background energy; a lack of regard for failure modes and stressors; surface temperature variability with load and ambient conditions; temperature gradient from internal source to surface; and the presence of convection, just to name a few. Standards, such as NFPA 70B try to address some of these issues by having very low threshold temperature limits, but this as well has issues including identifying an over-abundance of non-critical problems for repair. This paper will present a risk assessment process and matrix which classifies electrical problems based upon a variety of factors affecting both probability and consequence of electrical component failure. Inherent in this process will be a discussion of understanding and analysing electrical connection failure modes and failure stressors, as well as consideration of both heat energy flow and stored energy rather than only considering surface temperature as a single point predictor of catastrophic failure.

9861-28, Session 7

Flame attenuation effects on surface temperature measurements using IR thermography

Jaap de Vries, FM Global (United States)

The ability for long-wave infrared imaging to penetrate flames and smoke has been demonstrated in large-scale and intermediate-scale fire scenarios. However, the attenuation effects on the surface temperature measurements due to flame sheets is not well quantified. This work expands previous infrared thermography studies of industrial fires to quantitative surface temperature measurements, with emphasis on the flame attenuation effects. The experimental setup consists of a 12 by 12 in. (30 x 30 cm) blackbody radiant source and several laboratory-scale turbulent diffusion flames. The blackbody temperatures were measured using infrared thermography to capture both dynamic and time-averaged, two-dimensional attenuation profiles. The results are applied to adjust surface temperature data acquired in previous studies. This established an experimental method to characterize the flame attenuation effects so that the surface temperature data can be used for model validation and for understanding the spread of pyrolysis front on solid combustible materials.

9861-29, Session 7

A simplified method for the thermographic measurement of building dynamic behavior

Giovanni Ferrarini, Univ. degli Studi di Padova (Italy); Alessandro Bortolin, Gianluca Cadelano, Consiglio Nazionale delle Ricerche (Italy); Michele De Carli, Univ. degli Studi di Padova (Italy); Paolo Bison, Consiglio Nazionale delle Ricerche (Italy)

The accurate knowledge of the thermal performance could reduce significantly the impact of buildings on global energy consumption. Infrared thermography is widely recognized as one of the key technologies for building surveys, thanks to its ability to acquire at a glance thermal images of the building envelope. However, a spot measurement is ineffective for slow physical phenomena, such as the dynamic thermal behavior. In this case data must be acquired for hours or days, depending on the thermal properties of the walls. Long term thermographic monitoring are possible but imply strong challenges from a practical standpoint.

This work investigates the possibilities and limitations of a simplified method that relies on contact probes, that are able to acquire continuously the thermal signal for days, and infrared sensors, that are used for few spot measurement. The first goal is the extension of the local measurement, carried out with contact temperature sensors on the inner and outer surface of a wall, to a wider surface measured by infrared thermography. The second goal is the evaluation of the minimum number of thermographic images required for the measurement and of the accuracy, that depends both on the total number of images and on the time sampling strategy. Numerical simulations are performed to determine these parameters that are verified on an experimental case.

9861-30, Session 7

Automatic thermographic scanning with the creation of 3D panoramic views of buildings

Giovanni Ferrarini, Univ. degli Studi di Padova (Italy); Alessandro Bortolin, Gianluca Cadelano, Consiglio Nazionale delle Ricerche (Italy)

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Infrared thermography is widely applied to the inspection of building, enabling the individuation of thermal anomalies due to the presence of hidden structures, air leakages, and moisture. One of the main advantages of this technique is the possibility to acquire rapidly a temperature map of a surface. However, due to the actual low-resolution of thermal camera, during a building survey it is necessary to take multiple images in order to scan all the surfaces.

In this work a device based on quantitative infrared thermography, called alRview, has been applied during building surveys to automatically acquire thermograms with a camera mounted on a robotized pan tilt unit. The goal is to perform a first rapid survey of the building that could give useful information for the successive quantitative thermal investigations. For each data acquisition, the instrument covered a rotational field of view of 330° around the vertical axis and of 210° around the horizontal one. The obtained images have been processed in order to create an equirectangular projection of the ambient.

9861-33, Session 7

Building thermography: reporting and interpretation of results

Timo T. Kauppinen, Sami Siikanen, VTT Technical Research Ctr. of Finland Ltd. (Finland); Sauli Paloniitty, Paloniitty Oy (Finland)

The certification procedure for building thermographers in Finland was launched 2003, when also was published the first guidelines in interpretation of thermal images and reporting guidelines. After 12 years training courses a need has emerged to complement and modernize the interpretation and reporting, also to update what kind of thermal imagers can be used for various applications. Due to the technical progress, performance of devices has improved and image processing softwares have developed. The normal procedure is two-stage thermography in connection of air-tightness test.

The templates for interpretation and reporting are often used as a minimum level, without proper information for the customer. Also there is still lack of knowledge in building physics, even it has weighted in training. Partially it is caused by varied background of thermographers. The outdoor and indoor conditions in the building are varying, too. In case of mechanical ventilation and mechanical exhaust, one must pay attention to pressure conditions. The ventilation system must be balanced or then switched off. The thermographers in field work should also take all possible factors into account effecting the surface temperatures - building envelope, heating and ventilation systems etc. In this paper the new guidelines are introduced, as well some examples of the most common errors of interpretation.

9861-34, Session 7

Applications for oblique thermal infrared imaging

Gregory R. Stockton, Stockton Infrared Thermographic Services, Inc. (United States)

Many uses of infrared thermography for buildings and infrastructures have been well-documented over the past forty years. Thermal infrared surveying and associated testing can be used to find design flaws, construction defects and in-situ performance issues. There are many ways to accomplish building and infrastructure surveys depending on the ambient conditions and the use of controls.

There are three ways to view objects during an IR survey:

- 1) Perpendicular (straight-down or up)
- 2) Parallel (straight-ahead)
- 3) Oblique (sloping)

All three views have advantages and disadvantages during an IR survey.

The platform selected for a given survey is made based on many factors. Three platforms are discussed:

- 1) Rotar wing aircraft (helicopters)
- 2) Fixed wing aircraft (light airplanes)
- 3) UAVs (drones)

All three platforms all have advantages and disadvantages during an IR survey.

This paper focuses on applications that lend themselves to oblique thermal imaging and the platforms which work best for a given project.

9861-47, Session PWed

Emissivity retrieval from indoor hyperspectral imaging of mineral grains

Bardia Yousefi, Saeed Sojasi, Clemente Ibarra-Castanedo, Univ. Laval (Canada); Georges Beaudoin, Univ. Laval (Canada); François Huot, Xavier Maldague, Erik Lalonde, Univ. Laval (Canada)

The proposed approach addresses the problem of retrieving the emissivity of hyperspectral data in the spectroscopic imageries from indoor experiments. This methodology was tested on experimental data that have been recorded with hyperspectral imagery working in 7.71 to 11.76µm wavelength bands. The proposed technique provides a framework for computing down-welling spectral radiance applying non-negative matrix factorization (NMF) analysis. It provides the necessary means for the non-uniform correction of active thermographical experiments. The obtained results indicate promising accuracy. In addition, the application of the proposed technique is not limited for only non-uniform heating spectroscopy and has been applied for uniform spectroscopy as well.

9861-35, Session 8

DMD illuminated spatial-temporal modulated thermography

Joshua D. Pribe, Qizi Zhang, Srinivas C. Thandu, Zhaozheng Yin, Edward C. Kinzel, Missouri Univ. of Science and Technology (United States)

A spatially localized heat source, such as a focused laser beam, produces tangential thermal gradients which results in a heat flux away from the heat source. This can resolve anisotropy in the thermal conductivity, including cracks. The localized heat source is temporally modulated and can be flashed, scanned, or have sinusoidally modulated intensity. A critical obstacle is that the interrogation region is very small. In order to inspect an entire target, the heat source must be moved relative to the surface. Because the heat equation satisfies the principle of superposition, a better approach is to simultaneously excite multiple heat sources in parallel. Each heat source is modulated at a different frequency, and its response obtained by demodulating at its drive frequency. This paper reports on a system using a Digital Micromirror Device (DMD) to modulate a NIR laser source spatially and temporally. This source is used to illuminate a target, whose response is recorded with a thermal camera. The measured surface temperature is demodulated point-by-point at multiple frequencies in post processing. This paper demonstrates this concept and benchmarks the performance in terms of the resolution of the imager, DMD, and optical alignment. The resolvable thermal diffusivity contrast is studied at different depths and orientations. The optical alignment of the instrument is characterized in terms of the Modulation Transfer Function (MTF) of the combined projection/imaging system. Experimental results are compared to ideal images obtained from finite element simulation.

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9861-36, Session 8

Non-destructive testing of mid-IR optical fiber using infrared imaging

Marc-André Gagnon, Telops (Canada); Vincent Fortin, Réal Vallée, Ctr. d'Optique, Photonique et Laser (Canada); Vincent Farley, Philippe Lagueux, Telops (Canada); Éric Guyot, Telops France (France); Frédérick Marcotte, Telops (Canada)

There are many applications related to mid-infrared (IR) laser technologies which are very promising in the field of defense and security. Among the different types of laser technologies suitable for this spectral range are the one using rare-earth emission within optical fibers. These systems present the advantage of being relatively compact and efficient. However, the optical fibers typically used for such devices are made of unconventional materials such as fluoride and chalcogenide glasses. In order to make an efficient laser, the material must be exempt of defects as these translate into power lost which can even lead to laser failure. For these reasons, quality control (QC) of these materials represent a very important aspect in the development of this technology. However, existing QC techniques are not compatible with chalcogenide fibers because of their limited transparency in the visible spectral range. For this reason, the Centre d'optique, photonique et laser (COPL) has developed a novel non-destructive testing (NDT) methodology based on infrared imaging to address this problem. The experimental setup consists of an erbium doped fluoride fiber laser at 2.8 μm , optical fiber alignment stages and an InSb infrared camera. Infrared imaging of the material using different spectral filters allows to locate the defects along the fibres. The results illustrate how this simple screening technique ease the selection of quality fibers for the design of high power mid-IR lasers.

9861-37, Session 8

Wide dynamic rang logarithmic InGaAs SWIR sensor suitable for eye-safe active imaging

Yang Ni, New Imaging Technologies (France)

Eye-safe active imaging can be implemented by using 1.55 μm eye-safe laser with InGaAs image sensors. But classic InGaAs sensor with CTIA pixel structure can not be efficiently capture the light energy at very short exposure time. In this paper, we present a newly developed wide dynamic range InGaAs SWIR sensor capable of very short exposure time (<200ns). This InGaAs sensor uses a specially designed photodiode array hybridized to a CMOS ROIC with plurality of readout modes. The InGaAs photodiodes generate a logarithmic response for constant ambient illumination with a huge dynamic range (>120dB). Under very short pulsed illumination, they generate a response linearly dependent of illumination energy. Together with 3-memory based ROIC pixel design and flexible readout chain, an ambient light lit image and a laser pulsed illuminated image can be generated for each frame. Detailed results will be presented during the conference. A live demo camera will be also presented at the commercial exhibition session.

9861-38, Session 8

A simple blackbody simulator with several possibilities and applications on thermography

Laerte dos Santos, Alisson M. Lemos, Marco A. Abi Ramia Jr., Furnas Centrais Elétricas S.A. (Brazil)

This paper presents a blackbody simulator that initially was developed

to make possible the practical exams for the Brazilian thermography certification. However, the device proved to be very useful to be used in laboratories and classrooms. It has presented good temperature accuracy, uniformity and repeatability and can be used as a low cost blackbody.

It is a portable instrument controlled and monitored by computer via wireless communication, but what makes it unique are its accessories and software granting a number of very useful situations in radiation thermometry. Examples: changes in surface target emissivity using sheets with different emissivities or by graduated adjustment of viewing angle on the vertical or horizontal position allowing thus tests of angular dependence emissivity; enables transmittance tests of different materials; allows tests of spatial and measurement resolution; provides tests on which infrared reflections are involved through a controlled source of high temperature.

In addition to all features described above, a software developed in LabView allows continuously monitor the target area temperature. From the monitored data, the system is able to create spreadsheets and temperature versus time graphs, and permits the synchronization of its own clock with the thermographic camera's clock.

The simulator itself provides the means to perform the practical exams of the Brazilian thermography certification. With this solution, candidates are evaluated on their ability to carry out focus adjustment, to measure the reflected apparent temperature according to ASTM E1862 or ISO 18434-1 Annex A.1, to measure the emissivity according to ASTM E1933 or ISO 18434-1 Annex A.2, to measure the transmittance described by ASTM E1897, to perform tests involving reflections and to carry out tests related to spatial and measurement resolution as well. Testing related to thermal insulation and thermal conductivity evaluation are also possible.

9861-48, Session 8

IR camera system with an advanced image processing technologies

Syuichi Okubo, Tetsuo Tamura, Nippon Avionics Co., Ltd. (Japan)

We have developed image processing technologies for resolving issues caused by the inherent UFPA (uncooled focal plane array) sensor characteristics to spread its applications. For example, large time constant of an uncooled IR (infra-red) sensor limits its application field, because motion blur is caused in monitoring the objective moving at high speed. The developed image processing technologies can eliminate the blur and retrieve almost the equivalent image observed in still motion. This image processing is based on the idea that output of the IR sensor is construed as the convolution of radiated IR energy from the objective and impulse response of the IR sensor. With knowledge of the impulse response and moving speed of the objective, the IR energy from the objective can be de-convolved from the observed images. We have successfully retrieved the image without blur using the IR sensor of time constant of about 15 ms under the conditions in which the objective is moving at the speed of about 10 pixels/60 Hz.

The image processing for reducing FPN (fixed pattern noise) has also been developed. UFPA having the responsivity in the narrow wavelength region, e.g., around 8 μm , is appropriate for measuring the surface of glass. However, it suffers from severe FPN due to lower sensitivity compared with 8-13 μm . The developed image processing exploits the images of the shutter itself, and can reduce FPN significantly.

At the conference, the various applications of IR camera system, as well as the developed technologies will be discussed.

9861-39, Session 9

Quantitative dual-spectrum IR breast imaging system: early detection and chemotherapy response monitoring

Chi-En Lee, National Taiwan Univ. College of Medicine

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Thermosense: Thermal Infrared Applications XXXVIII**

(Taiwan); Chung-Ming Chen, Chia-Yen Lee, National Taiwan Univ. (Taiwan)

The underlying principle of the QDS-IR is to decompose the heat energy of each pixel on breast surface into the contributions from the high-temperature and normal-temperature tissues based on the heat energy measured by a pair of middle-wave and long-wave IR cameras. As a parametric map, which is computed from the middle-wave and long-wave contributions of the high-temperature tissue to characterize the tumor growth and chemotherapy response monitoring. It needs to be emphasized that the QDS-IR and the conventional thermal images are fundamentally different. The thermal images reveal only the heat energy of a heat equilibrium state among various heat-source tissues. On the other hand, the parametric map quantifies the middle-wave and long-wave IR energy and thermal properties of the high-temperature tissues.

Due to the longitudinal monitoring, the maker-free longitudinal IR image registration and temperature normalization are necessary. The new longitudinal IR image registration algorithm, is the genetic particle competition mechanism to select the corresponding points of two IR images fully automatically and may be easily extended to other parts of the human body. A linear temperature normalization is based on the longitudinal registration to minimize the effects of the physiology and environment by constructing a linear transformation function of the representative pixel-wise regions along the time. While the time course IR images have registered and normalized, the tumor tissue may be classified by the analysis of the heat change.

9861-40, Session 9

Standardization of infrared breast thermogram acquisition protocols and abnormality analysis of breast thermograms

Mrinal Kanti Bhowmik, Usha Rani Gogoi, Kakali Das, Anjan K. Ghosh, Tripura Univ. (India); Debotosh Bhattacharjee, Jadavpur Univ. (India); Gautam Majumdar, Agartala Government Medical College (India)

The non-invasive, painless, radiation-free and cost-effective infrared breast thermography (IBT) makes a significant contribution in improving the survival rate of breast cancer patients by early detecting the diseases. This paper presents a "set of standard breast thermogram acquisition protocols" to improve the potentiality and accuracy of breast thermograms in early breast cancer detection. Maintaining all these protocols, an infrared breast thermogram acquisition setup has been established at the Regional Cancer Centre (RCC) of Government Medical College (AGMC), Tripura, India. The acquisition of breast thermogram is followed by the breast thermogram interpretation, for identifying the presence of any abnormality. However, due to the presence of complex vascular patterns, accurate interpretation of breast thermogram is a very challenging task. The bilateral symmetry of the thermal patterns in each breast thermogram is quantitatively computed by statistical feature analysis. A series of statistical features are extracted from a set of 50 thermograms of both healthy and unhealthy patients. Finally, the extracted features are analyzed for breast abnormality detection. The key contributions of this paper are - a) the designing of a standard protocol suite for accurate acquisition of breast thermograms, b) creation of a new breast thermogram dataset by maintaining the protocol suite, and c) statistical analysis of the thermograms for abnormality detection. By doing so, this proposed work can minimize the rate of false findings in breast thermograms and thus, it will increase the utilization potentiality of breast thermograms in early breast cancer detection.

9861-41, Session 9

Pain related inflammation analysis using infrared images

Mrinal Kanti Bhowmik, Shawli Bardhan, Kakali Das, Tripura Univ. (India); Debotosh Bhattacharjee, Jadavpur Univ. (India); Satyabrata Nath, Agartala Government Medical College (India)

Medical Infrared Thermography (MIT) offers a potential non-invasive, non-contact and radiation free imaging modality for assessment of abnormal inflammation having pain in human body. The assessment of inflammation mainly depends on the emission of heat from the skin surface. Arthritis is a disease of joint damage that generates inflammation in one or more anatomical joints of body. Osteoarthritis (OA) is the most common appearing form of arthritis, and rheumatoid arthritis (RA) is the most threatening form of them. So, the study has been investigated the infrared images of patients suffering from RA and OA. For our investigation, a new dataset containing 40 thermograms of the bilateral knee has been captured from the patient of RA and OA by following a thermogram acquisition standard. The thermograms are pre-processed, and areas of interest are extracted for further processing. The investigation of the spread of inflammation is performed along with the statistical analysis of the pre-processed thermograms. The contribution of the investigation includes: i) A novel thermogram acquisition standard for inflammatory pain disease ii) Analysis of the spread of the inflammation related to RA and OA using K-means clustering. iii) First and second order statistical analysis of pre-processed thermograms. The conclusion reflects that, in case of RA, the inflammation effects bilateral knee whereas inflammation related to OA present in unilateral knee. Also due to the spread of inflammation in OA, contralateral asymmetries are detected through the statistical analysis.

9861-42, Session 9

IR camera temperature resolution enhancing using computer processing of IR image

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

We made computer processing of images, captured by commercially available IR camera (FLIR Inc.), with the aim of IR camera temperature resolution enhancing. We analyze IR images of a person, which drinks water or eats. We follow a temperature trace on human body skin, caused by changing of temperature inside the human body.

Some experiments were made with measurements of a body temperature covered by shirt. We try to see a human body temperature changing in experiments under consideration. For this aim achievement we developed a computer code for computer processing of these IR images.

Shown phenomena are very important for the detection of forbidden objects, cancelled under clothes or inside the human body, by using non-destructive control without using X-rays.

9861-43, Session 10

Mineral identification in hyperspectral image using sparse endmember estimation

Bardia Yousefi, Saeed Sojasi, Clemente Ibarra-Castanedo, Georges Beaudoin, François Huot, Xavier Maldague, Univ. Laval (Canada)

Hyperspectral imagery has been considerably developed during the recent decades. Application of hyperspectral imagery and infrared thermography, particularly for the automatic identification of minerals from satellite

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images, has been the subject of many interesting researches. In this study, a method is presented for the automated identification of the mineral grains typically used from satellite imagery and adapted for analyzing collected sample grains in a laboratory environment. For this, an approach involving Sparse Principle Components Analysis (SPCA) based on Spectral abundance mapping techniques (i.e. SAM, SID, NormXCorr) used for extraction of the representative spectral features. It develops an approximation of endmember as a reference spectrum process through the highest sparse principle component of the pure mineral grains. Consequently, the features categorized by kernel Extreme Learning Machine (Kernel- ELM) classify and identify the mineral grains in a supervised manner. Classification is conducted in the binary scenario and the results indicate the dependency to the training spectra.

9861-44, Session 10

Evaluation of terrestrial photogrammetric point clouds derived from thermal imagery

Jeremy P. Metcalf, Richard C. Olsen, Naval Postgraduate School (United States)

Computer vision and photogrammetric techniques have been widely applied to digital imagery producing high density 3D point clouds. Using thermal imagery as input, the same techniques can be applied to infrared data to produce point clouds in 3D space, providing surface temperature information. The work presented is an evaluation of the accuracy of 3D reconstruction of point clouds produced using thermal imagery. An urban scene was collected over an area at the Naval Postgraduate School, Monterey, CA, viewing from above as with an airborne system. Terrestrial thermal and RGB imagery were collected from a rooftop overlooking the site using a FLIR SC8200 MWIR camera and a Canon T7i DSLR. In order to spatially align each dataset, ground control points were placed throughout the study area using Trimble R10 GNSS receivers operating in RTK mode. Each image dataset is processed to produce a dense point cloud and textured mesh for 3D evaluation.

9861-45, Session 10

A comparative study of experimental and finite element analysis on submillimeter flaws by laser and ultrasonic excited thermography

Hai Zhang, Henrique C. Fernandes, Xavier Maldague, Univ. Laval (Canada)

Stitching is used to reduce dry-core (incomplete infusion of T-joint core) and reinforce T-joint structure. However, it might cause new types of flaws, especially submillimeter flaws.

Recently the authors proposed micro-laser line thermography (micro-LLT), which can detect internal submillimeter flaws. However, the depth and size of submillimeter flaws can affect the detection results. Submillimeter flaws with a diameter of less than 54 μ m were not detectable so far. Micro-LLT can detect the submillimeter porosity (a diameter of 0.162 mm) up to the depth of 90 μ m.

In this paper, micro-laser excited thermography and micro-ultrasonic excited thermography are used to investigate deeper submillimeter flaws in stitched T-joint CFRP. X-ray micro-computed tomography (micro-CT) is used to validate the infrared results. In particular, lock-in technique is used to address deeper layers. And pulse phase thermography (PPT) is used to calculate depth information, which is compared with micro-CT measurements.

Then, a finite element analysis (FEA) is performed. The geometrical model needed for finite element discretization was developed from micro-CT measurements. The model is validated for the experimental results.

Finally a comparison of micro-laser excited thermography and micro-

ultrasonic excited thermography is conducted. The infrared experimental phenomenon and results are explained based on the FEA results.

9861-46, Session 10

Nondestructive evaluation technique using infrared thermography and terahertz imaging

Takahide Sakagami, Daiki Shiozawa, Yoshitaka Tamaki, Tatsuya Iwama, Kobe Univ. (Japan)

Nondestructive testing (NDT) techniques using pulse heating infrared thermography and terahertz (THz) imaging were developed for detecting deterioration of materials. Experimental studies were conducted to demonstrate the practicability of developed techniques.

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9862-1, Session 1

Electrochemical sensing of an amperometric glucose sensor based on hydrothermal sol-gel synthesized ZnO nanorods

Sanghamitra Mandal, Univ. of Arkansas (United States)

The fabrication of an electrochemical sensor for glucose detection using hydrothermally grown zinc oxide (ZnO) nanorods is investigated. The working principle is based on the electrochemical reaction taking place between immobilized glucose oxidase adsorbed by the ZnO nanorods, and the electrolyte glucose. The synthesis of ZnO nanorods on indium tin oxide (ITO) coated glass substrate was performed using a hydrothermal sol-gel growth technique. Characterization of the ZnO nanorods was performed by using the absorption, micro-Raman, and scanning electron microscopies, and the X-ray diffraction analysis. Nafion/GOx/ZnO nanorods/ITO-coated glass substrate was used as a working electrode, while the reference electrode was a platinum plate. Amperometric response for clinical range of blood glucose concentration from 0.01 - 20 mM is measured at +0.8 V. The response time for the tested sensor obtained from the amperometric response curve is estimated to be less than 3 s. The analyzed sensitivity of 1151 $\mu\text{A}/\text{cm}^2 \text{mM}^{-1}$ and the lower detection limit of 0.089 mM for the sensor were estimated from the glucose linear concentration range of 0.01 - 1.6 mM. Electrochemical characterization of the sensor was performed using the cyclic voltammetry method for a voltage range of -0.8 - 0.8 V at a sweep rate of 100 mV/s. Long term stability of the investigated sensor is discussed based on the study of nafion membrane scanning electron microscopy results, performed before and after the amperometric titration.

9862-2, Session 1

Spatial multiplexing of whispering gallery mode sensors for trace species detection

Stephen Holler, Matthew Speck, Fordham Univ. (United States)

The whispering gallery mode biosensor has emerged as a robust tool for the sensitive detection of trace quantities of biological and chemical micro- and nano-particles, including bacteria, virus and protein. Relying on the specific biochemical interactions, perturbations to the cavity mode induced by the binding of such particles to the microcavity surface result in a quantifiable shift in the resonance mode frequency. The amount by which the resonance frequency shifts is directly proportional to the quantity of adsorbed material and the location at which it binds. The frequency shifts are often observed in transmission, typically through a waveguide. This approach suffers from several challenges, the foremost of which is the challenge in deconvolving signals from several resonators. The ability to simultaneously observe resonance shifts from different resonators allows a single device to target a multitude of chemical and biological agents. We will review the physics behind whispering gallery biosensing and introduce our detection/monitoring scheme, which employs a sensing geometry that offers the prospect for robust and simultaneous multi-sphere monitoring. This spatially multiplexed, multi-cavity approach allows for reference channels to account for common mode and environmental factors, and/or channels for additional target analytes. We will demonstrate the approach on a system on spheres using the human papillomavirus, the causative agent of cervical and head & neck cancers. Ultimately, this approach could be developed into a robust platform for a myriad of chemical and biological targets impacting medicine, the pharmaceutical industry, the food industry, and homeland security, to name a few.

9862-3, Session 1

Plasmonics-based biosensing and diagnostics systems

Tuan Vo-Dinh, Fitzpatrick Institute for Photonics, Duke Univ. (United States); Hsin-Neng Wang, Andrew M. Fales, Hoan Ngo, Bridget M. Crawford, Yang Liu, Duke Univ. (United States)

No Abstract Available

9862-4, Session 1

Compact surface plasmon resonance biosensor utilizing a disposable injection-molded prism in a free form

How-Foo Chen, Chih Han Chen, National Yang-Ming Univ. (Taiwan)

A commercially available surface plasmon resonance (SPR) biosensor usually comes with a high-cost testing chip or an expansive chip/prism assembly, which can easily go beyond \$100/each. Thus is not suitable for food safety testing, environmental bio-pollution monitoring, or clinical diagnosis. Most of the applications are currently limited to antibody development, drug screening, and biological science research though its high sensitivity. Different from those, the proposed SPR biosensor utilizes a low-cost injection-molded technology to produce a low-cost prism, which integrates the functions of optical coupling, the metallic thin film for excitation of SP, and an angle-tuning mechanism for a large dynamic range. The prism is shaped with two parabolic surfaces to control the SP excitation angle by impinging the light beam on different locations of the parabolic surfaces. Meanwhile, a common-path phase interrogation scheme is used to make sure ultra high sensitivity, which is about 10^{-7} refractive index unit (RIU), at any incident angle. This compact SPR biosensor with a large dynamic range in high sensitivity is then obtained to satisfy commercial needs in food safety, environmental bio-pollution monitoring, and fast clinical diagnosis. Because the Au thin film is directly coated on the top surface of this free-form prism, not on a glass slide, the design makes a matching-oil-free operation for testing. The disposability of this low-cost component, less than \$10/each, ensures testing or diagnosis free from cross contamination in bio-samples without high cost. The biosensor is also slim enough to be compatible to modern microscopy technology for further clinical verification.

9862-5, Session 1

Bioprocess rate-based bpCO₂ sensor

Prosper Adangwa, Yordan Kostov, Govind Rao, Madhubanti Chattergee, Univ. of Maryland, Baltimore County (United States)

A miniaturized, low power sensing device capable of measuring bioprocess CO₂ production is presented. It is based on a novel, rate-based approach and is capable of measuring the CO₂ concentration during a bioprocess. A CO₂ permeable sampling loop is inserted into the bioprocess chamber. Prior to measurement, it is purged with N₂. Then, the gas is recirculated between the sampling loop and an optical CO₂ sensor with the aid of a micro piezo-

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pump. The increase of the CO₂ concentration is monitored. As per Fick's second law, the slope of the increase is proportional to the concentration of the CO₂. The sensor features U-shaped gold-plated optical/gas path and uses infrared LED/photodiode as detection system. The device exhibits high sensitivity, which is due to its small sampling volume (~9 microliters).

The sensor is controlled by a custom software (LabVIEW). It controls the purge/recirculation cycles, measures the slope and converts it in CO₂ concentration. The software allows for direct monitoring of CO₂ in a fermenter. The miniaturized device has been used to perform continuous on-line monitoring of bacterial (E. Coli) fermentation.

9862-6, Session 1

Optical sensor for rapid microbial detection

Mustafa Al-Adhami, Dagmawi Tilahun, Govind Rao, Yordan Kostov, Univ. of Maryland, Baltimore County (United States)

In biotechnology, the ability to instantly detect contaminants is key to running a reliable bioprocess. Bioprocesses are prone to be contaminated by cells that are abundant in our environment; detection and quantification of these cells would aid in the preservation of the bioprocess product. This paper discusses the design and development of a portable kinetics fluorometer which acts as a single-excitation, single-emission photometer that continuously measures fluorescence intensity of an indicator dye, and plots it. Resazurin is used as an indicator dye since the viable contaminant cells reduce Resazurin to Resorufin, the latter being strongly fluorescent. A photodiode detects fluorescence change by generating current proportional to the intensity of the light that reached it, and a trans-impedance differential op-amp ensures amplification of the photodiodes' signal. A microfluidic chip was designed specifically for the device. It acts as a fully enclosed cuvette, which enhances the Resazurin reduction rate. E. coli in LB media, along with Resazurin were injected into the microfluidic chip. The optical sensor detected the presence of E. coli in the media based on the fluorescence change that occurred in the indicator dye in concentrations as low as 10 CFU/ml. A method was devised to detect and determine an approximate amount of contamination with this device. This paper discusses application of this method to detect and estimate sample contamination. This device provides fast, accurate, and inexpensive means to optically detect the presence of viable cells.

9862-7, Session 1

Handheld chem/biosensor using extreme conformational changes in designed binding proteins to enhance surface plasmon resonance (SPR)

Lori Lepak, Phoebus Optoelectronics, LLC (United States); Peter Schnatz, The City College of New York (United States); Igor Bendoym, Phoebus Optoelectronics, LLC (United States); Derek J. Kosciolk, Ronald L. Koder, The City College of New York (United States); David T. Crouse, Phoebus Optoelectronics, LLC (United States) and The City College of New York (United States)

We have developed a prototype of a simple, handheld, multiplexable diagnostic device for the rapid detection of chemical or biological agents. Our device employs metamaterials on which are bound de novo designed, supercharged analyte-binding proteins. The proteins are engineered to undergo exceptionally large conformational changes upon binding with their target with a specificity comparable to wild-type antibodies. This 'superfolding' causes a large change in the index of refraction immediately adjacent to the surface, enhancing the sensitivity of the SPR. As a model system, we designed, synthesized, and characterized a heme-binding

supercharged protein, called Mega(-). Mega(-) demonstrated a heme-specific, binding-induced refractive index change, calculated to correspond to a 100-1000-fold signal enhancement, relative to state-of-the-art ligand-antibody SPR detection systems.

The designed proteins are bound to metastructured gratings of gold wires on a fused silica substrate, allowing the device to operate in transmission mode. All optical components are aligned in a structurally robust, straight line configuration. Each fused silica chip is disposable, and may be easily multiplexed by functionalizing different spatial areas with different supercharged proteins designed to selectively bind to different targets. Analytes are delivered to the chip by simply pipetting a liquid sample directly onto the functionalized metasurface. Thus, in addition to its thousandfold enhanced sensitivity, our device has a much smaller footprint, is more resistant to misalignment, and is easier to use than any currently available reflection-based SPR systems. Potential commercial applications for our device are expected to include medical diagnostics, antiterrorism, forensics, environmental monitoring, agriculture, and food safety.

9862-8, Session 1

In-situ SERS study of Au-catalyzed hydrogen peroxide decomposition using nanostructured optical fiber

Kai Liu, Hui Chen, Fei Tian, Stevens Institute of Technology (United States)

Hydrogen peroxide is an important oxygen source for Au-catalyzed green production of hydrocarbon oxidation. The reaction pathways over gold catalyst has yet to be experimentally confirmed. We herein utilize our nanostructured optical fiber (NSOF) clad by nanoporous anodized aluminum oxide (AAO) with immobilized Au nanoparticle as a catalytic reactor and sensitive SERS probe to investigate the molecular level details during Au-catalyzed decomposition of hydrogen peroxide in situ. The method for stable anchoring of Au nanoparticle in AAO with optimal catalytic and SERS activities will be determined. The formation of intermediates and final products under acidic and non-acidic conditions are measured in situ at the H₂O₂ concentrations of 3%-30%. The resultant knowledge can aid in the derivation of the kinetic data and mechanism for Au-catalyzed decomposition of hydrogen peroxide.

9862-9, Session 2

Development of an autonomous unmanned aerial system for atmospheric data collection and research

David Hanlon, Belay B. Demoz, Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

This paper addresses the use of unmanned aerial systems (UAS) to carry out atmospheric data collection and studies. This is an emerging field with significance to NOAA, NASA, USDA, and other government agencies. The Joint Center for Earth Systems Technology (JCET), which operates under a cooperative agreement between the University of Maryland, Baltimore County (UMBC) and the NASA Goddard Space Flight Center (GSFC), is interested in the development of new technology for environmental remote sensing. In addition, Howard University's NOAA Center for Atmospheric Studies (NCAS) at Beltsville, Maryland and its partners have selected this research as one of the many inter-center activities. The center is involved with training graduate students and focuses on NOAA-targeted research. In particular, an important area of research is the study of the chemistry and physics of Earth's planetary boundary layer (PBL). The PBL, also known as the atmospheric boundary layer (ABL), is the lowest part of the atmosphere and its behavior is directly influenced by its contact with the planetary surface. Sampling of the PBL is performed in a timely and periodic manner. Currently, sensors and uncontrollable balloons are used to obtain relevant data and information. This method is cumbersome and can be ineffective

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in obtaining consistent environmental data. This paper proposes the use of autonomous UAS' to study the atmosphere in an effort to improve the efficiency and accuracy of the sampling process. The UAS setup and design is provided, and preliminary data collection information is shared.

9862-10, Session 2

Security control by Raman lidar at the objects fuel and energy complex

Alexandr S. Grishkanich, Sergey V. Kascheev, Alexandr P. Zhevlakov, ITMO Univ. (?????????? ????); Igor S. Sidorov, Univ. of Eastern Finland (Finland); Leonid Smirnov, ITMO Univ. (?????????? ????)

Raman lidar operating by the method of Raman scattering is suitable for detection of substances of indicators. As ethane(C₂H₆) and hydrogen Sulfide(H₂S) are the immediate constituents, and will be monitoring oil and gas pipelines.

Taking into account the spectral characteristics of substances subject to monitoring and that the maximum transmittance of the atmosphere is in the ultraviolet region of the spectrum indicates that the control network of oil and gas will be produced in this region of the spectrum. The radiation source in this device is a YAG-Nd laser, because the monitoring takes place in the ultraviolet region of the spectrum, the wavelength on which will be tracked substances are indicators equal to 266 nm, which is the 4 harmonic of this laser.

Using Raman lidar for the monitoring of safety of objects of fuel and energy complex it is safe to say that the resulting leakage will be detected for short periods of time, thereby greatly reducing the risk of disasters that may occur.

9862-11, Session 2

Local sensing of atmospheric electric field around Nalchik city

Aida A. Adzhieva, Kabardino-Balkarian State Agricultural Univ. (Russian Federation); Vitaliy A. Shapovalov, Idar Mashukhov, High-Mountain Geophysical Institute (Russian Federation)

The magnitude and direction of the atmospheric electric field are widely varied in time and space and depended on the weather conditions, the terrain orography, the time of the year, the time of the day and other factors. This feature of the electrical processes in the atmosphere is determined by the complex dual character: they simultaneously generate hardly dissociable effects of the local and the global scale.

With the help of the electric field mill network EFM550 (by Vaisala) the long-term researches (2005-2014) of atmospheric electric field dynamics around Nalchik city were executed. The lightning discharges were monitored using lightning sensors network LS8000.

The aim of this study is to investigate the influence of local phenomena (rainfall, clouds and thunderstorm activity) on the change of the atmospheric electric field variations. In general, there is a close relationship between the electric field and the meteorological elements. The diurnal variation of the electric field value is the object of the separation of global and local factors of atmospheric electricity. It was received that the thunderstorm processes bring the most significant distortions in the natural dynamic of the electric field values.

The atmospheric electric field variations under fair weather and thunderstorm conditions were studied.

9862-12, Session 2

Multispectral imaging of aircraft exhaust

Emily E. Berkson, David W. Messinger, Rochester Institute of Technology (United States)

Recent studies show that aircraft pollutants emitted during the landing-takeoff (LTO) cycle have significant effects on the local air quality surrounding airports. There are currently no inexpensive, portable sensors to quantify the amount of pollutants emitted from aircraft engines throughout the LTO cycle, or to monitor the spatial-temporal extent of the exhaust plume. We seek to first thoroughly characterize the emissions from jet engine plumes, and secondly to design an imaging system that can be deployed at any airport, which will quantify the emitted pollutants and temporally track the distribution of the plume. MWIR and LWIR spectral signatures of the main constituents in a jet engine plume were determined, along with the impact of each pollutant on local air quality. The spectral signatures dictated which filters were used in the prototype system. The current focus is on emitted nitrogen oxide and sulfur dioxide, which are difficult to suppress and not very well characterized, respectively. A plume was modeled using typical engine characteristics, and radiometric testing was done to assess the plume detectivity. These initial calculations determined the noise-equivalent radiance of a camera system that would be required to detect the presence of the plume. This paper will show results from the radiometric modeling of a jet engine exhaust plume and describe a prototype MWIR and LWIR imaging system capable of quantifying emitted pollutants and monitoring the spatial-temporal extent of the plume. This project will help monitor local pollution surrounding airports and allow better-informed decision-making regarding emission caps and pollution bylaws.

9862-13, Session 2

Integration of acoustic and light sensors for marine mining of anti-cancer compounds

Gordon W. Wiegand, EBc (United States)

A description of a human-mounted search-survey apparatus was illustrated to track specific invertebrates known to be a source of anti-tumor compounds. Sensors used to identify tunicates and analyze bacterial source of these chemicals were contrasted. Our system was expanded to include an echo sounder fitted within a 20 foot bay research vessel. A pre-search, scouting track was conducted within the upper Chesapeake bay by utilizing a 77/200 kHz acoustic wave produced by a Garmin echoMAP scanning sonar system. Integrated scatter pulses are detected by a hull-mounted transducer which records coordinates and timing of the sonar return during a systematic parallel transect survey. The resulting map with coastal reference is used to plan a 2nd more detailed survey using a diver with camera and strobe. CMOS, GPS and GPS/ photo integration software is used to construct image-time stamps and a geo-spatial map within the pre-surveyed location of the estuary. Acoustic images from the boat transducer and photo-images from the diver are combined geospatially by GPX integration software. Our principle invertebrate target is the orange tunicate, Ecteinascidia turbinata. Bacteria living within its biome produces Trabectedin which is used for treatment of soft-tissue sarcoma. This animal inhabits the Atlantic coast of the U.S. from Florida to Maryland. We exploit the unique morphology of all tunicates to find members of this class based on their inter-cavity siphon. A unique acoustic scatter pattern results from this animal's hollow structure.

9862-14, Session 2

Automated information-analytical system for thunderstorm monitoring and early warning alarms using modern physical sensors and information technologies with elements of artificial intelligence

Anton Boldyrev, Southern Federal Univ. (Russian Federation); Anatoly K. Adzhiev, High-Mountain Geophysical Institute (Russian Federation); Dmitriy Bepalov, Yaroslav Trubnikov, Southern Federal Univ. (Russian Federation)

Finding advanced ways of hazard assessment, forecasting and warning of multiscale extreme weather events (such as hail, thunderstorms and lightning) and related natural and technogenic disasters is considered in the paper. The research object is the territory of the North Caucasus with intensive development of extreme hydro-meteorological phenomena that causes significant damage to the economy and population.

The full range of modern sensor equipment, which is unique for the Russian Federation was applied. It is operated from 2008, includes networks of the lightning location sensors and the electric field mills, meteorological stations, hardware and software complex of radar and satellite information, meteorological radar and others. The applied measurement methods are endorsed and used by RosHydromet and the World Meteorological Organization. The modern hybrid information technologies with elements of artificial intelligence were used to develop the expert system for operation with such multiple and diversified physical information.

The method of data clustering on the geographical basis and scaling method (layering) were used. The approach of using physical-mathematical model data, the reduction of number of cluster parameters to the total value (or multiple values) was used in the system's neural core. It becomes available to connect a large number of clients, as well as modeling and testing tools via a software interface (API) without having to change the kernel, restart the software complex. It was shown that using of modern sensors and information technologies increases the effectiveness of warning alarms by 70% and improves the forecast criteria for preventing risks and damages.

9862-15, Session 2

Automated sensing of thunderstorm characteristics and lightning parameters in the south of the European part of Russia

Anatoly K. Adzhiev, High-Mountain Geophysical Institute (Russian Federation); Anton Boldyrev, Southern Federal Univ. (Russian Federation); Dalkhat Kuliev, High-Mountain Geophysical Institute (Russian Federation)

The North Caucasus of the Russian Federation, due to its geographical location, has a high cloud to ground lightning activity. According to the latest research, the number of thunderstorm days is 170 per year. The ground flash density is higher than 5 flash/km² on the south and 2 flash/km² on the north. Technique of simultaneous registration of thunderstorms, obtained from the Lightning Sensors Network, and atmospheric electric field, obtained from electric field mills network, is developed for the territory with radius of 650 km. The measurement methods and equipment were determined assumed the possibility of their operation without maintenance for a long time to provide the appropriate number of the monitored data for a short period. The hardware-software sensing complex was developed. It included the atmospheric electric field mill EFM550, the lightning sensor LS8000, the software for data mining, processing and visualization.

It was found that the part of cloud-to-ground lightnings (positive and negative) is 12% from their total quantity. The number of IC and CC

lightnings is 88%. According to received results, the positive discharges are about 23% of total quantity of CG lightnings. Average current in the negative lightnings is 13.5 kA and 10.6 kA in the positive lightnings.

The analysis of received results represents a good correlation of values of the lightning sensors network and atmospheric electric field. This correlation is most notably occurred for cloud-to-ground lightning discharges.

9862-16, Session 3

Standoff midwave infrared hyperspectral imaging of ship plumes

Marc-André Gagnon, Jean-Philippe Gagnon, Pierre Tremblay, Simon Savary, Vincent Farley, Philippe Lagueux, Telops (Canada); Éric Guyot, Telops France (France); Martin Chamberland, Frédérick Marcotte, Telops (Canada)

Characterization of ship plumes is very challenging due to the great variety of ships, fuel, and fuel grades, as well as the extent of a gas plume. In this work, imaging of ship plumes from an operating ferry boat was carried out using standoff midwave (3-5 μm) infrared hyperspectral imaging. Quantitative chemical imaging of combustion gases was achieved by fitting a radiative transfer model. Combustion efficiency maps and mass flow rates are presented for carbon monoxide (CO) and carbon dioxide (CO₂). The results illustrate how valuable information about the combustion process of a ship engine can be successfully obtained using passive hyperspectral remote sensing imaging.

9862-17, Session 3

Study of consolidating materials applied on wood by hyperspectral imaging

Silvia Serranti, Giuseppe Bonifazi, Giuseppe Capobianco, Sapienza Univ. di Roma (Italy); Giorgia Agresti, Ulderico Santamaria, Claudia Pelosi, Luca Calienno, Rodolfo Picchio, Angela Lo Monaco, Univ. degli Studi della Toscana (Italy)

The focus of this study was to investigate the potentiality of HyperSpectral Imaging (HSI) in the monitoring of commercial consolidant products applied on wood samples. Poplar (*Populus Sp.*) and walnut (*Juglans Regia L.*) were selected for the consolidant application. Both traditional and innovative products were selected based on acrylic, epoxy and aliphatic compounds. Wood samples were stressed by freeze/thaw cycles in order to cause degradation of the material. Then the consolidants were applied under vacuum. At last the samples were artificially aged for 168 hours in a Solar box [1].

The samples were acquired in the SWIR (1000-2500 nm) range by SISUCHEMA XL (Specim, Finland) before ageing and after 168 hours of irradiation. As comparison, color measurement was also used as economic, simple and noninvasive technique to evaluate the ageing effects of wood treatments. All data were then processed adopting a chemometric approach for defining correlation models, HSI based, between consolidating materials, wood species and short time ageing effects [2].

[1] G. Genco, A. Lo Monaco, C. Pelosi, R. Picchio, U. Santamaria, A study of colour change due to accelerated sunlight exposure in consolidated wood samples, *Wood Research*, 56 (4), 2011, 511-5241.

[2] G. Bonifazi, L. Calienno, G. Capobianco, A. Lo Monaco, C. Pelosi, R. Picchio, S. Serranti, Modelling color and chemical changes on normal and red heart beech wood by reflectance spectrophotometry, Fourier Transform infrared spectroscopy and hyperspectral imaging, *Polymer Degradation and Stability*, 113, 2015, 10-21.

9862-18, Session 3

Challenges in automatic sorting of construction and demolition waste by hyperspectral imaging

Frank Hollstein, RTT Steinert GmbH (Germany); Sixto Arnaiz, Inigo Cacho, GAIKER Centro Tecnológico (Spain); Markus Wohllebe, RTT Steinert GmbH (Germany)

EU-28 countries currently generate 461 Mt/year of construction and demolition waste (C&DW) and the generation rate is expected to reach around 570 Mt between 2025 and 2030. There is great potential for recycling C&DW materials since they are massively produced and contain valuable resources. But new C&DW is more complex than existing one and there is a need for shifting from traditional recycling approaches to novel recycling solutions. One basic step to achieve the objective is an improvement in (automatic) sorting technology. Hyperspectral Imaging is a promising candidate to support this process. However, the industrial distribution of Hyperspectral Imaging in the C&DW recycling branch is currently insufficiently pronounced due to high investment costs, still insufficient robustness of optical sensor hardware in harsh ambient conditions and, because of the need of sensor fusion, not well-engineered software methods to perform the (on line) sorting jobs. Frame rates of over 300 Hz are needed for a successful sorting result. Currently the biggest challenges with regard to C&DW detection cover the need of overlapping VIS hyperspectral images and NIR hyperspectral images in time and space, in particular for selective recognition of contaminated particles. In the study on hand a new approach for compact hyperspectral imagers is presented by exploiting VIS-NIR hyperspectral sensor fusion in real time. The contribution describes both laboratory results with regard to optical detection of the most important C&DW material composites as well as a development path for an industrial implementation in automatic sorting and separation lines.

9862-19, Session 3

Multispectral imaging and new methods to characterize flocs and colloidal aggregates in water

Charles R. Bostater Jr., Florida Institute of Technology (United States)

In-situ sampling, characterization and quantification of colloidal aggregates and flocs in ambient water is complex but needed in order to understand their role in development and maintenance of moving fluid muds, bottom boundary lutocline layers and nephelometric interfaces in estuarine systems. These bottom boundary interfaces and associated processes contribute to sedimentation, particle deposition and resuspension of total particulate matter and associated nutrients. Increasing the scientific understanding of the above requires advances in environmental sensing instrumentation (passive and active) to successfully address these analytical challenges. Standalone in-situ sensors that automatically perform multiple steps including sampling, sample transport, separation, and detection have the potential to greatly advance in-situ analytical science instruments related to the above. In this paper and presentation new systems for environmental monitoring and surveillance of these delicate particulate structures are reviewed and results described in relation to support of waterway dredging and related operations. Results using passive multispectral and hyperspectral optical imaging will be described along with active acoustic imaging, and the use of passive sondes for sediment sample collection and estimation of mass flux or movement of the particulate assemblages. The sensor systems developed will help address analytical needs reported in past studies and provide new standard methods for assessing the mass flux of cohesive particles in aquatic bottom boundary layers.

9862-20, Session 4

Case study sensitivity analysis of transmission spectra for water contaminant monitoring

Samuel C. Lambrakos, U.S. Naval Research Lab. (United States); Constantine Yapijakis, The Cooper Union for the Advancement of Science and Art (United States); Daniel C. Aiken, U.S. Naval Research Lab. (United States); Andrew Shabaev, George Mason Univ. (United States); Scott A. Ramsey, Joseph E. Peak, U.S. Naval Research Lab. (United States)

Monitoring of contaminants associated with specific water resources using transmission spectra, with respect to types and relative concentrations, requires tracking statistical profiles of water contaminants in terms of spatial-temporal distributions of electromagnetic absorption spectra ranging from the ultraviolet to infrared. For this purpose, correlation between spectral signatures and types of contaminants within specific water resources must be made, as well as correlation of spectral signatures with results of processes for removal of contaminants, such as ozonation. Correlation between absorption spectra and changes in chemical and physical characteristics of contaminants, within a volume of sampled solution, requires sufficient sensitivity. The present study examines the sensitivity of transmission spectra with respect to general characteristics of water contaminants for spectral analysis of water samples.

9862-22, Session 4

The role of topography in guiding axon outgrowth and Schwann cell migration in PEI microchannels

Paul M. Kasili, Bunker Hill Community College (United States); Ryan Koppes, Polina O. Anikeeva, Massachusetts Institute of Technology (United States)

Injuries to the peripheral nervous system (PNS) are devastating and can result in physical impairments, poor functional outcomes, and high levels of disability or life-long disability. Successful recovery of peripheral nerve injuries requires specific physical and molecular guidance cues. This work investigates the role of topography, as a physical cue, in guiding dorsal root ganglion (DRG) axon outgrowth and Schwann Cell (SC) migration in polyetherimide (PEI) channels. This work successfully demonstrates the role of topography in PEI-based neural guidance micro-channels in guiding axonal outgrowth and SC migration from DRG.

9862-23, Session PTue

Advanced remote sensing of thunderstorm events and atmospheric electric field

Anton Boldyrev, Southern Federal Univ. (Russian Federation); Anatoly K. Adzhiev, Saniya Kazakova, Ruslan Gyatov, Zaira Daurova, High-Mountain Geophysical Institute (Russian Federation)

Diurnal electric field variation is the object of separation of global and local atmospheric electricity factors. The most significant distortions in the natural course of the electric field is made by the lightning processes associated with the generation of space charge in clouds, fogs and precipitation zones. Detailed spatial-temporal analysis of simultaneous monitoring data of electric field variations and lightning parameters was made for the region of the south region of the Russian Federation. Modern lightning and electric field sensors with advanced measurement technique, algorithms of data

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mining and operation were developed to provide representative physical data.

The period of sixteen days including four thunderstorm days and twelve fair weather days was analyzed. About 3928 lightning discharges were fixed during this period. This number includes 3610 intracloud discharges (IC), 64 cloud-to-ground (CG) positive and 254 cloud-to-ground (CG) negative discharges. Simultaneously electric field was suddenly varied from normal values of +130 V/m up to range of -10 kV/m to +10 kV/m. The critical values of the atmospheric electric field for the CG discharges formation were found. The correlation analysis of electric field and number of discharges was made. It was found that CG discharges occurs when the atmospheric electric field exceeds ± 4 kV/m. The number of CG discharges grows while electric field increases. IC discharges are fixed if the electric field is more than ± 0.5 kV/m. The part of CG flashes (positive and negative) is about 8% from the total number. Positive flashes are 20% from the CG total number.

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9863-1, Session 1

Multiplexed chiral plasmonic assays

Affar S. Karimullah, Ryan Tullius, Paul Reynolds, Nikolaj Gadegaard, Malcolm Kadodwala, Univ. of Glasgow (United Kingdom); Oriol Roig, Univ. of Barcelona (Spain); Calum Jack, Anwer Saeed, Univ. of Glasgow (United Kingdom)

Plasmonic sensors with complex nanostructures, allow us to generate unique electromagnetic fields that can be applied to new forms of spectroscopy and detection schemes. However these nanostructures still depend on time consuming and expensive lithographic techniques making commercialization of the sensors onerous. Our work presents a new opportunity to utilize disposable plasmonic sensors for rapid diagnosis and drug discovery applications. We have developed high-throughput, injection molded templates that are coated with gold to produce metafilms (Karimullah et al, Adv. Mat. 2015). These metafilms have asymmetric structures that generate left and right handed (chiral) polarized evanescent fields that are sensitive to the higher order structure of surface bound biomolecules. Our metafilm based sensors can hence detect conformational changes due to biomolecular interactions (Tullius et al, J. Am. Chem. Soc. 2015). We apply these sensors to detect ligand induced changes in enzymes, cancer relevant proteins and antibody interactions to present their feasibility for high-throughput, label-free assay systems. When coupled with an imaging methodology, we demonstrate the potential to screen multiple protein ligand and protein-protein interactions with high sensitivity using minute sample quantities in a single experiment. With further advantages such as low temperature sensitivity and design flexibility, these multiplexed chiral plasmonic assays could potentially provide low-cost rapid diagnosis for multiple pathogens and phenotypic screening without complex laboratory testing.

9863-2, Session 1

Sensing the morphology of kidney stones; effect of pH on the morphology

Neelesh Agarwal, Univ. of Maryland, Baltimore County (United States); Sara Bohorfoush, Stacey Sova, Bradley Arnold, Fow-Sen Choa, Brian M. Cullum, Narsingh B. Singh, Univ. of Maryland, Baltimore County (United States)

There is a strong need to understand the growth of kidney stones since it is very painful for both men and women. At present there is no clear understanding why it grows in different form and why it is painful to some people from the start of growth and why it is not painful to some people even if it grows in large sizes. This paper is a preliminary effort to understand these issues.

9863-3, Session 1

Growth mechanism of nanowires: ternary chalcogenides

Narsingh B. Singh, Univ. of Maryland, Baltimore County (United States); Sam Coriell, Univ. of Maryland, Baltimore County (United States); Richard Hopkins, Hopkins, Inc. (United States); Ching-Hua Su, NASA Marshall Space Flight Ctr. (United States); Bradley Arnold, Brian M. Cullum,

Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

No Abstract Available

9863-4, Session 1

Rapid discovery of peptide capture candidates with demonstrated specificity for structurally similar toxins (*Invited Paper*)

Deborah A. Sarkes, Margaret M. Hurley, Matthew B. Coppock, Mikella E. Farrell, Paul M. Pellegrino, Dimitra N. Stratis-Cullum, U.S. Army Research Lab. (United States)

Peptides have emerged as viable alternatives to antibodies for molecular-based sensing due to their similarity in recognition ability despite their relative structural simplicity. Various methods for peptide capture reagent discovery exist, including phage display, yeast display, and bacterial display. One of the primary advantages of peptide discovery by bacterial display technology is the speed to candidate peptide capture agent, due to both rapid growth of bacteria and direct utilization of the sorted cells displaying each individual peptide for the subsequent round of biopanning. Portions of the biopanning protocol can be automated to further improve speed to candidate reagent through improved isolation from non-binders. These candidate reagents are easily characterized on-cell and off-cell, and the most promising reagents can be further matured for integration into various sensing platforms, including lateral flow assays and surface enhanced Raman scattering (SERS). In this work, non-toxic, recombinant variants of ricin and abrin, RiVax and abraX, respectively, were utilized for discovery of peptide capture reagents against these high-priority, weaponizable toxins. These toxins are structurally similar, in addition to having significant sequence homology. Several peptide capture candidates were isolated as a result, and their binding assessed on-cell using Fluorescence-Activated Cell Sorting (FACS). Most of the resulting candidates from biopanning for abraX binding peptides were able to bind abraX but not RiVax, demonstrating that short peptide sequences can be highly specific even at this early discovery stage. Current progress towards discovery, understanding, and maturation of abraX/riVax peptide materials will be discussed.

9863-5, Session 1

Development and use of genetically engineered peptides for inorganics (GEPI) for selective interfaces

Bryn L. Adams, Sarah Stellwagen, Deborah A. Sarkes, U.S. Army Research Lab. (United States); Justin P. Jahnke, U.S. Army Research Lab. (United States); Margaret M. Hurley, Dimitra N. Stratis-Cullum, U.S. Army Research Lab. (United States)

Bacterial cell surface display, in which a library of peptides is presented on the surface of bacteria for affinity selection against a specific target of interest has previously been demonstrated to be a powerful tool for the discovery and study of peptide-protein interactions. Recently, we have expanded bacterial cell surface display to include inorganic targets and have developed material specific peptides, also known as genetically engineered peptides for inorganics (GEPI), and have begun to study the peptide-

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material interactions, including relative binding affinity, amino acid character, and material specificity. The process of GEPI discovery from an E. coli cell surface display library will be discussed, including experimental challenges unique to peptide discovery with inorganics. GEPI characterization and analysis will be presented for material sets, including an aluminum alloy and gold, and selectivity for target material demonstrated to show the potential towards tailored material interactions for multicomponent materials will be shown.

9863-6, Session 2

Xerogel-based molecularly imprinted polymers for biorecognition (*Invited Paper*)

Ellen L. Holthoff, U.S. Army Research Lab. (United States)

Molecularly imprinted polymers (MIPs) can be utilized as artificial recognition elements for target chemical and biological analytes of interest. Molecular imprinting involves arranging polymerizable functional monomers around a template followed by polymerization and template removal. The selectivity for the target analyte is based on the spatial orientation of the binding site and covalent or non-covalent interactions between the functional monomer and the analyte. The objective of the present work is to demonstrate the usefulness of MIPs as substitutes for biorecognition elements. The polymer materials of particular interest are sol-gel-derived xerogels. The room temperature polymerization and aqueous chemistry of these materials are useful for molecular imprinting of water-soluble biomolecules. To allow for increased target recognition, the xerogel has specific functional groups, which allow for polymer interactions with the template molecule (and target analyte). The results will demonstrate the effectiveness of MIPs for the detection of proteins and biological toxins.

9863-7, Session 2

Switchable interfacing of living and abiotic materials through engineered bacterial attachment structures

Jessica L. Terrell, U.S. Army Research Lab. (United States); Ellen L. Holthoff, Deborah A. Sarkes, Hong Dong, Bryn L. Adams, Margaret M. Hurley, Dimitra N. Stratis-Cullum, U.S. Army Research Lab. (United States)

The convenience of cellular genetic engineering has afforded the power to build 'smart' synthetic biological tools with novel applications. Here, we have explored opportunities to hybridize engineered cells with inorganic materials to develop living, device-compatible systems. Cellular structures are engineerable by rewriting genetic code to generate recombinant, foreign, or even unnatural proteins. With this capability on the biological end, it should be possible to achieve superior abio-compatibility with inorganic materials that compose current microfabricated technology.

This work targets bacterial hair-like appendages known as fimbriae that enable natural adhesion to glycosylated substrates. Of interest, fimbriae interact with the substrate in a force-dependent, 'catch bonding' manner. By targeting sequence alterations within the fimbrial gene cluster, we demonstrated that engineered fimbriae, in turn, tune cell binding. Introduction of point mutations allowed for pre-programmed variations in affinity on carbohydrate-based surfaces. Additionally, binding to alternative substrates was enabled by insertion of affinity peptides. In particular, the fimbriae were fused with genetically optimized peptides-for-inorganics to enable metal binding.

By generating a suite of bacterial cell types with varying substrate affinity and catch-bond behavior through fimbrial modification, we have demonstrated spatiotemporally controlled cell patterning with reversibility and cell type specificity. Additionally, we have used this capability to interface inorganic materials with biology. In general, the incorporation of

'programmed' cells into devices is useful to provide the feature of dynamic and automated cell response. Through this work, the additional feature of switchable positioning of cells as reconfigurable biocomponentry could be integrated into bioMEMs for advanced sensing and actuation.

9863-8, Session 2

Bio-inspired patterned networks (BIPS) for development of wearable biosensors

Eric S. McLamore, Univ. of Florida (United States); Matteo Convertino, Univ. of Minnesota, Twin Cities (United States); Jonathan C. Claussen, Iowa State Univ. (United States); Diana C. Vanegas-Gamboa, Univ. del Valle (Colombia)

Here we demonstrate a novel approach for fabricating point of care (POC) electrochemical biosensors based on 3D patterning of bionanocomposite networks. To create Bio-Inspired Patterned network (BIPS) electrodes, we first generate fractal network models that optimize transport of network fluxes according to an energy function. Network patterns are then inkjet printed onto flexible substrate using conductive graphene ink. We then deposit fractal nanometal structures onto the graphene to create a 3D nanocomposite network using pulsed sonoelectrodeposition. Finally, we biofunctionalize the surface with proteins or aptamers using covalent bonding. The 3D BIPS sensors are used to develop high efficiency, low cost biosensors for measuring small molecules (lactate, jasmonate, glucose). Our results on the fundamental performance of BIPS sensors show that the biomimetic nanostructures significantly enhance biosensor sensitivity, accuracy, response time, limit of detection, and hysteresis compared to conventional POC electrodes (serpentine, interdigitated, and screen printed electrodes). BIPs represent a new generation of POC biosensors based on nanoscale and microscale fractal networks that significantly improve electrical connectivity, leading to enhanced sensor performance.

9863-9, Session 2

Multi-layered SERS substrates for enhanced sensing

Pietro Strobbia, Brian M. Cullum, Univ. of Maryland, Baltimore County (United States)

Surface enhanced Raman spectroscopy (SERS) has been shown to be a powerful analytical technique for various sensing scenarios due to its ability to provide molecular identification and multiplex detection in combination with a high sensitivity. However, the fabrication of substrates with the desired large and reproducible enhancement factors continues to be a challenge. In our laboratory a widely applicable enhancing geometry that takes advantage of the volume of the substrate has been developed. This geometry can be used to amplify a substrate's enhancement factor without disrupting its reproducibility or surface structure. The use of alternating layers of metal and dielectric was shown to enhance the sensitivity of various SERS sensing platforms by over an order of magnitude. This multi-layer architecture was initially developed on silver film over nanospheres taking advantage of the native oxide as spacer and has been recently extended to gold-based structures using atomic layer deposited (ALD) oxides, resulting in substrates with improved stability and enhanced sensitivity. Preliminary evidence into the principle of this enhancement mechanism suggests that the spacer material and thickness play a key role in the magnitude of the resulting enhancement. In this paper we investigate the relationship between the enhancement and the spacer layer's physical properties. In addition the use of multi-layered structures was extended to different substrates and plasmonic materials as a demonstration of its versatility.

9863-10, Session 3

The development of Army relevant peptide-based surface enhanced Raman scattering sensors for biological threat detection (*Invited Paper*)

Mikella E. Farrell, Deborah A. Sarkes, U.S. Army Research Lab. (United States); Dimitra N. Stratis-Cullum, U.S. Army Research Lab. (United States); Paul M. Pellegrino, U.S. Army Research Lab. (United States)

The utility of peptide-based molecular sensing for the development of novel biosensors has resulted in a significant increase in their development and usage for sensing targets like chemical, biological, energetic and toxic materials. Using peptides as a molecular recognition element is particularly advantageous because there are several mature peptide synthesis protocols that already exist, peptide structures can be tailored, selected and manipulated to be highly discerning towards desired targets, peptides can be modified to be very stable in a host of environments and stable under many different conditions, and through the development of bifunctionalized peptides can be synthesized to also bind onto desired sensing platforms (various metal materials, glass, etc.). Two examples of the several Army relevant biological targets for peptide-based sensing platforms include Ricin and Abrin. Ricin and Abrin are alarming threats because both can be weaponized and there is no antidote for exposure. We will discuss the optimization of peptide capture agents for biological simulant materials and metal gold binders. The effectiveness of this bifunctional peptide will be demonstrated through surface enhanced Raman scattering (SERS)-based sensing measurements of the capture capabilities, selectivity, material binding, and other relevant metrics.

9863-11, Session 3

Characterization of analytical figures of merit of a sub-diffraction limited fiber bundle array for SERS imaging

Eric R. Languirand, Brian M. Cullum, Univ. of Maryland, Baltimore County (United States)

Super resolution chemical imaging can provide high spatial resolution images that contain chemically specific information. Additionally, using a technique such as Raman scattering provides molecular specific information based on the inherent vibrations within the analyte of interest. Our group uses commercially available fiber bundle arrays (1mm diameter) consisting of 30,000 individual fiber elements (4µm diameter) that are then modified to obtain surface enhanced Raman scatter. This allows us to visualize vibrational information with high spatial resolution over the 30,000 individual points of interrogation that are tapered to a total imaging diameter of approximately 20µm and a fiber element diameter of approximately 50nm in a non-scanning wide-field format. Furthermore, it has been shown that dithering can increase the spatial resolution of non-tapered fiber bundle arrays further by obtaining several sub-element shifted images. However, there is a need to characterize the amount of cross talk on the nanoscale of our fiber-bundle arrays due to the tapering of the cladding material.

In this paper, a study of luminescent particles isolated in individual fiber wells has been performed to understand the cross talk associated with these fiber elements. While a scanning-electron microscope (SEM) provides nanometric characterization of the fiber array, luminescent signals show quantifiable differences in cross talk between adjacent fiber elements. This characterization is necessary to ensure the high spatial resolution (i.e. sub-diffraction limited) images expected are obtained.

9863-12, Session 3

Multianalyte electrochemical sensors on a monolith electrode (*Invited Paper*)

Ravi Saraf, Univ. of Nebraska-Lincoln (United States); Santanu Roy, Rahul Tevatia, Vajra Instruments Inc. (United States); Seung-Woo Lee, Korea Institute of Science and Technology (Korea, Republic of)

Electrochemical sensors are arguably the most successful chemical sensing devices primarily because of their high sensitivity at low cost. The key advantage of electrochemical devices is the active signal due to chemical reaction allowing specific recognition of the chemical with a low incidence of false positives. However, only one redox reaction per electrode is possible to detect. An opto-electrochemical method, called Scanning Electrometer for Electrical Double-layer (SEED), to quantitatively detect multiple, individual redox reactions on a monolith electrode will be described. By scanning a laser beam, local redox current density distribution can be quantitatively mapped to detect multiple analytes on a 1cm² size electrode. SEED is responsive to (redox) reactions of 0.1 atto-mole of molecules. The local redox current is measured by probing the change in the charge in the electrical double-layer which significantly changes due to redox reaction. SEED signal enhances as the sensing area reduces in size. Characteristics of SEED and application to chemical and biochemical sensing, and genomics will be described.

9863-13, Session 3

Enabling highly conductive printed graphene electronics on flexible substrates for sweat-based biosensing

Jonathan C. Claussen, Iowa State Univ. (United States)

Printed electronics developed with ink jet printing technology have become increasingly attractive for a variety of reasons including low cost, scalability, and the ability to print on a wide variety of surfaces such as paper and polymers that typically degrade during photolithographic processing. Furthermore, ink-jet printed graphene electronics also inherently incorporate the unique material properties of graphene (e.g., high conductivity, flexibility, strength, and biocompatibility) that make them well suited for a variety of applications including supercapacitors, thin film transistors, and biosensors. In this work we developed an exfoliated graphene ink for printable biosensors. The graphene ink is printed onto a textile-based flexible substrate along with a silver/silver chloride reference electrode ink to create a printed 3-electrode circuit for amperometric, electrochemical sensing. A key enabling technology of the printed biosensors is the ability to selectively anneal the printed graphene to remove non-conductive binders and subsequently improve electrical conductivity (sheet resistance < 1k?). An enzymatic layer consisting of the enzyme lactate oxidase is immobilized on the working electrode (printed graphene) for subsequent lactate sensing—a biomarker associated with muscle fatigue found within the sweat. The sensitivity of the printed circuit to lactate is analyzed as well as the durability of the biosensor during flexed and un-flexed scenarios. These results demonstrate the potential of graphene-printed electronics in epidermal biosensor applications.

9863-14, Session 4

Impedance biosensor for the rapid detection of Listeria spp. based on aptamer functionalized Pt-interdigitated microelectrodes array

Raminderdeep Sidhu, Texas A&M Univ. (United States); Yue Rong, Univ. of Florida (United States); Diana C. Vanegas-

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Gamboa, Univ. del Valle (Colombia); Jonathan C. Claussen, Iowa State Univ. (United States); Eric S. McLamore, Univ. of Florida (United States); Carmen L. Gomes, Texas A&M Univ. (United States)

Recent foodborne outbreaks have heightened public concern about food safety and created a greater impetus to improve methods for pathogen detection. *Listeria monocytogenes* is one of the most common causes of food illness deaths in the world, with multiple outbreaks in the United States alone. Current methods to detect foodborne pathogens are laborious and can take several hours to days to produce results. Thus, faster techniques are needed to detect bacteria within the same level of reliability as traditional techniques. This study reports on a rapid, accurate, and sensitive aptamer biosensor device for rapid detection of *Listeria* spp. based on platinum interdigitated array microelectrodes (Pt-IDEs). Pt-IDEs with different geometric electrode gaps were fabricated by lithographic techniques and characterized by cyclic voltammetric (CV), electrochemical impedance spectroscopy (EIS), and potential amperometry (DCPA) measurements of reversible redox species. Based on these results, 50 μm Pt-IDE was chosen to further functionalize with a *Listeria monocytogenes* DNA aptamer selective to the cell surface protein internalin A, via metal-thiol self-assembly at the 5' end of the 47-mer. EIS analysis was used to characterize the biosensor and detect *Listeria* spp. without the need for label amplification and pre-concentration steps reducing the detection time. The optimized aptamer concentration of 800 nM was selected to capture the bacteria through binding of internalin A and the hairpin structure near the 3' end of the aptamer. The aptasensor was capable of detecting a wide range of bacteria concentration from 10 to 106 CFU/mL at lower detection limit of 5.39 ± 0.21 CFU/mL with sensitivity of 268.1 ± 25.40 (Ohms/log [CFU/mL]) in 17 min. The aptamer based biosensor offers a portable, rapid and sensitive alternative for food safety applications with one of the lowest detection limits reported to date.

9863-15, Session 4

Investigation of magnetic microdiscs for bacterial pathogen detection

Keisha Castillo-Torres, Nicolas Garraud, David P. Arnold, Univ. of Florida (United States); Eric S McLamore, Univ of Florida (United States)

Despite strict regulations to control the presence of human pathogens in our food supply, recent foodborne outbreaks have heightened public concern about food safety and created urgency to improve methods for pathogen detection. Herein we explore a new portable, low-cost system that uses magnetic microdiscs for the detection of bacterial pathogens in liquid samples. The system operates by optically measuring the rotational dynamics of suspended magnetic microdiscs functionalized with pathogen-binding aptamers. The low-aspect-ratio soft ferromagnetic (Ni80Fe20) microdiscs exhibit a closed magnetic spin arrangement (i.e., spin vortex) with zero magnetic stray field, leading to no disc agglomeration when in free suspension. With very high surface area for functionalization and volumes 10,000x larger than commonly used superparamagnetic nanoparticles, these microdiscs are well suited for tagging, trapping, actuating, or interrogating biological targets. Using a previously reported magnetic actuation and optical detection system [1], we tested the signal output for biological materials of different size conjugated to the disc surface; namely a DNA aptamer and a relatively small soluble chemosensory binding protein. We are currently extending this detection principle with the aim to show how the technique can be used to measure binding of pathogenic bacteria (*E. coli* O157:H7 and *L. monocytogenes*) at levels that are associated with human illness in the presence of background nucleic acids and proteins not associated with pathogen contamination.

9863-16, Session 4

Dynamics of an electrochemical biosensor for the detection of toxic substances in water (Invited Paper)

Juan F. Ospina, Univ. EAFIT (Colombia)

A proposed analytical method focuses on electrolyte transport to the electrode of an electrochemical cell. The recombinant *Escherichia coli* whole-cell biosensor detects toxicity in water based on a set of biochemical reactors. Previous contributions elucidated the kinetics of product formation and validated a mathematical model for its diffusion in the chamber. This work introduces an approach to investigate the dynamics of the probe using Laplace transforms and an effective time constant. The transfer function between the electrolyte production and the total current revealed a faster response for larger electrode radii. Both the first-order and effective time constants increased with the chamber height and radius. Separation of variables yields closed-form solutions and helps estimate the kinetics of p-aminophenol generation. When the bacteria were exposed to phenol concentrations of 1.6, 8.3 and 16 ppm, the corresponding overall rate constants were 5.11×10^{-7} , 1.13×10^{-6} and 1.99×10^{-6} (product concentration unit/s²), respectively. In addition to parameter estimation, the method can be applied to perform sensitivity analysis and aid manufacturers in meeting design specifications of biosensors.

9863-17, Session 4

Predictive modeling in *Clostridium acetobutylicum* fermentations employing Raman spectroscopy and multivariate data analysis for real-time culture monitoring

Theresah N. K. Zu, U.S. Army Research Lab. (United States); Sanchao Liu, Katherine L. Germane, Matthew D. Servinsky, Elliot S. Gerlach, David M. Mackie, Christian J. Sund, U.S. Army Research Lab. (United States)

The coupling of optical fibers with Raman instrumentation has been demonstrated to be effective for real-time monitoring of chemical reactions as well as different fermentation cultures when combined with multivariate statistical data analysis. Raman spectroscopy is of interest because, the technique is relatively fast with little interference from the water peak present in fermentation cultures. Medical research has explored this technique for analysis of mammalian (Chinese Hamster Ovarian –CHO) cultures for potential diagnosis of some cancers. Other organisms that have been studied via this route include *Escherichia coli*, *Saccharomyces cerevisiae*, and some *Bacillus* sp., though very little work has been done in the area of *Clostridium acetobutylicum*. *C. acetobutylicum* is a gram-positive anaerobic bacterium which is highly sought after due to its ability to utilize different carbohydrate substrates in return and produce useful byproducts through the well-known Acetone-Butanol-Ethanol (ABE) fermentation. In this work, real-time Raman data was acquired from *C. acetobutylicum* cultures (wild type and a mutant) grown on glucose as the sole carbon source. Samples were collected concurrently using manual sampling for comparative off-line product analysis. Partial-least squares (PLS) models were built for both agitated cultures and static cultures from both datasets for different reaction components; (i) glucose, (ii) butyrate, (iii) acetate, and (iv) butanol. Models were cross-validated with independent datasets. Experiments with agitation were more favorable for modeling with goodness of fit (R²Y) values of 0.99 and goodness of prediction (Q²Y) values of 0.98. Static experiments did not model well and were chaotic especially at time points where manual samples were acquired.

9863-18, Session 4

Modelling and implementation of a fixed-length-extension to measure fluorescent intensity in bioprocesses using an optical sensor

Neha R. Sardesai, Mustafa Al-Adhami, Govind Rao, Yordan Kostov, Univ. of Maryland, Baltimore County (United States)

Fluorescent proteins are often used as reporters of protein concentration in biology and biomedicine applications. They can be detected using a fluorometer equipped with fiber optics for ease of access. However, small changes in the path length due to change in the position or immersion depth of the optical fiber results in large changes in readings. To alleviate the situation, the fiber is equipped with a fixed-length-extension that provides constant path length. The operation of the fiber equipped fluorometer is theoretically modelled and practically verified in this paper.

9863-19, Session 5

Application of the Black-Scholes equation in pharmaceutical engineering

Esteban Higueta, Univ. EAFIT (Colombia)

The Black-Scholes equation is applied in pharmaceutical engineering. The Black-Scholes equation is a classic equation in computational finance. In this work certain case of a modified Black-Scholes equation is analytically solved in the context of a problem of absorption of a drug by a tissue. The analytical solution is obtained using computer algebra specifically Maple. The solution is written as one series of associated Laguerre polynomials. In the procedure the Kummer M functions are used. The analytical solution is numerically tested and using experimental data is possible to estimate the pharmacological parameters of the tissue. We claim that our analytical solution will have important applications in pharmaceutical engineering.

9863-20, Session 5

Developing portable Raman spectroscopy methods for identification of raw materials used in pharmaceutical development and manufacturing

Michael Dotlich, Eli Lilly and Co. (United States)

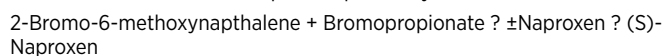
Portable instrumentation for Raman spectroscopy has rapidly evolved over the last decade, where sample testing that once occurred in the laboratory is now executed in the field (e.g. warehouse). Portable Raman spectroscopy is a powerful technique for the rapid identification of diversely sourced raw materials used in pharmaceutical processing. In addition to portability; reduced cost, rapid data acquisition and ease of use make this powerful technique attractive and accessible to both expert spectroscopists and non-specialists. In most cases, the method development can be easily accomplished in the laboratory after which the instrument and method are transferred to field for sample analysis. Qualitative Raman methods for identification of raw materials typically utilize spectral libraries for sample to standard comparison. When developing Raman spectral libraries for raw material identification, great care is required when considering critical factors (e.g. instrument type, Raman capability, container type, container interference, background interference, material variability) that influence the identity of the material. This talk will discuss portable Raman techniques and approaches for raw material identification, as well as key considerations for developing and validating Raman spectral libraries.

9863-21, Session 5

Molecular isotopic engineering (MIE): Industrial manufacture of naproxen of predetermined stable-isotopic compositions for reasons of identity and security

John P. Jasper, Nature's Fingerprint (United States)

Molecular Isotope Technologies LLC has developed four patented or patent-pending generations of stable-isotopic methods and technologies: (i) product characterization (for both small molecules and biologics), (ii) process characterization (notably, process patent protection), (iii) in-process (continuous) analysis, and now (iv) molecular isotopic engineering. Early work in cooperation with the US FDA on the product characterization of naproxen revealed manufacturer-level isotopic provenance of this small analgesic molecule (Wokovich et al., 2004) which was referred to as "The Manufacturer's Fingerprint." This isotopic provenance represented the convergence of the effects of the stable-isotopic compositions of starting materials and isotopic effects of the synthetic process. Rather than merely accepting the random effects of variable sourcing and synthetic process on the stable-isotopic compositions of products, we take a proactive approach to purposefully determine the stable-isotopic composition of bio/pharmaceutical products. The main rationale for MIE is to predetermine the isotopic ranges of products for reasons of product identification and of product security, and also for intellectual property considerations. As an example of MIE, we analyzed the products of the isotopic-synthetic reactions for the last two steps of naproxen synthesis:



Pre-selection of the stable-isotopic compositions of the starting material, 2-Bromo-6-methoxynaphthalene (e.g., ^{13}C -12%, -22%, -32% vs VPDB) yields the product of discrete stable-isotopic ranges. The resulting MIE naproxen is very different from a naproxen molecule that has merely been substituted at a single position with a different isotope. Our directed isotopic synthesis is just one example of MIE to predetermine the discrete isotopic ranges of bio/pharmaceutical products. In principle, the MIE approach should be readily adapted to existing bio/pharmaceutical manufacturing units. The main difference in the manufacturing process would be the use of starting materials or synthetic intermediates of pre-measured stable-isotopic compositions. The manufacturing apparatus would remain unchanged. This approach could have broad application in securing drug identity/provenance from manufacturing plant to consumer.

9863-22, Session 5

A paper based graphene-nanocauliflower hybrid composite for point of care biosensing

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Medhir Bhargava, John Kiernan-Lewis, Neil Schwalb, Univ. of Florida (United States); Yue Rong, Univ. of Florida (United States);
Carmen L. Gomes, Texas A&M Univ. (United States); Jonathan C. Claussen, Iowa State Univ. (United States);
Diana C. Vanegas-Gamboa, Univ. del Valle (Colombia); Eric S. McLamore, Univ. of Florida (United States)

Graphene paper has diverse applications in printed circuit board electronics, bioassays, 3D cell culture, and biosensing. Although development of nanometal-graphene hybrid composites is commonplace in the sensing literature, to date there are only a few examples of nanometal-decorated graphene paper for use in biosensing. In this manuscript, we demonstrate

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the synthesis and application of Pt nano cauliflower-functionalized graphene paper for use in electrochemical biosensing of small molecules (glucose, acetone, methanol) or detection of pathogenic bacteria (*Escherichia coli* O157:H7). Raman spectroscopy, scanning electron microscopy and energy dispersive spectroscopy were used to show that graphene oxide deposited on nanocellulose crystals was partially reduced by both thermal and chemical treatment. Fractal platinum nanostructures were formed on the reduced graphene oxide paper, producing a conductive paper with an extremely high electroactive surface area, confirmed by cyclic voltammetry and electrochemical impedance spectroscopy. To show the broad applicability of the material, the platinum surface was functionalized with three different biomaterials: 1) glucose oxidase (via chitosan encapsulation); 2) a DNA aptamer (via covalent linking), or 3) a chemosensory protein (via his linking). We demonstrate the application of this device for point of care biosensing. The results demonstrate that the nanocellulose-graphene-nanoplatinum paper is an excellent material platform for development of electrochemical biosensors targeting small molecules or whole cells.

warfare agents, toxins, and poisons traditionally involve blood collection by phlebotomists, cold transport of biomedical samples, and costly sample preparation techniques. Use of dried blood spots can increase analyte stability, decrease infection hazard for those handling samples, greatly reduce the cost of shipping/storing samples by removing the need for refrigeration and cold chain transportation, and be self-prepared by potentially exposed individuals using a simple finger prick. Our laboratory has developed clinical assays to detect human exposures to a wide variety of chemical agents through the analysis of specific protein adducts, metabolites, and intact agents for which a simple extraction from a dried blood spot is sufficient for removing matrix interferences and attaining sensitivities on par with traditional sampling methods. The use of dried blood spots can bridge the gap between the laboratory and the field allowing for large scale sample collection with minimal impact on hospital resources while maintaining sensitivity, specificity, traceability, and quality requirements for both clinical and forensic applications.

9863-23, Session 6

Special challenges and opportunities for application of bio-medical sensors *(Invited Paper)*

Michael Weinrich, National Institute of Child Health and Human Development (United States)

Data from wide-spread application of sensors has the potential to transform the practice of medicine, both in delivery of care and in improving clinical research. Care can be transformed as providers receive data from patients in their homes and communities, and can respond with advice and therapeutics delivered to the home. Clinical research can benefit from analysis of large-scale, real time data collected from individuals in the community, as opposed to the more restricted subject samples enrolled in current clinical trials. Large initiatives are already underway to expand the role of mobile health (see the Center of Excellence for Mobile Sensor Data-to-Knowledge <https://md2k.org/>) and to utilize the potential of large cohorts for clinical research (NIH Precision Data Initiative <http://www.nih.gov/precisionmedicine/>).

However, in this context it may be worth considering some of the special challenges presented by specific populations. Monitoring the health of children remotely could improve clinical care, and reduce the number of office and emergency room visits. For example, early detection of deteriorating asthma could lead to early therapeutic intervention that forestalls potentially life-threatening exacerbations. An obvious issue is establishing normative standards for clinical variables measured at different ages, but more difficult issues involve the application of sensors to children with disabilities, especially intellectual impairments. Not only may normative standards for activity, sleep, etc., be difficult to apply, but these children may not tolerate the application of devices.

This presentation will review data and challenges for application of sensors to special populations and present a framework for future research.

9863-24, Session 6

Bridging the gap between sample collection and laboratory analysis: using dried blood spots to identify human exposure to chemical agents

Elizabeth Hamelin, Thomas A. Blake, Jonas Perez, Rebecca L. Shaner, Rudolph C. Johnson, Ctrs. for Disease Control and Prevention (United States)

Public health response to large scale chemical emergencies presents logistical challenges for sample collection, transport, and analysis. Diagnostic methods used to identify and determine exposure to chemical

9863-25, Session 6

The integration of biochemical sensors into wearable health platforms

Michael Angelo Daniele, Univ. of North Carolina at Chapel Hill (United States); Sidhartha Jandhyala, The Univ. of North Carolina at Chapel Hill (United States); Allison Cargill, Navel Research Enterprise Internship Program (United States); Abigail Ozual, NRL Summer Research Program for HBCU/MI Undergraduates (United States)

With rapidly inflating healthcare costs, a limited supply of physicians and an alarming surge in lifestyle diseases, radical changes must be made to improve preventative medicine and ensure a sustainable healthcare system. A compelling solution is to equip the population with wearable health monitors to continuously record representative and actionable physiological data. To date, wearable health monitors for sensing electrical and mechanical bio-signals have matured into viable commercial technologies; however, unlike these biophysical sensors which function "on chip", a typical biochemical sensor must extract, separate and condition the sample with a suite of fluid-handling tools. Accordingly, biochemical testing is typically performed in clinical and laboratory facilities. So this raises a compelling question: How do we design wearable health monitors with a complement of biochemical analysis tools that can be localized "on-body"? Such a technology requires the re-imagining and re-engineering of costly and complex bio-molecular detection platforms, miniaturization of sample processing systems and new motifs for signal transduction and transmission. This presentation will introduce the importance of collecting the information stored in biochemical signals, discuss the challenges associated with integrating biochemical sensors into wearable health monitors, describe recent efforts to develop a set of nanomaterials to enable such biochemical sensors, and explore the potential material motifs and fabrication approaches needed to realize epidermal/intradermal biochemical sensors.

9863-26, Session 6

Development of VIPER: a simulator for assessing vision performance of warfighters

Jide Familoni, Roger W. Thompson, Steven K. Moyer, Gregory Mueller, Timothy J. Williams, Hung-Quang Nguyen, Richard L. Espinola, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Rose K. Sia, Denise Ryan, Fort Belvoir Community Hospital (United States); Bruce Rivers, Fort Belvoir Community Hospital (United States)

Background: As part of the Warfighter Refractive Eye Surgery Program

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(WRESP), visual outcomes are assessed before and after refractive surgery. A Warfighter's ability to read signs and detect and identify objects is crucial not only when deployed in a military setting, but also in their civilian lives.

Objective: VIPER, a VIsion PERformance simulator was envisioned as a video based simulated driving experience to test warfighters' vision under realistic conditions. Design considerations duplicated the experience of driving in interactive video image controlled environments, including daytime, dusk, night, and thermal imaging vision. Color Visible Uncooled LWIR sensors were employed to collect video images of six targets placed at randomly selected, GPS located coordinates on a 1.1 mile of deserted roadway.

Study Design: The initial study will recruit candidates to establish a baseline for VIPER performance and validate the simulator. Once completed, VIPER will be used to evaluate functional performance before and after refractive surgery. VIPER records and returns distance from a target, and how quickly a viewer detects and correctly identifies the target.

Relevance: Ultimately, patients are interested in how their vision will impact their ability to perform daily activities. In the military context, in addition to reading road signs, this includes vision with night sensors and identification of objects of military interest. We hypothesize that VIPER will facilitate efficient and quantifiable assessment of changes in vision and measurement of functional military performance.

Future reports should include data on VIPER's validity in evaluating vision performance in patients undergoing refractive eye surgery.

9863-27, Session 6

Comparative analysis of recorded brain EEG signals generated from the right and left hand while writing

Neha R. Sardesai, Seyed Ehsan Jamali Mahabadi, Qinglei Meng, Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

This paper work provides a comparative analysis of EEG signals from right handed people and left handed people when they write with both their hands. Two left handed and one right handed subject were asked to write their respective names on a paper using both, their left and right handed, and their brain signals were measured using an EEG. Similarly, they were asked to perform simple mathematical calculations using both their hand. The data collected from the EEG from writing with both hands was compared, and it is observed that though it is expected that the right brain only would contribute to left handed writing and vice versa, it is not so. When a right handed person writes with his/her left hand, the initial instinct is to go for writing with the right hand. Hence, both parts of the brain are active when a subject writes with the other hand. However, when the activity is repeated, the brain learns to expect to write with the other hand as the activity is repeated and then only the expected part of the brain is active.

9863-28, Session 6

The control of hepatitis B using a model with age-specific susceptibility

Juan F. Ospina, Univ. EAFIT (Colombia)

We estimate the critical proportion of immunity (P_c) to control hepatitis B after 15 years of mass immunization in Medellin - Colombia, based on a random population survey of 2077 individuals of 6-64 years of age. The weighted proportion of susceptibility was 71.3%. The force of infection (F_i) was estimated according to empirical data of susceptibility by age $S(a)$, assuming a quadratic expression. Parameters were estimated by adjusting data to a nonlinear regression using NLREG® v. 6.5 (P. Sherrod, TN, EE.UU.) and MAPLE®, v12 (Maplesoft Inc., Canada). F_i was defined by $-(ds(a)/da)/s(a)$ and according to the form of the empirical curve $S(a)$ we assume a quadratic expression given by $S(a) = Ea^2 + Ba + C$. Then we have the explicit

expression for the accumulated F_i by age given by $F(a) = -a(Ea+B)/c$. The expression of average infection age A is obtained as $A = L + EL^3 / (3C) + BL^2 / (2C)$ and the basic reproductive number R_0 is obtained as $R_0 = 1 + 6C / (6C + 2EL^2 + 3BL)$. From the last result we obtain the P_c given by $P_c = 6C / (12C + 2EL^2 + 3BL)$. Numerical simulations were performed with the age-specific proportion of susceptibility and initial values ($a=0.02$, $b=20$, $c=100$), obtaining an adjusted coefficient of multiple determination of 64.83%. According to the best estimate obtained from NLREG, the algebraic expressions for $S(a)$ and the infection force were derived. Using the result of the infection force we obtain $A = 30$, $L = 85$ and then the 95% confidence interval of R_0 : 1.42 - 1.64 and P_c : 0-0.29. These results indicate that at the worst case, to maintain control of the disease should be immunized at least 30% of susceptible individuals. Similar results were obtained by sex and residential area

9863-29, Session 7

Magnetocardiography in unshielded, commercial environment using optical atomic magnetometers

Rahul Mhaskar, Nobuko Fujikawa, Mark D. Prouty, Geometrics, Inc. (United States)

We present the next generation total-field atomic magnetometers based on laser-pumped alkali atoms that can discriminate very weak magnetic signals in commercial, unshielded environments. These ultra-sensitive magnetometers were used to measure the magnetic field caused by the electrophysiological activity of the heart in the presence of urban noise.

Currently, the measurement of the cardiac magnetic field, called Magnetocardiography (MCG), requires sensors that need cryogenic cooling and operate primarily in a magnetically shielded environment. The resulting operational cost of these sensors has limited the adoption of MCG.

Recent advances in atomic magnetometry have provided alternatives to the existing technologies for biomagnetic measurements. Particularly, the development of Microfabricated Atomic Magnetometer (MFAM) sensors that operate in the Earth's field enables the measurement of the very weak signals, only tens of picoteslas in amplitude, essential for MCG.

We used two MFAM sensors to measure the MCG signals in gradiometer configuration with a very short baseline. The reference sensor measures the background field in close proximity to a sensor that measures the MCG signal. The readout difference is filtered and stacked based on ECG trigger. Waveform averaged for less than 3 minutes of acquisition clearly shows the QRS complex and the T-wave repolarization signature.

We also present the potential for imaging of the cardiac magnetic dipole in presence of urban noise upon increasing the system sensor count. Advanced signal processing algorithms in conjunction with sensors optimized for MCG can complement ECG measurements in development of highly reliable predictive metrics for early detection of heart diseases.

9863-30, Session 7

Portable NIRS devices for hematoma detection: Performance evaluation using tissue mimicking phantoms with in vivo validation

Jianting Wang, Stanley Huang, Matthew R. Myers, U.S. Food and Drug Administration (United States); Yu Chen, Univ. of Maryland, College Park (United States); Cristin G. Welle, T. Joshua Pfefer, U.S. Food and Drug Administration (United States)

Near-Infrared Spectroscopy (NIRS) is emerging as a promising technology for rapid detection of hematomas caused by traumatic brain injury (TBI), for which early diagnosis is crucial for effective patient outcome. To

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facilitate technological advancement and clinical translation, well-validated test methods for objective, quantitative and consistent performance testing for device intercomparison and quality assurance are in demand. We are developing a biomimicking polymer phantom for performance assessment of NIRS-based TBI detection devices. The method is being evaluated with a novel in vivo murine hematoma model, induced using high-intensity focused ultrasound (HIFU). This approach is capable of generating hematomas with controlled sizes and locations at calibrated positioning and dose. A multi-wavelength NIRS system with a fiber-optic interface designed for noninvasive, transcranial hematoma detection in a murine model was developed. This system is capable of detecting changes in hemoglobin concentration and oxygen saturation. We have developed a polymer phantom that accurately mimics the behavior of mouse-TBI model. The phantom can be used to elucidate the effect of NIRS design parameters such as source-detector separation distance, wavelength, as well as biological factors such as skin bruise, lesion size and depth, on hematoma detectability. Insights gained from these studies will inform development of biologically relevant phantoms for full-scale NIRS systems. The final, validated test methods will benefit research on basic light propagation mechanisms as well as development and validation of portable NIRS devices for hematoma detection.

9863-31, Session 7

Vessel extraction using the Buckmaster-Airy filter

Valentina Sanchez, Univ. EAFIT (Colombia)

A new and powerful technique for vessel extraction from biomedical images using the so called Buckmaster-Airy Filter is designed, prototyped and tested. The design, the prototyping and the testing were performed using computer algebra software, specifically the Maple package ImageTools. Some preliminary experiments were performed and the results were excellent. Our new technique is based on partial differential equations. Specifically two dimensional Airy diffusion equation and the two dimensional Buckmaster equation were used for designing the new Buckmaster-Airy Filter. Such new filter is able to enhance the quality of an image, producing simultaneously noise elimination, but without altering the edges of the image. The new Bukmaster-Airy filter is applied to the target image via discrete convolution. The results of some experiments of vessel extraction will be presented; and some lines for future research such as the possible implementation of the Buckmaster-Airy Filter as a new plugging for the program ImageJ, will be proposed.

9863-32, Session 7

Electroencephalogram (EEG) study on self-contemplating image formation

Qinglei Meng, Univ. of Maryland, Baltimore County (United States); Elliot Hong, Univ. of Maryland School of Medicine (United States); Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

As one of the most widely used electrophysiological monitoring methods, EEG has already played a significant role in studies of human brain electrical activity recording. Default mode network (DMN) is a network of brain region that will be activated while subjects are not focused on task positive activities. DMN is also functioning as a self-referencing network. In this study, EEG operation was performed to record brain signals while all subjects were asked to sit down quietly on a chair with eyes closed and think about some parts of their own body, such as left and right hands, left and right ears, lips, nose etc. There was also a time marker, which was used to display the time points when an image of what was thinking about by subjects was formed in the mind, and each EEG dataset was recorded for around 30 seconds. By analyzing both time domain and frequency domain signals for each of the 4 wave bands, Delta, Theta, Alpha and Beta waves, it was observed that for most EEG datasets, alpha wave dominance was

presented about half a second to one second before the image was formed in the subject's mind. Experimental results also indicated that the central and parietal regions, namely channels of C3, C4, P3 and P4 on cortex map, have a higher probability that alpha oscillation dominates within the period of around one second prior to each time marker. This indicates that image formation of self body parts may be mediated by the default mode network through the visual dorsal path.

9863-34, Session 7

Hyperspectral oximetry of image-defined, 3D-printed vascular phantoms

Pejman Ghassemi, Jianting Wang, U.S. Food and Drug Administration (United States); Anthony Melchiorri, Univ. of Maryland, College Park (United States); James Coburn, U.S. Food and Drug Administration (United States); Brian S. Sorg, National Institutes of Health (United States); Yu Chen, Univ. of Maryland, College Park (United States); T. Joshua Pfefer, U.S. Food and Drug Administration (United States)

Three dimensional (3D) printing is an innovative technique to make objects with arbitrary shapes. This approach can be used for constructing biologically relevant phantoms for biophotonics device evaluation. This work focuses on near-infrared hyperspectral reflectance imaging (HRI) technology for tissue oximetry. In this study, we used a stereolithographic (SLA) 3D printer and photoreactive resins to fabricate phantoms. Simple cylindrical channel phantoms with different geometries were printed to assess printer quality and to evaluate the performance of an HRI system. In order to generate a more realistic vascular-tissue-mimicking model, we printed a segmented volumetric map derived from a human retina image. A phantom with two layers of vascular arrays was also created to mimic biological tissue with blood vessels of varied oxygenation levels. The optical properties and morphology of 3D printed samples were validated using spectrophotometry and x-ray microtomography. To further investigate the effect of depth variation on HRI performance, a vascular phantom with a tilted channel array at a range of depths of 0.5-2.8 mm was also fabricated. Channels were filled with hemoglobin solutions at varying saturation (SO₂) levels and HRI measurements of the phantoms were performed. Relative concentrations of phantom chromophores (e.g. oxyhemoglobin, deoxyhemoglobin) were estimated by applying a minimization technique on raw HRI data and SO₂ values calculated. Results illustrated the effect of vessel density and depth on estimation of chromophore concentration and saturation. Overall, this work indicated that 3D printed phantoms have the potential to enhance the evaluation of device performance and improve understanding of light-tissue interactions.

9863-35, Session 7

**A highly sensitive pressure sensor using
conductive composite elastomers with
wavy structures**Rujie Sun, Xiao-Chong Zhang, Jonathan M. Rossiter,
Fabrizio Scarpa, Univ. of Bristol (United Kingdom)

The next generation of biomedical devices for human physiological information monitoring should be highly flexible, stretchable and sensitive. Pressure sensing is an important function for biomedical devices. Existing technologies with relatively less flexibility, stretchability and low sensitivity, however, would not be effectively applied on the monitoring of human body. Here, we present an ultra-sensitive resistance pressure sensor based on the hybrid design of the graphene/polyurethane (GPU) sponge and carbon nanotube (CNT)/polydimethylsiloxane (PDMS) elastomer. The porous sponge coated with graphene exhibits promising electronic conductivities and mechanical flexibilities, while the infiltrated PDMS elastomer could stabilize the electrical and mechanical properties under external deformation. The sensitivity could be enhanced by the CNT/PDMS elastomer based on the sensing mechanism of contact resistance variation. Upon applied pressure or strain, the contact area between CNT/PDMS elastomer and GPU sponge changes, enabling significant resistance change to detect low pressure with high sensitivity. A sensor array based on this strategy is fabricated to demonstrate its potential in human health monitoring.

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9864-1, Session 1

Development of nanoporous anodic aluminum-based localized surface plasmon resonance biosensor for methicillin-resistant staphylococcus aureus detection (Invited Paper)

Momna Rubab, Haeng Mi Byeon, Mi-Kyung Park, Kyungpook National Univ. (Korea, Republic of)

Methicillin-resistant *Staphylococcus aureus* (MRSA) has been emerged as one of the leading foodborne pathogens. Rapid detection and enumeration of MRSA is of critical importance for the prevention of MRSA outbreaks. Therefore, a nanoporous anodic aluminum (NAA)-based localized surface plasmon resonance (LSPR) biosensor has been developed for the MRSA detection. NAA sensors with various pore diameters were fabricated by a two-step anodization method under different voltages and times. Reflectance spectrum and fringe pattern of each NAA sensor were measured by using LSPR system. The NAA sensor was then immobilized with different concentrations of anti-*S. aureus* polyclonal antibody after modification with 11-mercaptopundecanoic acid. A selectivity was confirmed by exposing NAA immunosensor to 11 bacteria with concentration of 10⁴ CFU/mL. Finally, five different pore diameters of sensors (50, 100, 150, 200, and 250 nm) were applied to detect MRSA (10¹ CFU/mL-10⁸ CFU/mL). The number of fringes and reflectance intensity decreased with increase in pore diameter. The optimal concentration of antibody was determined to be 0.00004 µg/mL. The wavelength shift of NAA immunosensor was significantly increased with increase in pore diameter up to 200 nm ($p < 0.05$). In addition, the wavelength shift of NAA immunosensor linearly increased with an increase in MRSA concentration. SEM confirmed that sensor with 200 nm pore diameter showed the greatest bindings of MRSA. Therefore, the NAA-based LSPR biosensor was able to detect MRSA with simple, specific and sensitive manners.

9864-2, Session 1

Hyperspectral fluorescence in-situ hybridization (FISH) imaging for simultaneous detection of foodborne bacterial pathogens

Seung-Chul Yoon, Agricultural Research Service (United States); Brian Oakley, Western Univ. of Health Sciences (United States); Johnna Garrish, Bosoon Park, Kurt C. Lawrence, John E. Line, Jerrie Barnett, Agricultural Research Service (United States)

Fluorescence in-situ hybridization (FISH) is a molecular technique that can detect and enumerate whole bacterial cells, which is important for numerous food safety applications. In this paper, hyperspectral microscope imaging using a multiplex FISH-based assay was studied for simultaneous detection of different foodborne pathogens associated with poultry. FISH probes for multiplexing were designed to discriminate the entire genus or family of different pathogens. FISH sample preparation and hyperspectral imaging protocols were optimized. A novel data processing pipeline from microscope image acquisition to detection and classification of cells was developed to rapidly analyze the hyperspectral images. An automatic cell segmentation algorithm was also developed as a part of a future system for automation of scanning and analysis. Preliminary study results done with pure cultures showed the unambiguous differentiation of test bacteria

when combined with a linear unmixing technique of acquired hyperspectral images. The sensitivity and specificity of the developed hyperspectral FISH imaging still need to be evaluated with mixed cultures and a food matrix but this study paved an important first step towards the development of a powerful DNA-based probing tool for pathogen detection.

9864-3, Session 1

Characterization of multilayer planar coil detectors for improved salmonella detection on food

Yuzhe Liu, Songtao Du, Horikawa Shin, Howard C. Wikle III, Jiajia Hu, Fengen Wang, Bryan A. Chin, Auburn Univ. (United States)

A method that combines magnetoelastic (ME) biosensors and a surface-scanning detector has been previously reported for direct detection of bacteria on food surfaces. Various fresh fruits and vegetables (apples, tomatoes, watermelons, etc.) have been tested without sample preparation and/or enrichment, showing the promise for rapid screening of foods. Double layer coil detectors may greatly increase the amplitude and increase the stand-off distance of single coil designs. This paper, hence, investigates the design and characterization of multilayer planar coil detectors. In contrast to the single-layer coil detectors, multilayer coil detectors can supply more excitation power for the actuation of ME biosensor and read the sensors more sensitively. In addition, smaller ME biosensors (sub-millimeter in length) with higher mass sensitivity can also be measured with these sensitive detectors. Several design parameters, including the width, thickness, and spacing of coil turns and the number of coil layers, were studied. These coils were fabricated using standard microelectronic fabrication techniques (photolithography, electroplating, etching and sputtering), tested and characterized. Both theoretical calculations and experimental data show that double coil geometric parameters greatly increase signal amplitude and stand-off distance. These multilayer coil detectors are therefore anticipated to facilitate the detection of pathogens on food and food contact surfaces with large roughness and curvatures.

9864-4, Session 1

Active fluid mixing with magnetic microactuators for capture of salmonella

Peter J. Hesketh, Srinivas Hanasoge, Drew Owen, Matt Ballard, Zachary Mills, Georgia Institute of Technology (United States); Jie Xu, Georgia Tech Research Institute (United States); Marilyn Erickson, Univ. of Georgia (United States); Alexander Alexeev, Georgia Institute of Technology (United States)

Detection of low concentrations of bacteria in food samples is a challenging process. Key to this process is the separation of the target from the food matrix. We demonstrate magnetic micro-cilia and magnetic beads based microfluidic mixing and capture in a microfluidic channel. Simple easy to fabricate high aspect ratio cilia, which are externally actuated magnetically. These micro-features were fabricated by evaporating NiFe alloy at room temperature, on to patterned photoresist. When the seed layer is removed the cilia are released and form free standing microstructure that are flexible. This is actuated using an external magnet up to a frequency of 50Hz. We demonstrate active mixing produced by cilia in a microchannel. Also, we demonstrate the capture of target species in a sample using these fast

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oscillating cilia. The surface of the cilia are functionalized with streptavidin which binds to biotin labelled fluorescent microspheres and mimic the capture of bacteria.

9864-5, Session 2

Detection of fresh bruises in apples by structured-illumination reflectance imaging

Yuzhen Lu, Richard Li, Renfu Lu, Michigan State Univ. (United States)

Detection of fresh bruises in apples remains a challenging task due to the absence of visual symptoms and significant chemical alterations of fruit tissues during the initial stage after the fruit have been bruised. This paper reports on a structured-illumination reflectance imaging (SIRI) technique for enhanced detection of fresh bruises in apples. Using a digital light projector engine, sinusoidally-modulated illumination at specific spatial frequencies was generated for tissue imaging, in contrast to conventional uniform illumination. A high-performance digital camera was then used to capture the reflectance images from apples. Bruises were induced in apples of two varieties by impact tests and the bruised apples were imaged immediately after the bruising. A three-phase shifting demodulation scheme was applied to the acquired images for obtaining the planar (direct component) and amplitude (alternating component) images. Bruise regions were identified in the amplitude images with varying resolutions depending on the modulation frequency. The bruise visibility was further enhanced through post-processing of the resultant amplitude images. Furthermore, optimization of the three-phase shifting demodulation was achieved by performing spiral phase transform (SPT)-based demodulation, which reduced the time by 1/3 to 2/3 for image acquisition. SIRI technique was capable of detecting fresh bruises in apples, which, otherwise, could not be achieved using conventional imaging technique with planar or uniform diffuse illumination.

9864-6, Session 2

Relationship between shelf-life and optical properties of “Yuanhuang” pear in the region of 400-1150 nm

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An automated integrating sphere (AIS) system was used to measure the total reflectance, total transmittance of “Yuanhuang” pear flesh tissue in the wavelength range 400-1150 nm. These two measurements were used to estimate the bulk optical properties (absorption coefficient and reduced scattering coefficient) of tissue samples with an inverse adding doubling (IAD) light propagation model. The accuracy of the AIS system was verified by using a solid phantom, the relative error of measurement of and is 9.83%, 3.90%, 2.23%, 3.60% and 2.12%, 3.24%, 4.53%, 4.01% in wavelength of 525.4nm, 632.1nm, 710.3nm and 780.1nm respectively. Shelf-life test was conducted in 27 days, 10 pears were tested every other day, a total of 140 samples were used. Two sections were taken from each sample in the opposite two positions and used to measure optical properties. All samples were stored at room temperature (about 24 °C). The detected results of pear tissue showed that was decreased with the increase of shelf-life, the was just the opposite. This result confirmed the changes of both fruit tissue components and structure after harvest, which indicated the potential of optical property measurements for assessing fruit quality.

9864-7, Session 2

Fluorescence diagnosis a seed quality

Alexsandr S. Grishkanich, Sergey V. Kascheev, Alexsandr P. Zhevlakov, Julia Ruzankina, Polina Timokhina, ITMO Univ. (Russian Federation); Igor S. Sidorov, Univ. of Eastern Finland (Finland)

Largely the technology of modern agricultural production is determines by the sowing qualities of seeds. It is widely known application of optical radiation for pre-sowing treatment of seeds with the purpose of increasing its germination and vigour. A particularly strong effect on seeds of various crops has ultra-violet and visible radiation. Optical spectral and color characteristics are uses for sorting fruit, roots and other products. Optical radiation is also use in agricultural production to kill pests and disinfection of grain. Existing methods of quality assessment of air-dry seeds by their germination require a significant investment of time and labor required for sample preparation and the process of seed germination, completely eliminating the possibility of operational control of sowing qualities, so it is necessary to develop rapid methods of assessing the quality of seeds based on the study of spectral optical characteristics of the seeds.

9864-9, Session 2

Comparative analysis of Worldview-2 and Landsat 8 for coastal saltmarsh mapping accuracy assessment

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Coastal saltmarsh and their constituent components and processes are a considerable scientific interest due to their ecological function and services. However, due to their heterogeneity and seasonal dynamic system it is more difficult to map them with remote sensing data. We selected four important saltmarsh species *Pragmites australis*, *Sporobolus virginicus*, *Ficinia nodosa* and *Schoeleplectus* sp. with two dominant tree species Mangrove tree *Avecinia* and other Pine tree *Casuarina* sp. Due to the similarity of spectral band two different sensor High Spatial Resolution Worldview 2 data and Coarse Spatial resolution Landsat 8 were selected for this study. Among the selected vegetation types some patch was fragmented and close to spatial resolution of Worldview 2 data and some patch was more than 30 meter resolution of Landsat 8 data. This is the main reason to see the effectiveness of different classifier over spatial and spectral resolution. Three different classification algorithm, Maximum Likelihood Classifier (MLC), Support Vector Machine (SVM) and Artificial Neural Network (ANN) were compared to test the mapping accuracy from two different sources sensor. For Worldview 2 data SVM was giving the higher overall accuracy (92.12%, kappa =0.90) compare to ANN (90.82%, Kappa 0.89) and MLC (90.55%, kappa = 0.88). When within SVM classifier, Radial Basis Function (RBF) and Polynomial Order were compared. SVM machine with 8 polynomial order and 4000 penalty was giving the highest overall accuracy compare to RBF parameter. On the other hand for Landsat 8 MLC (82.12%) was giving the highest classification accuracy compare to ANN (76.89%) and SVM (75.45%). When producer accuracy was compared for each vegetation type, Mangrove and Casuarina tree species were effectively mapped by coarse resolution Landsat data. But saltmarsh species were clearly mapped by high spatial resolution Worldview 2 data.

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9864-29, Session PWed

Nondestructive and rapid detection of potato black heart based on machine vision technology

Tianfeng Xu, Yankun Peng, Wensong Wei, China Agricultural Univ. (China)

Potatoes are one of the major food crops in the world. Potato black heart is a kind of defect that the surface is intact while the tissues in skin become black. This kind of potato has lost the edibility, and it's difficult to be detected with conventional method. This study proposed a nondestructive detection system that based on the machine vision technology to distinguish the normal and black heart of potato according to the different transmittance of them. Firstly, the detection system was built with a monochrome CCD camera, LED light source for transmitted illumination and a computer. The CCD camera was sensitive to both visible and near-infrared light. The wavelength of the LED was 700 nm which had been confirmed to be the best transmission wavelength for potato in the existing research. The transmission images of potatoes which were normal or black heart were taken by the detection system successively. Then the image processing algorithm was written with VC++. Because the transmittance of the black heart of potato was weaker than the normal one in the same condition, the uniformity of the gray value distribution of the former was worse than the latter. In addition, the change trend of near the peaks and valleys on the gray histogram were different. Based on the above characteristics, the proper threshold condition was confirmed to distinguish the normal and black heart of potatoes after image preprocessing. Through the research, the best incident angle and number of light sources were defined. Results showed that, a nondestructive system was built for the detection of potato black heart. The normal and black heart of potatoes could be detected at a considerable accuracy rate using the method and the system introduced above. The system could detect the potatoes within 1 second. The transmission detection technique based on machine vision is nondestructive, rapid and reliable to realize the detection of potato black heart.

9864-30, Session PWed

Rapid discrimination of main red meat species based on near-infrared hyperspectral imaging technology

Lu Qiao, Yankun Peng, China Agricultural Univ. (China); Kuanglin Chao, Jianwei Qin, Agricultural Research Service (United States)

Meat is the necessary source of essential nutrients for people including protein, fat, and et al. The discrimination of meat species and the determination of meat authenticity have been an important issue in the meat industry. The objective of this study is to realize the fast and accurate identification of three main red meats containing beef, lamb and pork by applying near-infrared hyperspectral imaging (HSI) technology. After acquiring the hyperspectral images of meat samples, the calibration of acquired images and selection of the region of Interest (ROI) were carried out. Then different spectral pre-processing methods were operated to reduce the light scattering and random noise before the spectral analysis. By comparison, the most suitable method for spectral pre-processing was selected and used for further experiments. Finally, after the extraction of characteristic wavelengths by principal component analysis (PCA), the support vector machines (SVM) and the partial least square-discriminant analysis (PLS-DA) methods were applied to establish the discrimination models. The calibration set included 51 samples (beef=17, lamb=17 and pork=17), and another 24 samples (beef=8, lamb=8 and pork=8) were used to validate the identification effect. All the samples were collected from different batches in order to improve the coverage of the models. The most satisfactory classification model could be obtained by comparison of the identification accuracy. Then three different meat samples were sliced at the size of 2 cm² x 2 cm approximately and were spliced together in one

interface to be scanned by HSI system. The acquired hyperspectral data was applied to further validate the discriminant model. The results demonstrated that the near-infrared hyperspectral imaging technology could be applied as an effective, rapid and non-destructive discrimination method for main red meats.

9864-31, Session PWed

A portable nondestructive real-time detection system for inspection of pork quality attributes using Vis/NIR spectral technique

Hongwei Sun, Yankun Peng, China Agricultural Univ. (China)

Visible and near infrared (Vis/NIR) spectral information reflected indicates the freshness of agro-product according to researches published. In spite of high accuracy, short-time, traditional optical equipment detecting agro-product runs heavily, needs strict operation environment, which restricts the wide-spread of optical detection technology. To meet the demand of rapid quality detection in pork market, a portable device developed, with a simple application software designed. During the development of device, the spectra of 60 pieces of pork were acquired using it. Forty-five of them were as calibration set, others as validation set. Calibration set was processed by Savitzky-Golay (SG) filter for noise removal, and then operated by standard normal variable transformation (SNV) for baseline drifts relieving. Quality attributes of pork people cared mainly include water content, pH, color (L*, a*, b*), total volatile basic nitrogen (TVB-N). So the real quality attribute's values were measured by methods of industry regulations. Finally, Vis/NIR spectrum (400-1000nm) data was used to build model by partial least squares regression (PLSR). The coefficients matrix of model was loaded into pork quality detection software. After debugged, the application program for detecting the quality of pork was cross-compiled, and downloaded into the device. To test the accuracy of model, the reflect spectra of 41 pork samples were analyzed by the device. At the same time, the real values of these samples' pH, L*, a* and b* were measured in national standard methods. For pH value, the prediction model could give satisfactory results with the correlation coefficient (Rv) of 0.88 and root mean square error (SEP) of 0.19. For color L*, a*, b*, the prediction models could gain prediction results with Rv of 0.90, 0.97 and 0.97, SEP of 1.77, 1.17 and 0.63, respectively. The results illustrate the high detection precision of this portable device, which can satisfy the requirements of practical detection.

9864-32, Session PWed

Development of hand-held nondestructive detection device for assessing meat freshness

Wensong Wei, Yankun Peng, China Agricultural Univ. (China); Lu Qiao, CAU (China)

Meat freshness is directly related to the health of consumers, and total volatile basic nitrogen (TVB-N) content is an important reference index for evaluating pork freshness. This paper attempted to measure TVB-N content for assessing pork meat freshness using a new self-developed portable and low cost detection device designed by ourselves basing on near infrared technique. The front-end part of this device was an integrated detection component containing three mini probes which meshed with each other at 120 degree in a circumferential angle and the whole bottom detection zone of three mini probes was about 5cm in diameter circle, in addition, six different Light Emitting Diode wavelengths of which the center wavelengths were 525, 575, 760, 810, 910nm, 940nm were embedded in each mini probe respectively to form a ring light source and 1 mm thickness high light transmittance optical glass was also embedded in the bottom of three mini probes. In the signal acquiring component, three silicon photodiode detectors were embedded in the center of light source in each probe and

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each spectral response range was 400-1100nm to receive diffuse light from pork meat surface in three mini probes respectively. The main circuits in this device included Stabilized current supply circuit which was used to provide a stable power supply for each LED light source in three probes and signal processing circuit which was utilized to complete signal amplification, data sample and data transmission functions including A/D conversion and showing detection results on display screen. In addition, another vital function of the signal processing circuit was to merge three different detection signals from three mini probes in the detection component. All circuits of control based on a microcontroller were basically designed to offer the proper, steady voltage and current for the LED arrays and various protective, control functions for their smooth operation. For verifying this device performance, 60 pork samples with different freshness attributes were collected for data acquisition. Multiple Linear Regression (MLR) mathematical method was employed to build pork color content prediction model. The samples were divided into calibration and validation sets according to the proportion of 3:1 to achieve more reasonable prediction results. The correlation coefficient of validation (RV) for prediction of TVB-N was about 0.9. Compared with other spectral detection technique, the developed device has its own superiority such as simplicity in structure, convenient to use, small in size and low cost. This device has realized collecting diffuse reflectance signal, storing, displaying and processing as integration with the weight of less than 1.2 kg and volume of less than 15cm?10cm?8cm. This work demonstrates that it has the potential in nondestructive detection of TVB-N content in pork meat using this device, which could not only significantly improve pork meat freshness prediction performance but also simplify instruments design structure and reduce their price in future.

9864-33, Session PWed

Geographical origin traceability of winter jujube (Chinese date) using near infrared reflectance spectrometry

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A method was developed for identification of winter jujube with Near Infrared Reflectance Spectroscopy (NIRs) technology. Zhanhua jujube is a prized variety of Chinese winter jujube whose production and trade is protected by geographical indication designation and is valued more than similar varieties. In order to protect the geographical indication and ensure product quality, it is necessary to authenticate Zhanhua jujube products effectively. This study used a portable NIRs method with Soft Independent Modeling of Class Analogy (SIMCA) and Partial Least Squares Discriminant Analysis (PLS-DA) models to identify the origin of two winter jujube varieties - Zhanhua jujube and Shaanxi jujube. Samples of each variety were analyzed in the 950 to 1650 nm wavelength region. The research showed that the NIRs combination of SIMCA and PLS-DA methods are capable recognizing the origin of Zhanhua and Shaanxi jujubes. The results also showed that different pretreatment of NIRs affect the recognition rate. The recognition rate of winter jujube samples was 100% with the PLS-DA method exhibiting higher accuracy.

9864-34, Session PWed

Raman spectroscopy-based detection of chemical contaminants in food powders

Kuanglin Chao, Sagar Dhakal, Jianwei Qin, Moon S. Kim, Agricultural Research Service (United States)

Human illnesses and even deaths resulting from economically motivated addition of chemical contaminants in food powders has caused growing concerns regarding food safety worldwide. Notable instances include the deliberate adulteration of milk products with melamine and the use of excessive maleic anhydride in starch production. Raman spectroscopy has been demonstrated effective for qualitative detection of contaminants in

dry food powders and Raman imaging-based detection methods may be able to screen larger volumes of food powders for quantitative contaminant detection. The depth of laser penetration into the food powder, the power of the laser and the spatial resolution needed for effective quantitative imaging-based Raman detection of contaminant particles in food powder are investigated in this study for tapioca starch and wheat flour using a point-scan Raman spectral imaging system. Laser depth and power were evaluated by testing the detection of melamine through layers of the food powders, while spatial resolution was tested for detection of benzoyl peroxide in flour and maleic acid in starch. Using the selected experimental parameters, a linear correlation between the detected numbers of contaminant pixels and the actual contaminant concentrations in the mixed powder samples was demonstrated, showing that the method developed in this study can be used for quantitative detection of chemical contaminants present in food powders at low concentrations. This Raman imaging-based technique shows promise for quantitative analysis of food ingredients that will benefit food processors and regulatory agencies.

9864-35, Session PWed

Whole-surface round object imaging method using line-scan hyperspectral imaging system

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To achieve comprehensive online quality and safety inspection of fruits, whole-surface sample presentation and imaging regimes must be considered. A round object sample presentation method is under development to achieve effective whole-surface sample evaluation based on the use of a single hyperspectral line-scan imaging device. In this paper, whole-surface apple inspection methods using hyperspectral line-scan imaging techniques are presented.

9864-36, Session PWed

MCT-based SWIR hyperspectral imaging system for biological sample evaluation

Seok Min Hong, Agricultural Research Service (United States) and Agency for Defense Development (Korea, Republic of); Hoonsoo Lee, Moon S. Kim, Agricultural Research Service (United States)

Hyperspectral imaging has shown to be powerful tools for nondestructive evaluations of biological samples. We recently developed a new line-scan based short wavelength infrared (SWIR) hyperspectral imaging system. Critical sensing components include a SWIR spectrograph and an MCT (HgCdTe) array detector. The system has effective imaging range from 1000 nm to 2500 nm. In this paper, we present SWIR hyperspectral images of various biological sample materials including fruits and vegetables, and preliminary results for evaluation of safety and quality attributes of produce.

9864-37, Session PWed

Determination of animal feed ingredients by hyperspectral imaging

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National Agricultural Products Quality Management Service (Korea, Republic of); Sang-Ho Moon, Eun-Kyung Kim, Konkuk Univ. (Korea, Republic of); Moon S. Kim, Agricultural Research Service (United States)

Feed ingredients affect the growth of animal and economy of feed industry. Traditional analytical methods for measurement of feed ingredients have several disadvantages such as time consuming and labor intensive, and require destructive procedures. In contrast, spectral imaging technique may allow rapid and non-destructive assessment of various foods and feeds. The aim of this study was to develop rapid and accurate spectral imaging methods for determining ingredients in animal feeds. A preliminary investigation of hyperspectral imaging techniques for assessment of ingredients in animal feeds is presented in this paper.

9864-38, Session PWed

Alternative soaking media for the FDA procedure in the detection of salmonella from tomatoes and spinach leaf using phage magnetoelastic biosensors

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Phage Magnetoelastic (ME) biosensors have been successfully shown to directly detect various pathogens, including Salmonella, on the fruit and vegetable surfaces with high sensitivity and specificity. According to the FDA, it is difficult to conduct rapid q-PCR techniques in spinach juice due to the enzymatic inhibition in PCR reactions. It normally takes 3-4 days to detect Salmonella on Spinach leaves by traditional microbiological methods in the FDA Bacteriological Analytical Manual (BAM). The efforts were made to incorporate this sensor platform in a Spinach Soaking Procedures (Lactose broth/ twenty-four hours incubation time) according to 2015 FDA BAM method. Subsequently, the evaluation of phage ME sensors in other alternative soaking materials (LB broth and Peptone water) and soaking times were investigated. Using merely one-hundred Salmonella cells spiked on the produce surfaces, the phage ME biosensors detected Salmonella within five hours when the tomatoes were soaked in LB broth as opposed to taking up to twenty-four hours. Salmonella was detected on spinach leaves within seven hours incubation. These results demonstrate that phage ME biosensors provide a promising rapid detection platform using LB broth in FDA's soaking procedures while shortening the incubation period.

9864-39, Session PWed

Environmental monitoring for the detection heavy metals with using photonics methods

Alexsandr S. Grishkanich, Julia Ruzankina, Sergey V. Kascheev, Alexsandr P. Zhevnikov, Polina Timokhina, ITMO Univ. (Russian Federation); Igor S. Sidorov, Univ. of Eastern Finland (Finland)

The leading position occupied by the severity of the consequences of emergencies at nuclear facilities ("Lighthouse" 1957 Sarov, 1997; Fukushima, 2011). In such cases, the determining factor of radioactive isotopes are pollution inert gas, cesium, iodine, strontium, and others. Control and prevention of accidental releases of radionuclides into the atmosphere are the key to the safe operation of nuclear power plants and radiochemical cycle. Monitoring and prevention of the accidental radionuclide's emission in atmosphere are the most important elements of human safety. The amount

of radioactive isotopes in environment defines the level of radioactive air pollution. Current inspection methods are performed by the contact, because they are based on registration of γ -types of radiation (distance not more 20 m). Other checking methods of the radioactivity in atmosphere are performed by the spectroscopic diagnostic of isotopes. Development of methods and devices for the control of these emissions is of great scientific and practical interest. It is also important that these methods were remote.

9864-40, Session PWed

Rotating fluorescence imaging technology for monitoring water stress on plants

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Plant growth is affected by environmental stress such as water deficit, drought, extreme temperatures, and nutrient deficiency. This study explored a measurement method of water stress of soybean plants with fluorescence imaging technology. The monitoring system of water stress on plants was developed using hyperspectral fluorescence imaging with violet LED excitation of 405 nm. Rotating fluorescence images were acquired when soybean plants with treatment and non-treatment of water stress were rotating. The effect of water stress of soybean plants was investigated. The results show rotating fluorescence imaging technology has the potential to measure the water stress contents on plants.

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9864-41, Session PWed

Raman mapping of intact biofilms on stainless steel surfaces

Julie K Nguyen, Lynne Heighton, Yunfeng Xu, Xiangwu Nou, Walter F. Schmidt, Agricultural Research Service (United States)

No Abstract Available

9864-42, Session PWed

Identifying fecal matter contamination on spinach leaves using field spectroscopy

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No Abstract Available

9864-43, Session PWed

Non-destructive detection of trace heavy metals in paddy based on collinear DP-LIBS

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of Physical Science (China)

Heavy metal pollution of paddy has become a common and serious problem in many developing countries. However, the traditional detection methods are not very effective either having low detection sensitivity or being destructive in the measurement. Recently, we developed the technique of collinear Double Pluses Laser-Induced Breakdown Spectroscopy (DP-LIBS) for the detection of trace-amount of heavy metals in paddy seeds. We optimized the parameters such as laser energy, gate delay and the interval of two laser pulses to achieve the precise evaluation of the metals Cd and Cu in the paddy seeds. The effects of plasma temperature, electron density, continuous spectrum and signal stability on the collinear DP-LIBS system were also investigated. The results will be theoretically and technically important for rice quality monitoring, breeding and other related applications.

9864-44, Session PWed

On-line measuring the moisture content of powdered food by microwave free-space transmission technique

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In this study, on-line moisture measurement system for powdered food was developed using microwave free-space transmission. A simple microwave moisture meter was introduced to reduce the size and volume of the instrument by means of patch antennas. The attenuation and phase shift produced by powdered food (wheat flour and coffee and milk powders) were analyzed to estimate the relationships between moisture content of powdered food and the attenuation and phase shift. A non-contact moisture meter was constructed using microwave transceivers with patch antennas at multiple frequencies (2 to 11 GHz). All components such as oscillators, isolators, antennas, detectors, and power amplifiers were designed and fabricated for this study. The on-line measurement system having prototype moisture meter, conveying system of powdered food, temperature sensor, tachometer and signal processing units was constructed. The multiple linear regression models for measurement of moisture content were developed and those performances were tested.

9864-10, Session 3

Detection of dimethyl yellow contamination in curry powder using FT-Raman and FT-IR spectroscopy

Sagar Dhakal, Kuanglin Chao, Jianwei Qin, Moon S. Kim, Agricultural Research Service (United States)

Economically motivated contamination of food by unwanted materials has become a global problem. Food contamination may occur at any point in food supply chain. Although traditional technologies can detect such adulterants in food, high operational cost and operational complexities has limited their use to laboratory only. A Fourier Transform Raman spectroscopy (FT-Raman) and Fourier Transform - Infrared Spectroscopy (FT-IR) was used to identify dimethyl yellow adulteration in curry powder. Ten different concentration of curry powder contaminated with dimethyl yellow was obtained by mixing the powders in bench top acoustic mixer for 5 minutes. Five sets of sub-sample for each concentration were obtained. FT-Raman spectral signal of sample was measured by scanning each sample at 10 different points using a laser source at 1064nm. After collection of FT-Raman signal, the same sample was used in FT-IR compartment to measure the FT-IR spectral signal. FT-Raman spectra and FT-IR spectral signal of

pure curry powder and pure dimethyl yellow was obtained to determine the spectral peak of each powder. Spectral signal obtained from the FT-Raman spectroscopy system and FT-IR spectroscopy system was analyzed independently to identify the dimethyl yellow contamination in curry powder. Results show that both the system can identify dimethyl yellow contaminated in curry powder to trace amount value.

9864-11, Session 3

Detection of Chemical Residues in Food Oil via Surface-Enhanced Raman Spectroscopy

Xexi Sun, Qing Huang, Hefei Institutes of Physical Science (China)

Nowadays, food safety becomes a serious problem worldwide and especially in China which causes the government and researchers' special concern. For ultrasensitive and noninvasive detection of the trace-amount chemicals, the technique of surface-enhanced Raman spectroscopy (SERS) has aroused increasing attention and interest and developed very rapidly in recent years. Here we report our new development in the design and fabrication of a new SERS sensor which consists of highly-ordered Ag-nanorod (Ag-NR) arrays obtained via conical-pore anodic aluminium oxide (AAO) template and silver-sputtering protocol, and in the usage it is integrated with a fluidic device so that we can achieve convenient and rapid detection of various harmful substances such as pesticide residues (e.g. parathion-methyl and tetramethylthiuram disulfide), environmental pollutants (e.g. Persistent organic pollutants -POPs including polychlorinated biphenyls-PCBs) and harmful additives (e.g. rhodamine B) in a varied of food with high sensitivity.

9864-12, Session 3

Line-scan spatially offset Raman spectroscopy for inspecting subsurface food safety and quality

Jianwei Qin, Kuanglin Chao, Moon S. Kim, Agricultural Research Service (United States)

Spatially offset Raman spectroscopy (SORS) is a technique capable of obtaining subsurface layered information by collecting Raman spectra from a series of surface positions laterally offset from the excitation laser. Current SORS measurement methods using optical fiber probes are either slow (single fiber probe with mechanical movement) or restricted in selecting offset range and interval (fiber probe array) for acquiring the spectral data. This research aims to develop a line-scan SORS measurement technique for subsurface inspection of food safety and quality. A 785 nm point laser is used as an excitation source in a line-scan hyperspectral Raman imaging system. A detection module consisting of an imaging spectrograph and a CCD camera is used to acquire line-shape SORS data. Using a single scan from one CCD exposure, the system is able to simultaneously acquire a series of Raman spectra in a broad offset range with a narrow interval. Layered samples involving foods (e.g., food powders and slices of fruits and vegetables) and other materials (e.g., chemical adulterants and food packaging materials) are created to test the technique for evaluating subsurface food safety and quality. Mixture analysis algorithms are developed to analyze the SORS data to extract pure component Raman spectra from each layer. The line-scan SORS technique provides a flexible and efficient method for subsurface inspection of food safety and quality.

9864-13, Session 3

Classification of cucumber green mottle mosaic virus (CGMMV) infected watermelon seeds using Raman spectroscopy

Hoonsoo Lee, Agricultural Research Service (United States); Byoung-Kwan Cho, Chungnam National Univ. (Korea, Republic of)

The cucumber green mottle mosaic virus (CGMMV) is known as a globally widely distributed plant virus. The plants infected with CGMMV cause severe mosaic symptoms, discoloration, and deformation of plants. Therefore, rapidly and early detection of CGMMV infected seeds is very important for preventing damage by diseases. Raman spectroscopy was used to classify infected seeds from healthy seeds as a rapid, accurate, and nondestructive detection tool. The spectra of seeds were obtained from 400 cm⁻¹ to 1800 cm⁻¹ and algorithm based on partial least square discriminant analysis (PLS-DA) was developed to classify between infected and healthy seeds. The total calibration and prediction accuracy were 100% and 91.7%, respectively. Results showed that the Raman spectroscopic technique has good potential for detection of virus-infected seeds.

9864-14, Session 3

Continuous Gradient Temperature Raman Spectroscopy of the Long Chain Polyunsaturated Fatty Acids Docosapentaenoic (DPA, 22:5n-6) and Docosahexaenoic (DHA; 22:6n-3) from -100 to 20° C

Leigh Broadhurst, Walter F. Schmidt, Moon S. Kim, Julie K. Nguyen, Jianwei Qin, Kuanglin Chao, Daniel R. Shelton, Agricultural Research Service (United States)

One of the greatest challenges in biological science is the absolute necessity of docosahexaenoic acid (DHA; 22:6n-3) in fast signal processing tissues such as neuronal, retinal and cardiac. Over 600 million years of evolution the difference of just a single diene group has not been overcome. DHA is now considered an essential nutrient for humans, but is highly perishable and abundant only in marine foods. Severe neural and visual functional deficits arise from replacement of DHA with docosapentaenoic acid (DPA; 22:5n-3 or 22:5n-6), but the mechanism remains unknown. New analytical techniques are required to understand the biophysics of highly unsaturated fatty acids.

We analyzed DHA and both DPAs from -110 to 30°C with gradient temperature Raman spectroscopy (GTRS). GTRS applies the precise temperature gradients utilized in differential scanning calorimetry to Raman spectroscopy, providing straightforward identification of molecular rearrangements occurring at phase transitions. 20 Mb three-dimensional data arrays with 0.2°C increments and first/second derivatives allowed complete assignment of solid, liquid and transition state vibrational modes. Standard 25°C Raman spectra of DHA and DPA are indistinguishable; however GTRS spectra are completely different. The DHA melting range extends from -75°C to -35°C, as opposed to the single reported temperature of -44°C. Overall, melting in these molecules begins with the diene group near the methyl end (n-3), moves to mid chain (n-6), then progresses towards the carbonyl end. A dynamic DHA solid state agrees with other recent work showing that DHA within cell membranes is flexible, changing conformations in <100 picoseconds.

9864-15, Session 4

Portable NIR bottled liquid explosive detector (Invited Paper)

Hideo Itozaki, Masaki Ono, Shiori Ito, Keisuke Uekawa, Yuji Miyato, Hideo Sato-Akaba, Osaka Univ. (Japan)

No Abstract Available

9864-16, Session 4

Rapid detection of pathogens by a 3D biomolecular filter and automated biosensor measurement system for liquid

Songtao Du, Shin Horikawa, Yuzhe Liu, M. Crumpler, Yating Chai, Jiajia Hu, Fengen Wang, Bryan A. Chin, Auburn Univ. (United States)

A new method of rapid detection of pathogens by 3D biomolecular filtering and automated indexing plate measurement has been demonstrated. In this process, a liquid containing pathogens is passed through a 3D biomolecular filter composed of planar arrays of MagnetoElastic (ME) biosensors held by a magnetic field. This filter captures specific target pathogens (in our demonstration case, Salmonella) in the liquid as it passes over the filter. The experiment will be under different Salmonella concentrations, different flowing rate, different number of ME biosensors and different solution volume. Capture of the pathogens is by specific biomolecular recognition, not size exclusion as with traditional filters. After the entire liquid has passed over the filter, the magnetic field is shut off and the individual biosensors collected and dried. The biosensors are then placed on an indexing plate consisting of an array of rectangular cavities approximately 10% larger in size than the ME biosensors. A vibrating table is used to vibrate the ME biosensors into motion until each cavity of the plate is occupied by a single ME biosensor. The biosensors are then measured by sequentially positioning the sensors under a surface scanning detection coil for measurement of the final resonance frequency of the biosensors using an automated translation system. In this manner, a single sensor can be measured in less than 2 seconds with 1000 sensors being measured in less than 30 minutes.

9864-17, Session 4

Method for detection of a few pathogenic bacteria and determination of live versus dead cells

Shin Horikawa, I-Hsuan Chen, Songtao Du, Yuzhe Liu, Howard C. Wickle III, Sang-Jin Suh, James M. Barbaree, Bryan A. Chin, Auburn Univ. (United States)

This paper presents a rapid method of detecting live versus dead bacteria. The method combines phage-coated magnetoelastic (ME) biosensors and a wireless interrogator, enabling real-time monitoring of the growth and viability of specific bacteria in a nutrient broth. The ME biosensor used in this investigation is composed of a strip-shaped ME resonator (1 mm x 0.2 mm x 30 μm) upon which a landscape phage is coated to capture specific bacteria. E2 phage with high binding affinity for Salmonella Typhimurium was used as a model study. The specificity of E2 phage has been reported to be 2 in 10⁶ background bacteria. When the binding of Salmonella occurs, the mass of the biosensor increases, which simultaneously results in a decrease in the biosensor's resonant frequency. Monitoring of this mass-induced resonant frequency change allows for the instantaneous detection and quantification of Salmonella. ME biosensors with a pre-determined resonant frequency were first exposed to a low-concentration Salmonella suspension to capture a small but detectable amount of the bacteria on the sensor surface. The wireless interrogator was then used to measure

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the resonant frequency changes of the biosensors as a function of time in a nutrient broth. Live cells can grow, while dead ones can't, which leads to distinct differences in the resonant frequency changes over time. Hence, this methodology offers direct, real-time detection, quantification, and viability determination of specific bacteria.

9864-18, Session 4

Portable handheld imaging for contamination and sanitation inspection

Moon S. Kim, Agricultural Research Service (United States)

No Abstract Available

9864-19, Session 5

Characterization by hyperspectral imaging of a new fertilizer during field trials

Silvia Serranti, Giuseppe Bonifazi, Agata Trella, Sapienza Univ. di Roma (Italy)

This work was carried out in the framework of the LIFE RESAFE Project (LIFE12 ENV/IT/000356) "Innovative fertilizer from urban waste, bio-char and farm residues as substitute of chemical fertilizers". The aim of RESAFE project is the production of a new fertilizer from waste for agricultural practices. The new fertilizer, HQ-ORBP (High Quality Organic Based Product), was tested on different crops. For each crop six different treatments were applied and compared to verify HQ-ORBP quality. HyperSpectral Imaging (HSI) was applied to perform soil evolution monitoring and characterization in respect to the HQ-ORBP fertilizers utilization and quality of the resulting crops. HSI is an emerging analytical technique integrating conventional imaging and spectroscopy, allowing to obtain both spatial and spectral information from an object [1]. For each pixel of the acquired image a full spectrum constituted by all the wavelengths, belonging to the investigated spectral range (UV-Visible, NIR) [2], can be collected. HSI is non-destructive, non-polluting, fast and relatively inexpensive. Hyperspectral data were analyzed adopting a chemometric approach through application of Principal Component Analysis (PCA) for exploratory purposes and Partial Least Squares Analysis (PLS) for modelling.

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9864-20, Session 5

Development of a real-time hyperspectral-based whole surface leafy green inspection system

Hoonsoo Lee, Agricultural Research Service (United States); Changyeun Mo, National Academy of Agricultural Science (Korea, Republic of); Byoung-Kwan Cho, Chungnam National Univ. (Korea, Republic of); Moon S. Kim, Agricultural Research Service (United States)

To inspect the whole surfaces of flat leafy greens for safety and quality attributes, images of the two sides (adaxial and abaxial surfaces) of each leaf sample are needed. The food industry processes large volumes of

individual leaves on fast-moving conveyors. To enable whole-surface imaging of leafy greens, two conveyors in tandem, but traveling in opposite directions, were developed such that leaf samples are flipped from one conveyor onto the other conveyor and each leaf has traveled twice across the instantaneous field of view (IFOV) of a real-time hyperspectral line-scan system by the end of the second conveyor. A leaf travels the length of first conveyor and is then "caught" by the second conveyor which begins directly below the terminal end of the first conveyor. During the transition between the two conveyors, the leaf is flipped so that the previous face-up side is now facing down on the second conveyor, allowing both surfaces of the samples to be inspected, in sequence, as the leaf travels through the IFOV twice.

9864-21, Session 5

Rapid decomposition assessment of bovine manure composts using hyperspectral fluorescence imaging

Hyunjeong Cho, Sungyoun Kim, Dongho Kim, Hyungdal Park, Jaehwon Lee, NAQS (Korea, Republic of); Mirae Oh, Diane Chan, Moon S. Kim, Agricultural Research Service (United States)

Compost is a rich source of organic matter and is beneficial for production of a wide variety of annual vegetables, especially organic produce grown without the use of pesticides, synthetic fertilizers. Manure composting involves decomposition of organic residuals including reduction of pathogens in animal fecal matter. For compost applications as fertilizers for producing produce, complete decomposition of pathogens in fecal matters is required. Fluorescence imaging techniques have been shown effective in detecting relatively low concentration of animal fecal matter on produce such as lettuce, spinach, and apples. In this investigation, a hyperspectral fluorescence imaging system was used to evaluate various stages of bovine manure composts for potential use of fluorescence imaging techniques as rapid nondestructive means to assess decomposition stages of composts.

9864-22, Session 5

Hyperspectral imaging system for disease scanning on banana plants

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Generally, plant disease symptoms can be observed at late infection stages. By that time, Black Sigatoka disease (BSD) has probably spread to other plants in a crop. HS data can be used to assess the physiological status of plants by measuring light reflectance patterns at different spectrum bands. In this paper, we present our current work on building a hyper-spectral imaging system aimed at in-vivo detection of (BDS) pre-symptomatic responses in banana leaves. The proposed imaging system comprises a motorized stage, a high-sensitivity VIS-NIR camera and an optical spectrograph. The spectrograph's optical and spatial parameters were adjusted according to the manufacturer's specifications. However, to capture images of the whole banana leaf the stage's speed and frame rate must be computed to reduce motion blur and to obtain the same spatial resolution along the x and y dimensions of the resulting HS cube. Another issue is frame buffering, simple acquisition tools does not provide a constant frame rate which negatively affect the resulting image geometry. To eliminate dropped frames, we implement a circular buffer algorithm such that camera frame acquisition, memory management and image file disk-writing operations are managed by independent operating system threads in a desktop computer. Our continuous leaf scanning approach allows imaging leaves of arbitrary length without frame lost. Once, the images are captured a denoising step is performed to improve image quality and spectral profile

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extraction. The specificity of image features will eventually be analysed using banana plants under several biotic and abiotic conditions. The proposed system can acquire images in the spectral range of 400 to 1100 nm. and a spatial resolution of 0.5 mm. and a spectral resolution of 9 nm. It generates large amounts of image data (3 gigabytes per leaf) and can be easily adapted for scanning both sides of a leaf without removing the leaf from the plant. These images allowed to visualize the progress of BSD at different developmental stages that correlate well with metabolic changes measured using a mass spectrometer in posterior destructive test. Even in its current development status our system can provide high-resolution HS at a reduced cost compared to custom made commercial grade system.

9864-23, Session 5

Food inspection using hyperspectral imaging and SVDD

Faruk S. Uslu, Hamidullah Binol, Abdullah Bal, Yildiz Technical Univ. (Turkey)

Food inspection are composed of physical (texture, color, tenderness etc.), chemical (fat content, lean content, pH etc.), and biological (total bacterial count etc.) properties of materials. Generally, visual assessment of food quality and safety has been performed with the chemical or biological analysis with human visual assessment. But, this can be time-consuming, inaccurate, and sometimes environmentally unfriendly. Instead of human visual assessment, optical sensing methods which are robust, fast, and environmentally have been widely used as a potential tool for this purpose with the properties of being non-destructive and accurate. However, conventional imaging may not have enough information to perform sufficient inspection and evaluation for food items. Therefore, Hyperspectral imaging (HSI) is rapidly gaining technique for food processing area because of having large amounts of spatial and spectral information on the objects being studied. HSI is a form of three dimensional hyperspectral cube, with two dimensions of spatial information of the image, one dimension of the spectral information It is being successfully applied by researchers in the food industry such as meat quality assessment, quality evaluation of fish, detection of skin tumors on chicken carcasses, and classification of wheat kernels, because of having both spatial and detailed spectral information about studied material. In this study, we have performed to detect fat percentage in ground meat using HSI with Support Vector Data Description (SVDD). The proposed method performs to classify the fat of the ground meat as a target class to be separated from the remaining (non-target). Support Vector Data Description is a nonparametric, accurate and fast one-class classifier in HSI. In the SVDD, it is tried to enclose target data with a minimum closed hypersphere boundary. It is expected that all or almost all the trained data should be inside the sphere. The experimental results show that the proposed approach gives better results for food inspection.

9864-24, Session 6

Online sorting system for the detection of disease infected root vegetables

Byoung-Kwan Cho, Dae Yong Kim, Jae-Young Lee, Youngwook Seo, Chungnam National Univ. (Korea, Republic of)

No Abstract Available

9864-25, Session 6

Applicability of ion mobility spectrometry for detection of quarantine pests in wood

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Agriculture (United States); Angela M. Ervin, U.S. Dept. of Homeland Security (United States); Cindy Carey, George Gleason, Bruker Detection Corp. (United States); Lisa Mosser, Laurene Levy, Michael Hennessey, Russ Bulluck, U.S. Dept. of Agriculture (United States)

Visual inspection is the most commonly used method for detecting quarantine pests in agricultural cargo items at ports. For example, solid wood packing material (SWPM) at ports may be a pathway for wood pests and is a frequent item of inspection at ports. The inspection process includes examination of the external surface of the item and often destructive sampling to detect internal pest targets. There are few tools available to inspectors to increase the efficiency of inspection and reduce the labor involved. Ion mobility spectrometry (IMS) has promise as an aid for inspection. Because pests emit volatile organic compounds (VOCs) such as hormone like substances, Ion Mobility Spectrometry (IMS) was investigated for possible utility for detecting pests during inspection. SWPM is a major pest pathway in trade, and fumigation of many kinds of wood, including SWPM, with methyl bromide (MeBr) following a published schedule is regularly conducted for phytosanitary reasons prior to shipment to the United States. However, the question remains as to how long the methyl bromide remains in the wood samples after fumigation such that it could act as an interferent to the detection of pest related VOC emissions. This work investigates the capability of ion mobility spectrometry to detect the presence of residual methyl bromide in fumigated maple and poplar wood samples at different times post fumigation up to 118 days after fumigation. Data show that MeBr can be detected in the less dense poplar wood up to 118 days after fumigation while MeBr can be detected in the denser maple wood 55 days after fumigation.

9864-26, Session 6

A sequential method for estimating optical properties of two-layer tissues from spatially-resolved diffuse reflectance

Aichen Wang, Zhejiang Univ. (China) and Michigan State Univ. (United States); Renfu Lu, Agricultural Research Service (United States); Lijuan Xie, Zhejiang Univ. (China)

Spatially-resolved spectroscopy has been successfully used to determine the optical properties of food products like fruit. For simplification, the sample is treated as a one-layer homogeneous medium so that analytical solution to the diffusion equation for semi-infinite homogeneous media can be used to estimate the optical absorption and scattering coefficients with acceptable accuracy. However, the one-layer simplification does not accurately describe the structural properties of fruit that contains two distinctive layers of relatively homogeneous tissues, i.e., peel and flesh. Thus a two-layer model describing light propagation within tissues is necessary. This research was intended to develop a sequential method for estimating the five unknown parameters, i.e., absorption and scattering coefficients for top layer, thickness of top layer and absorption and scattering coefficients for second layer, for the two-layer diffusion model. Previous studies have reported unsatisfactory results with large estimation errors, when all parameters were estimated simultaneously. In this study, we proposed a sequential method to improve the optical property estimations of two-layer media from spatially-resolved diffuse reflectance. First, the optical properties of top layer are estimated using the diffuse reflectance close to the light source with the analytical solution to diffusion equation for one-layer homogeneous media. The remaining three unknown parameters (thickness of top layer and absorption and scattering coefficients for the second layer) are then estimated using the diffuse reflectance profile covering a greater distance range. The key to this method lies in the fact that the close region of the reflectance profile is determined by the top layer, while the far region of the reflectance profile is mainly influenced by the second layer. In addition, we found that the reflectance profiles up to 7 mfp' (mean free path) and 12 mfp' are sufficient for estimating scattering and absorption coefficients, respectively, which enables estimating the optical parameters for the two layers separately. Preliminary results showed that the proposed sequential

method improved the estimation accuracy by at least 10%, compared with conventional method.

9864-27, Session 6

Automated cart-mounted hyperspectral LIF imaging system for detection of fecal materials in produce fields

Alan M. Lefcourt, Agricultural Research Service (United States); Ross Kistler, S. Andrew Gadsden, Univ. of Maryland, Baltimore County (United States)

No Abstract Available

9864-28, Session 6

Moving-window waveband screening integrated with PCA-LDA method applied to non-destructive discriminant analysis of transgenic sugarcane leaves with Vis-NIR spectroscopy

Kaisheng Ma, Bin Yang, Lijun Yao, Jiemei Chen, Tao Pan, Jinan Univ. (China)

Sugarcane is the major sugar crop and cane sugar accounts for approximately 70% of total world sugar production. China's sugar production ranks third in the world. With the development of agricultural biotechnology, transgenic sugarcane breeding is increasingly receiving attention. In the present study, the moving-window waveband screening integrated with principal component analysis and linear discriminant analysis (MW-PCA-LDA) was successfully employed for non-destructive discriminant analysis of transgenic sugarcane leaves with visible and near-infrared (Vis-NIR) spectroscopy. A Kennard-Stone algorithm-based process of calibration, prediction, and validation in consideration of uniformity and representative was performed to produce objective models.

A total of 306 transgenic sugarcane leaves samples that contain both Bacillus thuringiensis and Bialaphos resistance genes and 181 non-transgenic samples were collected and used spectral measurement. The selected optimal waveband was 766–812 nm with MW-PCA-LDA. With the use of random validation samples (106 transgenic and 81 non-transgenic) excluded from the modeling process, the recognition rates of transgenic and non-transgenic samples achieved 97.2% and 96.3%, respectively. Compared with the full PCA-LDA model that used the entire scanning region (400–2498 nm), the optimal MW-PCA-LDA model produced an obvious better recognition effect, and significantly reduced model complexity.

The results indicated that Vis-NIR spectroscopy combined with MW-PCA-LDA method provided a potential and promising tool for screening transgenic sugarcane breeding for large-scale agriculture, and could also provide valuable references for designing a small dedicated spectrometer with a high signal-to-noise ratio.

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9865-1, Session 1

Advanced management and protection of energy storage devices (AMPED) (Keynote Presentation)

Patrick McGrath, Advanced Research Projects Agency-Energy (ARPA-E) (United States)

We need better battery systems in order to meet the performance, lifetime, and cost requirements for energy storage applications. To date, most battery R&D has focused “inside” the battery cell, utilizing approaches to higher energy density chemistries, more robust materials, and optimized cell constructions. ARPA-E recognized the opportunity to push battery system performance by focusing “outside” of the cell, and in 2012 launched the AMPED program set out to create a new generation of chemistry agnostic battery diagnostics and management systems. Even with continual improvements in lithium ion cell technology, heterogeneity and uncertainty in their true operating conditions force conservative constraints on how we utilize batteries in every application. AMPED is developing novel sensors & diagnostics, advanced physics-based models & controls, and flexible power architectures to unlock greater performance, reliability, and safety from batteries.

9865-2, Session 1

Optimization of material/device parameters of CdTe photovoltaic for solar cells applications (Invited Paper)

Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

Cadmium Telluride (CdTe) has been recognized as a promising photovoltaic material for thin-film solar cell applications due to its near optimum bandgap of ~1.5 eV and high absorption coefficient. The energy gap is near optimum for a single junction solar cell and the high absorption coefficient allows films as thin as 3 μm to absorb more than 98% of the above-bandgap radiation. Cells with efficiencies near 20% have been produced with poly-CdTe materials. This paper will examine N/P hetero-structure device architecture. The performance limitations related to doping concentrations, minority carrier lifetimes, absorber layer thickness, and surface recombination velocities at the back and front interfaces is assessed. Ultimately, the paper explores device architectures of poly-CdTe and crystalline CdTe to achieve performance comparable to GaAs.

9865-3, Session 1

Flexible solar cells based on curved surface nano-pyramids

Anil Shrestha, Banpil Photonics, Inc. (United States); Genki Mizuno, Patrick Oduor, Achyut K. Dutta, Banpil Photonics, Inc. (United States) and Banpil Photonics, Inc. (United States); Nibir K. Dhar, Night Vision and Electronic Sensors Directorate (United States); Jay S. Lewis, MTO/Defense Advanced Research Projects Agency (United States)

The advent of ultrathin crystalline silicon (c-Si) solar cells has significantly

reduced the cost of silicon solar cells by consuming less material. However, the very small thickness of ultrathin solar cells poses a challenge to the absorption of sufficient light to provide efficiency that is competitive to commercial solar cells. Light trapping mechanism utilizing nanostructure technologies have been utilized to alleviate this problem. Unfortunately, a significant portion of light is still being lost even before entering the solar cells because of reflection. Different kinds of nanostructures have been employed to reduce reflection from solar cells, but reflection losses still prevail. In an effort to reduce reflection loss, we have used an array of modified nanostructures based cone or pyramids with curved sides, which matches the refractive index of air to that of silicon. Moreover, use of these modified pyramids provides a quintic (fifth power) gradient index layer between air and silicon, which significantly reduces reflection. The solar cells made of such nanostructures not only significantly increase conversion efficiency at reduced usage of crystalline silicon (e.g. thinner), but it also helps to make the c-Si based solar cell flexible. Design and optimization of flexible c-Si solar cell will be presented in the paper.

9865-4, Session 1

High efficiency nanostructured thin film solar cells for energy harvesting

Roger E. Welsler, Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Jay S. Lewis, Defense Advanced Research Projects Agency (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Thin-film III-V materials are an attractive candidate material for solar energy harvesting devices capable of supplying portable and mobile power in both terrestrial and space environments. Nanostructured quantum well and quantum dot solar cells are being widely investigated as a means of extending infrared absorption and enhancing photovoltaic device performance.

In this paper, we will review recent progress on realizing high-voltage InGaAs/GaAs quantum well solar cells that operate at or near the radiative limit of performance. These high-voltage nanostructured device designs provide a pathway to enhance the performance of existing device technologies, and can also be leveraged for next-generation solar cells.

9865-5, Session 1

Development of FDTD simulation tool for designing micro-nanostructures based optical devices

Anil Shrestha, Genki Mizuno, Patrick Oduor, Saif Islam, Achyut K. Dutta, Banpil Photonics, Inc. (United States); Nibir K. Dhar, Night Vision and Electronic Sensors Directorate (United States)

The Finite-Difference Time-Domain (FDTD) analysis method is one of the simplest and most effective methods for the characterization of optical devices. The optical properties of a device under test, over a band of frequency spectrum, can be extracted from a single simulation, which is the most compelling attribute for the selection of the method. However, FDTD analysis is computationally expensive and takes a lot of time for a large domain of simulation. This drawback can be negated in modern

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computers by making use of a graphics processing unit (GPU) chip. The GPU parallelizes the computation work and cuts down on the time required for simulations. We have developed an algorithm for FDTD analysis of optical devices with micro and nano-structures using Compute Unified Device Architecture (CUDA). The developed algorithm exploits the benefit of multiple cores of GPU and boosts the speed of simulation without sacrificing its accuracy, and provides a path towards the development of FDTD Simulation Tool for designing micro-nanostructured based optical devices.

9865-6, Session 2

Electrostatic spray deposition of Li₄Ti₅O₁₂ based anode with enhanced rate capability and energy density for lithium-ion batteries (*Invited Paper*)

Chunhui Chen, Florida International Univ. (United States); Richa Agrawal, Florida International Univ (United States) and Florida International Univ. (United States); Chunlei Wang, Florida International Univ. (United States)

Li₄Ti₅O₁₂ (LTO) is one of the most promising anode materials for lithium-ion batteries (LIBs) due to its excellent cyclability and extraordinary structure stability during lithium-ion intercalation and deintercalation. However, LTO suffers from the low electronic conductivity (< 10⁻¹³ S cm⁻¹) and low theoretical capacity which result in poor rate capability and low energy density. In this talk, we will present our recent progress on LTO based anode materials for LIBs. The electrodes were prepared by electrostatic spray deposition (ESD), a versatile deposition method that can produce thin film electrodes with various structures. Both LTO and its composites were studied. For pristine LTO, it exhibits high rate capability and long cycle life. In the voltage range of 0.05-3 V, reversible specific capacities of 357, 307, 270, 207, 153 and 98 mAh g⁻¹ were delivered at different current rates of 0.5 C, 1 C, 2 C, 5 C, 10 C and 20 C, respectively. Excellent electrochemical performance was observed even after 20 C harsh condition. Greatly enhanced rate performance and energy density of LTO based composites and detailed results and discussion will be presented in the meeting.

9865-7, Session 2

Electrostatic spray deposition based lithium ion capacitor

Richa Agrawal, Chunhui Chen, Chunlei Wang, Florida International Univ. (United States)

Conventional Electrochemical double-layer capacitors (EDLCs) are well suited as power devices that can provide large bursts of energy in short time periods. However, their relatively inferior energy densities as compared to their secondary battery counterparts limit their application in devices that require simultaneous supplies of both high energy and high power. In the wake of addressing this shortcoming of EDLCs, the concept of hybridization of lithium-ion batteries (LIBs) and EDLCs has attracted a lot of scientific interest in recent years. Such a device, generally referred to as the "lithium-ion capacitor" typically utilizes a lithium intercalating electrode along with a fast charging capacitor electrode. Herein we have constructed a lithium hybrid electrochemical capacitor comprising a Li₄Ti₅O₁₂ (LTO) anode and a graphene and carbon nanotube (G-CNT) composite cathode using electrostatic spray deposition (ESD). The electrodes were characterized using scanning electron microscopy and X-ray diffraction studies. Cyclic voltammetry, galvanostatic charge-discharge and electrochemical impedance spectroscopy measurements were carried out to evaluate the electrochemical performance of the individual electrodes and the full hybrid cells.

9865-8, Session 2

Low temperature processing of dielectric perovskites for energy storage

Narsingh B. Singh, Univ. of Maryland, Baltimore County (United States); Kamdeo Mandal, Institute of Technology, Banaras Hindu Univ. (India); Michael DeVisbiss, David House, Abhishek Singh, Julian Loiacono, Fow-Sen Choa, Bradley Arnold, Univ. of Maryland, Baltimore County (United States)

There is a strong need for high dielectric and high resistivity material for high voltage applications. The calcium copper titanate of the stoichiometry CaCu₃Ti₄O₁₂ (CCTO) and several of its analogs such as Yttrium copper titanate Y₂/3Cu₃Ti₄O₁₂ (YCTO) will be great materials if resistivity can be increased by two orders of magnitude.,

9865-9, Session 2

Piezoelectric-based hybrid reserve power sources for munitions

Jahangir Rastegar, Omnitek Partners, LLC (United States); Carlos M. Pereira, U.S. Army Armament Research, Development and Engineering Ctr. (United States); Dake Feng, Omnitek Partners, LLC (United States)

Reserve power sources are used extensively in munitions and other devices such as emergency devices or remote sensors that have to be powered only once and for a relatively short duration. Current chemical reserve power sources, including thermal batteries and liquid reserve batteries require sometimes in excess of 100 msec to become fully activated. In many applications, however, electrical energy is required in a few msec following the launch event. In such applications, other power sources have to be provided to provide power until the reserve battery is fully activated.

The amount of electrical energy that is required by most munitions before chemical reserve batteries are fully activated is generally small and can be provided by properly designed piezoelectric-based energy harvesting devices. In this paper the development of a hybrid reserve power source is being reported that is obtained by the integration of a piezoelectric-based energy harvesting device with a thermal battery that can provide power almost instantaneously upon munitions firing or other similar events in other applications.

This article provides a review of the state of the art in piezoelectric-based electrical energy harvesting methods and devices and their charge collection electronics for use in the developed hybrid power sources. The design of such a hybrid piezoelectric and thermal battery based power source is described in detail. Computer modeling of the power source and simulation of its operation once subjected to activation event is provided. The testing platform developed for testing the piezoelectric component of the power source and its electronic safety and charge collection electronics is described and test results are provided and discussed in detail.

9865-10, Session PTue

Powering an in-space 3D printer using solar light energy

Skye Leake, Univ. of North Dakota (United States); Thomas McGuire, North Dakota State Univ. (United States); Michael Parsons, Michael Hirsch, Jeremy Straub, Univ. of North Dakota (United States)

This paper describes how a solar power source is used to enable in-space 3D printing without requiring the conversion to electric power and back

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into thermal energy that is highly loss-causing. A design for an in-space 3D printer is presented, with a particular focus on the power generation system. Then, key benefits are presented and evaluated. The use of solar light power presents a number of benefits over other substrate heating methods. Specifically, the passive nature of the approach facilitates the design of a spacecraft that can be built, launched, and operated at very low cost levels.

The monetary benefits are derived from several key features of the system. First, the primary solar collector is capable of being broken down into several smaller components in order to reduce the launch volume footprint, to minimize launch costs. The design utilizes a compact mirror arrangement (as has been recently demonstrated on the James Webb Space Telescope). This design is evaluated as is the precision that is required. From this, it is demonstrated that, for this application, only limited precision is required to achieve near maximum efficiency levels from the array.

The proposed approach also facilitates easy configuration of the amount of energy that is supplied. For a 3D printer that is capable of printer several fundamentally different materials, input energy must be able to be easily varied to support providing the appropriate level for each material. With a properly sized array the constituent elements can be directed in order to control the amount of input energy supplied. This allows objects to be constructed from multiple materials, with supply sources changed over at appropriate times during the printing process. Having this control facilitates printing advanced objects using materials including metals, polymers, and silicon. The ability to easily control the output of the array (without significant loss or conversion to thermal energy on undesirable areas of the spacecraft) offers a distinct advantage offer other methods, such as a nuclear solution. The limited unneeded thermal energy is managed via radiative cooling using a cooling system located on the back of the primary array. Excess thermal energy is also used for temperature maintenance of key electronics, batteries and other temperature sensitive components.

The use of solar energy power also provides the distinct advantage of removing the need for the heavy metals and radioactive materials required for a nuclear-power solution. This facilitates an easy de-orbit plan, as the spacecraft can be demonstrated to completely burn up in Earth's atmosphere (and doesn't require specific mitigation measures or placement in a 'graveyard' orbit).

After presenting the design and evaluating its efficacy and the benefits that it provides, the paper concludes with a discussion of future work required in this area. Specifically, a set of milestones for a test mission and operational spacecraft are presented.

9865-11, Session PTue

A CubeSat deployable solar panel system

Thomas McGuire, Michael Hirsch, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

CubeSats are facilitating low-cost access to space for educational, research, commercial and governmental purposes. Their power usage has increased with the complexity of the systems included. Spacecraft spend only a fraction of their time in direct sunlight and, with solar panels mounted to all sides of the spacecraft, at best only one is receiving directly normal light. Others are receiving highly angled light or none at all.

This paper presents a deployment system which creates a plane of solar panels allowing more panels to be in directly normal sunlight at any given point. In conjunction with onboard reaction wheels (which allow the CubeSat to be orientated correctly relative to the sun), this will maximize the level of power generated.

The deployable system is comprised of a printed circuit board (holding the solar cells) which is attached to an aluminum hinge. A small, simple mechanism is incorporated that locks the panels into place, after deployment. A custom hinge was developed based on a modified barrel hinge design that is used in conjunction with torsion springs to deploy the panels. A Ni-chrome wire loop (which is burned to deploy the panels) restrains the panels in the closed orientation.

The system (which is the first step towards a larger multi-leaf design) was designed to be easily incorporated into existing CubeSat designs.

The efficacy of this approach for power generation and its simplicity, as compared to other prospective approaches are assessed herein. The paper concludes with a discussion of ongoing development and testing activities.

9865-12, Session PTue

Development of origami-style solar panels for use in support of a Mars mission

Alexander Holland, Jeremy Straub, Univ. of North Dakota (United States)

This paper presents work on the development of an Origami-style solar panel technology. This approach increases a satellite's solar array's power generation surface area, given constrained space and mass. The same deployable structure (for the solar panels) can also house a phased array on the reverse side. For the proposed Mars demonstration mission, this array is used for communications and microwave wireless power transmission. The design of the solution is presented in detail, including a discussion of the pre-deployment configuration, deployment process and final configuration. The panels, prior to deployment, are folded around the square base of the spacecraft, covering all four of its sides. To deploy them a slight circular motion is introduced to use centrifugal force to cause each side to fold out from the side of the satellite. A simple hinging mechanism is used to interconnect the panels and inflatable tubes or wire that is designed to stiffen in a straightened orientation when electrified are used to move the panels into their final position and provide rigidity.

The efficacy of the proposed technology is considered in the context of the Martian mission which demonstrates its mass and volume efficiency (which are characterized and compared to other prospective solutions) as well as the utility of the approach for enabling the mission. A qualitative analysis of the benefits and drawbacks of the approach is presented. Quantitative analysis of the technology's overall impact on mission design is presented, before concluding with a discussion of the next steps for the research.

9865-13, Session PTue

Consideration of the use of origami-style solar panels for use on a terrestrial / orbital wireless power generation and transmission spacecraft

Alexander Holland, Jeremy Straub, Univ. of North Dakota (United States)

This paper presents work on the development of Origami-style solar panels and their adaption and efficacy for use in Earth orbit, focusing on the enabling capability of this technology for the generation and transmission of power. The proposed approach provides increased collection (solar panel) and transmission (microwave radiation) surface area, compared to other systems with similar mass and volume. An overview of the system is presented including its pre-deployment configuration, the deployment process and its final configuration. Its utility for the wireless power transmission mission is then considered. Economic analysis is performed to assess how the mass and volume efficiencies provided enable the system to approach target willingness-to-pay values that were presented and considered in prior work.

A key consideration regarding the use of wireless power transfer in Earth orbit is the reliability of the technology. This has several different areas of consideration. It must reliably supply power to its customers (or they would have to have local generation capabilities sufficient for their needs, defeating the benefit of this system. It must also be shown to reliably supply power only to designated locations (and not inadvertently or otherwise beam power at other locations). The effect of the system design (including the Origami structure and deployment / rigidity mechanisms is considered to assess whether the use of this technology may impair either of these key

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mission/safety-critical goals. This analysis is presented and a discussion of mitigation techniques to several prospective problems is presented, before concluding with a discussion of future work.

9865-14, Session PTue

Charging system using solar panels and highly resonant wireless power transfer model for small UAS applications

Sydney N. Hallman, The Univ. of Oklahoma (United States) and ONEOK (United States); Robert Huck, James Sluss, The Univ. of Oklahoma (United States)

The use of a wireless charging system for small, unmanned aircraft system applications is useful for both military and commercial consumers. An efficient way to keep the aircraft's batteries charged without interrupting flight would be highly marketable. While the general concepts behind highly resonant wireless power transfer are discussed in a few publications, the details behind the system designs are not available even in academic journals, especially in relation to avionics. Combining a highly resonant charging system with a solar panel charging system can produce enough power to extend the flight time of a small, unmanned aircraft system without interruption. This paper provides an overview of a few of the wireless-charging technologies currently available and outlines a preliminary design for an aircraft-mounted battery charging system.

9865-15, Session PTue

Nano-manufactured catalyst for the production of hydrogen via solar thermal water splitting

William J. Clower, Chester G. Wilson, Louisiana Tech Univ. (United States)

This paper reports on the creation of nano-manufactured catalyst for the production of hydrogen fuel via the solar thermal water splitting process. The solar thermal water splitting process is considered the holy grail of green energy producing zero carbon emissions. This is made possible by focusing solar energy as the heating source, while the only reactant consumed in the process is water. For this work we are investigating the reaction dynamics of cobalt ferrite catalyst on an aluminum oxide support. Solar thermal water splitting occurs in two steps: reduction and oxidation reactions. The reduction step occurs by heating the catalyst, which produces oxygen and converts the cobalt ferrite/aluminum oxide to metal aluminates. The oxidation step begins by flowing water over the newly created metal aluminates. The metal aluminates react with the oxygen creating the original cobalt ferrite/aluminum oxide catalyst as well as hydrogen gas. The catalyst created for this work was done utilizing an electrospinning technique. In a one-step process the aluminum oxide support material can be incorporated with cobalt ferrite catalyst into a single nanofiber. With this technique nanofiber catalyst can be created with diameters ranging from 20 to 80 nm. Nanostructured materials allow for large surface areas >50 m²/g and surface area to volume ratios >9e7m⁻¹. The large surface area creates the opportunity for more active sites where the reactions can occur. An increase in reactivity has the potential to move fuel production rate for solar thermal water splitting closer to large-scale commercialization.

9865-16, Session PTue

Consideration of space solar power from a force enablement perspective

Jeremy Straub, Univ. of North Dakota (United States)

Previous work has considered the use of wireless power transfer

(technologies generating power in one location and transmitting it to another) and specifically space solar power from an economic perspective. This work concluded that several previously proposed approaches were unable to meet the requisite cost-per-unit-of-power levels to be economically viable, based on cost levels previously determined. This analysis, however, did not look at qualitative benefits that could be provided by wireless power transfer and space solar power. It also didn't consider the quantitative benefits under certain circumstances (such as wartime conditions) where the prior work's cost levels may not be applicable. This paper seeks to expand the analysis of this prior work. It considers the efficacy of the use of space solar power as an enabler for certain aerial and orbital missions.

The assessment process begins with the definition of several scenarios that demonstrate areas of application where space solar power and wireless power transfer provide special benefits. These scenarios are assessed to identify other prospective ways of providing power, under the scenario, and other ways that the same ends could be achieved. These scenarios, as well as the base scenario discussed in prior work, are then assessed qualitatively and quantitatively to determine if cases exist where space solar power and wireless power transfer is justified and to determine what characteristics define these cases to facilitate extrapolation. The paper concludes with a discussion of the impediments to the implementation of these technologies and a look at the possible road ahead.

9865-17, Session PTue

Optimum design of cantilever slitted beams for broadband vibration energy harvesting

Mina R. Dawoud, Hesham Hegazi, Cairo Univ. (Egypt); Mustafa Arafa, The American Univ. in Cairo (Egypt)

This paper presents the design and optimization of a multi-modal vibration energy harvester to enable extracting energy from wideband excitations from a base motion. The harvester consists of a tapered cantilever beam having a straight longitudinal slit that extends from the beam tip, partially dividing the beam into two sub-beams. Each sub-beam carries a proof mass and a permanent magnet at its tip. The two permanent magnets oscillate past stationary coils in order to convert the mechanical motion into electrical energy. The main system design variables, namely the beam geometry, slit length, mass values and their positions affect the spacing of the harvester's natural frequencies and output power. The beam design is optimized so as to possess four closely-spaced natural frequencies, which provide the desirable bandwidth across which the harvester could extract energy. A dynamic model was built to simulate the harvester, and this model is supported by experimental validation.

9865-18, Session PTue

Application of bias voltage to tune the resonant frequency of membrane-based electroactive polymer energy harvesters

Lin Dong, Stevens Institute of Technology (United States); Michael Grissom, KCF Technologies (United States); Frank Fisher, Stevens Institute of Technology (United States)

Vibration-based energy harvesting has been widely investigated to as a means to generate low levels of electrical energy for applications such as wireless sensor networks for areas such as Homeland Security and Structural Health Monitoring of critical civil infrastructure. However, for optimal performance it is necessary to ensure that resonant frequencies of the device match the ambient vibration frequencies for maximum energy harvested. Here a novel resonant frequency tuning approach is proposed by applying a bias-voltage to a pre-stretched electroactive polymers (EAP) membrane, such that the resulting changes in membrane tension can tune the device to match the environmental vibration source. The feasibility of

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changing the membrane stretch ratios to adjust the resonant frequencies of the energy harvesters is first presented. Both experimental and FEM results from ANSYS agree well with the analytical hyperelastic model of the vibration response of the EAP membrane. Furthermore, the effect of the bias-voltage on the EAP membrane, which induces an electrostatic pressure and corresponding reduction in membrane thickness are determined. Through the mass-loaded circular membrane vibration model, the effective resonant frequency of the energy harvester can be determined as a function of bias-voltage due to the changes in membrane tensions. Experiments verified the resonant frequencies corresponding to the bias-voltages predicted from the appropriate models. The proposed bias-voltage tuning approach for the EAP membrane may provide a novel tuning approach to enable energy harvesting from various ambient vibration sources in various application environments.

9865-19, Session PTue

A composite beam with dual bistability for enhanced vibration energy harvesting

Christopher R. Bowen, Univ. of Bath (United Kingdom); Mustafa Arafa, The American Univ. in Cairo (Egypt); Peter Harris, Univ. of Bath (United Kingdom); Grzegorz Litak, Lublin Univ. of Technology (Poland)

In this paper a bistable composite cantilever beam comprising asymmetric laminates is studied for vibration energy harvesting. Additional magnetic bistability is introduced to lower the level of excitation that triggers the snap, while retaining the favorable broadband performance. To this end, the beam is fitted with a permanent magnet at its tip that is oriented in magnetic repulsion with a stationary magnet. The system performance can be adjusted by varying the gap between the magnets. Experimental results reveal that the use of magnetic bistability enhances broadband performance and improves the output power within a certain level of drive level and magnet separation. The load-deflection characteristic of the bistable beam is experimentally determined, and is subsequently used to model the system by a reduced single-degree-of-freedom (SDOF) system having the form of the Duffing equation for a double-well potential system. The dynamics of the beam are investigated using bifurcation diagrams and shows that the qualitative behavior given by the measured response is predicted well by the simple SDOF model.

9865-20, Session PTue

Broadband magnetic levitation-based nonlinear energy harvester

Abdullah Nammari, Dustin Savage, Seth Doughty, Leland Weiss, Arun Jaganathan, Hamzeh Bardaweel, Louisiana Tech Univ. (United States)

A typical linear electromagnetic energy harvester scavenges power at single frequency. Operating linear harvester off-resonance reduces scavenged energy significantly. Nonetheless, targeted sources of vibrational energy are wideband. Several techniques have been explored to achieve broadband operation. To date, miniaturized broadband self-powered energy harvester ceases to exist.

Here, development of novel broadband nonlinear electromagnetic energy harvester is described. The energy harvester consists of three permanent magnets housed in a chamber. The arrangement of the three magnets, intentionally, results in levitated magnet in the middle between two stationary top and bottom magnets. The levitated magnet is guided using identical oblique mechanical springs attached to it. This unique arrangement produces desirable nonlinearities using a combination of oblique mechanical springs and magnetic springs. When energy harvester is excited, oblique springs are stretched in vertical direction rather along their longitudinal axes. Moreover, repulsive forces between levitated magnet and stationary ones are described with nonlinear magnetic springs. Another advantage of this design is the ability of oblique springs to perform "store-and-release" actuation mechanism to continuously "perturb" the harvester as it approaches its low-energy state. This results in longer oscillation time of levitated magnet before it arrives to complete rest. Oblique springs also align levitated magnet along stationary magnets' common axis. Thus, lateral movement and friction damping are reduced. Voltage is induced in a coil wrapped around the chamber by the oscillatory motion of levitated magnet. Obtained results show clear broadband frequency operation. A nonlinear dynamic model of the energy harvester is developed and solved numerically.

Conference 9866: Autonomous Air and Ground Sensing Systems for Agricultural Optimization and Phenotyping

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9866-1, Session 1

Applying remote sensing expertise to crop improvement: Progress and challenges to scale up high throughput field phenotyping from research to industry (Invited Paper)

David Gouache, Katia Beauchene, Antoine Fournier, Benoit de Solan, ARVALIS - Institut du végétal (France); Fred Baret, INRA PACA (France); Alexis Comar, Hi-phen SAS (France)

Digital and image analysis technologies in greenhouses have become commonplace in plant science research and started to move into the plant breeding industry. However, the core of plant breeding work takes place in fields. We will present successive technological developments that have allowed the migration and application of remote sensing approaches at large into the field of crop genetics and physiology research, with a number of projects that have taken place in France. These projects have allowed us to develop combined sensor plus vector systems, from tractor mounted and UAV mounted spectroradiometry to autonomous vehicle mounted spectroradiometry, RGB imagery and LIDAR. We have tested these systems for deciphering the genetics of complex plant improvement targets such as the robustness to nitrogen and water deficiency of wheat and maize. We will present our view on the next critical steps in terms of technology and data analysis that will be required to reach cost effective implementation in industrial plant breeding programs. If this can be achieved, these technologies will largely contribute to resolving the equation of increasing food supply in the resource limited world that lies ahead.

9866-2, Session 1

Estimating fresh biomass of maize plants from their RGB images in greenhouse phenotyping

Yufeng Ge, Univ. of Nebraska-Lincoln (United States); Piyush Pandey, University of Nebraska - Lincoln (United States); Bai Geng, Univ. of Nebraska-Lincoln (United States)

There have been increasing uses of high throughput imaging to characterize morphological and physiological traits of plants and their temporal dynamics. In this study we investigated the usefulness of four different imaging modalities to characterize the traits of maize plants. The plant material used in the experiment are inbred B73 (n=40) and inbred Mini Maize (n=40), representing two extremes of maize morphology. Half of the plants were maintained under well-watered condition and the other half under drought condition. The imaging run started five days after planting and implemented once a day. Four different types of images were collected: RGB, fluorescence, thermal IR and hyperspectral. Twenty plants were destructively sampled to measure plant traits including total leaf area, fresh shoot biomass, dry biomass, water content, and leaf chlorophyll content during the course of the experiment. These measured traits were then used to correlate with the image-based phenotypes extracted from the images. The results showed that the destructively measured traits and image-based phenotypes are highly correlated. The growth curves derived from images revealed distinctive growth patterns of B73 and Mini-Maize in response to

water application rate. As the greenhouse is also equipped with a precise water application unit and pot weighing station, daily water use efficiency of each plant can also be accurately calculated. Finally, hyperspectral imaging is useful to derive plant water content and chlorophyll content.

9866-3, Session 1

Estimating crop water stress with standard deviation of canopy temperature in thermal imagery

Ming Han, Colorado State Univ. (United States); Huihui Zhang, Kendall DeJonge, Louise Comas, Thomas Trout, Agricultural Research Service (United States)

A new crop water stress index using standard deviation of canopy temperature as an input was developed to monitor crop water status. In this study, thermal imagery was taken from maize under various levels of deficit irrigation treatments in different crop growing stages. The Expectation-Maximization algorithm was used to estimate canopy temperature distribution from thermal imagery under various crop coverage and water stress conditions. Soil water deficit (SWD), leaf water potential (?), stomatal conductance, and other crop water stress indices were used to evaluate the newly developed water stress index, named the canopy temperature variance water stress index (CTVWSI). The CTVWSI responded to irrigation events, and all water stress indices show statistical significant relationship with CTVWSI. Although CTVWSI is not sensitive to small water stress changes, the result still suggests that the index calculated from standard deviation of canopy temperature in thermal imagery could be used as a crop water stress indicator.

9866-4, Session 1

High clearance phenotyping systems for season-long measurement of corn, sorghum and other row crops to complement unmanned aerial vehicle systems

Seth C. Murray, Texas A&M AgriLife Research (United States); Leighton Knox, Wildcat Manufacturing (United States); Brandon Hartley, Texas A&M AgriLife Research (United States); Mario A. Méndez-Dorado, Texas A&M Univ. (United States); Grant Richardson, Texas A&M AgriLife Research (United States); J. Alex Thomasson, Texas A&M Univ. (United States); Yeyin Shi, Nithya Rajan, Muthu K. Bagavathiannan, Xuejun Dong, William L. Rooney, Texas A&M AgriLife Research (United States)

The next generation of plant breeding progress requires accurately estimating plant growth and development parameters to be made over routine intervals within large field experiments. Hand measurements are laborious and the most promising tools under development are sensors carried by ground vehicles or unmanned aerial vehicles, with each specific vehicle having unique limitations. Previously available ground vehicles have primarily been restricted to monitoring shorter crops or early growth in corn and sorghum, since plants taller than a meter could be damaged by a tractor or spray rig passing over them. Here we have designed two and already

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constructed one of these self-propelled ground vehicles with adjustable heights that can clear mature corn and sorghum without damage (over three meters of clearance), which will work for shorter row crops as well. In addition to regular RGB image capture, sensor suites are incorporated to estimate plant height, vegetation indices, canopy temperature and photosynthetically active solar radiation capture, all referenced using RTK GPS to individual plots. These ground vehicles will be useful to validate data collected from unmanned aerial vehicles and support hand measurements taken on plots.

9866-5, Session 1

Plant phenotyping using multi-view stereo vision with structured lights

Thuy T. Nguyen, David C. Slaughter, Julin N. Maloof, Neelima Sinha, Univ. of California, Davis (United States)

Different camera based 3D plant phenotyping systems have been built recently. There is lack of a full 3D reconstruction and phenotyping system that incorporates computer algorithms, including camera calibration, excessive-green based plant segmentation, semi-global stereo block matching, disparity bilateral filtering, 3D point cloud processing, and 3D feature extraction, and hardware that consists of an arc superstructure to hold five pairs of cameras and a custom designed structured light pattern illumination system. In this paper, without destroying any parts of the plant, we are able to extract 3D features of whole plants modeled from multiple pairs of stereo images taken at different view angles. The 3D plant features presented in this study include plant height, total leaf area, and total leaf shading area. For plants having appropriate distances between leaves and in leaf size, the algorithms used in our system yielded satisfactory experimental results where plants were repeatedly imaged and phenotyped over the time.

9866-6, Session 1

Cotton height and canopy structure measurement using a lidar sensor

Shangpeng Sun, Changying Li, Yu Jiang, Andrew Paterson, The Univ. of Georgia (United States)

An automatic cotton height measurement system was developed in this research, which is one component of a multi-sensor platform for high throughput field-based phenotyping in cotton breeding. A tractor-based mobile platform and robust data acquisition system were created to ensure that high quality of raw data could be collected for both static situation (the sensor was kept at a fixed position) and dynamic situation (the sensor was moved with the tractor-based platform along certain direction). A LiDAR sensor mounted on the tractor was used to scan the cotton field from the top view, while a RTK GPS unit was used to obtain the corresponding position information. Three factors, tractor moving speed, mounting height, and angular resolution of the LiDAR, were considered in this process. A 3D model of the scanned cotton was reconstructed based on the collected data and the cotton height was derived. An average error of 2.49% with a maximum error of 4.77% and a minimum error of 1.10% were achieved for the static situation; an average error of 6.21% with a maximum error of 12.25% and a minimum error of 2.03% were achieved for the dynamic situation. The results of the field experiments showed that the proposed system can measure cotton height accurately and effectively.

9866-27, Session 1

Towards robotic agriculture (Invited Paper)

Simon Blackmore, Harper Adams Univ. College (United Kingdom)

Developed agriculture uses massive amounts of energy in a myriad of forms, from the energy associated with chemicals used to control pests and diseases, through fertilisers, to the tractors themselves and the fuel to power them. This energy is often wasted as it goes off-target, is expensive and will become more so in the future. Smarter machines should use the minimum amount of energy to turn the natural environment into useful agriculture thus cutting out wasted energy and reducing costs. As agricultural engineers we are continually looking to find ways of making the crop and animal production processes more efficient and have developed the concept of Precision Farming, where we recognise the natural variability found on our farms and change the management and treatments to suit. This variability takes both spatial and temporal forms. Spatial variability can be understood and managed by creating yield maps and soil maps. Temporal variability is often fundamentally linked to changes in weather over time resulting in the need for real-time management. In industry, we used to have a production line mass producing one item and are now moving over to flexible manufacturing, where each item is developed individually. In agriculture we can see a similar approach by reducing the scale of treatments from farm scale, to field scale, to sub-field scale and even individual plant treatment.

9866-28, Session 1

Comprehensive UAV agricultural remote-sensing research at Texas A&M University

J. Alex Thomasson, Yeyin Shi, Jeffrey Olsenholler, John Valasek, Seth C. Murray, Michael P. Bishop, Texas A&M Univ. (United States)

Unmanned aerial vehicles (UAVs) have some major advantages over manned aircraft for agricultural remote sensing. Flying UAVs is much less expensive, is much more flexible in scheduling, enables lower altitudes, uses lower speeds, and ultimately provides much better spatial resolution in resulting images. The main technical disadvantage is that, at the lower altitudes and speeds, only relatively small areas can be imaged. However, on large farms with contiguous fields, it is possible to collect high-quality images on a regular basis by using UAVs with appropriate sensing technologies that enable high-quality image mosaics to be created with sufficient metadata and ground-control points. UAVs also have some major advantages over ground-based vehicles for high-throughput phenotyping in agricultural fields. UAVs can collect data regardless of whether the field is muddy. They can also collect data after the crop canopy has closed and remove the possibility of damaging plants. In the summer of 2015 Texas A&M University's agricultural research agency, Texas A&M AgriLife Research, embarked on a comprehensive program of remote sensing with UAVs at its 568-ha Brazos Bottom Research Farm. This farm is made up of numerous fields on which various crops are grown in plots or complete fields. Among the crops grown at the farm are cotton, corn, and sorghum. After gaining FAA permission to fly at the farm, the research team used multiple fixed-wing and rotary-wing UAVs along with various sensors including multispectral, hyperspectral, and lidar to collect image data over all parts of the farm at least once per week. This article will report on the details of flight operations and sensing and analysis protocols, and it will include a large number of lessons learned in the process of developing a comprehensive UAV remote-sensing effort of this sort.

9866-7, Session 2

Development of a ground sensing platform for infield phenotyping of cotton plants

Yu Jiang, Changying Li, Andrew Paterson, Jon S. Robertson, The Univ. of Georgia (United States)

Breeding of crops has to be more efficient to fulfil the requirement of feeding over nine billion people in the world. In order to improve breeding efficiency, phenotypic traits of crops need to be quickly and accurately measured in the field, and thus requiring new technologies of infield high-

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throughput phenotyping of crops. The goal of this paper was to develop a ground sensing platform measuring typical phenotypic traits of cotton plants such as canopy height. A high clearance tractor equipped with a real time kinematic (RTK) GPS was used as the platform base on which an enclosure was mounted at the back end. A Microsoft Kinect v2 camera was installed inside the enclosure to acquire color and depth images of cotton plants from top view. The Kinect v2 camera and RTK GPS were controlled for data acquisition by a custom software developed using LabVIEW. The software was built on a multithreading structure that interfaced with Kinect v2 and GPS at different sampling rates and data formats. An experimental cotton field planted in 2015 was used for data collection including 216 plots, and three datasets were acquired at different growth stages. The height of cotton plants was extracted from the depth images, and the average height of individual plots was calculated by associating with GPS information. In addition, canopy structure was retrieved using both color and depth information. The experimental results showed that the extracted canopy heights were highly correlated to the manual measurements, indicating that the ground sensing platform could be an efficient way to measure morphologic traits of cotton plants in the field.

9866-8, Session 2

Cotton phenotyping with a thermal infrared camera and lidar from a track-mounted platform

Andrew N. French, U.S. Arid-Land Agriculture Research Ctr. (United States); Michael A. Gore, Cornell Univ. (United States); Alison Thompson, U.S. Arid-Land Agriculture Research Ctr. (United States)

High-Throughput Phenotyping (HTP) is a discipline for rapidly identifying plant architectural and physiological responses to factors such as heat and drought stress. Experiments conducted since 2010 at Maricopa, Arizona using a three-fold sensor group---thermal infrared radiometers, active visible/near infrared reflectance sensors, and acoustic plant height sensors---have shown the validity of HTP with a tractor-based system. However, results from these experiments also show that accuracy of plant phenotyping is limited by the system's inability to discriminate plant components and their local environmental conditions. This limitation may be overcome with plant imaging and laser scanning which can help map details in plant architecture and sunlit/shaded leaves. In an initial test, a track-mounted platform was deployed in 2015 over a senescent cotton crop consisting of a thermal infrared camera and scanning LIDAR driven by Arduino-controlled stepper motors. Using custom-written Python and Tkinter code, the platform moved autonomously along a pipe-track at <1 m/s while collecting thermal infrared imagery (640x480 resolution) and LIDAR scans at 25 Hz (0.1667 deg. beam). This late growth stage test showed the ability to map and count cotton boll distributions and to separately map plant and soil temperatures. Results from the test and plans for transferring the imaging/scanning technology to a more practical field-scale platform will be discussed.

9866-9, Session 2

Predicting cotton yield of small field plots in a cotton breeding program using UAV imagery data

Joe Mari Maja, Clemson Univ. (United States); Todd Campbell, Agricultural Research Service (United States); Joao Camargo Neto, EMBRAPA (Brazil); Philip Astillo, Clemson Univ. (United States)

One of the major criteria used for advancing experimental lines in a breeding program is yield performance. Obtaining yield performance data requires machine picking each plot with a cotton picker, modified to

weigh individual plots. Harvesting thousands of small field plots requires a great deal of time and resources. The efficiency of cotton breeding could be increased significantly while the cost could be decreased with the availability of accurate methods to predict yield performance.

This work is investigating the feasibility of using image processing technique using a commercial off-the-shelf (COTS) camera mounted on an Unmanned Aerial Vehicle (UAV) to collect normal and infrared images in predicting cotton yield on small plot. Presented in this paper is a comparison of images taken from three different altitude; 25, 30, and 40 meters on a 290,000 square meters cotton breeding plot located at Pee Dee REC, Florence, SC. An orthonormal images was generated from multiple images and was used to process multiple segmented plot. A Gaussian blur was used to eliminate the high frequency component of the images which correspond to the cotton pixels and used image subtraction technique to generate the high frequency pixels images. The cotton pixels was then separated using k-means cluster with 5 classes. Based on the current work, the calculated percentage cotton area was computed using the generated high frequency image (cotton pixels) divided by the total area of the plot. Preliminary results showed (five flights, 3 altitudes) that cotton cover on multiple pre-selected 227 sq. m. plot size produce an average of 8% which translate to approximately 22.3 kgs. of cotton. Comparisons on the different altitude and its relation to the calculated cotton percentage will also be presented in this paper.

9866-10, Session 2

Relating hyperspectral reflectance to plant productivity and stress in crops

Darren Drewry, Jet Propulsion Lab. (United States); Jorge C. Berny, Paul Gepts, Univ. of California, Davis (United States)

Crop breeding programs rely on identifying plant traits that convey enhanced productivity and/or improvements in resource use efficiency across a large set of genotypes and locations, and throughout the crop growth cycle. Observations of spectral reflectance have the potential to revolutionize our ability to rapidly identify a range of advantageous traits related to the biochemical, nutrient and hydrological status of leaves and canopies of agricultural systems. Incorporation of these dense spectral data into high-throughput phenotyping systems will require robust algorithms to relate hyper-spectral data to traits correlated with yield enhancement. Here we examine the potential of high spectral resolution visible through shortwave infrared (VSWIR) reflectance observations to characterize variations in photosynthetic capacity, nutrient contents and water stress across genetic and treatment diversity of field-grown wheat and beans. These two crops account for a significant fraction of human protein and calorie consumption globally, with significant potential for yield improvement to meet future food demand over the coming decades. This work provides a basis for application of spatially extensive, autonomous data collection platforms emerging with recent advances in sensor and vehicle technology. We discuss the scaling of these algorithms to airborne data collected at a study site in northern California.

9866-11, Session 2

Corn and sorghum phenotyping using a fixed-wing UAV-based remote sensing system

Yeyin Shi, Seth C. Murray, William L. Rooney, Texas A&M AgriLife Research (United States); Jeffrey Olsenholler, Texas A&M Univ. (United States); Nicholas Pugh, Dongyan Zhang, Texas A&M AgriLife Research (United States); John Valasek, J. Alex Thomasson, Texas A&M Univ. (United States)

Recent development of unmanned aerial systems has created opportunities

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in automation of field-based high-throughput phenotyping by lowering flight operational cost and complexity and allowing flexible re-visit time and higher image resolution than satellite or manned airborne remote sensing. In this study, flights were conducted over corn and sorghum breeding trials in College Station, Texas, with a fixed-wing unmanned aerial vehicle (UAV) carrying two multispectral cameras and a high resolution digital camera. The objectives were to establish the workflow and investigate the ability of UAV-based remote sensing for automating data collection of plant traits to develop genetic and physiological models. Most important among these traits were plant height and number of plants which are currently manually collected with high labor costs. Vegetation indices were calculated for each breeding cultivar from mosaicked and radiometrically calibrated multi-band imagery in order to be correlated with ground-measured plant heights, populations and yield across high genetic-diversity breeding cultivars. The variation of canopy-texture features was also investigated from high resolution RGB imagery to reveal new traits that might potentially allow for better understanding of biological and genetic relationships and tradeoffs in the crop phenotypic data.

9866-12, Session 2

Exploratory use of a UAV platform for variety selection in peanut

Maria Balota, Joseph Oakes, Virginia Polytechnic Institute (United States)

Variety choice is the most important production decision farmers make because high yielding varieties can increase profit with no additional production costs. Therefore, yield improvement has been the major objective for peanut (*Arachis hypogaea* L.) breeding programs worldwide, but the current breeding approach (selecting for yield under optimal production conditions) is slow and inconsistent with the needs derived from population demand and climate change. Recent developments in remote sensing-based high throughput phenotyping platforms using unmanned aerial vehicles (UAV) have shown good potential for future breeding advancements. Recently, we initiated a study for the evaluation of suitability of digital imagery, Normalized Difference Vegetation Index (NDVI), and canopy temperature (CT) taken from an UAV platform for peanut variety differentiation. Peanut is unique for setting its yield underground and resilience to drought and heat, for which yield is difficult to pre-harvest estimate; although the need for early yield estimation within the breeding programs exists. Twenty six peanut cultivars and breeding lines were grown in replicated plots either optimally or deficient irrigated under rain exclusion shelters at Suffolk, Virginia. NDVI and CT were constantly monitored during the growing season with ground-based sensors and at pre-harvest with the UAV multispectral sensors. Disease ratings were also taken pre-harvest. Ground and UAV derived vegetation indices were further analyzed for disease and yield prediction. Preliminary results will be presented.

9866-13, Session 2

UAV-based high-throughput phenotyping in legume crops

Sindhuja Sankaran, Lav R. Khot, Washington State Univ. (United States); Juan Quiros, Washington State University (United States) and University of São Paulo (Brazil); George Vandemark, Washington State Univ. (United States); Rebecca J McGee, USDA-ARS (United States) and Washington State University (United States)

With increasing global population and food demand, there is a need to sustain food production through plant breeding efforts and optimizing agricultural production practices. In plant breeding, one of the biggest obstacle in genetic improvement is the lack of proven rapid methods for measuring plant responses in field condition. Therefore, major objective of this research was to evaluate the feasibility of utilizing high-throughput

remote sensing technology for rapid measurement of phenotyping traits in legume crops. The plant responses of several dry bean and chickpea varieties to the environment were assessed with an unmanned aerial system (UAS) integrated with multispectral imaging sensors. Acquired images were post-processed to characteristics canopy density and key vegetation indices which were correlated with ground-reference plant traits. Our preliminary assessment showed that the vegetation indices are strongly correlated ($p < 0.05$) with several phenotypes and seed yield of legume crops. Results endorse the potential of UAS-based sensing technology to rapidly measure those phenotyping traits. Such rapid phenotyping techniques can further accelerate the breeding efforts by providing valuable information on plant performances that can be utilized for variety selection or marker-assisted breeding.

9866-14, Session 2

Detection of wine grape nutrient levels using visible and near infrared 1 nm spectral resolution remote sensing

Grant Anderson, Rochester Institute of Technology (United States) and Canadian Armed Forces (Canada); Jan A. N. van Aardt, Peter Bajorski, Rochester Institute of Technology (United States); Justine Vanden Heuvel, Cornell Univ. (United States)

The grape industry relies on regular crop assessment to aid in the day-to-day and seasonal management of their crop. More specifically, there are six key nutrients of interest to viticulturists in the growing of wine grapes, namely nitrogen, potassium, phosphorous, magnesium, zinc and boron. Traditional methods of determining the levels of these nutrients are through collection and chemical analysis of petiole samples from the grape vines themselves. Using a hyperspectral spectrometer (0.4-2.5um) we collected ground-level samples of the spectra of the grape vines at the same time that petioles samples were harvested. We then interpolated the data into a consistent 1 nm spectral resolution before comparing it to the nutrient data collected. This nutrient data came from both the industry standard petiole analysis, as well as an additional leaf-level analysis. The data were collected for two different grape types, both during bloom and veraison periods to provide variability of grapes types, while considering the impact of temporal/seasonal change. A narrow-band NDVI style index, as well as a simple ratio index, was used to determine the correlation of the reflectance data to the nutrient data. This analysis was limited to the silicon photodiode range to increase the utility of our approach for wavelength-specific cameras (via spectral filters) in a low cost drone platform. The NDVI style index generated correlation coefficients as high as 0.80 and 0.86 for bloom and veraison, respectively, while the ratio index produced correlation coefficient results of 0.80 and 0.95. These results bode well for eventual non-destructive, accurate and precise assessment of vineyard nutrient status.

9866-16, Session 3

Application of machine learning for the evaluation of turfgrass plots using aerial images

Kern Ding, Amar Raheja, Subodh Bhandari, California State Polytechnic Univ., Pomona (United States)

Historically, investigation of turfgrass characteristics have been limited to visual ratings. Although relevant information may result from such evaluations, final inferences may be questionable because of the subjective nature in which the data as collected. Recent advances in computer vision techniques allow researchers to objectively measure turfgrass characteristics such as percent ground cover, turf color, and turf quality. This paper focuses on developing a methodology for automated assessment of turfgrass from aerial images. Images of several turfgrass plots of varying quality were

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gathered using a camera mounted on an unmanned aerial vehicle (UAV). The quality of these plots were also evaluated based on visual ratings. The goal was to use the aerial images to generate quality evaluations on a regular basis for the optimization of water treatment.

This work uses the aerial images to train a neural network so that appropriate features such as intensity, color, and texture of the turfgrass can be extracted from these images. Neural network is a nonlinear classifier commonly used in machine learning. The output of the neural network trained file is the ratings of the grass, which is compared to the visual ratings. Currently, the quality and the color of turfgrass, measured as the greenness of the grass, are evaluated. The textures are calculated using the Gabor filter and co-occurrence matrix. Other classifiers such as Support Vector Machines (SVMs) and simpler linear regression models like Ridge regression and LARS regression will also be used. Future work will involve using multispectral images.

9866-17, Session 3

Calibration of UAS imagery inside and outside of shadows for improved vegetation index computation

Elizabeth Bondi, Carl Salvaggio, Rochester Institute of Technology (United States)

Many years of research and practice have shown that vegetation health and vigor can be assessed with data from multi- and hyperspectral airborne and satellite-borne sensors using index products such as the normalized difference vegetation index (NDVI). Recent advances in unmanned aerial systems (UAS) technology have created the opportunity to access these same image data sets in a more cost effective manner with higher temporal and spatial resolution. Another advantage of these systems includes the ability to gather data in almost any weather condition, including complete cloud cover, when data has not been available before from traditional platforms. The ability to collect in these varied conditions, meteorological and temporal, will present researchers and producers with many challenges that were avoided by collecting at local noon under ideal clear conditions. Particularly, cloud shadows and self-shadowing by vegetation must be taken into consideration in imagery collected from UAS platforms to avoid variation in NDVI due to changes in illumination within a single scene, and between collection flights.

A workflow will be presented to compensate for these variations in vegetation indices due to shadows in high resolution imagery. The workflow includes radiometric calibration to determine the appropriate exposure for varied environmental conditions during capture. This is followed by shadow detection to determine which pixels are indirectly or directly illuminated. Pixel illumination type will be used to guide in-scene calibration, both in and out of shadows, using in situ reflectance panels producing true reflectance at each image location. These reflectance products can then be utilized to calculate mosaicked vegetation index products that are temporally invariant and spatially consistent, providing producers with data products that they may trust to make growing decisions.

9866-18, Session 3

Strategies for soil-based precision agriculture in cotton

Haly Neely, Texas A&M AgriLife Research (United States); Cristine L. S. Morgan, John Valasek, Texas A&M Univ. (United States); Yeyin Shi, Texas A&M AgriLife Research (United States); J. Alex Thomasson, Jeffrey Olsenholler, Texas A&M Univ. (United States)

The goal of precision agriculture is to increase crop yield while maximizing the use efficiency of farm resources. UAV-based systems are presenting agricultural researchers an opportunity to study crop response to environmental and management factors in real-time without disturbing

the crop. Soil properties can influence the yield and fiber quality of cotton, which are two variables that determine farm profitability. While delivery systems can manage production inputs such as water and nutrients, the spatial variability soil properties cannot be changed and thus keen agronomic choices with soil variability in mind have the potential to increase profits. Additionally, measuring crop stress over time and in response to management and environmental conditions may enable agronomists and plant breeders to make more informed decisions about variety selection than the traditional end-of-season yield and quality measurements. In a previous study, cotton yield lint quality was measured over 4 years and across soil variability. As well a plant density study was implemented over 2 years to investigate the interaction between cotton stress and soil variability. Measurements of crop water use, height, yield and fiber quality were taken and compared within and between management zones as mapped by a proximal soil sensor. It was found that soil properties had a significant effect on both yield and fiber quality, and the effect was not consistent across years due to different precipitation conditions. Long-term goals of this research include detecting stress before yield is reduced and selecting better adapted varieties.

9866-19, Session 3

Multispectral and DSLR sensors for assessing crop stress in corn and cotton using fixed-wing unmanned air systems

John Valasek, Texas A&M Univ. (United States); Yeyin Shi, Texas A&M AgriLife Research (United States); James V. Henrickson III, Ezekiel A. Bowden, Haly Neely, Cristine L. S. Morgan, Texas A&M Univ. (United States)

Obtaining usable aerial data on soil and crop condition for precision agriculture applications requires a careful balance of sensor selection and settings, sensor integration to a platform with suitable flight characteristics, mission planning, and image processing. This paper presents the results of a five-month practical field trial effort to evaluate the quality of data from multispectral cameras and a Digital Single Lens Reflex (DSLR) camera for assessing spatial variability cotton crop performance. Two different types of multispectral camera were flown and compared for their performance on sensing crop spectral reflectance. One was a single-lens multispectral camera imaging in RGB bands with a relatively lower frame rate; the other one was a dual-lens multispectral camera imaging in RGB and NIR bands with a relatively faster frame rate. The DSLR camera was used to obtain high resolution imagery for plant height and percent plant cover. The multispectral camera was used to create various vegetation indices. These spatial coverages will be related to ground measurements of the crop. Mission planning and camera configurations have a major impact on the quality of data collected, so various combinations of altitude, airspeed, and ground coverage swaths were evaluated to produce high quality mosaicked images. This presentation will also address the suitability and practical use of fixed-wing Unmanned Air Systems (UAS) for precision agriculture.

9866-20, Session 3

Disease detection and tracking in agricultural crops using UAV based NDVI image analysis

Charles Malveaux, Louisiana State Univ. (United States)

Robust aerial robots have the ability to rapidly accomplish multiple remote sensing missions on farms. UAV systems can be the farmer's eyes while feeding data to automated farm management, irrigation, fertilization, and harvesting systems. Multispectral image analysis can differentiate diseased from normal areas. Research shows measurable differences in nonvisible light reflectance values between diseased and healthy plants. UAV's can be an integral part of an automated agricultural control system that will revolutionize farming.

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For this research diseased soybean and sweet potato fields were selected and flown over using a UAV equipped with a near infrared (NIR) camera system. Once images were taken these images were processed with software to produce Normalized Difference Vegetative Index false color field imagery by assigning color values to the number values generated by difference in infrared reflectance and visible light absorption throughout the farm fields being surveyed. Ground truthing was performed in order to confirm diseased areas using visual inspection as well as a handheld NDVI scanner. Once image data was processed comparisons to ground truthing showed that diseased areas were readily detected in multispectral imagery. High resolution mapping showed that diseased areas could be monitored. As all the image data is georeferenced agronomists using this technology have the potential ability to map, monitor, and manage an entire farm.

Cabernet Sauvignon orchard block to achieve increased water availability directly to the roots, reduced surface evaporation losses, and weed growth among others. The objective of this study was to evaluate and compare the water-use efficiency resulting from (i) surface drip (control) and subsurface drip irrigation treatments, and (ii) irrigation rates in grapevine using high-throughput remote sensing technologies. Treatments included two rates of subsurface irrigation with emitters placed at 0, 0.3 m, 0.6 m, 0.9 m, and 1.2 m underground. Multispectral and thermal images were acquired from field plots using unmanned aerial systems at three critical growth stages. Results pertinent to applicability of aerial image data to characterize plant responses to different irrigation treatments and established relationship with ground-reference grape yield data will be presented.

9866-21, Session 3

Insect detection and nitrogen management for irrigated potatoes using remote sensing from small unmanned aircraft systems

E. Raymond Hunt Jr., Agricultural Research Service (United States); Silvia I. Rondon, Philip B. Hamm, Oregon State Univ. (United States); Robert W. Turner, Alan E. Bruce, Boeing Research and Technology (United States); Josh J. Brungardt, PARADIGM (United States)

Remote sensing with small unmanned aircraft systems (sUAS) has potential applications in agriculture because low flight altitudes allow image acquisition at very high spatial resolution. We set up experiments at the Oregon State University Hermiston Agricultural Research and Extension Center with different platforms and sensors to assess advantages and disadvantages of sUAS for precision farming. In 2013, we conducted an experiment with 4 levels of nitrogen fertilizer. A Tetracam Hawkeye and a Mini ADC were used to follow the changes of vegetation indices over time. There were no differences in chlorophyll content early in the growing season. However, there were significant differences in LAI, but NDVI were saturated. Later in the growing season, nitrogen stress was highly detectable, but it was too late to mitigate losses in potato yield and quality. Damage to potato fields by the Colorado potato beetle rapidly increases from initial infestations. In 2014, we conducted an experiment with 4 levels of infestation. Daily, we flew a hexacopter at two altitudes with a Tetracam MCA with 5 bands and one up-looking calibration channel. Over three days, damage in some plots increased from 0 to 29%. Damage was correlated with the total number of beetles. Plot-scale vegetation indices were not well correlated with initial levels of damage, whereas plot heterogeneity of NDVI was highly correlated. Traditional methods for satellite data may not downsize well for remote sensing from sUAS. Methods based on object-based image analysis and computer vision have potential for early detection and reduced cost.

9866-22, Session 3

Remote sensing based water-use efficiency evaluation in sub-surface irrigated wine grape vines

Carlos L. Zuniga, Sanaz Jarolmasjed, Lav R. Khot, Pete W. Jacoby, Sindhuja Sankaran, Washington State Univ. (United States)

Increased water demands have forced agriculture industry to investigate better management strategies towards optimal water use in crop production. Efficient irrigation systems, improved irrigation scheduling, and selection of crop varieties with better water-use efficiencies can aid towards conserving water. In one of our ongoing research projects, subsurface irrigation system was implemented and experimented in

9866-23, Session PTue

Detection of pollution entering the Chesapeake Bay area using a tethered unmanned aerial system

Jacob Goodman, Univ. of Maryland, Baltimore County (United States); John McKay, William Evans, Maryland Dept. of the Environment (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

The proposed paper is based on an unmanned aerial system platform that is outfitted with high-resolution sensors. The proposed system is to be tethered to a moveable ground station, which may be a research vessel or some form of ground vehicle (e.g., car, truck, or rover). The sensors include, at a minimum: camera, infrared sensor, thermal, normalized difference vegetation index (NDVI) camera, global positioning system (GPS), and a light-based radar (LIDAR). The high-resolution data from the sensors will need to be integrated through a process called information fusion. Typically, this process is done using the popular and well-published Kalman filter (or its nonlinear formulations, such as the extended Kalman filter). However, this paper proposes to use a new type of strategy based on variable structure estimation for the information fusion portion of the data processing. It is hypothesized that fusing data from the thermal and NDVI sensors will be more accurate and reliable for a multitude of applications, including the detection of pollution entering the Chesapeake Bay area.

9866-24, Session PTue

A survey of unmanned ground systems with applications to agricultural and environmental sensing

Stephanie Bonadies, Univ. of Maryland, Baltimore County (United States); Alan M. Lefcourt, Agricultural Research Service (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

Unmanned ground systems have been utilized in the last few decades in an effort to increase the efficiency of agriculture. These systems can be used for a variety of purposes, and include: locating failing crop sections, collecting soil samples for analysis, finding optimal growing areas in a failing field, discovering areas for increased fertilization and watering, and searching for sources of contaminants or pollution. The purpose of this paper is to provide a comprehensive survey of unmanned ground vehicles and their applications to agriculture and the environment. Future trends and potential global issues will also be considered.

9866-25, Session PTue

NDVI based crop yield prediction in sugar cane using aerial imagery

Charles Malveaux, Louisiana State Univ. (United States)

Active NDVI scanners have been used to predict farm yields, but scan range of these sensors is limited to a swath width of only a few feet meaning that they are not temporally suited to analyze an entire farm. However aerial imagery with multi-spectral cameras can be used to quickly survey and map an entire farm in just a few hours. Camera NDVI data has a strong correlation with NDVI scanners so algorithms used to make farm management prescriptions and predict yields based on scanner data may soon be applied to multispectral UAV crop surveillance data. Despite differences in calculated NDVI index values data shows parallel reflectance curves indicating that an NIR camera can effectively be used for crop analysis.

The current system is capable of imaging 1000 acres in under 2 hours and its data will allow for a revolutionary whole farm approach to crop scouting and farm management. This will result in the implementation of multispectral imager equipped UAV's as part of a networked and integrated farm management system. The orders of magnitude increased scan range of UAV and full sized aircraft mounted multi-spectral camera systems over terrestrially mounted active NDVI scanners makes a whole farm approach possible and thereby allow researchers to correlate whole farm NDVI scans to farm yields.

9866-26, Session PTue

The use of remote sensing data for vegetative drought monitoring of mountain ecosystem (Armenia)

Vahagn Muradyan, National Academy of Sciences of Armenia (Armenia)

Drought is a natural phenomenon that has been recurring at a regional scale throughout history. In fact, the monitoring and assessment of drought conditions in a region is usually performed through drought indices. There are several drought indices based on ground (conventional) and/or remotely sensed data. A number of drought indices have been developed based on NOAA-AVHRR, LANDSAT data exploiting the remote sensing potential at different temporal scales. Being a mountainous country, Armenia has undergone different kinds of natural disasters, such as droughts.

As a modeling area were selected Syunik marz and Sevan region. The impact of drought on vegetation, referred to as vegetative drought, is commonly monitored at a regional scale using satellite based vegetation indices such as the Normalized Difference Vegetation Index (NDVI). Vegetation conditions can be characterized by the deviation of the current NDVI Values from their corresponding temporal mean NDVI values, usually calculated over a long period such as one or more decades.

Deciphering satellite images through NDVI enabled us to indicate the monitoring and assessment of drought of the mountainous ecosystem of Lake Sevan basin and Syunik region in a period 1973 to 2014. For the last 40 years the study area has displayed were detected changes of drought duration and periodicity and also drought-sensitive areas increased approximately by three times. The results of this study will be used for the development of a regional drought monitoring system.

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9867-1, Session 1

3D multi-view system using electrowetting liquid lenticular lenses (*Invited Paper*)

Yong Hyub Won, Junoh Kim, Cheoljoong Kim, Dooseub Shin, Junsik Lee, Gyohyun Koo, KAIST (Korea, Republic of)

Lenticular multi-view systems which has great potential of 3D image realization has a limitation of increasing view points with a finite pixel resolution. This paper introduces an active liquid device to solve the problem by time division multiplexing method. The liquid lenticular device consists of a chamber, two different liquids and a sealing plate. The chamber material used is NOA81 of which the index is 1.56. Two immiscible liquids are D.I water and oil which are a mixture of 1-chloronaphthalene and dodecane. The mixture rate is 50:50 of which the index is matched to the index of chamber. To fabricate the device, an <100> silicon wafer is wet-etched by KOH solution. Timely stopped etching results in trapezoid shaped chamber enabling slanted walls which is advantageous for electro-wetting lens achieving high diopter. An <110> silicon wafer is etched to use as a floating mask for deposition divided electrodes on the chamber. Attaching the <110> floating mask, ITO (indium tin oxide) is sputtered and the mask is removed. For dielectric layer, PDVB (poly divinyl benzene) and parylene C are deposited with the thickness of 200nm and 200nm individually. For surface material, 50nm of Teflon AF1600 was dip-coated. Finally two liquids are injected and a glass plate as a sealing plate is covered with PDMS gaskets and sealed by UV adhesive. The left and right electrodes for all elements of lenticular are induced by different voltage resulting in tilted optical axis. Fast switching the optical axis, two times of view points is achieved with a same pixel resolution.

9867-2, Session 1

Large aerial information display with aerial imaging by retro-reflection (AIRR) (*Invited Paper*)

Hirotsugu Yamamoto, Utsunomiya Univ (Japan); Yutaka Tokuda, Masashi Takahashi, Kenta Onuki, Sho Onose, Tomoyuki Okamoto, Utsunomiya Univ. (Japan)

Aerial displays have gained more attentions for advertising, digital signage, and car interior. Re-imaging optics have been developed to form the real image of a display source in a hand-reachable space and allow users to make intuitive interaction with digital information. The formed aerial image is free from accommodation-vergence conflicts. Furthermore, the real image gives ultra-smooth motion parallax. In order to form such aerial screen with a wide viewing angle, we have proposed aerial imaging by retro-reflection (AIRR). AIRR enables us to form a large-area aerial screen because of its scalability.

This invited paper aims to introduce our developments of large-area aerial display with AIRR.

AIRR employs light sources, a beam splitter, and retro-reflector. Lights are reflected on the beam splitter and then impinge the retro-reflector. After the retro-reflection, the lights travel reversely toward the light sources. A part of the retro-reflected lights are transmitted through the beam splitter and form the real images of the light sources. Thus, aerial images are formed at the symmetrical positions of the light sources with respect to the beam splitter.

We have realized two types of large-area aerial displays: a 42-inch aerial display for gesture interaction and a 100-inch aerial display for signage. The former display performs high contrast because we have introduced a reflective polarizer for the beam splitter and a quarter-wave plate on the

retro-reflector. The latter display employs transparent retro-reflector to enlarge its viewing angle. We have developed a 100-inch LED panel and succeeded in forming the world-largest aerial screen.

9867-3, Session 1

Use of display technologies for augmented reality enhancement (*Invited Paper*)

Kevin G. Harding, GE Global Research (United States)

Augmented reality (AR) is seen as an important tool for the future of user interfaces as well as training applications. An important application area for AR is expected to be in the digitization of training and worker instructions used in the Brilliant Factory environment. The transition of work instructions methods from printed pages in a book or taped to a machine to virtual simulations is a long step with many challenges along the way. A variety of augmented reality tools are being explored today for industrial applications that range from simple programmable projections in the work space to 3D displays and head mounted gear. This paper will review where some of these tool are today and some of the pros and cons being considered for the future worker environment.

9867-4, Session 1

A horizontal parallax table-top floating image system with freeform optical film structure

Ping-Yen Chou, Yi-Pai Huang, National Chiao Tung Univ. (Taiwan); Chien-Chung Liao, Chuan-Chung Chang, Fu-Ming F. Chuang, Coretronic Corp. (Taiwan); Chao-Hsu Tsai, Industrial Technology Research Institute (Taiwan)

In this paper, a new structure of horizontal parallax light field 3D floating image display system was proposed. The structure consists of pico-projectors, Fresnel lens, micro lens array and sub lens array with freeform shape. By the functions of optical components, each light field of projectors could be controlled as a fan ray, which has high directivity in horizontal and wide scattered angle in vertical. Furthermore, according to the reverse light tracing and integral image display technique, horizontal parallax floating 3D could be demonstrated in the system. Simulated results show that the proposed 3D display structure has a good image quality and the crosstalk is also limited below 22.6%. Compared with other 3D technologies, this structure could have more benefits, including displaying real high resolution floating image, unnecessary of physical hardware on the image plane, scalability of large size system, without the noise from spinning component, and so on.

9867-5, Session 1

Display of travelling 3D scenes from single integral-imaging capture

Manuel Martínez-Corral, Adrián Dorado, Seokmin Hong, Jorge Sola-Pikabea, Genaro Saavedra, Univ. de València (Spain)

Our final goal is to generate a sequence of plenoptic images with different FOV and focused plane in order to obtain the "camera travelling" video.

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To face these tasks, we need to apply a slightly different version of SPOC 2.0 to obtain the new set of EIs. It is important to realize that each time this algorithm is applied using a different size and position of the cropped area, we generate a new plenoptic image with different FOV and focused plane. Performing this procedure several times a set of different plenoptic images is obtained which forms a plenoptic video if the plenoptic images are displayed in sequence. As a result, when this video is projected into an integral imaging monitor, a travelling camera can be simulated. Note that the 3D information projected is reconstructed with full parallax.

9867-6, Session 2

A study on the effects of RGB-D database scale and quality on depth analogy performance (*Invited Paper*)

Sunok Kim, Youngjung Kim, Yonsei Univ. (Korea, Republic of); Kwanghoon Sohn, Yonsei Univ (Korea, Republic of)

In the past few years, depth estimation from a single image has received increased attentions due to its wide applicability in image and video understanding. For realizing these tasks, many approaches have been developed for estimating depth from a single image based on various depth cues such as shading, motion, etc. However, they failed to estimate plausible depth map when input color image is derived from different category in training images. To alleviate these problems, data-driven approaches have been popularly developed by leveraging the discriminative power of a large scale RGB-D database. These approaches assume that there exists appearance-depth correlation in natural scenes. However, this assumption is likely to be ambiguous when local image regions have similar appearance but different geometric placement within the scene. Recently, a depth analogy (DA) has been developed by using the correlation between color image and depth gradient. DA addresses depth ambiguity problem effectively and shows reliable performance. However, no experiments are conducted to investigate the relationship between database scale and the quality of estimated depth map. In this paper, we extensively examine the effects of database scale and quality on the performance of DA method. In order to compare the quality of DA, we collect a large scale RGB-D database using Microsoft Kinect v1 and Kinect v2 on indoor and outdoor environments. Since the depth map obtained by Kinect v2 has high quality compared to that of Kinect v1, the depth maps from the database from Kinect v2 are more reliable. It represents that the high quality and large scale RGB-D database guarantees the high quality of the depth estimation. The experimental results show that the high quality and large scale training database leads high quality estimated depth map in both indoor and outdoor scenes.

9867-7, Session 2

An exact and efficient 3D reconstruction method from captured light-fields using the fractional Fourier transform (*Invited Paper*)

Ziv Mhabary, Eran Small, Ofer Levi, Adrian Stern, Ben-Gurion Univ. of the Negev (Israel)

Recently we have introduced a new method for refocusing images from captured light fields. The method is based on the fractional Fourier transform and allows refocusing a stack of images with a single step. The new techniques is computational efficient and more exact than alternative ones as it doesn't need any interpolations. Here we present a comparison of our technique to other refocusing techniques.

9867-8, Session 2

Shape grammars for compact 3D scene representation

Andrew R. Willis, The Univ. of North Carolina at Charlotte (United States); Kevin M. Brink, Air Force Research Lab. (United States)

This article describes a novel 3D shape grammar and its application as a surface model for 3D Simultaneous Localization and Mapping (SLAM) from LiDAR or RGBD sensor data. In contrast to most conventional approaches, shape grammars seek to extract and explain large-scale geometries in the scene first. Fit models approximate large regions of dense 3D sensed data using a low-dimensional combination of surface primitives, e.g., parts of boxes, cylinders and spheres. Once fit, estimated grammatical models can be substituted for sensed data providing data compression levels that significantly outperform state-of-the-art and are plausible to share across low-bandwidth communication channels which is critical for cooperative mapping applications.

9867-9, Session 3

Free segmentation in rendered 3D images through synthetic impulse response in integral imaging (*Invited Paper*)

Manuel Martínez-Corral, Anabel Llavador, Emilio Sánchez-Ortiga, Genaro Saavedra, Univ. de València (Spain); Bahram Javidi, Univ. of Connecticut (United States)

Integral Imaging provides spatial and angular information of three-dimensional (3D) objects, which can be used both for 3D display and for computational post-processing purposes. In order to recover the depth information from an integral image, several algorithms have been developed. In this contribution, we propose a new free depth synthesis and reconstruction method based on the two-dimensional (2D) deconvolution between the integral image and a simplified version of the periodic impulse response function (IRF) of the system. The period of the IRF depends directly on the axial position within the object space. Then, we can retrieve the depth information by performing the deconvolution with computed impulse responses with different periods. In addition, alternative reconstructions can be obtained by deconvolving with non-conventional synthetic impulses responses. Our experiments show the feasibility of the proposed method as well as its potential applications.

9867-10, Session 3

3D in natural random refractive distortions (*Invited Paper*)

Marina Alterman, Northwestern Univ. (United States); Yoav Y. Schechner, Technion-Israel Institute of Technology (Israel)

Random distortions naturally affect images taken through atmospheric turbulence or wavy water. They pose new 3D recovery problems. Distortions are caused by the volumetric field of turbulent air or the 3D shape of water waves. We show methods that recover these 3D distorting media. Moreover, it is possible to triangulate objects beyond the refracting medium. Applications include sensing and study of random refractive media in nature, and enhanced imaging including possibilities for a virtual periscope.

9867-13, Session 3

Estimation of the degree of polarization in low-light 3D integral imaging (*Invited Paper*)

Artur Carnicer, Univ. de Barcelona (Spain); Bahram Javidi, Univ. of Connecticut (United States)

The calculation of the Stokes Parameters and the Degree of Polarization in 3D integral images requires a careful manipulation of the polarimetric elemental images. This fact is particularly important if the scenes are taken in low light conditions. In this communication, we show that the Degree of Polarization can be effectively estimated when elemental images are recorded with few photons. First, we use the Maximum Likelihood Estimation approach for generating the 3D integral image. Nevertheless, this method produces very noisy images and thus, the degree of polarization cannot be calculated. We suggest using a Total Variation Denoising filter as a way to improve the quality of the generated 3D images. As a result, noise is suppressed but high frequency information is preserved. Finally, the degree of polarization is obtained successfully.

9867-14, Session 4

Full-color 3D display using binary phase modulation and speckle reduction

Osamu Matoba, Kazunobu Masuda, Kobe Univ. (Japan)

A 3D display system using binary phase modulation is presented. In the proposed 3D display system, two steps are employed to improve the reconstructed image quality. In the first step, the binary phase distribution is optimized to improve the reconstructed image quality by the iterative Fresnel ping-pong algorithm. Next, the intensity accumulation is implemented for speckle reduction. The experimental results are presented.

9867-15, Session 4

Evaluation of the use of 3D printing and imaging to create working replica keys

Jeremy Straub, Scott Kerlin, Univ. of North Dakota (United States)

This paper considers the efficacy of 3D scanning and printing technologies to produce duplicate keys. Duplication of keys, based on remote-sensed data, represents a significant security threat, as it may remove all pathways to determining who illicitly gained access to a secured premises. The key-holder whose keys were copied may have no idea that this has happened and those witnessing the unauthorized access by the user of the replica key will not have the typical indications of someone trying to gain illicit access (i.e., the process of them trying to pick the lock). The prevalence of 3D printers increases the risk of this type of attack.

Key to understanding the threat posed is the characterization of the easiness of gaining the required data for key production and an understanding of how well keys produced under this method work. To this end, the results of an experiment to characterize this are discussed. This experiment compares the number of images utilized to create the model of a key with the quality (determined by its ability to open a lock) of the key. Having presented this data, focus then turns to approaches which could be used to reduce the level of imagery required based on a priori knowledge or knowledge that could be gained in other ways. The paper concludes with a discussion of the impact of key complexity on duplicability as well as the extrapolation of the results to other styles of keys, before concluding with a discussion of prospective future work.

9867-16, Session 5

Resolution of electro-holographic image (*Invited Paper*)

Jung-Young Son, Oleksii O. Chernyshov, Konyang Univ. (Korea, Republic of); Beom-Ryeol Lee, Electronics and Telecommunications Research Institute (Korea, Republic of); Min-Chul Park, Korea Institute of Science and Technology (Korea, Republic of)

Electro-holographic and super-multiview imagings are expected to be the main 3-D displays of future. These two imagings could be incorporated in a display system to be a home TV. One of main parameters of measuring quality of display systems is the ability to show the fine details of the features presented by the objects/scenes displayed on the displays. These details in the displays are expressed by resolution. In this paper, the resolution of holographic images reconstructed from DMDs of different pixel sizes such as 7.637 and 10.8 is examined. The resolution is investigated with reconstructed images of a point, point arrays, and a line and line array in both tparallel and normal directions to the DMD active surface. The reconstructed image size of the point corresponds to the first ring diameter of the Fresnel zone pattern and the minimum separation distance between two parallel lines are more than the line thickness. In the depth direction, two lines can be separated when they are distanced about 5 mm.

9867-17, Session 5

Generalized phase-shifting color digital holography (*Invited Paper*)

Takanori Nomura, Takaaki Kawakami, Kazuma Shinomura, Wakayama Univ. (Japan)

We have proposed single-exposure wave-splitting generalized phase-shifting techniques for digital holography. In this approach, the phase-shift quantity, which corresponds to the difference between the phase quantities of the reference wave on the adjacent pixels, is not restricted but generalized. In this presentation, the generalized phase-shifting digital holography is expanded to two kinds of color digital holography. One is the straightforward extension of our previously proposed monochromatic wave-splitting generalized phase-shifting method. In the color digital holography, the color Bayer camera is used. In the camera, the pixel interval of the same color is not same (red and blue pixels are longer than green pixels). Namely, for example, the phase difference between neighboring pixels is suitable for red and blue pixels is not suitable for green pixels. This causes unevenness of the image quality for each color channel. In this presentation, the occurred problems are pointed out and the solutions are discussed. Another is the color sequential or multi-exposure phase-shifting digital holography. The proposed method enables us to realize phase-shifting method using wavelength-dependent phase-shifting devices such as wavelength plates. Experimental results for both generalized phase-shifting color digital holography are presented to confirm the proposed method.

9867-18, Session 5

Full-color holographic 3D imaging system using color optical scanning holography (*Invited Paper*)

Hayan Kim, Youseok Kim, Taegeun Kim, Sejong Univ. (Korea, Republic of)

In this paper, we propose a full-color holographic 3D imaging system using color optical scanning holography(C-OSH). First, we record the color hologram of a real object using C-OSH. Second, we convert the color hologram to an off-axis color hologram numerically. Finally, we reconstruct the off-axis color hologram using amplitude-only spatial light modulators.

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To the best of our knowledge, this is the first time to demonstrate a full-color holographic 3D imaging system using C-OSH.

9867-19, Session 5

Wavefront printing technique with overlapping approach toward high definition holographic image reconstruction *(Invited Paper)*

Koki Wakunami, Yasuyuki Ichihashi, Hisayuki Sasaki, Takanori Senoh, Ryutaro Oi, Kenji Yamamoto, National Institute of Information and Communications Technology (Japan)

Recently a new hologram recording technique, generally called as "wavefront printer", in which digitized hologram data is divided into sub-cells and optically recorded in tiling manner, has been proposed by several research groups. Since wavefront used as an object beam is reconstructed by computer-generated holograms, ideally higher definition of 3D reconstruction can be realized comparing with well-known technique "holographic stereogram printer" that is based on the reconstruction of dense rays. However since previous works of wavefront printer do not optimize cell size, the reconstructed images were degraded by obtrusive split line due to visible cell size, or by diffraction effect due to too small cell size.

In this paper, we propose overlapping recording to achieve both conditions: enough small of apparent cell size to make it unperceivable and enough large of recording cell size to suppress diffraction effect. The apparent cell size that is decided by amount of overlapping is set smaller than the observer's visual resolution, and so split line can become invisible to observer. Because the recording cell size can become independent to the appearance cell size, it is possible to be set the recording cell size enough large to suppress the image degradation caused by diffraction effect. In addition, multiple exposures at same position by overlapping recording make it robust to unevenness of light distribution due to alignment error or unexpected vibration of optical system. In the experiment, we confirmed that the overlapping recording improves the definition of reconstructed image comparing with non-overlapping recording.

9867-20, Session 6

Experimental verification of phase retrieval of microbeads in high-speed phase imaging using digital holography *(Invited Paper)*

Osamu Matoba, Peng Xia, Xiangyu Quan, Naoya Nagahama, Shunsuke Tanimoto, Kouichi Nitta, Kobe Univ. (Japan); Yasuhiro Awatsuji, Kyoto Institute of Technology (Japan)

In this paper, we presented the experimental results on the measurement of microbeads in a high-speed digital holographic microscope. Three-dimensional positions of the microbeads can be determined by modified autofocus algorithm and then the blurred phase distribution is improved by the deconvolution filter. Influence of the depth position of the microbeads will be discussed.

9867-21, Session 6

Three dimensional object recognition using a high-speed optical corrector *(Invited Paper)*

Kanami Ikeda, Suguru Wakita, Eriko Watanabe, The Univ. of Electro-Communications (Japan)

In recent years, the generation of three-dimensional (3D) data has rapidly increased owing to applications such as 3D printing. The use of low-cost sensors by common people has also increased the generation of 3D data. Therefore, there is a need to recognize such huge amount of 3D data. However, this task has a high calculation cost. We have earlier constructed a high-speed optical correlation system using holographic discs in which huge amount of data can be stored. The optical correlation system has a simple configuration and uses a coaxial holography system. Using this system, a correlation speed of 79.8 Gbps was achieved. In this paper, we propose a 3D object recognition system using a high-speed optical correlator, whose input data comprise 3D data generated by using multiple consumer-level camera systems. We also propose some binary features for 3D object recognition by using optical correlators, which utilize two-dimensional images from different viewpoints and extracted from the reconstructed 3D surface. To obtain optical correlation results with high accuracy, we used our coding method with the white rate of recording data uniformed. Thanks to the high speed transfer rate for the vast databases, this system enable us to recognize 3D object in detail accurately. Preliminary 3D object recognition experiments with the holographic optical disk setup are also presented.

9867-22, Session 6

Random phase-free computer holography and its applications *(Invited Paper)*

Tomoyoshi Shimobaba, Chiba Univ (Japan); Takashi Kakue, Tomoyoshi Ito, Chiba Univ. (Japan)

Addition of random phase to the object light is required in computer holography to widely diffuse the object light and to avoid its concentration on the CGH; however, this addition causes considerable speckle noise in the reconstructed image. For improving the speckle noise problem, techniques such as iterative phase retrieval algorithms and multi-random phase method are used; however, they are time consuming and are of limited effectiveness. Herein, we present a simple and computationally inexpensive method that drastically improves the image quality and reduces the speckle noise by multiplying the object light with the virtual convergence light. Feasibility of the proposed method is shown using simulations and optical reconstructions. Moreover, we introduce the applications of the proposed method: lens-less zoom-able holographic projection, optical encryption, and holographic three-dimensional display. The proposed method is useful for the speckle problems in holographic applications.

9867-23, Session 7

Integral imaging acquisition and processing for visualization of photon counting images in the mid-wave infrared range *(Invited Paper)*

Pedro Latorre Carmona, Filiberto Pla, Univ. Jaume I (Spain); Bahram Javidi, Univ. of Connecticut (United States)

In this paper, we present the results of the application of two types of methods for the visualization of 3D scenes in photon starved conditions, acquired with a Mid-Wave Infrared camera for scenes and objects located at distances ranging from 50m to more than 2km. In particular, we use

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the maximum likelihood (ML) and the penalized maximum-likelihood expectation maximization (PMLEM) reconstruction methods on two different types of scenes: one of them consisting of a road, a group of trees and a vehicle just behind one of the trees (being the car at a distance of around 200m from the camera), and the other consisting of a view of the airfield of Wright Air Force Base, where several hangars appear, located at distances ranging from 900m to 2km. Noise sources like dark current are considered taking into account the particular nature and behavior of Mid-Wave Infrared sensors currently available. Results, using the Peak Signal to Noise Ratio (PSNR) figure of merit, for different levels of dark current noise, show that both methods, using multi-perspective photon-counted images, improve visualization, as compared to the information provided by each photon-counted elemental image.

9867-24, Session 7

Implementing real-time RGBD odometry on a quad-rotor UAV

Andrew R. Willis, The Univ. of North Carolina at Charlotte (United States); Kevin M. Brink, Air Force Research Lab. (United States)

This article describes the theoretical and implementation challenges associated with designing a quad-rotor UAV system that generates 3D position and orientation estimates from RGBD sensor data in real-time to facilitate UAV navigation in cluttered indoor environments. Discussion outlines the overall software pipeline for sensor processing and details important optimizations, trade-offs and algorithm choices required to simultaneously achieve real-time performance and accurate and robust position and orientation estimates.

9867-25, Session 7

iGRaND: A new RGBD image feature

Andrew R. Willis, The Univ. of North Carolina at Charlotte (United States); Kevin M. Brink, Air Force Research Lab. (United States)

This article describes a new 3D RGBD image feature, referred to as iGRaND, for use in real-time systems that use these sensors for tracking, motion capture, or robotic vision applications. iGRaND features use a novel local reference frame derived from the image gradient and depth normal (hence iGRaND) that is invariant to scale and viewpoint for Lambertian surfaces. Using this reference frame Euclidean invariant feature components are computed at keypoints which fuse local geometric shape information with surface appearance information. The performance of the feature for real-time odometry is analyzed and its computational complexity and accuracy is compared with leading alternative 3D features.

9867-30, Session 7

Stereoscopic field of depth: Why we can easy perceive and distinguish the depth of neighboring objects under binocular condition than monocular (Invited Paper)

Kwang-Hoon Lee, Korea Photonics Technology Institute (Korea, Republic of); Min-Chul Park, Korea Institute of Science and Technology (Korea, Republic of)

This work reinterprets the roll of field of depth (FOD) in stereoscopy. FOD width represents the range on same focused object space in monocular condition. Human visual system (HVS) is basically binocular system. So each eye may have an independent FOD state relatively. Hence they will

construct the different forms of the superposed area when the convergence is activated. As the result the area would be reduced with as to a lozenge shaping. For example, the shape of superposed area becomes a lozenge shape from a square and its size would be smaller. The main factor inducing this phenomenon is convergence angle increment. When the angle is increased, the convergence distance would be shorter and the optical power of pupil lens would be increased. So the total f-number of each eye would be decreased and then the width of FOD region would be narrowed. The difference gave us a hint for understanding the reason why we can easy perceive and distinguish the depth in neighboring objects under the binocular condition than the monocular. To verify the reason we proposed a concept which called as the stereoscopic field of depth (SFOD). It presents the quantitative relation between the power of depth perception and the constraints of the superposed area formed by binocular condition, and shows the difference of perceived depth between the conditions. Consequently SFOD showed the narrowed superposed area has higher the depth distinguishable power than the widen area. The power is also proportional to the converging angle increment.

9867-27, Session 8

Time multiplexed pinhole array based lensless three-dimensional imager (Invited Paper)

Ariel Schwarz, Jingang Wang, Univ. of Connecticut (United States); Amir Shemer, Zeev Zalevsky, Bar-Ilan Univ. (Israel); Bahram Javidi, Univ. of Connecticut (United States)

We present a multi variable coded aperture (MVCA) for lensless three-dimensional integral imaging (3D II) systems. The new configuration is based on a time multiplexing method using a variable pinholes array design. The system provides higher resolution 3D images with improved light intensity and signal to noise ratio as compared to single pinhole system. The MVCA 3D II system configuration can be designed to achieve high light intensity for practical use as micro lenslets arrays. This new configuration preserves the advantages of pinhole optics while solving the resolution limitation problem and the long exposure time of such systems. The three dimensional images are obtained with improved resolution, signal to noise ratio and sensitivity efficiency. This integral imaging lensless system is characterized by large depth of focus, simplicity and low cost. In this paper we present numerical simulations as well as experimental results that validate the proposed lensless imaging configuration.

9867-28, Session 8

Light field display and 3D image reconstruction (Invited Paper)

Toru Iwane, Nikon Corp. (Japan)

Light field optics and its applications become rather popular in these days. With light field optics or light field thesis, real 3D space can be described in 2D plane as 4D data, which we call as light field data. This process can be divided in two procedures. First, real 3D scene is optically reduced with imaging lens. Second, this optically reduced 3D image is encoded into light field data. In later procedure we can say that 3D information is encoded onto a plane as 2D data by lens array plate. This transformation is reversible and acquired light field data can be decoded again into 3D image with the arrayed lens plate. "Refocusing" (focusing image on your favorite point after taking a picture), light-field camera's most popular function, is some kind of sectioning process from encoded 3D data (light field data) to 2D image.

In this paper at first I show our actual light field camera and our 3D display using acquired and computer-simulated light field data, on which real 3D image is reconstructed. In second I explain our data processing method whose arithmetic operation is performed not in Fourier domain but in real domain. Then our 3D display system is characterized by a few features; reconstructed image is of finer resolutions than density of arrayed lenses

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and it is not necessary to adjust lens array plate to flat display on which light field data is displayed.

9867-29, Session 8

Increasing the depth of field in multiview 3D images (Invited Paper)

Beom-Ryeol Lee, Electronics and Telecommunications Research Institute (Korea, Republic of); Jung-Young Son, Konyang Univ. (Korea, Republic of); Sumio Yano, Shimane Univ. (Japan); Ilkwon Jeong, Electronics and Telecommunications Research Institute (Korea, Republic of)

In the 3 dimensional displays, the depth of field is defined as the space along the display panel, where a viewer can converge his/her two eyes on a point within the space without losing the image clearness. The depth of field in typical 3-D images can be $\pm 0.3D$ when the viewer distance from the panel is expressed as D diopter. It is possible to increase the depth of field by making two neighboring view images be simultaneously getting into the pupils of the viewer's two eyes [1]. This is known as the super-multiview condition. This condition is based on the concept which states that simultaneous projection of many neighboring view images can induce a continuous parallax as in a hologram. Two neighboring view images are the basic requirement to satisfy the condition. It is expected that by increasing the number of simultaneously projected view images to each pupil, the depth of field can be extended more and more because the increasing will make the viewing condition close to the natural view ing condition. In this paper, up to four neighboring view images are made to simultaneously projected to the pupil of the viewer's each eye to examine the possible extension of the depth of field and the image projecting system is introduced.

9867-31, Session 9

Three-dimensional far-infrared imaging by using perspective thermal images (Invited Paper)

Daisuke Barada, Utsunomiya Univ. (Japan)

As well-known as computed tomography (CT), three-dimensional tomographic images can be synthesized from some projection images captured by different viewing conditions. CT is widely used for medical diagnosis. In general CT, an X-ray is used as a source and the attenuation of the X-ray by a subject is measured. If the subject radiates an X-ray or other light, the three-dimensional source position can be measured. In this study, far-infrared light is paid attention. Far-infrared light is radiated or scattered from living bodies and most of objects under natural environment. By using a far-infrared camera, the thermal images of a subject can be captured. The imaging method is well-known as thermography. Thermography is used for simple medical imaging such as viral infection check and building diagnostics. In order to improve the diagnostic accuracy, three-dimensional thermal imaging is investigated by utilizing stereo method. However, it is difficult to reconstruct a layered structure by stereo method. In this study, three-dimensional far-infrared imaging is investigated by using some perspective thermal images. By capturing a thermal image, a camera lens for far-infrared light is used. Then, the image has perspective and incident angle is dependent on the pixel position of a far-infrared image sensor. When some thermal images are captured by shifting the camera position and the data of identical pixels are collected, oblique projection images can be synthesized. By using the oblique projection images, a three-dimensional far-infrared source imaging is demonstrated.

9867-32, Session 9

A method of quantifying moirés on 3D displays (Invited Paper)

Gwangsoon Lee, Eungdon Lee, Yang-Su Kim, Namho Hur, Jung-Young Son, Electronics and Telecommunications Research Institute (Korea, Republic of)

Moirés are an annoying phenomenon in contact-type 3-D displays. Their presence in the 3-D displays only deteriorates the image quality of the display. Since the moirés are inherent to the 3-D displays due to their physical structure, complete elimination of the moirés is almost impossible in the current structure. Hence it is necessary to develop a method of quantifying the moirés in the 3-D display to define the admissible level of the moirés in the displays. In this regard, a method of quantifying the moirés on the 3-D displays is developed. This method is based on the simulation of the moirés for possible slant angles of the viewing zone forming optics to the panel. This simulation will provides moire contrast to the 3-D images displayed on panel. The quantification is obtained by comparing the 3-D images laden with the simulated moire with those from the 3-D displays.

9867-33, Session 9

Liquid crystal lens array for 3D light field microscopy (Invited Paper)

Yi-Pai Huang, Po-Yuan Hsieh, Chao-Yu Chu, Yun Hsuan, National Chiao Tung Univ. (Taiwan)

The concept of using tunable LC-lens array for 3D light field microscopy is shown in Fig. 1. By changing the focal length of LC-lens array, the total DoF in 3D light field microscopy can be extended. Comparing with fixed lens array, our LC-MLA can provide higher adjustability for bio-specimens. We used liquid crystal lens array to adjust focal lengths from 2.4 mm to 2.9 mm for different depth regions respectively. As the results shown, light field image of with tunable LC-lens array can capture the clear image on both the rear and front lag, which is at 7.2mm and 17.25mm in the real space. The results successfully demonstrated the extended DoF with LC-MLA.

9867-34, Session 9

Requirement for measurement of accommodation response based image blur due to the integral photography (Invited Paper)

Sumio Yano, Shimane Univ. (Japan); Min-Chul Park, Korea Institute of Science and Technology (Korea, Republic of)

Requirements for the measurement of the accommodation response based image blur due to the integral photography were examined. The image blur are generally generated on the integral photography, and the degree of the image blur are increased when the displayed image are positioned far from the screen.

In the range of the binocular single vision in the Donder's line, the tolerance of the coincidence between convergence and accommodation are enlarged, if the image blur are permitted in the visual perception. We experimentally showed this enlargement range of the coincidence between convergence and accommodation using blur stereoscopic images at the point of the spatial frequency. Because of the effect of blur images, the coincidence between convergence and accommodation is generated even in the stereoscopic images, which has generally the conflict between convergence and accommodation response. Therefore, it is necessary to examine the accommodation response for the integral photography over higher spatial frequency than that spatial frequency, which showed the maximum limitation of the enlargement range. That is the accommodation response

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for the integral photography in the enlargement range is not correctly measured because even the convergence and accommodation response in the stereoscopic images are coincidence.

9867-12, Session PWed

3D augmented reality with integral imaging display

Xin Shen, Bahram Javidi, Univ. of Connecticut (United States); Hong Hua, Univ. of Arizona (United States)

In this paper, a three-dimensional (3D) integral imaging display for augmented reality is presented. Virtual objects generated by computer software and real objects captured by imaging devices always with different display formats which are not match with each other. By implementing the pseudoscopic-to-orthoscopic conversion method, elemental image arrays with different formats can be first transferred into the identical format for 3D display. With the proposed merging algorithm, a new set of elemental images for augmented reality display can be generated. The newly generated elemental images contain both the virtual objects and real objects with desired depth information and transparency parameters. The experimental results indicate the feasibility of the proposed 3D augmented reality with integral imaging.

9867-36, Session PWed

Avalanche effect and bit independence behaviors of double random phase encoding schemes

Inkyu Moon, Chosun Univ. (Korea, Republic of); Faliu Yi, The Univ. of Texas Southwestern Medical Ctr. (United States)

With the application of digital data in varied fields, digital information security has attracted more and more attention. Consequently, many encryption algorithms as a way to enhance the system security have been proposed. For a robust encoding method, it should satisfy with some criterions. Among them, avalanche effect and bit independence characteristics are two important measurement factors. It is necessary for an encryption algorithm to achieve good avalanche and bit independence performances such that it will be not susceptible to statistical attacks. Optical encryption systems such as double random phase encoding (DRPE) have been investigated in the last decade. In this paper, we overview that the DRPE algorithm has good bit independence characteristics in both Fourier and Fresnel domain. However, DRPE in Fresnel domain achieve better avalanche effect results than that in Fourier domain.

9867-37, Session PWed

Automated quantitative analysis of red blood cell 3D geometric changes in the storage lesion using digital holographic microscopy

Inkyu Moon, Keyvan Jaferzadeh, Chosun Univ. (Korea, Republic of)

Quantitative phase information about red blood cells (RBCs) obtained by digital holographic microscopy (DHM) can provide new insight into their functions and morphology. Since RBC functionalities are related to its 3D shape, quantitative 3D geometric changes induced by storage time can help scientists in realizing RBC's optimal functionality period. In this paper, we overview an automated method for calculating 3D geometric features of RBCs such as surface area, surface to volume ratio (SVR), morphological

functionality factors during storage lesion. Moreover, sphericity index changes related to deformability is evaluated using the surface area. Additionally, other important properties of sphericity coefficient, RBC diameter and oxygen capacity and their changes in a period of 57 days are analyzed. Dataset composed of donated blood samples from healthy persons consists of more than 3,300 blood cells and is classified into 11 groups of 8, 13, 16, 23, 27, 30, 34, 37, 40, 47 and 57 days, respectively.

9867-38, Session PWed

Incoherent holography by a Michelson type interferometer with a lens for a radial shear

Kaho Watanabe, Takanori Nomura, Wakayama Univ. (Japan)

Incoherent holography has been widely studied in recent years. It enables us to record hologram of an object without coherent illumination such as a laser. We have proposed the system to record incoherent Fourier hologram of an object (incoherently illuminated or self-luminous object) using a rotational shearing interferometer. The interferometer can record incoherent hologram by self-interference. The interference pattern is obtained as the figure of the cosine transformation of an object at the zero optical path difference. The system also has an eighth wave plate, the interference pattern is also obtained as the sine transformation in orthogonal polarization. Although the method has the advantage of increasing space-bandwidth product performance, no depth information is obtained. In this paper, we propose a Michelson type interferometer with a lens for a radial shear. A radial shear caused by a lens gives depth information of an incoherent object. The advantages of using a lens are easy adjustment of the magnification and simplification of the optical system. A preliminary experiment was performed to confirm our proposed system. An LED with a central wavelength of 447 nm was used as an incoherent object. Its full width at half maximum was 10.0 nm. The Fresnel zone-like intensity was recorded because of the difference of the curvatures of wave fronts. These results confirm the proposed system of incoherent holography by a Michelson type interferometer with a lens for a radial shear.

9867-40, Session PWed

Accurate characterization of mask defects by combination of phase retrieval and deterministic approach

Min-Chul Park, Thibault Leportier, Korea Institute of Science and Technology (Korea, Republic of); Wooshik Kim, Sejong Univ. (Korea, Republic of); Jindong Song, Korea Institute of Science and Technology (Korea, Republic of)

In extreme ultraviolet lithography (EUVL), it is important to detect and characterize mask defects, as the presence of defects as small as a few tenths of nanometers is already a critical issue.

Coherent diffraction imaging methods have been proposed for defect inspection. However, in this case mask shape is not directly obtained. Only diffraction patterns are measured. Then, phase information is lost and phase retrieval techniques should be applied to recover images. The hybrid input-output algorithm as developed by Fienup is the most widely used method for reconstructing phase information from the Fourier transform modulus. In the case of mask inspection for EUVL, periodic patterns can be reconstructed and defects' width can be estimated. However, accuracy is not high enough to estimate the actual depth of the defect.

Deterministic approach can also be applied instead of phase retrieval algorithm in the case where a reference, such as diffraction pattern by a defect-free mask, is known in addition of the pattern diffracted by the mask under inspection. In this case, shape of the defect can be determined

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precisely in addition of its width. However, in practice reference are not always available.

In this paper, we propose to use phase retrieval algorithm to retrieve the shape of defect, and to use it as a reference to determine more precisely defects shape with deterministic approach. Our proposed method is presented for application in mask inspection in EUVL, but it can be generalized to other cases of defect detection problem.

9867-41, Session PWed

Modification of the reconstruction distance of Fresnel holograms for display with multiple spatial light modulators

Thibault Leportier, Min-Chul Park, Korea Institute of Science and Technology (Korea, Republic of); Taegeun Kim, Sejong Univ. (Korea, Republic of)

In digital holography, spatial light modulators (SLMs) devices are used to display the holographic patterns. However, modulation is imperfect because SLMs cannot modulate phase and amplitude at the same time. Then undesired terms such as twin image can be observed in the image plane.

One solution to remove twin image contribution without physical spatial filter is to perform complex modulation. Phase and amplitude modulation can be performed sequentially with two different SLMs. Similarly, real and imaginary part of hologram can be displayed and combined in an additive configuration through a polarizing beam splitter. In both case, a major problem is the alignment of the two display devices since misalignment as small as one pixel may degrade significantly quality of the reconstruction. For our experiment, we used OSH data that provides separately real and imaginary part of hologram. Then, we focused on additive configuration where two SLMs are displaying real and imaginary part of hologram respectively.

Reconstruction distance of hologram is fixed and distance between SLM and beam splitter should be the same for the two devices. In this paper, we study the effect of having different reconstruction distance for the real and imaginary hologram. We performed simulations and explained the result with the scalar diffraction theory. A method to compensate numerically the reconstruction distance is proposed for on-axis and off-axis hologram. This method can also be applied to modified reconstruction distance of Fresnel hologram displayed with a single SLM and has potential application in RGB holographic reconstruction.

9867-42, Session PWed

Local frequency estimation from intensity gradients in spatial carrier fringe pattern analysis

Ruihua Zhang, Hongwei Guo, Shanghai Univ. (China)

Spatial carrier fringe pattern analysis is an effective tool in optical measurement, e.g. in interferometry and fringe projection technique. With it, the very large phase deformations in a spatial carrier fringe pattern may increase the bandwidth of fringe component thus leading to difficulties in retrieving its phase map. In order to overcome this problem, many local-adaptive methods have been developed for processing the spatial carrier fringe pattern with large phase variations, and in fact the local spatial frequency estimation is central to these methods. This paper introduces a simple algorithm for estimating the local frequencies of a fringe pattern with spatial carrier. First, the intensity gradients of the fringe pattern are calculated, and then the standard deviations (SDs) of the intensity gradients at each pixel are estimated from its neighborhood. Finally the local frequencies are estimated from the SDs just calculated simply using an arccosine function. This algorithm is potential in developing effective techniques for retrieving phases from a spatial carrier fringe pattern with large phase variations. For example, we can recover the phase map by

directly integrating the local frequencies or by use of an adaptive spatial carrier phase shifting algorithm (SCPS) with the local frequencies being the local phase shifts. It can also be used in Fourier transform method for exactly determining the carrier frequencies, or for extrapolating aperture in order to reduce the boundary effect. Combined with time-frequency techniques such as windowed Fourier transform and wavelet transform methods, it is helpful for alleviating the computational burdens.

9867-43, Session PWed

Comparison of the impact of different key types on ease of imaging and printing for replica key production

Jeremy Straub, Univ. of North Dakota (United States)

The prospective capability of 3D printing and scanning to allow the easy replication of keys is problematic. This is particularly true due to the vast number of keyed locks installed, in addition to the other hardware (doors, locking systems, electric wiring, etc.) that would be impacted or required to replace keyed locks. To this end, this paper considers whether certain types of keys / locks may be more resistant to 3D scanning and printing. Specifically, multiple types of keys are scanned, printed and tested in corresponding locks, under various imaging conditions, to ascertain whether they are easier to scan (i.e., whether a complete and printable model is generated across the imaging conditions) and whether the models produced by scanning are comparatively more or less likely to work.

This data is analyzed to determine whether a set of common features exist between keys that are more or less resistant to 3D scanning and printing-based duplication. Key features which show correlation with or against successful scanning / printing are identified.

Based on this analysis, the short (1-3 year), medium term (3-7 years) and long term (beyond 7 years) viability of keyed locks is considered. Data concerning the current and project proliferation of 3D printers and visible light and laser 3D scanning technology during these timeframes is used to inform this discussion. The paper concludes with a brief discussion of other technologies that could replace keyed locks and the level of effort required to convert to them.

9867-44, Session PWed

The effect of object shape and laser beam shape on lidar system resolution

Hongchang Cheng, Science and Technology on Low-Light-Level Night Vision Lab. (China); Jingyi Wang, Jun Ke, Beijing Institute of Technology (China)

In a LIDAR system, a pulsed laser beam is propagated to a scene, and then reflected back by objects. Ideally if the beam diameter and the pulse width are close to zero, then the reflected beam in time domain is similar to a delta function, which can accurately locate an object's position. However, in a practical system, the beam has finite size. Therefore, even if the pulse width is small, an object shape will make the reflected beam stretched along the time axis, then affect system resolution.

In this paper, we assume the beam with Gaussian shape. The beam can be formulated as a delta function convolved with a shape function, such as a rectangular function, in time domain. Then the reflected beam can be defined as a system response function convolved with the shape function.

We use symmetric objects to analyze the reflected beam. Corn, sphere, and cylinder objects are used to find a LIDAR system's response function. The case for large beam size is discussed. We assume the beam shape is similar to plane wave. With this assumption, we get the simplified LIDAR system response functions for the three kinds of objects. Then the beam reflected back from a scene with multiple symmetric objects is analyzed. After that, we use tiny spheres and cylinders to emulate an arbitrary object, and study its effect to the returned beam. With these results, finally we discuss the axial resolutions of a LIDAR system.

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9867-46, Session PWed

Peplography: An image restoration technique through scattering media

Myungjin Cho, Ki-Ok Cho, Hankyong National Univ. (Korea, Republic of); Youngjun Kim, Hankyong National Univ (Korea, Republic of)

Image sensing and restoration through scattering media with natural light is a very difficult problem. However, this technique may be used to many applications - finding hidden cars in dense fog, rescuing survivors inside a smoky fire, detecting enemy crafts in clouds, and observing biological cells through tissues, to name a few. In this paper, we report a new image restoration technique which is named as "Peplography" by using statistical optics. Peplography comes from the Greek words πεπλό (péplo; "veiled") and γραφή (grafis; "writing"). In this technique, the scattering media can be estimated based on statistical optics, then ballistic photons can be detected by photon detection. To enhance the visual quality of the reconstructed image, passive 3D imaging technique such as integral imaging is applied.

9867-48, Session PWed

Compact and high resolution virtual mouse using lens array and light sensor

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Virtual mouse based on IR source, lens array and light sensor was designed and implemented. Optical architecture including lens amount, lens pitch, baseline length, sensor length, lens-sensor gap, focal length etc. was carefully designed to achieve low detective error, high resolution, and simultaneously, compact system volume. System volume is 3.1mm (thickness) x 4.5mm (length) x 2, which is much smaller than that of camera-based device. Relative detective error of 0.41mm and minimum resolution of 26ppi were verified in experiments, so that it can replace conventional touchpad/touchscreen. If system thickness is eased to 20mm, resolution higher than 200ppi can be achieved to replace real mouse.

9867-49, Session PWed

Hierarchical bilateral filtering based disparity estimation for view synthesis

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In this paper, we introduce a high efficient and practical disparity estimation using hierarchical bilateral filtering for real-time view synthesis. Proposed method is based on hierarchical stereo matching with hardware-efficient bilateral filtering. Hardware-efficient bilateral filtering is different from the exact bilateral filter. The purpose of the method is to design an edge-preserving filter that can be efficiently parallelized on hardware. The proposed hierarchical bilateral based disparity estimation is essentially a coarse-to-fine use of stereo matching with bilateral filtering. It works as follows: firstly, the hierarchical image pyramid are obtained; the multi-scale algorithm then starts by applying a local stereo matching to the downsampled images at the coarsest level of the hierarchy. After the stereo matching, the estimated disparity map is filtered with the bilateral filtering. And then the filtered image will be adaptively upsampled to the next finer level. The upsampled image used as a prior of the corresponding local stereo matching at the next level, and filtered and so on. The method is essentially a combination of hierarchical stereo matching and high-efficient bilateral filtering. It can be efficiently parallelized on hardware.

9867-50, Session PWed

Whole field imaging of micro-objects by iterative phase retrieval

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In the case of phase objects, bright field microscopy yields only low contrast amplitude images and that too only of a single object plane. Whole field imaging (amplitude and phase) of technical and biological micro-objects provides information on its optical thickness, which in turn can be used for their characterization and identification. Interference techniques are widely used for this. These techniques require the superposition of the object wavefront with a reference wavefront. The phase information of the object is encoded as the modulation of the resulting interference patterns. Phase is retrieved by numerical processing of the interference patterns. But the technique requires temporally coherent sources and adjustment of beam ratios for high contrast interference patterns. The wavefront scattered from the object contains information about the structures in the object in the form of diffraction pattern. The object whole field information can be retrieved from the diffraction pattern by sequentially sampling of the diffraction pattern in the axial direction, leading to iterative quantitative phase microscopy. Since the method is a single beam technique, which involves the sampling of the diffraction pattern only, low temporally coherent sources can be used to illuminate the object. The work presented here details our efforts in the development of single beam phase retrieval quantitative phase microscope techniques.

9867-51, Session PWed

3D imaging and visualization of optically trapped micro-objects

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Optical tweezers can be used for immobilization and manipulation of micrometer sized objects and finds use in single cell isolation, identification and sorting. These traps can also be used to observe the dynamics (morphology changes) of the object in its natural environment. Optical traps makes use of Gaussian laser beams focused to a tight spot to trap the micro-particles. Trapping could be achieved if the laser has enough power. The trapped micro-object undergoes Brownian motion due to thermal fluctuations and is characterized by a frequency of this movement. Also the object may change its morphology due to its surroundings. The morphological changes can be studied using quantitative phase imaging techniques. Digital holography is one of the widely used quantitative phase imaging modality, which can be used for dynamic 3D imaging of micro-objects. If digital holographic microscope can be integrated into an optical trapping device, it can be used for observing and quantifying morphological changes occurring to technical and biological objects immobilized in any desired environment. In common-path self-referencing mode, digital holographic microscope unit can be implemented with the use of very few optical elements. Since the two interfering beams in common path mode, encounters the same set of optical elements, it leads to higher temporal stability. This work describes our efforts in the area of integrated optical trap and 3D imaging unit for quantitative dynamic imaging of technical and biological objects.

9867-52, Session PWed

3D imaging of plant cell and sub cellular organelle in various conditions using digital holographic microscopy

Priyanka Vora, Nimit R. Patel, Swapnil Mahajan, Vismay Trivedi, Vani K. Chhaniwal, The Maharaja Sayajirao Univ. of Baroda (India); Bahram Javidi, Univ. of Connecticut (United States); Arun Anand, The Maharaja Sayajirao Univ. of Baroda (India)

It is important to study size of plant cells in various conditions, such as cells from different layers of the biological specimen or in various growth periods, or treated with preservatives. Sub cellular organelles also play a vital role in explaining cell's characteristics and morphology. Quantitative study of these micro-objects can provide information about their morphology and dynamics. Digital holographic interference microscopy (DHIM) is a suitable technique for quantitative phase contrast imaging of phase objects, through which real time inspection of cells is possible without staining and altering the cell properties and without mechanical scanning of microscope objective to focus on to different layers of the object. DHIM is implemented in Mach-Zehnder geometry. This microscope provides dynamic optical thickness of the cells in various conditions. For dynamic studies a time series of holograms were recorded. The numerically reconstructed holograms yield the phase of the object wavefront, which in turn provides the optical thickness of the cells. Onion skin cells were observed under microscope. Thicknesses of the outer and inner epidermis layers are compared. Cell nucleus is also investigated, as it is an organelle of plant cell performing major function of coordinating the cell's activities. Using DHIM, variation in size of nucleus of plant cell treated with preservatives with time was also studied. This work describes the details of this study.

9867-53, Session PWed

Three-dimensional integral imaging displays using a quick-response encoded elemental image array: An Overview

Adam S. Markman, Bahram Javidi, Univ. of Connecticut (United States)

Mobile devices are a ubiquitous technology, and many researchers are trying to implement three-dimensional (3D) displays on mobile devices for a variety of applications. We investigate a method to store compressed and encrypted elemental images (EIs) used for 3D integral imaging displays in multiple quick-response (QR) codes. This approach allows user friendly access, readout, and 3D display with mobile devices. We first compress the EIs and then use double-random-phase encryption to encrypt the compressed image and store this information in multiple QR codes. The QR codes are then scanned using a commercial Smartphone to reveal the encrypted information, which can be decrypted and decompressed. We also introduce an alternative scheme by applying photon counting to each color channel of the EIs prior to the aforementioned compression and encryption scheme to generate sparsity and nonlinearity for improved compression and security. Experimental results are presented to demonstrate both 3D computational reconstruction and optical 3D integral imaging display with a Smartphone using EIs from the QR codes. This work utilizing compressed QR encoded EIs for secure integral imaging displays using mobile devices may enable secure 3D displays with mobile devices.

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9868-1, Session 1

Detailed analysis of an optimized FPP based 3D imaging system

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In the past two decades, huge amount of research on fast, high resolution, and low cost 3D imaging technologies have been conducted due to the rapid demand from industry. Non-interferometric techniques such as fringe projection profilometry (FPP) based 3D imaging techniques are often used in computer vision because they are immune to vibration, compact, portable, highly precise, scalable, and cost effective using off-the-shelf components. In this work we present in details an optimized step by step implementation of a FPP based 3D shape measurement system. First, we employ a multi-frequency and multiple phase shifting sinusoidal fringe pattern for an optimal angle to increase accuracy and sensitivity accompanied by nonlinear intensity correction of the projector and camera. Second, we study the synchronization between fringe projection and data acquisition exposure time. Third, to obtain the wrapped phase map, fringe analysis is performed using several phase-shifting techniques where a trade-off between accuracy and computational cost are critical in choosing the appropriate scheme. Fourth, phase unwrapping using spatial or temporal techniques is performed and a tradeoff between processing speed and high accuracy is discussed. Fifth, camera and system calibration are conducted for phase to real world coordinates. The calibration coefficients are estimated accurately using a reference plane and several gauge blocks with precisely known heights and by employing a nonlinear least square fitting method. Finally, the system is experimentally constructed using a custom made hardware and a custom made GUI is developed for control and synchronization of the system.

9868-2, Session 1

A comparative study on 3D range data compression methods

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Over recent decades, 3D range scanning techniques have advanced rapidly and show great potential to penetrate our daily lives. Yet, unlike their 2D counterparts, raw 3D data is enormously large in terms of file size; this becomes an issue as 3D range data compression techniques have not been well established. 3D range data are predominantly stored as mesh formats (e.g., STL, OBJ, PLY) which are generically designed such that they can be used to represent arbitrary topologies. These formats usually store (x, y, z) coordinates for each vertex of a polygon, the connectivity between vertices, and often normal and (u, v) maps. However, these formats require large storage space. The effort of converting 3D range data into standard 2D images offers numerous merits including large compression ratios with high-quality data reconstruction. In literature, there are three major methods to convert 3D data into 2D images: (1) virtual fringe projection; (2) direct depth encoding; and (3) multi-wavelength encoding. This paper compares the effectiveness and limitations of these compression methods, especially when the resultant 2D images are stored with low-quality lossy image formats (i.e., JPEG). Both ideal shape (i.e., sphere) and complex shape (i.e., statue) were tested under the same settings. Experimental data found that multi-wavelength encoding outperforms the other methods as it: achieves the highest compression ratios; provides the lowest error percentages; and

requires the least filtering to reduce lossy compression artifacts. Principles of each method will be explained, and experimental data will be presented to evaluate each method.

9868-3, Session 1

A guide to properly select the defocusing distance for accurate solution of transport of intensity equation while testing aspheric surfaces

Peyman Soltani, Ahmad Darudi, Ali Reza Moradi, Javad Amiri, Univ. of Zanjan (Iran, Islamic Republic of); George Nehmetallah, The Catholic Univ. of America (United States)

Phase reconstruction of objects using the Transport of Intensity Equation (TIE) depends on the accuracy of intensity derivative in the longitudinal direction. Therefore, proper selection of the defocus distance dz is very important to obtain accurate results. There are few methods that employ higher order intensity derivatives to improve the accuracy of the solution on the expense of more computational complexity. In an earlier work we have demonstrated by simulation that the solution of the Transport of Intensity Equation (TIE) for testing an aspheric surface depends on distance of two recorded intensity distributions along the z axes (dz), and the optimum value for dz is related to the peak-to-valley (PV) variation of the phase distribution. For estimating the PV, the contribution of piston, the tilt, and the quadric term have been removed. In this work, in order to verify the simulation results an experiment is carried out in which a Shack-Hartmann (SH) sensor is incorporated in the setup. The reconstructed high resolution phase distribution of TIE technique is compared with low resolution phase distribution measured using the SH sensor. An aspheric surface is measured in a non-nulled configuration is used in the experiment. The value of dz is chosen from the prediction of the simulation and the results of TIE technique are compared with SH sensor.

9868-5, Session 1

ISO 10360 verification tests applied to CMMs equipped with a laser line scanner

Bart Boeckmans, Gabriel Probst, Wim Dewulf, Jean-Pierre Kruth, KU Leuven (Belgium)

Coordinate measuring machines (CMMs) are widely accepted tools for verifying geometrical product specifications (GPS) of produced workpieces. Among the sensors a CMM can be equipped with are touch-trigger probes, tactile scanning probes and laser line scanners. Recent improvements for laser line scanners decreased their measurement uncertainty and increased their employability for multi-color and higher surface finish workpieces. However, the verification of the sensor-machine integration of the laser line scanner with the CMM is not fully standardized as is the case for tactile measurement probes. The ISO 10360 document series comprises a part, namely 10360-8, with assessment methods focusing on CMMs with optical distance sensors. This ISO standard can be applied for all kinds of optical sensors that can be utilized on a CMM, e.g. laser triangulation probes, laser line scanners, structured light projection, interferometry and confocal systems.

This paper first discusses how the ISO 10360 methods can be applied to

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verify the uncertainty statements of a CMM equipped with a laser line scanner. Several high accuracy artefacts with optical cooperative spheres were used to overcome surface reflection issues that usually arise when using polished calibration spheres. A second part presents results of a thorough analysis of the performance of two CMM setups using a laser line scanner. The performance parameters are determined for both machines and verified with the specifications provided by the manufacturer.

9868-6, Session 1

Affects of light wavelength and coherence in structured light sensors

Kevin G. Harding, Rajesh Ramamurthy, GE Global Research (United States); Zirong Zhai, Jie Han, GE Global Research (China); Dongmin Yang, GE Oil and Gas (United States)

Structured light methods are used by many commercial products on the market today. Many such systems using white light projectors while many line gages use standard red laser diodes. However, in recent years there has been much claimed about using blue light, polarized light and partially coherent systems to obtain better performance. Unlike interferometer system, the comparison of red to blue light for a system using only geometric shape information does not gain an automatic advantage from the shorter wavelength. The sensitivity metric does not have a wavelength component to it. However, the ability to measure some feature is also a function of other parameters such as signal to noise ratio, reflectivity variations, and depth of field over which a clear pattern can be seen clearly. This paper will explore the theoretical and experimental data relating to what works and what can be expected from variations on the old methods.

9868-7, Session 2

Optical emission spectroscopy for monitoring metal-based additive manufacturing processes

Abdalla R. Nassar, Edward W. Reutzel, Applied Research Lab. (United States)

Optical emission spectroscopy (OES) is a well-established means for characterizing and monitoring processes involving plume or plasma formation. However, few attempts have been made towards sensing of laser-based additive manufacturing processes using OES. Here, recent developments on OES monitoring of additive manufacturing processes for defect detection and quality monitoring of 3D metallic structures will be presented.

9868-8, Session 2

High resolution layer-by-layer imaging for process monitoring of metal-based powder bed fusion additive manufacturing

Edward W. Reutzel, Abdalla R. Nassar, Jacob P. Morgan, John P. Morgan, Donald J. Natale, Sean D. Knecht, Richard L. Tutwiler, Applied Research Lab. (United States)

Powder bed additive manufacturing (PBAM) of metal components has attracted much attention, but the inability to quickly and easily ensure quality has limited its pervasiveness in industry. Since the technology is currently unsuitable for high volume production, traditional statistical quality control methods cannot be readily applied, and comprehensive post-process inspection is often prohibitively time consuming and expensive. Here, a strategy for layerwise process monitoring and quality control is presented, whereby multiple high resolution images are collected each

layer with various lighting schemes to enhance contrast, the images are processed to detect build anomalies, and the results are correlated in three dimensions to the final product. The system is exercised and evaluated with builds designed to intentionally generate common defects in PBFAM system—including lack-of-fusion, distortion, and powder inconsistencies—and results are discussed.

9868-9, Session 2

DeSCJOB: the deep space cam joined observation bot

Thomas McGuire, Michael Hirsch, Michael Parsons, Skye Leake, Jeremy Straub, Univ. of North Dakota (United States)

This paper presents a sub-spacecraft concept (which can be deployed from a larger spacecraft) that aids both technical and political needs, the Deep Space Cam Joined Observation Bot (DeSCJOB). DeSCJOB can be used to assess the condition of a spacecraft in orbit or in deep space. It can also be used to capture images of the spacecraft performing its mission to generate public interest and support.

The DeSCJOB sub-spacecraft is launched using a simple spring loaded release mechanism. A Nylon monofilament (as it retains its strength and flexibility) tether line is slowly released from an onboard winch, concurrent with deployment. The spring mechanism allows for repeated use, as no (exhaustible) propellant is required.

The system uses a rotating docking system base allowing the release mechanism to be able to deploy the sub-satellite at virtually any desired angle allowing it to slowly move to a desired position where it can take the required images using its onboard, adjustable multi-camera system. Reaction wheels orient the sub-satellite for optimal imaging. Once the imaging mission is complete, the winch is used to wind the tether back creating a controlled approach. Once the satellite reaches its dock, it slides into place, guided by the retrieval coupling system.

The efficacy of the DeSCJOB spacecraft for supporting both operational and public relations imaging is considered and assessed. The paper concludes by demonstrating that the DeSCJOB spacecraft can be built using currently available technologies and a combination of commercial off-the-shelf (COTS) hardware and custom components.

9868-10, Session 2

An algorithm to estimate building heights from Google street-view imagery using single view metrology across a representational state transfer system

Elkin David Díaz Plata, Henry Arguello Fuentes, Univ. Industrial de Santander (Colombia)

Urban ecosystem studies require monitoring, controlling and planning to analyze building density, urban density, urban planning, atmospheric modeling and land use. In urban planning, there are many methods for buildings height estimation from optical remote sensing images. These methods however highly depend on sun illumination and cloud-free weather. In response to this, high resolution synthetic aperture radar is capable of providing images independent from daytime and weather conditions. However high resolution images rely on special hardware and expensive acquisition. Most of the significant cities of the world have been photographed by Google street view imagery under different conditions. Thus, thousands of images from the principal streets of a city can be easily accessed. The availability of this and similar (StreetSide from Microsoft) rich imagery of cities, represents huge opportunities in computer vision. This paper proposes a novel algorithm to estimate building heights using public Google Street-View imagery. The objective of this work is to automatically obtain thousand of geo-referenced images from the Google Street-View

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Imagery across a representational state transfer system and estimate their average height using single view metrology. Furthermore, the resulting measurements and the metadata of the images are used to derive a layer of heights in a Google map available in the web. The experimental results show that the proposed algorithm can estimate an accurate average building height map of thousands of images from the Google-Street Imagery of any city.

9868-11, Session 2

Design of an aid to visual inspection workstation

Robert Tait, Kevin G. Harding, GE Global Research (United States)

Visual Inspection is the most common means for inspecting manufactured parts for random defects such as pits, scratches, breaks, corrosion or general wear. The reason for the need for visual inspection is the very random nature of what might be a defect. Some defects may be very rare, being seen once or twice a year, but may still be critical to part performance. Because of this random and rare nature, even the most sophisticated image analysis programs have not been able to recognize all possible defects. Key to any future automation of inspection is obtaining good sample images of what might be a defect. However, most visual check take no images and consequently generate no digital data or historical record beyond a simple count. Any additional tool to captures such images must be able to do so without taking addition time. This paper outlines the design of a potential visual inspection station that would be compatible with current visual inspection methods, but afford the means for reliable digital imaging and in many cases augmented capabilities to assist the inspection. Considerations in this study included: resolution, depth of field, feature highlighting, ease of digital capture, annotations and inspection augmentation for repeatable registration as well as operator assistance and training.

9868-12, Session 2

Non-destructive 3D shape measurement of transparent and black objects with thermal fringes

Anika Brahm, Conrad Rössler, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Patrick Dietrich, Stefan Heist, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Gunther Notni, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Technische Univ. Ilmenau (Germany)

Fringe projection is a well-established optical method for the non-destructive contactless three-dimensional (3D) measurement of object surfaces. Typically, fringe sequences in the visible wavelength range (VIS) are projected onto the surfaces of objects to be measured and are observed by two cameras in a stereo vision setup. The reconstruction is done by finding corresponding pixels in both cameras followed by triangulation. Problems can occur if the properties of some materials disturb the measurements. If the objects are too transparent, translucent, reflective, or strongly absorbing in the VIS range the projected patterns cannot be recorded properly. To overcome these challenges we present a new alternative approach in the infrared (IR) region of the electromagnetic spectrum. For this purpose, two long-wavelength infrared (LWIR) cameras (7.5 - 13 μm) are used to detect the emitted heat radiation from surfaces which is induced by a pattern projection unit that consists of a CO2 laser (10.6 μm) and specialized optics. Thus, materials like glass or black objects, e.g. carbon fiber materials, can be measured non-destructively without the

need of any additional paintings. We demonstrate the basic principles and the functionality of our automated heat pattern system.

9868-13, Session 3

Multi-focus, high resolution inspection system for extended range applications

Kevin G. Harding, GE Global Research (United States)

Visual inspection of parts or structures for defects typically requires good spatial resolution to see the defects, but may also require a large focus range. But to obtain the best resolution from an imaging system, it needs to have a low f-number which limits the usable depth of field. Methods to use autofocus or focus stacking provides more range at high resolution, but often at the expense of computation time, loss of a real time image and uncertainty in scale changes. This paper describes an approach to quickly move through a range of focus positions without the need to move optics mechanically in a manner that is highly repeatable, maintains high resolution and provides the potential for a live image directly viewable by an inspector, even at microscope level magnifications. This paper will present the approach we investigated and discuss the pros and cons for a range of applications from large structures to small feature inspection. The paper will present examples of what resolution was achieved and how the multiple images might also be used to determine other parameters such as pose of a test surface.

9868-14, Session 3

High-contrast 3D surface measurement without changing camera exposures

Chufan Jiang, Song Zhang, Purdue Univ. (United States)

Optically measuring 3D surfaces with high contrast poses significant challenges to the optical metrology community since it is difficult to consistently measurement the whole surface with high quality. In the past few years, a few methods have been developed but they can classified into two major categories: 1) use multiple exposures without pre-analysis; 2) use optimal exposures through pre-analysis. The former methods capture a sequence of images with different exposures and select the best one for each measurement points and then combine them into a single surface. The latter methods capture a sequence of images with different exposures, analyze these images to determine the optimal exposure time for measurement, and then perform measurements with determined exposures. Though successful, they all require to capture a lot of images and the change of camera exposures, which pose challenges for high-speed applications. This paper proposes a method that does not require to change exposure time of the camera. The idea of this proposed method is that three inverted fringe patterns will be used to complement regular three fringe patterns for phase retrieval. For saturated pixels, the inverse fringe patterns will be used in lieu of the original patterns for phase extraction. Though not as robust as previously proposed time consuming methods, the proposed method can indeed substantially increase measurement quality for high-contrast surfaces. Principles of the proposed method will be detailed in this paper, and experimental data will be provided to verify the performance of the proposed method.

9868-15, Session 3

GOBO projection-based high-speed three-dimensional shape measurement

Stefan Heist, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Peter Lutzke, Ingo Schmidt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik

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Pattern projection-based three-dimensional (3-D) measurement systems are well established in various application fields, as they allow accurate full-field measurement and contactless operation. However, for some time, there has been an increasing demand in terms of a higher measurement speed. For instance, fast processes like moving people or crash tests are to be analyzed three-dimensionally.

In order to increase the measurement speed, the number of projected patterns per 3-D dataset has to be reduced and/or pattern projection and image recording have to be speeded up. As the first approach, in general, is accompanied by a reduced measurement accuracy or a limitation to objects without sharp edges or great depth, it seems reasonable to pursue the second approach. In particular, this means to develop high-speed projectors since high-speed cameras have already been commercially available.

Recently, new projection principles have been proposed which enable fast pattern switching in the kHz range, e.g., digital binary defocusing technique, array projection, or laser speckle projection. However, they all have minor drawbacks like low brightness, a complex and expensive construction, or safety concerns due to coherent radiation.

Therefore, we introduce a GOBO slide-based projector (GOes Before Optics) providing high speed, high radiant flux, and eye-safe incoherent light at low cost. We present its setup as well as the generation and change of the projected patterns. We explain the 3-D measurement principle and show first measurements of an inflating airbag and a rope skipper conducted at a 3-D frame rate of more than 1.3 kHz.

9868-16, Session 3

Computed tomography: a powerful imaging technique in the fields of dimensional metrology and quality control

Gabriel Probst, Bart Boeckmans, Wim Dewulf, Jean-Pierre Kruth, KU Leuven (Belgium)

X-ray computed tomography (CT) is a non-invasive and non-destructive optical measurement technique applied in the fields of dimensional metrology and quality control that allows full 3D visualization, of both inner and outer features, of an object through a contactless probing system. This paper presents one of its many applications where through a 3D representation of the workpiece it was possible to verify the connectivity between the mate interfaces of an assembled component made of aluminum and titanium. With the aid of CT, flaws in the design/manufacturing process that could lead to gaps at the connections could be assessed.

9868-17, Session 3

SLM based tomography of phase objects using single-shot transport of intensity technique

George Nehmetallah, Thanh C. Nguyen, Dat Tran, The Catholic Univ. of America (United States); Ahmad Darudi, Peyman Soltani, Univ. of Zanjan (Iran, Islamic Republic of)

Interferometric or holographic based techniques are often used for 3D quantitative phase imaging. While these techniques are sensitive to vibrations, non-interferometric intensity based techniques for phase

retrieval such as the transport of intensity equation (TIE) do not suffer from such a drawback. TIE employs a simple experimental technique for phase reconstruction of objects by recording several diffraction patterns at different observation planes through axially translating the CCD. Recently, instead of the slow mechanical translation, a single-shot using SLM was proposed to modify the TIE setup (SLM-TIE) for dynamic phase objects.

In this work we purpose to extend the SLM-TIE by employing an SLM in a 3D tomographic optical setup for phase objects. This modified setup will reduce the acquisition time making the TIE technique useful for dynamic events such as biological samples. We illustrate how 3D phase objects can also be reconstructed tomographically by constructing a rotating mechanism for the sample. The object will be mounted on a rotating stage and at each angle of rotation two laterally separated diffraction patterns are captured on the CCD in a single shot fashion using the SLM and a reference mirror. The reconstructed optical fields are tomographically recomposed to yield the final 3D shape using a simple multiplicative or backprojection technique. Finally, a reconfigurable hardware will be employed for synchronization of the CCD the SLM and the rotating stage.

9868-18, Session 3

High contrast optical imaging through adaptive transmittance control in the focal plane

Harbans S. Dhadwal, Jahangir Rastegar, Dake Feng, Omnitek Partners, LLC (United States)

High contrast imaging, in the presence of a bright background, is a challenging problem encountered in diverse applications ranging from the daily chore of driving into a sun-drenched scene to in vivo use of biomedical imaging in various types of keyhole surgeries. Imaging in the presence of bright sources saturates the vision system, resulting in loss of scene fidelity, corresponding to low image contrast and reduced resolution. The problem is exacerbated in retro-reflective imaging systems where the light sources illuminating the object are unavoidably strong, typically masking the object features.

This manuscript presents a novel theoretical framework, based on nonlinear analysis and adaptive focal plane transmittance, to selectively remove object domain sources of background light from the image plane, resulting in local and global increases in image contrast. The background signal can either be of a global specular nature, giving rise to parallel illumination from the entire object surface or can be represented by a mosaic of randomly orientated, small specular surfaces. The latter is more representative of real world practical imaging systems. Thus, the background signal comprises of groups of oblique rays corresponding to distributions of the mosaic surfaces. Through the imaging system, light from group of like surfaces, converges to a localized spot in the focal plane of the lens and then diverges to cast a localized bright spot in the image plane. Thus, transmittance of a spatial light modulator, positioned in the focal plane, can be adaptively controlled to block a particular source of background light. Consequently, the image plane intensity is entirely due to the object features. Experimental image data is presented to verify the efficacy of the methodology.

9868-19, Session 3

Fiber faceplate modulation readout in Bi-material micro-cantilever mirrors array imaging system

Mei Hui, Zhengzheng Xia, Ming Liu, Liquan Dong, Xiaohua Liu, Yuejin Zhao, Beijing Institute of Technology (China)

Fiber faceplate modulation was applied to read out the precise actuation of silicon-based, surface micro-fabricated cantilever mirrors array in optical imaging application. The faceplate was made by ordered bundles consisting of as many as ten thousands fibers. The transmission loss of an individual fiber in the bundles was 0.35dB/cm and the cross talk between neighboring

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fibers in the faceplate was about 15%. Bi-material micro-cantilever mirrors array composed of two-level bi-material micro-cantilever pixels which absorb incident infrared flux, resulting in a temperature increase of each pixel which plays the roles of target sensing and high detection sensitivity optical readout. The temperature distribution of emitted source is obtained on the basis of measurement of the distribution of thermal deformation in the bi-material cantilever microstructure which has a very big difference in coefficients of thermal expansion. Each cantilever beam deflects proportionally to the temperature rise due to bi-material effect. The micro-electro mechanical system mirrors array set at focal plane described here incorporates continuous mirror sheets actuated at discrete points, the deformation being normal to the surface and continuous over a desired range. Fiber faceplate can modulate the beam reflected by the units of mirrors array instead of general filter such as knife edge or pinhole. An optical readout signal brings a visible spectrum into pattern recognition system, yielding a thermal image on monitor. Thermal images of bodies at room temperature have been obtained. The noise equivalent temperature differences (NETD) of the images was improved.

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9869-1, Session 1

Simultaneous binary hash and features learning for image retrieval

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Content-based image-retrieval have attracted attention of many researchers in the field of computer vision in recent years. Despite the huge progress in the field, semantically accurate image retrieval is still very challenging task. This paper addresses the problem by simultaneous learning of global image features and binary hash codes for large scale image search. Our approach employ deep learning technique which is able to produce good features with properties of similarity preserving, balance and independence. As opposed to existing feature learning techniques our approach is able to take advantage of weakly labeled datasets. Another advantage of our method in contrast to existing methods is ability to fine-tune retrieval on particular application case. The experimental results on several data sets show that proposed methods outperform state-of-the-art methods.

9869-2, Session 1

Facial Expression Identification Using 3D Geometric Features from Microsoft Kinect Device

Dongxu Han, Naseer Al Jawad, Hongbo Du, The Univ. of Buckingham (United Kingdom)

Facial expression identification is an important part of face recognition and closely related to emotion detection from face images. Various solutions have been proposed in the past using different types of cameras and features. Microsoft Kinect device has been widely used for multimedia interactions.

More recently, the device has been increasingly deployed for supporting serious scientific investigations. Our research explores the effectiveness of using the device in identifying emotional facial expressions such as shock, smile, sad, etc. and evaluates the usefulness of 3D data points on a face mesh structure from the Kinect device.

In this paper, we present a distance-based geometric feature component that is derived from the distances between points on the face mesh and 4 selected reference points in a single frame. The feature components extracted across a sequence of frames starting and ending by neutral emotion are then concatenated into a complete feature vector to represent an expression. The feature vector eliminates the need for complex face orientation correction, simplifying the feature extraction process and making the process more efficient. We applied the kNN classifier that uses a proximity measure based on the principle of dynamic time warping to determine the closest neighbours. This paper also investigates the effect of PCA dimension reduction to the classification results and compares the performance of the kNN classifier against another commonly used SVM classifier. Preliminary tests on a small scale database of different facial expressions show promises of the newly developed feature vector for facial expression identification.

9869-3, Session 1

A new color transfer quality measure

Long Bao, Karen Panetta, Tufts Univ. (United States); Sos S. Aгаian, The Univ. of Texas at San Antonio (United States)

Image color transfer aims at recoloring a target image with color extracted from a source image. This can be used to capture the artistic ambience or "mood" of the source image and transfer that same ambience to the target image. In addition, it can also be applied in medical imaging, image restoration, and space image coloring.

In color transfer research, a persistence challenge is determining how to properly evaluate the performance of each method. There are a limited number of existing measures, including Peak signal-to-noise ratio (PSNR), Xiao's measure and Xiang's measure. The Peak signal-to-noise ratio (PSNR) is limited in that it requires a reference image, which is typically non-existent. Xiao's method does not take the colorfulness factor into consideration and Xiang's method uses measuring the closeness values of colorfulness as an indicator for good performance, especially when the source image has a low colorfulness attribute. This impairs the measure's performance.

In this paper, we propose a new color transfer measure. The measure calculates and fuses three characteristic properties: color map similarity, colorfulness and content similarity. To compare the performance's agreement with a human's judgment, we introduce a subjective measure to calculate the mean opinion score (MOS). Three different kinds of correlation, including Spearman's rank order correlation (SROCC), Kendall's tau correlation (KRCC) and Pearson's product moment correlation (PRCC), will be calculated individually between the values of each measure and MOS. The results from these correlation values demonstrate the proposed color transfer measure outperforms two other current state-of-the-art methods.

9869-4, Session 1

Missing Data Reconstruction using Gaussian Mixture Models for Fingerprints Image

Rushikesh D. Yeole, Sos S. Aгаian, The Univ. of Texas at San Antonio (United States); Marzena Mulawka, Mike Troy, Postmortem Fingerprints (United States); Gary Reinecke, Boston University (United States)

Fingerprints have been widely used in personal identification because there are much more reliable than other kinds of commonly used personal identification methods such as signature, face, and speech. Recently, significant progress has been made in designing automatic fingerprint identification systems for missing fingerprints' data and also the real fingerprint images are of poor quality as a result of degradation by noise elements which generate false minutiae and reject the actual features.

This paper presents an algorithm for reconstructing the missing data in fingerprint image recognition. It is based on Gaussian regression trees which contains the following key blocks such as

- Gaussian mixture model (GMM)
- Basis functions and feedback error
- Error concealment
- Correlation model
- Image Interpolation

Experimental results acquired for matching are accurate and reliable for implementation using a PC and a fingerprint scanner, can provide an efficient way of automated identification. The proposed missing data fingerprint reconstruction and recognition system can provide an efficient way of automated identification and can be extended to numerous other security or other application such as postmortems, forensics, investigation of crimes, artificial intelligence, robotics, access control, financial security, and verification of firearm purchasers and driver license applicants etc.

9869-5, Session 1

Color image enhancement of fingerprints using 2D-QDFT and 2D-DFT

Aparna John, Artyom M. Grigoryan, Sos S. Aghaian, The Univ. of Texas at San Antonio (United States)

Image processing has developed rapidly since its beginning, in the early 20th century. The fast development of the various image processing techniques and algorithms is mainly because, vision plays an important role in human perception. Now, image processing has a candid significant role in various fields like biometrics, defense, security, medicine, atmospheric science, astronomy etc. The enhancement of the image is mainly achieved by increasing the contrast, sharpening the edges, reducing the noise etc. One of the two broad classification of image enhancement techniques is frequency domain enhancement techniques. And among the many enhancement techniques and algorithms in frequency domain, two dimensional discrete Fourier transform (2D DFT) is an effective and popular one. In the enhancement of color images using 2D DFT, the individual existence of the color channels are considered. While in the quaternion discrete Fourier transform (QDFT), all the color channels of a color image are considered as a single unit. A quaternion is a four dimensional hyper-complex numbers and the Fourier transform based on quaternions is QDFT. The virtue of enhancing the fingerprint color image with QDFT is that the many shades of the color are obtained by the intermixing effects of these separate color data in the channels. In alpha-rooting method the frequency values are amended before taking the inverse of the transform. The fingerprint images so enhanced by these Fourier transforms and alpha-rooting method give a vivid visual discernments. The optimum value of alpha is chosen by genetic algorithm based on the estimation measure value called the Color Enhancement Measure Estimation (CEME) of the color images.

9869-6, Session 1

Wavelet domain retinex algorithm for image contrast enhancement

Numan Unaldi, Turkish Air Force Academy (Turkey)

Multiscale Retinex with Color Restoration (MSRCR) is one of the most commonly used image enhancement algorithm which has an extensive usage in many different applications and performs well for a very large variety of natural images. However, processing in three spectral channels for at least three scales makes the algorithm hard to implement for real-time applications on contemporary mobile devices. In addition, optimal performance is not always obtained with default parameter settings, especially when images that have a dark subject with a very bright background are being processed. Besides, MSRCR with default parameters cannot handle the images with a very narrow dynamic range. Finally, the "halo effect" appearing at the boundaries with a large luminance change even though reduced, is not totally removed.

In this paper, to overcome the drawbacks addressed in the previous paragraph, a wavelet transform (WT) based Retinex approach is proposed, in which a modified version of the MSRCR algorithm is applied to the approximation coefficients of the transformed image. The detail coefficients are also changed in order to provide sharpness besides contrast enhancement. During the course of the enhancement process, based on the local statistics of the approximations coefficients, enhancement gain

and offset parameters are determined to improve the overall brightness, contrast, and sharpness of the image. Thus, image features such as edges, boundaries and local contrast are enhanced while global dynamic range is compressed mimicking the human visual system.

Preliminary results are encouraging in showing the superiority of the proposed algorithm over the state-of-the-art enhancement technique in terms of rendition and statistical visual quality measures.

9869-7, Session 2

Video stabilization using space-time video completion

Viacheslav V. Voronin, Vladimir A. Frantc, Don State Technical Univ. (Russian Federation); Vladimir I. Marchuk, Don State Technical Univ. (Russian Federation); Igor Shrayfel, Sergei Stradanchenko, Don State Technical Univ. (Russian Federation); Sos S. Aghaian, The Univ. of Texas at San Antonio (United States)

This paper proposes a video stabilization method using space-time video completion for effective static and dynamic textures reconstruction. The proposed method can produce full-frame videos by naturally filling in missing image parts by locally aligning image data of neighboring frames. In our work, we exploit the concept of sparse representation, which takes group of nonlocal patches with similar textures as the basic unit instead of patch. The proposed completion method used multi-direction features into the inpainting algorithm, and employs deep learning technique which is able to produce good features with properties of similarity preserving. Moreover, the color and multi-direction constraints are incorporated into the optimization criterion to obtain sharp inpainting results. The sparsely represents natural texture images in the domain of group, which results intrinsic local sparsity and nonlocal self-similarity of images simultaneously. Experimental results demonstrate the effectiveness of the proposed method in the task of full-frame video stabilization.

9869-8, Session 2

Improved deadzone modeling for bivariate wavelet shrinkage-based image denoising

Stephen P. DelMarco, BAE Systems (United States)

Modern image processing performed on-board low Size, Weight, and Power (SWaP) platforms, must provide high-performance while simultaneously reducing memory footprint, power consumption, and computational complexity. Image preprocessing along with downstream image exploitation algorithms, such as object detection and recognition, and georegistration, place a heavy burden on low-SWaP platform power and processing resources. Image preprocessing often includes image denoising to improve data quality for downstream exploitation algorithms. High-performance image denoising is typically performed in the wavelet domain, where noise generally spreads and the wavelet transform compactly captures high information-bearing image characteristics. In this paper, we improve denoising performance of a previously-developed, computationally-efficient wavelet-based denoising algorithm, without significantly increasing computational cost. That is, we improve modeling fidelity to provide enhanced denoising performance, for no significant additional computational cost, thus making the approach suitable for low-SWaP platforms. Specifically, this paper presents modeling improvements to the Sendur-Selesnick model (SSM) which implements a bivariate wavelet shrinkage denoising algorithm exploiting interscale dependency between wavelet coefficients. We formulate optimization problems for parameters controlling deadzone size which leads to improved denoising performance. Two formulations are provided; one which has a simple, closed form solution which we use for numerical result generation, and a second integral equation formulation involving elliptic integrals. We generate image denoising performance results over different image sets drawn from

public domain imagery, and investigate the effect of wavelet filter tap length on denoising performance. We demonstrate denoising performance improvement when using the enhanced modeling over performance obtained with the baseline SSM model.

9869-9, Session 2

Fruit bruise detection based on 3D meshes and machine learning technologies

Zhilong Hu, Jinshan Tang, Michigan Technological Univ. (United States); Ping Zhang, Alcorn State University (United States)

In this paper, we present an automatic 3D apple bruise detection system, which is directly working on 3-D triangular mesh data. The mesh data is firstly down-sampled to smaller size in order to improve the processing efficiency. The principal curvature are calculated on each vertex and coded into Local Binary Pattern. At last we use a support vector machine to classify bruised and unbruised fruits. 200 bruised apples and 100 unbruised apples were utilized in our experiment, and the classification result shows that, based on the input data, we can get the classification accuracy as high as 89.1%.

9869-10, Session 2

Automatic segmentation and measurements of gestational sac using static B-mode ultrasound images

Dheyaa Ibrahim, Sabah Jassim, Hongbo Du, Hisham Al-Assam, The Univ. of Buckingham (United Kingdom)

Ultrasound imagery has been widely used for medical diagnoses. Ultrasound scanning is safe and non-intrusive and hence repeatedly used throughout the pregnancy for monitoring the Gestational Sac (GS) growth. The task of measuring the GS size from an ultrasound image is done manually by a Gynaecologist. This paper presents a new framework to segment a GS from a static B-mode image by exploiting the object's geometric features, and to automatically measure the segmented GS for early identification of miscarriage cases. To accurately locate GS in the image, the proposed solution uses wavelet transform to suppress the speckle noise by eliminating the high-frequency sub-bands and prepare an enhanced image. This is followed by a segmentation step that isolates the GS through the following stages. First, the mean value is used as a threshold to binarize the image followed by filtering unwanted objects based on their circularity, size and solidity. Then the mean value of each object is used to further select candidate objects. A new neighbourhood adaptive threshold is applied as post-processing to finally identify the GS. We evaluated the effectiveness of the proposed solution by first comparing the automatic size measurements of the segmented GS against the manual measurements, and then integrating the proposed segmentation solution into a classification framework for identifying miscarriage cases and pregnancy of unknown viability (PUV). Both test results demonstrate that the proposed method is effective in segmentation of GS that then leads to classification outcomes with high accuracy (sensitivity (miscarriage) of 100% and specificity (PUV) of 94%).

9869-11, Session 2

Automatic layer segmentation of H&E microscopic images of mice skin

Saif Hussein, Sabah Jassim, Joanne Selway, Hisham Al-Assam, The Univ. of Buckingham (United Kingdom)

Mammalian skin is a complex organ composed of a variety of cell and

tissue types. The automatic detection and quantification of changes in skin structures has a variety of different applications for biological research. To accurately segment and quantify nuclei, sebaceous gland, hair follicles, and other skin structures, there is a need for a reliable segmentation of different skin layers.

This paper presents an efficient segmentation algorithm to segment the three main layers in mice skin, namely epidermis, dermis, and subcutaneous layers. It also segments the epidermis layer into two sub layers, basal and cornified layers. The proposed algorithm uses adaptive colour deconvolution technique on the H&E stain images to separate different tissue structures. Max entropy, inter-modes, and Otsu thresholding techniques were effectively combined to segment the layers. It then uses a set of morphological and logical operations on each layer to removing unwanted objects. A dataset of 7500 H&E microscopic images of mutant and wild type mice were used to evaluate the effectiveness of the algorithm. Experimental results examined by domain experts have confirmed the viability of the proposed algorithms

9869-12, Session 2

Automatic detection of the hippocampus region associated with Alzheimer's disease from microscopic images of mice brain

Tahseen Albaidhani, Sabah Jassim, Hisham Al-Assam, The Univ. of Buckingham (United Kingdom)

Hippocampus is the region of the brain that is primarily associated with memory and spatial navigation. It is one of the first body part to be damaged when a person suffers from In Alzheimer's disease.

An automatic system to count and classify different blood vessels such as capillaries, veins, and arteries in the hippocampus efficiently and accurately can provide biologists with effective tool in their research into Alzheimer's disease. Locating the Region of Interest (ROI) in the hippocampus is the first essential stage towards developing such a system.

This paper proposes an automatic solution for detecting the ROI from microscopic images of mice brain. The proposed method starts by locating the hippocampus edge based on linear Hough transforms. The output is then used to split the brain image into two sides, the hippocampus region and the outside region based on calculating the determinant of each pixel with two points on the located edge. The proposal then employ a mix of colour and texture to automatically identify the hippocampus regions. Experimental results on a set of microscopic images have shown the effectiveness of the proposal in automatically segmenting the region of interest.

9869-13, Session 2

A combined criterion for the image denoising

Evgeny A. Semenishchev, South-Russian State Univ. of Economics and Service (Russian Federation)

A new image denoising method is proposed in this paper. We are considering an optimization problem with a linear objective function based on two criteria, namely, L2 norm and the first order square difference; then solving it and proving a convergence and uniqueness of solutions of the developed method. This method is a parametric one, by a choice of the parameters one can tune a given criteria of the objective function. The denoising algorithm consists of the following steps: 1) multiple denoising estimates are found on local areas of the image; 2) image edges are determined; 3) parameters of the method are fixed and denoised estimates of the local area are found; 4) local window is moved to the next position (local windows are overlapping) in order to produce the final estimate. A proper choice of parameters of the introduced method is discussed. A comparative analysis of a new denoising method with existed ones is performed on a set of test images.

9869-14, Session 3

Consideration of techniques to mitigate the unauthorized 3D printing production of keys

Jeremy Straub, Scott Kerlin, Univ. of North Dakota (United States)

The illicit production of 3D printed keys based on remote-sensed imagery is problematic as it allows a would-be intruder to access a secured facility without the attack attempt being as obviously detectable as conventional (i.e., lock picking) techniques. This approach is particularly problematic as there may be no obvious way to determine who the intruder was from assessing who had access to keys (to use, copy, etc.).

This paper considers the problem from multiple perspectives. First, it looks at different attack types and considers the prospective attack from a digital information perspective. This involves looking at how the combination of different pieces of information (e.g., access to multiple keys and/or routine access to a limited-importance key and remote sensed imagery of a higher-importance one) can provide a pathway to illicit key replica creation. Second, based on this, techniques for securing keys are considered. These range from discussing treatments that could be applied to keys to make them more difficult to image to a consideration of human factors which may make keys more or less accessible for imaging or other data acquisition. Third, the design of keys is considered from the perspective of making them more difficult to duplicate using visible light sensing and 3D printing.

From the foregoing, the utility of keys for providing security is assessed. Their efficacy for use in multiple environments is considered and conclusions are drawn. The paper concludes with a discussion of laws and policies that might prolong the utility of keys for certain applications.

9869-15, Session 3

Real-time object tracking using optical flow data and histogram backprojection for drone surveillance

Atinderpal Singh, Indian Institute of Technology Roorkee (India); Aakash Sinha, Omnipresent Robot Technologies Pvt. Ltd. (India)

This paper describes a real-time object tracking method based on optical flow and histogram backprojection. The approach is divided into three parts (i) Video stabilization using optical flow on downsampled frames and applying calculated transform to actual size image (ii) Feature extraction on interest window containing the object (iii) Using optical flow data of tracked features and weighted color histogram backprojection to estimate the correct mean shift and then updating the interest window. The use of optical flow makes mean-shift algorithm to work in low contrast conditions and also during short interval partial occlusions. Experiments were conducted and the results were compared with optical flow based tracking and color mean-shift based tracking. This approach has shown high accuracy and invariance to pose change and partial occlusion.

9869-16, Session 3

A semi-supervised machine learning method using neural network/probabilistic PCA for image recognition

Jesus Antonio Motta, Jacques Ladouceur, Univ. Laval (Canada)

This research presents an efficient method of machine learning based on a neural network for image recognition. These images are taken from a

database of images and classified according to the scenes they represent. Each image is converted to an array of $32 * 32$ pixels. These images are converted into a matrix of n images by 1024 pixels. The training set has been created from the selection of the images carrying the most information that were obtained using the attribute extraction technique Probabilistic Principal Component Analysis on a covariance matrix of image array. From the identification of the first eigenvectors containing as much information as we used the Jaccard coefficient to find the most similar images with the corresponding class that will be selected to be part of the training set. Different neural network parameters such as number of neurons, learning rate, and number of layers, were tested in order to obtain the most efficient classification function. The performance evaluation model was made using various techniques in order to have a set of criteria from different points of view. These techniques are: Precision, Recall, F_measure, curve vs. Accuracy Recall, Confusion Matrix and ROC curve for multi-class models. The evaluation results show that our model can be trained to be implemented efficiently in image recognition and could be used / adapted in different applications and scenes.

9869-17, Session 3

Single authentication: exposing weighted splining artifacts

Rimba Whidiana Ciptasari, Telkom Univ. (Indonesia)

A common form of manipulation is to combine parts of the image fragment into another different image either to remove or blend the objects. Inspired by this situation, we propose a single authentication technique for detecting traces of weighted average splining technique. In this paper, we assume that image composite could be created by joining two images so that the edge between them is imperceptible. The weighted average technique is constructed from overlapped images so that it is possible to compute the gray level value of points within a transition zone.

This approach works on the assumption that although splining process leaves the transition zone smoothly. They may, nevertheless, alter the underlying statistics of an image. In other words, it introduces specific correlation into the image. The proposed idea dealing with identifying these correlations is to generate an original model of both weighting function, left and right functions, as references to their synthetic models. To construct a relatively accurate model of cubic interpolation, we employ Newton Polynomial. The overall process of the authentication is divided into two main stages, which are pixel predictive coding and weighting function estimation. In the former stage, the set of intensity pairs $\{I_{left}(x,y), I_{right}(x,y)\}$ is computed by exploiting pixel extrapolation technique. The resulting intensity values is then employed to construct the linear systems to estimate the weighting function coefficients.

We show the efficacy of the proposed scheme on revealing the splining artifacts from 300 splined images. We believe that this is the first work that exposes the image splining artifact as evidence of digital tampering.

9869-18, Session 3

3D change detection in staggered voxels model for robotic sensing and navigation

Ruixu Liu, Vijayan K. Asari, Univ. of Dayton (United States)

3D scene change detection is a challenging problem in robotic sensing and navigation. There are several unpredictable aspects in performing scene change detection. A change detection method which can support robotic applications in varying environmental conditions is proposed in this paper. We create a point cloud model from video captured by a Microsoft Kinect, which provides the required depth information. Iterative Closest Point algorithm is used to align the target frame with the reference frame. We perform change detection on a large scene in the RGB-D model. First, we create a point voxel model which defines voxels as surface or free space. The threshold for the voxels which define as the surface is the number of points estimated by computing the nearest neighborhood voxels. Then

we create a color model which defines each voxel with a color that is the mean of RGB values of all the points in the voxel. The preliminary change detection is performed by combining the two staggered models. Next, we use a Truncated Signed Distance Function to detect surface of objects. This enables to find the voxels that are belonging to the surface in the staggered voxel model. If more than one front or rear point model's voxel is detected as a change, the respective points in the staggered model's voxel are identified as the change in the scene. The experimental evaluations performed to evaluate the capability of our algorithm have shown promising results for scene change detection indicating all the changing objects with very limited false alarm rate.

9869-19, Session 3

A Hybrid Algorithm for the Segmentation of Books in Libraries

Zhilong Hu, Jinshan Tang, Michigan Technological Univ. (United States); Liang Lei, Chongqing University of Science & Technology (China)

This paper presents a book identification system based on the recognition of the name, as well as the book label on the book spine. We combined color segmentation, line detection as well as label region detection to implement the book spine segmentation. After that, we applied machine learning technologies to recognize the title and labels of the book.

9869-20, Session 3

Wireless imaging sensor network design and performance analysis

Ramakrishnan Sundaram, Gannon Univ. (United States)

This paper discusses the design and characterization of a wireless sensor network for imaging applications. Radio Tomographic Imaging (RTI) is the technique using radio signals to track an object that is not emitting its own radio signals. An RTI sensor network consists of nodes of radio devices which broadcast messages to each other and measure the received signal strength (RSS) of all possible radio links in the network. The object which enters the area being monitored will obstruct several radio links, and the change in RSS enables the network to image and track the position of the obstruction. In this paper, the RTI sensor network is tested for operation in different field environments. The paper explores the physical model for RTI measurements that incorporates the effects of foliage. In existing work on RTI, it is assumed that all radio links have a line of sight (LOS) path and the effect of non-line of sight (NLOS) paths, such as multiple weak reflections from foliage and terrain, are not considered. The presence or absence of the NLOS paths will result in a drop in the RSS when an obstruction is present. In the physical model, the NLOS effects are characterized in terms of terrain and foliage characteristics. The physical model includes the number and strength of NLOS paths, their coherence with the LOS path, and their mitigation by directional antennas on the sensors. The interface between the real-time RSS data collection process and the image formation and display process is also documented.

9869-31, Session 3

Comparison of feature based with deep net techniques for rib segmentation in chest x-ray images

Sumit Chakravarty, Kennesaw State Univ. (United States); Weiqi Diao, Rui Zou, Kennesaw State Univ. (United States) and North China Univ. of Technology (China); Yanan Zhao, Kennesaw State Univ. (United States) and North China

Univ. of Technology (China)

Traditional Image processing techniques rely on the Feature Detection – Category Classification framework. Suitable features are first extracted from images by various schemes. Classifier is then employed on the extracted features to decide whether the object of interest is present in the scene or not. Variations of this technique allow different choices of feature detectors and classifiers. Feature detectors can be low level techniques like intensity, shape or texture or can be high level methods like active shape or contour models. Simple or complex classifier can also be chosen. A new approach in Image segmentation paradigm is the use of Deep-Net techniques. This involved training multi layer neural networks on a huge volume of data in a pseudo supervised manner. The trained classifier can then perform the segmentation task. Although such neural networks are tailored to handle Images and have achieved excellent classification rates, many aspects of their use still remain to be investigated. This paper researches on issues such as how to apply such networks in limited data situations, how to use pre-trained classifiers on new data types and finally how to effectively combine and compare the new paradigm with the prevalent feature detection-classification model. Results as applied on Chest X-Ray data are presented in this study

9869-21, Session PTue

2D hexagonal quaternion Fourier transform in color image processing

Artyom M. Grigoryan, Sos S. Agaian, The Univ. of Texas at San Antonio (United States)

We present a novel concept of the 2D hexagonal quaternion discrete Fourier transform (HQDFT) defined on hexagonal lattices which are important for many problems in image processing and require 13.4% less sampling points than square images and the human vision system relates best to the regular hexagonal tessellation, which has a lower number of neighbors than the rectangular lattice. The color images on the hexagonal lattice are considered in the RGB model and transformed into the imaginary subspace of quaternion numbers. The concepts of right-side and two-side 2D HQDFTs are described and properties and fast algorithms of these transforms are described. We present a new approach in processing color images in the frequency domain on hexagonal lattices, which is based on the tensor representation of color images. Between the spatial and frequency spaces exists an intermediate space, the frequency-and-time space, or image representation in the form of 1D signals which are generated by a specific set of frequencies. In tensor representation, color components of images are described by 1D signal in the quaternion algebra. The tensor representation is effective, since it allows for processing the color image by 1D quaternion signals which can be processed separately. This representation also splits the algebraic structure of the 2-D HQDFT, since each of the quaternion signals defines the 2-D HQDFT in the corresponding subset of frequency-points. The tensor transform-based 2D HQDFT is effective and simple to apply and design, which makes it very practical in color image processing in the frequency domain.

9869-22, Session PTue

New epidermal feature descriptor models and their performance in computerized skin tone, texture, and moisture recognition

John A. Jenkinson, Artyom M. Grigoryan, Sos S. Agaian, The Univ. of Texas at San Antonio (United States)

Automating the diagnosis of visible skin conditions is performed for skin cancer diagnosis and other applications [2,3,4,5]. To automate the diagnosis using a supervised machine learning algorithm for the input image, feature descriptors must be extracted for target objects in a segmented image

[6,7]. The feature values then become the training data set for the machine classifier. Feature selection influences the accuracy of classification [8]. We plan to show that new feature models based on intensity, histogram analysis, form, multi-resolution analysis, and transform outputs [9,10,11,12,13] present a feature set which can be used for the novel automated recognition of skin tone, texture, and moisture level, that when applicable, is comparable with the state-of-the-art methods in terms of classification accuracy [1].

9869-23, Session PTue

Quaternion Fourier transform-based prediction of coding region in DNA sequences

John A. Jenkinson, Artyom M. Grigoryan, Sos S. Aghaian, The Univ. of Texas at San Antonio (United States)

DNA or Deoxyribonucleic Acid, which is a double stranded structure made up of four nucleotides -Adenine, Cytosine, Guanine and Thymine, consists of inter-genic regions and is found inside a nucleus of the cell [1,2]. The genes are divided into small protein coding regions known as exons and non-coding spacers known introns. The base sequences in the protein-coding regions of DNA molecules have a period-3 component and this property is used to indicate the gene location, by using a band pass digital filter or computing the discrete Fourier transform. The ability of the discrete Fourier transform to identify the accurate boundaries of the 3-period signal is limited by its requirement of chosen window size over which the spectrum is calculated. In this paper, we present a novel method for prediction of coding region in the DNA sequences, which is based on the presentation of sequences in the quaternion algebra. We choose the quaternion Fourier transform because it well-suited for four-dimension data and allows us to process all four components or dimensions simultaneously, and it captures the inherent correlation between the components [3,4,5]. Experimental results show that the proposed method with the representation of nucleotide with quaternion numbers instead of four independent indicator sequences together with the Fourier transform is highly effective in identifying the approximate locations of coding regions. The sufficiencies of the proposed method of prediction of coding regions and comparison with the known methods are described.

9869-24, Session PTue

Recognition of vehicle number plate based on wavelet differentiation

Dmitriy Bezuglov, Alexander Kuzin, The Russian Customs Academy (Russian Federation); Viacheslav V. Voronin, Don State Technical Univ. (Russian Federation)

Basically video surveillance system is used for security purpose as well as monitoring systems. Automatic number plate recognition (ANPR) is a mass surveillance method that uses optical character recognition on images to read vehicle registration plates. It is observed that the number plates of vehicles are in different shape and size and also have different color in various countries. The complexity of this problem is related to the presence of digital noise on the input images obtained in the process of their registration, digitization, and as a result of various factors. This work proposes a method for the detection and identification of vehicle number plate that will help in the detection of number plates of authorized and unauthorized vehicles. The proposed approach based on simple wavelet differentiation method. To solve the noise effect on the result of peaking in this paper we consider the direct and inverse wavelet differentiation. After segmentation of numbers and characters present on number plate, template matching approach is used to recognition of numbers and characters. We compare our results to proposed method with some other algorithms.

9869-25, Session PTue

Automatic image cracks detection and removal on mobile devices

Viacheslav V. Voronin, Vladimir I. Marchuk, Roman Sizyakin, Nikolay Gapon, Svetlana Tokareva, Sergey V. Makov, Don State Technical Univ. (Russian Federation)

Some of old photographs are damaged due to improper archiving (e.g. affected by direct sunlight, humidity, insects, etc.) or have a physical damage resulting on appearance of cracks, scratches on photographs, non-necessary signs, spots, dust, and so on. This paper focuses on detection and removal of cracks from digital images. The proposed method consists of the following steps: pre-processing, crack detection and image reconstruction. A pre-processing step is used to suppress a noise and small defects in images. For a crack identification we use modified local binary patterns to form a feature vectors, and a non-linear SVM for a crack recognition. The combined inpainting method using structure and texture restoration is applied at the image reconstruction step. Image inpainting is the process of restoring the lost or damaged regions or modifying the image contents imperceptibly. This technique detects and removes the horizontal, vertical, diagonal cracks and other defects on complex scenes of image. We implemented proposed method on some mobile platforms for automatic image enhancement. We have found PSNR of the images in which the cracks are restored by proposed approach and compared the results with the other methods. Presented examples demonstrate the effectiveness of the algorithm in cracks detection and removal.

9869-26, Session PTue

A method for modelling post mortem biometric 3-D fingerprint

Srijith Rajeev, Shreyas Kamath K. M., Sos S. Aghaian, The Univ. of Texas at San Antonio (United States)

Fingerprints are a common biometric modality which is widely used because it provides higher efficiency, user convenience and feasibility. Despite the advancements made in automated fingerprint recognition, matching incomplete or partial fingerprints continue to be an important challenge. This problem became more sophisticated when verification of post mortem fingerprints were required. This paper presents a method to perform post mortem fingerprint 3-D modelling, recognition and classification. The modelling algorithm performed should change the structure of the surface alone maintaining the integrity of the ridges. The key steps of this method involve masking, filtering, unrolling, and resampling. Computer simulations performed are robust but comparisons could not be made because of the lack of similar methods. The proposed fingerprint modelling scheme can provide an efficient way of automated fingerprint identification of deformed models and can be extended to other biometric traits such as palm, foot, tongue etc. for security and administrative applications.

9869-27, Session PTue

Automated classification of histopathology images of prostate cancer using a Bag-of-Words approach

Foram Sanghavi, Sos S. Aghaian, The Univ. of Texas at San Antonio (United States)

Prostate cancer (PC) is the most commonly occurring non-cutaneous cancer among more than 2 million men in US but can be often treated successfully [1]. Currently, diagnosis of PC is based on the assessment (Gleason grading and scoring) of the histopathology images done by the pathologists. Also, this procedure is time consuming and not very robust. Automated classification of histopathology images into the different

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Gleason scores plays a critical role in cancer detection, treatment decision, improving accuracy and decreasing the reading time of the images for the pathologists. The intricate presence of cancerous and the normal tissues of different sub-grades in the histopathology images proves a challenge in automatic detection and assessment of PC. Another difficulty in analysis is the presence of different visual patterns in the histopathology images. Currently, the Bag-of-Words method is the most prevalent method in the Computer Vision system or in many modern recognition system. One solution of automatic detection and classification of PC histopathology images could be representation of the image in the form of visual patterns or dictionary of Words.

In this paper, Computer Aided Diagnosis (CAD) based joint system of Bag-of-Words, Voronoi diagram and LBP descriptors is presented. The presented CAD system can be used by the pathologists for fast and automated detection and Gleason scoring of the PC images. The presented method will be compared with different feature descriptors and texture analysis methods in-conjunction with multi-class prostate cancer SVM classification method.

[1] "Prostate Cancer." American Cancer Society. Web 05 Oct 2015 < <http://www.cancer.org/cancer/prostatecancr> >

9869-28, Session PTue

**Alpha Trimmed Correlation for Touchless
Finger Image Mosaicing**

Shishir Paramathma Rao, Rahul Rajendran, Sos S. Agaian, The Univ. of Texas at San Antonio (United States); Marzena Mulawka, FlashScan3D (United States)

Recently, the field of fingerprint recognition has seen growth not only in biometric verification purposes but also in a number of commercial, civil, and forensic application. The commonly used fingerprint registration methods are based on contact of finger on a surface. These methods face a number of problems, such as, non-linear plastic distortion leading to altered geometry, improper finger placement, accumulation of dirt, slippage, smearing, sensor noise and lesser effective area. To overcome these problems multiview contactless fingerprint recognition systems are recommended.

In this paper, we present novel methods to combine multiple views of the finger, to generate a stitched image. The proposed methods include new concepts like alpha-trimmed correlation, alpha-winsorized correlation, and weighted rank order statistic correlation. The computer simulations performed shows the following advantage of the proposed method:

- More accurate and reliable stitched image.
- Robustness of the proposed method as it is not limited to finger images.
- Generate scenic panoramic images.
- Generate underwater 360 degree panorama
- Implemented towards various biometric applications including palm-print and footprint mosaicking.

In future, this method can be extended to obtain a 3-D model of the finger using multiple views of the finger.

9869-29, Session PTue

**Histogram of oriented phase (HOP): a new
descriptor based on phase congruency**

Hussin K. Ragb, Vijayan K. Asari, Univ. of Dayton (United States)

Human detection is considered as one of the most challenging tasks in the computer vision systems. In the last decade, local descriptors based on gradient approach such as Histogram of Oriented Gradient (HOG), Local Binary Pattern (LBP), and Scale Invariant Feature Transform (SIFT) were developed for detecting Human in the images and video sequences.

These algorithms played vital role in human detection, however they were lacking to deal effectively with images impacted by noise, and illumination variations. In this paper we propose a new descriptor based on phase congruency concept that can improve the performance of the human detection systems exposed to these challenges. Since the phase of the signal conveys more information regarding signal structure than the magnitude, the proposed descriptor can precisely identify and localize image features over the gradient based techniques especially in the regions affected by illumination changes. The proposed features can be formed by extracting the phase congruency information for each pixel in the image with respect to its neighborhood. Histograms of the phase congruency values of the local regions in the image are computed with respect to its orientation. These histograms are concatenated to construct the proposed descriptor; named Histogram of Oriented Phase (HOP). The dimensionless quantity of the phase congruency leads the HOP descriptor to be more robust to the image scale variations as well as contrast and illumination changes. Several experiments were performed using (INRIA and DaimlerChrysler) datasets to evaluate the performance of the HOP descriptor. The experimental results show that the proposed descriptor has better detection performance and less error rates than a set of the state of art feature extraction methodologies.

9869-30, Session PTue

**Simulated annealing framework for
automated audio video summarization**

Sumit Chakravarty, Kennesaw State Univ. (United States); Yixuan Sun, Hong Kong Univ. (Hong Kong, China); Madhushri Banerjee, Georgia Gwinnett College (United States)

Video summarization is a form of Compression. It provides a condensed version of video stream by analyzing the audio-video content. It is an essential element of context based video browsing and retrieval as well. Although numerous scene segmentation algorithms have been developed, work on video scene structure study is fairly rare. Inclusion of audio to this environment makes this even rarer.

This work addresses this issue by using Simulated Annealing (SA) as the framework for audio-video scene structure analysis and summarization. SA is a probabilistic optimization technique to find global minimum of functions. It has been successfully applied in the field of Image Analysis. In this paper we propose it to be used in the context of video summarization by choosing an optimal sequence of states for representing a video segment. These states are a combination of audio as well as video features as well as interrelated audio-video features. An audio feature includes semantic data like silence, speech and music or background noise. Video analyses include features like shot change speed, scene object and background analysis. By combining the two unique sources namely audio and video in a robust stochastic framework like SA, we show results is better video structure analysis and summarization.

Conference 9870: Computational Imaging

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9870-1, Session 1

A concept for multispectral imaging using compressive sensing (*Invited Paper*)

Robert R. Muise, Johann Veras, Jamie C. Perez, Lockheed Martin Missiles and Fire Control (United States)

We postulate an optical configuration which takes a multispectral scene and collects a multiplexed spectral sample on the Focal Plane Array (FPA) with a diffractive element in the optical pathway. From such a measurement paradigm, the data is then processed with compressive imaging techniques and we recover the full multispectral cube from a single frame of information. We compare several reconstruction algorithms and encoding techniques. We also show reconstruction results from a lab prototype multispectral computational imager with promising results.

9870-2, Session 1

Computational hyperspectral unmixing using the AFSSI-C

Phillip K. Poon, The Univ. of Arizona (United States); Esteban Vera, Michael Gehm, Duke Univ. (United States)

Hyperspectral unmixing is the task of estimating the fractional abundances of spectra in each spatial pixel of an object scene. Traditional spectral imaging instruments are inefficient in light collection, so even the most sophisticated spectral unmixing algorithms are ultimately limited by signal-to-noise ratio. We have previously introduced a high throughput computational sensing instrument for spectral imaging classification—the Adaptive Feature Specific Spectral Imaging-Classifer (AFSSI-C). The AFSSI-C is able to measure adaptive (dynamic) projections of the hyperspectral datacube to perform spectral classification without the need to first reconstruct the datacube. In this talk, we will show that this device can also be used to directly estimate fractional abundances and that it outperforms conventional post-processing spectral unmixing. Further gains are possible when operation of the instrument is combined with a sparse estimation algorithm (taking advantage of the fact that each spatial location represents a mixture of only a small number of spectral endmembers). We will report on the progress of our simulations and experiments.

9870-3, Session 1

Compressive spectral imaging using multiple snapshot colored-mosaic detector measurements

Carlos A. Hinojosa, Univ. Industrial de Santander (Colombia); Claudia V. Correa, Univ. of Delaware (United States); Henry Arguello Fuentes, Univ. Industrial de Santander (Colombia); Gonzalo R. Arce, Univ. of Delaware (United States)

Compressive spectral imaging (CSI) captures coded and dispersed projections of the spatio-spectral source rather than direct measurements of the voxels. Using the coded projections, an ℓ_1 minimization reconstruction algorithm is then used to reconstruct the underlying scene. An architecture known as the snapshot colored compressive spectral imager (SCCSI) exploits the compression capabilities of CSI techniques and efficiently senses a spectral image using a single snapshot by means of a colored mosaic FPA detector and a dispersive element. In CSI, different coding patterns are used for acquiring multiple snapshots, yielding

improved reconstructions of spatially detailed and spectrally rich scenes. SCCSI however, does not admit multiple coding patterns since the pixelated tiling of optical filters is directly attached to the detector. This paper extends the concept of SCCSI to a system admitting multiple measurement shots by rotating the dispersive element such that the dispersed spatio-spectral source is coded and integrated at different detector pixels on each rotation. This approach allows the acquisition of a different set of coded projections on each measurement shot. Simulations show that increasing the number of measurement snapshots results on improved reconstructions. More specifically, a gain up to 7 dB is obtained when results from four measurement shots are compared to the reconstruction from a single SCCSI snapshot.

9870-4, Session 1

Broadband multimode fiber spectrometer

Seng Fatt Liew, Brandon Redding, Hemant Tagare, Hui Cao, Yale Univ. (United States)

Spectrometers are widely used tools in chemical and biological sensing, material analysis, and light source characterization. The traditional spectrometers rely on a grating or prism to disperse light and provide one-to-one spectral to spatial mapping. Recently we developed a new type of spectrometer that relies on complex spectral-to-spatial mapping. For example, the speckle pattern produced by a multimode fiber is used as a fingerprint of input wavelength. After calibrating the distinct speckle patterns at different wavelengths, we can reconstruct an arbitrary spectrum of a probe signal after recording the speckle pattern it generates. The multimode fiber spectrometer is compact, lightweight, and low cost while providing ultrahigh resolution and low loss, it is difficult to recover extremely broadband spectrum due to reduced speckle contrast. However, many practical applications such as the spectral domain optical coherence tomography requires a single-shot measurement of a broadband spectrum with fine spectral resolution.

To solve this problem, we have used a wavelength division multiplexer to increase the spectral bandwidth of the fiber spectrometer while maintaining the fine spectral resolution. This approach enables a simultaneous reconstruction of over 1000 independent spectral channels. In addition, we have developed an effective reconstruction algorithm that is robust against noise. It can rapidly recover diversified spectra, e.g., continuous broadband, multiple discrete lines, and both, thus greatly enhancing the performance of the fiber spectrometer.

9870-5, Session 2

Hurdles in the implementation of compressive sensing for imaging and ways to overcome them (*Invited Paper*)

Adrian Stern, Ben-Gurion Univ. of the Negev (Israel)

The theory of compressive sensing (CS) has opened up new opportunities in the field of imaging. However, its implementation in this field is often not straight-forward and the optical imaging system engineer encounters several hurdles on the way of compressive imaging (CI) realization. The principles of CI design may differ drastically from the principles used for conventional imaging. Analytical tools developed for conventional imaging, may not be optimal for compressive imaging. Nor are the conventional imaging components. Therefore often the CI designer needs to develop new tools, and imaging schemes. In this paper we enumerate the main challenges that might arise in the design of compressive imaging systems. We draw some possible solutions and discuss the merit of their realization, which may depend on the imaging task and conditions, and on the working spectral regime.

9870-6, Session 2

Independent component analysis for improving the quality InSAR products

Arlinda Saqellari-Likoka, National Technical Univ. of Athens (Greece); Eleni Vafeiadi-Billa, Univ. of Piraeus (Greece); Vassilia Karathanassi, National Technical Univ. of Athens (Greece)

One powerful technique for generating Digital Elevation Models (DEM) is the interferometric synthetic aperture radar technique. However, the accuracy of such DEMs is affected by the temporal decorrelation of the SAR images which includes atmosphere, land use/cover, soil moisture and texture changes. Elimination of the temporal decorrelation of the master and slave images leads to higher accuracy DEMs. In this study the Independent Component Analysis (ICA) has been applied before the interferometric process. In signal theory, ICA is mainly used for separating mixed signals into their sources, which are unknown and represent the information searched. It aims at the linear representation of non-gaussian data so that the components are statistically independent, or as independent as possible. ICA components of remotely sensed images depend on the initial images. For example for images acquired on different dates, the components from ICA transformation represent background image and changed image respectively. This study explores this separation for improving the accuracy of the InSAR DEMs. It employs the ICA method on the SAR images to analyze the mixed values of the master and slave images into independent non-Gaussian signals. Experiments showed that three images including the master and three images including the slave are enough for the ICA method produces the optimum results. Except the master and slave images, the other ICA entries should be the same. Interpretation of the independent signals enables the selection of the appropriate components which will be used for the interferometric process. The proposed approach is validated using real data.

9870-7, Session 2

Scalable information-optimal compressive target recognition

Ronan Kerviche, Amit Ashok, College of Optical Sciences, The Univ. of Arizona (United States)

Recognizing target(s) embedded in scenes with complex background is of vital interest in EO/IR security/surveillance. Traditional EO/IR target recognition techniques employ sophisticated image exploration algorithms operating on high-fidelity images of the scene. Given the task-specific and compressible nature of relevant information in a scene, several compressive sensing techniques have been explored in the literature, such as smashed filter based on random projections and structured projections such as the SECANT design. However, these compressive sensing inspired techniques do not scale with the dimensionality of the scene (e.g. FoV), both in terms of compressive imaging implementation and measurement design. We present a scalable information theoretic approach to compressive measurement design that employs the Cauchy-Schwartz divergence measure to design compressive measurements. Our target/class conditional scene prior employs dense mixtures of Gaussians (MoG) to capture the relevant underlying scene statistics. Using an analytic, computationally tractable expression of the gradient of our information theoretic design metric we can design photon efficient compressive measurements that incorporate the fixed photon count measurement constraint. Our optimized compressive imaging system design outperforms existing compressive designs, such as random and SECANT projections, and is capable of recognizing targets with a probability approaching 90% at a measurement signal-to-noise-ratio (SNR) of 20dB, gracefully degrading to 85% for SNR of 10dB at a compression ratio of 20x. We validate these simulation system performance results with experimental data acquired from a scalable optical compressive imaging testbed.

9870-8, Session 2

Parallel computing for simultaneous iterative tomographic imaging by graphics processing units

Yuanwei Jin, Univ. of Maryland Eastern Shore (United States); Pedro Bello-Maldonado, Univ. of Illinois (United States); Ricardo Lopez, Univ. of Puerto Rico (United States); Colleen Rogers, Enyue Lu, Salisbury Univ. (United States)

Computational imaging methods such as tomography for reconstructing material properties in a spatial domain by electromagnetic waves or ultrasonic waves have wide applications in medical imaging, non-destructive testing, and seismic explorations. Mathematically, full wave based tomographic imaging can be formulated as a nonlinear inverse problem, often requiring extensive computations due to increased sophistication of the inversion algorithms, desired high resolutions, and significant amount of data to be processed. Therefore, the computational complexity of tomographic imaging algorithms limit their applicability in real world applications. To address this challenge, research in developing parallel computing strategies and algorithms has drawn renewed attention in order to exploit the underlying parallel computation mechanism of the imaging algorithms to accelerate image reconstruction process on low-cost commercially accessible computing hardware. Graphics processing units (GPUs) have emerged as a competitive platform for computing massively parallel problems.

In this paper, we address the problem of accelerating inversion algorithms for nonlinear acoustic tomographic imaging by parallel computing on GPUs. Nonlinear inversion algorithms often rely on iterative algorithms, thus computationally intensive. In this paper, we demonstrate accelerated inversion algorithms by the Simultaneous Iterative Reconstruction Technique (SIRT) on low cost programmable GPUs. Classic SIRT algorithm has a large memory footprint and slow convergence. We develop a weighted SIRT algorithm and scalable implementation strategies to overcome memory constraints of GPUs, and a novel adaptive weighting method that utilizes non-uniform weights and iterative relaxation to accelerate convergence. We evaluate the performance of our algorithms by the NVIDIA Compute Unified Device Architecture (CUDA) programming model on GeForce GPUs and demonstrate a significant speedup in image reconstruction compared with classic iterative algorithms.

9870-9, Session 3

An optimized transport of intensity solution for imaged phase objects (*Invited Paper*)

Partha Banerjee, Mahmudunnabi Basunia, Univ. of Dayton (United States); Ting-Chung Poon, Hongbo Zhang, Virginia Polytechnic Institute and State Univ. (United States)

The transport of intensity equation (TIE) is often used to determine the phase and amplitude profile of a complex object by monitoring the intensities at different distances of propagation or around the image plane. TIE results from the imaginary part of the paraxial wave equation and is equivalent to the conservation of energy. The real part of the paraxial wave equation gives the eikonal equation in the presence of diffraction. Since propagation of the optical field between different planes is governed by the (paraxial) wave equation, both real and imaginary parts need to be satisfied at every propagation plane. In this work, we optimize the solution of the TIE by using the real part of the paraxial wave equation as a constraint. The technique is applied to the more exact determination of the imaged induced phase of a liquid heated by a focused laser beam, which has been previously computed using TIE only.

9870-10, Session 3

Digital holographic phase imaging of particles embedded in microscopic structures in three dimensions

Jun Yong Park, Univ. at Albany (United States); Habben Desta, Maxwell C Maloney, Univ at Albany (United States); Anna Sharikova, Alexander T. Khmaladze, Univ. at Albany (United States)

We present a three-dimensional microscopic technique based on digital holographic microscopic imaging, which allows highly accurate axial localization of features inside of a three dimensional sample. When a light wave is propagating through, or reflecting from, a microscopic object, the phase changes can be converted into the intensity variations, by using the existing digital microscopic techniques. The phase change indicates the change in the optical path length, which can be then converted to physical thickness, providing the sample height information. This property of holograms offers a phase-contrast techniques, which can then be used for quantitative 3D imaging. However, if the sample contains features with different indices of refraction, this method can only provide the overall optical thickness and cannot determine where in the axial direction the particular feature is located. As a result, the application of DHM to imaging of organelles within live cells or defects within semiconductor substrates is limited to overall morphology the sample. To determine the axial location of features inside of a three dimensional sample, we developed a phase image processing method based on analyzing images taken from non-zero incident angles. When compared, these images can discriminate between various axial depths of features, while still retaining the information about the overall thickness profile of the sample.

9870-11, Session 3

Improved transport of intensity phase imaging using Bessel sources

Jonathan C. Petrucci, Tonmoy Chakraborty, Univ. at Albany (United States)

Propagation-based phase imaging is of interest because it allows quantitative reconstruction of phase with images captured using only defocus. For extremely short defocus distances, a linear equation known as the transport of intensity equation (TIE) holds between measured intensity and phase, allowing deterministic phase retrieval. For weakly attenuating objects, the TIE allows near-real-time phase reconstruction from a single defocused intensity image by computationally applying an inverse Laplacian operator to the measured intensity.

A major limitation to rapid phase imaging with the TIE is that low spatial frequency phase features refract light weakly, and therefore have poor SNR in reconstructions. This can be mitigated somewhat by using additional defocused planes or sophisticated regularization techniques at the cost of slower image acquisition and processing. We propose a method to improve the performance of TIE imaging by modulating partially coherent illumination to an optimal pattern for reconstruction.

Partially coherent illumination causes blurring of the image captured in a defocused plane by convolution with a scaled source spot. We use the fact that the application of a regularized “inverse Laplacian” to solve the TIE has a closely matched form to convolution with a source having an intensity profile of a modified Bessel function of the 2nd kind of zero order. A source patterned to approximate this Bessel function “solves” the TIE optically over a range of spatial frequencies: the defocused intensity is proportional to the sample’s phase. For samples with features outside of that range, Bessel spots improve noise performance at low spatial frequencies.

9870-12, Session 4

Designing application-specific optical gratings for computational diffractive sensing and imaging (Invited Paper)

David G. Stork, Rambus Inc. (United States); Luke Pfister, Univ. of Illinois at Urbana-Champaign (United States); Mehjabin Monjur, Northwestern Univ. (United States); Patrick R. Gill, Rambus Inc. (United States)

In computational lensless diffractive imaging the light from the scene passes through special diffraction gratings and forms complicated, apparently chaotic patterns of light on the photodetector array. The resulting two-dimensional sensor signals are then processed by Tikhonov regularization, Fourier-domain deconvolution, or other method in order to produce the final digital image. For such simple imaging the grating must produce sensor signals that retain as much of the spatial information in the scene as possible given Poisson photon noise, sensor read noise, and sensor Nyquist rate. For application-specific sensing (bar-code reading, face presence detection, point tracking, visual flow estimation, ...), however, the grating should be designed to optimally extract only the visual features relevant to the sensing task and, if possible, simplify and reduce the cost of associated digital computation. The design constraints on such application-specific gratings involve the wave physics of light, the physical properties of diffraction grating materials, and limitations on manufacturability, and the non-negativity of sensor signals; many of these constraints differ from those often found in application-specific compressive sensing. This talk will present methods and heuristics for solving the non-convex problem of designing such gratings as well as several classes of application-specific gratings and associated signal-processing algorithms appropriate to a range of feature-extraction, classification, and sensing tasks. The talk will conclude with some initial, tentative steps toward a general design framework, digital optical basis functions for representations, and end-to-end merit functions for this class of computational diffractive sensors.

9870-13, Session 4

Optimal LED illuminator design for Fourier ptychographic microscopy

Gautam Gunjala, Zachary F. Phillips, Laura Waller, Univ. of California, Berkeley (United States)

Computational illumination enables entirely new imaging capabilities in a traditional microscope, achieved by replacing standard illumination with a programmable array of LEDs. These LEDs can be selectively patterned in multiple ways, to achieve both conventional microscopy methods, such as brightfield and darkfield imaging, as well as new methods including differential phase contrast (DPC) and Fourier Ptychography, which achieves resolution well beyond the diffraction limit of the objective used. The original LED array microscopes used planar LED arrays, which are simple to purchase or fabricate, but limit the usable illumination NA and do not provide sufficient uniformity of intensity across the field of view, due to vignetting. In this paper, we discuss the design of an optimal curved LED array for computational illumination. We consider the conditions under which our image reconstruction algorithms are well-posed and translate these conditions into design constraints which determine both the surface profile of the illuminator and the distribution of light sources on it. Given these constraints, we develop several algorithms for finding suitable configurations of LEDs and assess their optimality. We consider a naive approach of constrained charged-particle distribution, a procedure that implements biased Poisson disc sampling, and finally, an algorithm that applies the Marching Triangles algorithm in the context of our problem. Using the point source locations specified by these algorithms, we discuss the implications on the image acquisition and reconstruction processes. We then evaluate a constructed realization of our optimal illuminator and demonstrate its results.

9870-14, Session 4

High resolution image reconstruction from projection of low resolution images differing in sub-pixel shifts

Manohar Mareboyana, Bowie State Univ. (United States);
Jacqueline Le Moigne, Jerome Bennett, NASA Goddard Space Flight Ctr. (United States)

In this paper, we demonstrate that a simple algorithm that projects low resolution images differing in subpixel shifts on a high resolution grid to reconstruct the high resolution image is very effective in accuracy as well as time efficiency. A number of spatial interpolation techniques such as nearest neighbor, distance-weighted averages, etc., are used in projection yield comparable results. In this algorithm, for best accuracy of reconstructing high resolution image by a factor of two requires four low resolution images differing in four independent subpixel shifts. The algorithm has two steps: i) registration of low resolution images and (ii) shifting the low resolution images to align with reference image and projecting them on high resolution grid based on the shifts of each low resolution image using different interpolation techniques. Experiments are conducted by simulating low resolution images by subpixel shifts and subsampling of original high resolution image and the reconstructing the high resolution images from the simulated low resolution images. The results of accuracy of reconstruction are compared by using mean squared error measure between original high resolution image and reconstructed image. The algorithm was tested on remote sensing images and found to outperform previously proposed techniques such as Iterative Back Projection algorithm (IBP), Maximum Likelihood (ML), and Maximum a posteriori (MAP) algorithms. The algorithm is robust and is not overly sensitive to the registration inaccuracies.

9870-15, Session 4

Evaluation of the durability of 3D printed keys produced by computational processing of image data

Jeremy Straub, Scott Kerlin, Univ. of North Dakota (United States)

The use of visible light and other sensing approaches to capture images of keys and turn them into a replica key presents a security challenge. Possession of a working 3D printed key can, for most practical purposes, convince observers (who might notice another technique such as lock picking) that an illicit attempt to gain premises access is authorized. Prior work has demonstrated that the generation of such keys is possible; however, their efficacy for use has not been fully evaluated. This paper seeks to determine three things. First, it characterizes the durability of a 3D printed key for repeated use. This use is evaluated under both delicate-handling and typical use scenarios. Second, it evaluates the efficacy of using a 3D printed key to produce a metal key using conventional key duplication methods. A key produced in this way would be nearly undiscernible from an authorized copy or original. Third, it evaluates whether the software processing and model design process affects the usability of a 3D printed key, its durability (under both delicate and non-delicate handling) and the ability to produce a metal key from it.

Based on this analysis, the threat posed by long-term possession of a 3D printed key or its metal derivative is characterized. This threat is considered in the context of other prospective facility security considerations and compared to the threat posed by alternate techniques a would-be unauthorized entrant could attempt to secure illicit access, before the paper concludes with a discussion of techniques for possible protection.

9870-16, Session 5

Stochastic approaches for computational sensing (Invited Paper)

Aristide Dogariu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Non-stationary properties of excitation fields can be purposely manipulated to assist in recovering information about distant targets. We will present different sensing approaches for characterizing static and dynamic targets and will discuss their robustness against various sources of perturbations.

9870-17, Session 5

Amplitude and phase recovery from motion blur deconvolution

Zachary F. Phillips, Michael Chen, Univ. of California, Berkeley (United States); Chenguang Ma, Tsinghua Univ. (China); Lei Tian, Laura Waller, Univ. of California, Berkeley (United States)

Recent advances in using LED array illuminators for transmission microscopy have shown the versatility of a programmable illumination source for multi-contrast and super-resolution imaging. Previous work considered spatial coding of the illumination for angular patterning at the sample. Here, we demonstrate a new approach for patterning LED illumination in both space and time, in order to capture both phase and amplitude images at high speeds for moving samples. We use temporal modulation of the LEDs and spatial coding of colors in order to induce structure in the motion blur, which can then be inverted to deblur the image digitally. The temporal coding uses grayscale modulation of the LED brightness during the exposure time of a single frame, implemented with a dimmable, three-channel LED array. The sample is in constant motion, being raster scanned quickly across a large field-of-view using a commercial XY stage. We exploit the color channels of our LED array and a Bayer-patterned color camera to multiplex our illumination pattern spatially in color, enabling the recovery of both amplitude and quantitative phase of our sample using differential phase-contrast (DPC) methods from a single frame. Our motion deblur algorithm uses a well-posed deconvolution process due to the use of grayscale LED array illumination. These methods enhance the space-bandwidth product (SBP) per unit time, as compared to conventional slide-scanning systems, because we continuously scan the sample, avoiding stop-and-stare behavior. Further, we add the capability of recovering quantitative phase, which can reduce sample preparation time for transparent biological samples.

9870-18, Session 5

Segmentation and outline detection in underwater video images using particle filters

Edward J. Yoerger, Dimitrios Charalampidis, George Ioup, Juliette Ioup, Univ. of New Orleans (United States)

Recently, we have been concerned with locating and tracking images of fish in underwater videos. While obtaining some advances using Kalman filtering in this effort, a more extensive, non-linear approach appears necessary for improved results. In particular, the use of particle filtering applied to contour detection in natural images has met with some success. Following recent ideas in the literature, we use a recursive Bayesian model which is estimated with a sequential Monte Carlo approach or the Particle Filter. This approach uses the corroboration between 2 scales of an image to produce various local features which characterize the different probability densities required by the particle filter. Since our data consist of video images of fish recorded by a stationary camera, we augment this process by means of background subtraction, fish shape congruence, Canny edge detection, etc. All of the

above capabilities are applied to our data set for the purpose of using contour detection to perform segmentation of the fish images with the aim of eventual species classification. We show results and examples of this analysis and discuss the particle filter application to our data set. Although our data set consists only of fish images, the techniques can be employed in applications involving different kinds of non-stationary underwater objects.

9870-19, Session 6

Quantum performance limits in a few simple problems in passive and active optical imaging (*Invited Paper*)

Saikat Guha, Raytheon BBN Technologies (United States)

The fundamental limits to optical information processing — be it the maximum rate of reliable communication, imaging resolution of an optical sensor or the computational power of an optical computer — are all governed by the laws of quantum mechanics. Most current-day systems, which do not exploit the manifestly quantum effects of light, are limited to performance inferior to these limits. In this talk, I will discuss a few simple problems in both active and passive optical imaging, where exploiting the quantum effects of light — either by using a non-classical optical transmitter, or by employing non-classical optical processing locally at the receiver (or doing both) — can yield improved performance over a classical optical imager that uses the same transmit power and bandwidth. These classical imagers whose performance I will compare to their respective quantum limits, will be allowed to have ideal laser-light transmitters and ideal (shot-noise-limited) receivers. I will discuss the following problems: standoff target detection in the presence of loss and noise, discriminating one from two point targets using an active imager, active range estimation using a pulsed laser transmitter, phase sensing in a low-loss environment, and a passive imaging problem of discriminating between one and two monochromatic point sources in the far field. I will conclude the talk with a summary of our current understanding of the various characteristics of optical imaging problems where quantum improvements can be expected to be had, and the respective natures of such improvements in imaging performance.

9870-20, Session 6

Panoramic high-resolution imaging using spherically-symmetric optics (*Invited Paper*)

Joseph Ford, Univ. of California, San Diego (United States)

Most wide-angle digital cameras use complex lens systems, such as a retro-telephoto “fisheye” lens, and detect the image formed on a single CMOS focal plane. But extremely wide-angle film cameras based on concentric spherical surfaces date back to the 19th century, and such “monocentric” lenses can easily form multi-gigapixel images. The challenge lies in translating the image surface into digital data, because deeply curved spherical image sensors are currently impossible to make. In this talk I will describe the optical design of high performance monocentric lenses, and show how they have been integrated into panoramic cameras in the DARPA “SCENICC” research program. These imagers transfer the optical signal using dense multimode fiber bundles, introducing challenges and opportunities in system integration and image processing. I'll show results from two 25Mpixel current prototypes, both based on a 127° field of view F/1.35 12mm focal length monocentric achromat. The “Letterbox” imager resolves a 124° wide image uses 5 adjacent 5Mpixel focal planes, each coupled via a 2.5µm pitch straight fiber bundle to the shared lens. The second prototype is a 127° square full field of view imager coupled to a single conventional CMOS focal plane by a “3D” waveguide machined from a 3:1 taper 2.9 micron pitch fiber bundle. The internally curved fibers enable wide-field imaging onto a full frame image sensor. Video taken with this imager compares well to a dramatically larger conventional DSLR benchmark camera, and five of these curved fiber bundle imagers will be

integrated into a 125Mpixel/frame, 53 fps 360° video camera intended for cinematic-grade panoramic virtual reality imaging.

9870-21, Session 6

The algorithm stitching for medical imaging

Evgeny A. Semenishchev, South-Russian State Univ. of Economics and Service (Russian Federation)

In this paper is proposed an algorithm stitching medical images into one. The algorithm is designed to stitching the medical x-ray imaging, biological particles in microscopic images, medical microscopic images and other. The united image can improve the accuracy of diagnosis and quality in minimally invasive studies the (for example - laparoscopy, ophthalmology and other). The automatic algorithm is based on the following steps: the search and selection of domains with boundaries in areas of overlap; Finding reference points and their correlation; Changing size; The preliminary stitching images and of transformation to reduce the action of visible distortion; Search single unified borders on general area; Converting the brightness, contrast and white balance; Superimposition into a single image. The images is pre-cleared by the noise. A proper choice of parameters of the introduced algorithm is discussed. A comparative analysis of a algorithm stitching is performed on a set of test images.

9870-22, Session 6

Iterative deconvolution methods for ghost imaging

Wei Wang, Guohai Situ, Shanghai Institute of Optics and Fine Mechanics (China)

Ghost imaging (GI) is a new technique in single-pixel imaging. It has been demonstrated that GI has applications in various areas such as imaging through harsh environments and optical encryption.

Correlation is widely used to reconstruct the object image in GI. But it only offers the signal-to-noise ratios (SNR) of the reconstructed image linearly proportional to the number of measurements. Here, we develop a kind of iterative deconvolution methods for GI. With the known image transmission matrix in GI, the first one uses an iterative algorithm to decrease the error between the reconstructed image and the ground-truth image. Ideally, the error converges to a minimum for Gaussian speckle patterns when the number of measurements is larger than the number of resolution cells. The second technique, Gerchberg-Saxton (GS) like GI, takes the advantage of the integral property of the Fourier transform, and treats the captured data as constraints for image reconstruction. According to this property, we can regard the data recorded by the bucket detector as the Fourier transform of the object image evaluated at the origin ($k = 0$). Each of the speckle patterns randomly select certain spectral components of the object and shift them to the origin in the Fourier space. One can use these constraints to reconstruct the image with the GS algorithm. This deconvolution method is suitable for any single pixel imaging models. Compared to conventional GI, both techniques offer a nonlinear growth of the SNR value with respect to the number of measurements.

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9871-1, Session 1

Deconstructing and constructing innate immune functions using molecular sensors and actuators (*Invited Paper*)

Takanari Inoue, Johns Hopkins Univ. (United States)

In multicellular organisms, cells undergo proliferation and differentiation into specialized cell types which are then able to exhibit complex specialized behaviors such as phagocytosis and chemotaxis. All of these processes are tightly regulated by complex webs of signaling that have proved difficult to disentangle. Recently, we put forth new concepts and tools to both break down and reconstitute these complex cellular behaviors. In the seminar, I will discuss with our recent findings of minimal signaling events to make normally inert cells chemotax and phagocytose using chemical biology techniques combined with fluorescence imaging and microfluidics device. Our synthetic cell biology approach could make major contributions to future studies of these issues, including potential clinical applications.

9871-2, Session 1

Remote heartbeat signal detection from visible spectrum recordings based on blind deconvolution

Balvinder Kaur, Sophia Moses, Megha Luthra, Vasiliki N. Ikonomidou, George Mason Univ. (United States)

While recent advances have shown that it is possible to acquire a signal equivalent to the heartbeat from visual spectrum video recordings of the human skin, extracting the heartbeat's exact timing information from it, for the purpose of heart rate variability analysis, remains a challenge. In this paper, we explore two novel methods to estimate remote cardiac signal peak positions, aiming at a close representation of the R-peaks of the ECG signal. The first method is based on curve fitting (CF) using a modified filtered least mean square (LMS) optimization and the second method is based on system estimation using blind deconvolution (BDC). To prove the efficacy of the developed algorithms, we compared results obtained with the ground truth (ECG) signal. Both methods achieved a low relative error between the peaks of the two signals. This work, performed under an IRB approved protocol, provides initial proof that blind deconvolution techniques can be used to estimate timing information of the cardiac signal closely related to the one obtained by traditional ECG. The results show promise for further development of a remote sensing of cardiac signals for the purpose of remote vital sign and stress detection for medical, security, military and civilian applications.

9871-3, Session 1

Robustness of remote stress detection from visible spectrum recordings

Balvinder Kaur, Sophia Moses, Megha Luthra, Vasiliki N. Ikonomidou, George Mason Univ. (United States)

In our recent work, we have shown that it is possible to extract high fidelity timing information of the cardiac pulse wave from visible spectrum videos, which can then be used as a basis for stress detection. In that approach, we used both heart rate variability (HRV) metrics and the differential pulse

transit time (dPTT) as indicators of the presence of stress. One of the main concerns in this analysis is its robustness in the presence of noise, as the remotely acquired signal that we call blood wave (BW) signal is degraded with respect to the signal acquired using contact sensors. In this work, we discuss the robustness of our metrics in the presence of multiplicative noise. Specifically, we study the effects of subtle motion due to respiration and changes in illumination levels due to light flickering on the BW signal, the HRV-driven features, and the dPTT. Our sensitivity study involved both Monte Carlo simulations and experimental data from human facial videos and indicates that our metrics are robust even under moderate amounts of noise. Generated results will help the remote stress detection community with developing requirements for visual spectrum based stress detection systems.

9871-4, Session 1

Custom instruction for NIOS processor FFT implementation for image processing

Sindhuja Sundararajana, Uwe Meyer-Bäse, Florida State Univ. (United States); Guillermo Botella, Univ. Complutense de Madrid (Spain)

Image processing can be considered as signal processing in two dimensions (2D). Filtering is one of the basic image processing operation. Filtering in frequency domain is computationally faster when compared to the corresponding spatial domain operation as the complex convolution process is modified as multiplication in frequency domain. The popular 2D transforms used in image processing are Fast Fourier Transform (FFT), Discrete Cosine Transform (DCT) and Discrete Wavelet Transform (DWT). The common values for resolution of an image are 640x480, 800x600, 1024x768 and 1280x1024. As it can be seen, the image formats are generally not a power of 2. So power of 2 FFT lengths are not required and these cannot be built using shorter Discrete Fourier Transform (DFT) blocks. Split radix based FFT algorithms like Good-Thomas FFT algorithm simplifies the implementation logic required for such applications and hence can be implemented in low area and power consumption and also meet the timing constraints thereby operating at high frequency. The Good-Thomas FFT algorithm provides the means of computing DFT with least number of multiplication and addition operations. We will be providing an Altera FPGA based NIOS II custom instruction implementation of Good-Thomas FFT algorithm to improve the system performance and also provide the comparison when the same algorithm is completely implemented in software.

9871-5, Session 1

Real-time fetal ECG system design using embedded microprocessors

Uwe Meyer-Bäse, Florida State Univ. (United States); Harikrishna Muddu, Sebastian Schinhaerl, Florida State Univ (United States); Martin Kumm, Peter Zipf, Univ. Kassel (Germany)

The emphasis of this project lies in the development and evaluation of new robust and high fidelity fetal electrocardiogram (FECG) systems to determine the fetal heart rate (FHR). Recently several powerful algorithms have been suggested to improve the FECG fidelity. Until now it is unknown if these algorithms allow a real-time processing, can be used in mobile

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systems (low power), and which algorithm produces the best error rate for a given system configuration. In this work we have developed high performance, low power microprocessor-based biomedical systems that allows a fair comparison of proposed, state-of-the-art FECG algorithms. We will evaluate different soft-core microprocessors and compare these solutions to other commercial off-the-shelf (COTS) hardware solution in terms of price, size, power, speed, and fidelity.

9871-6, Session 1

Predicting healthcare associated infections using patients' experiences

Michael A. Pratt, Henry Chu, Univ. of Louisiana at Lafayette (United States)

Healthcare Associated Infections (HAI) is one of the leading causes of illnesses and deaths in the U.S.

As the name suggests, an infection is classified as healthcare associated if the patient is considered to not have it prior to entering a healthcare facility for treatment of some other problem.

The U.S. Center for Disease Control and Prevention tracks HAI data for blood stream infections, catheter-associated urinary tract infections, surgical site infections from certain procedures, and intestinal infections.

Prediction of HAI levels at a particular hospital can help to raise the awareness to lower the HAI risk.

To facilitate fair comparisons between hospitals, we use the Standardized Infection Ratio (SIR), where the national benchmark is set at 1.0. Our interest is in predicting for each hospital whether its SIR is above the national benchmark (vs no different from or worse than the benchmark) or whether its SIR is worse than the national benchmark.

We use as features the survey results of patients' experiences, developed by the Centers for Medicare and Medicaid Services and the Agency for Healthcare Research Quality. We use results for six composite topics, two individual topics, and two global topics. Preliminary results show that we were successful in using a Support Vector Machine to predict HAI with 82% accuracy.

9871-7, Session 2

Acoustic angiography: a new high frequency contrast ultrasound technique for biomedical imaging (Invited Paper)

Paul Dayton, Sarah Shelton, Brooks Lindsey, The Univ. of North Carolina at Chapel Hill (United States); Ryan Gessner, SonoVol, Inc. (United States); Yueh Lee, The Univ. of North Carolina at Chapel Hill (United States); Stephen Aylward, Kitware, Inc. (United States); Hyunggyun Lee, Emmanuel Cherin, F. Stuart Foster, Sunnybrook Health Sciences Ctr. (Canada)

Contrast enhanced ultrasound imaging performs poorly at high frequencies. This is partially due to the poor nonlinear response of microbubble contrast agents when excited with frequencies far above their resonance (<10 MHz) and challenges with pulse customization using high frequency transducers. However, it has been known for over a decade that when excited near resonance, microbubbles can produce an extremely broadband acoustic response that can exceed even 45 MHz. The challenge to taking advantage of this broadband response is that commercial ultrasound transducers do not have a bandwidth that can excite contrast agents near resonance and receive higher order (ie 3-5) harmonics. Thus, our team has been developing and evaluating multi-frequency transducers to take advantage of this broadband bubble response. Imaging with dual-frequency transducers designed to capture higher order harmonics from oscillating microbubbles at 15-45 MHz has since demonstrated the capability for very high resolution

imaging with very effective tissue suppression due to non-overlapping tissue echoes and receive bandwidths. The resulting images resemble x-ray angiography, leading us to refer to this technique as "acoustic angiography". Data shows that acoustic angiography can provide important information about the presence of disease based on vascular patterns, and may enable a new paradigm in medical imaging.

9871-8, Session 2

Medical image reconstruction algorithm based on the geometric information between sensor detector and ROI

Woonchul Ham, Kangsan Lee, Chonbuk National Univ. (Korea, Republic of); Seungkuk Roh, Chulgyu Song, Chonbuk National Univ (Korea, Republic of)

In this paper, we propose an algorithm to improve the quality of image by considering the geometric parameters between sensor detector and ROI and the size and shape of the sensor detector. At first, we use the conventional image reconstruction algorithm to obtain above mentioned parameters. Next, we manipulate the sensor signal based on the geometric information and then apply the conventional image reconstruction algorithm again by using synthesized sensor signal. We demonstrate the efficacy of the proposed algorithm by using k-wave Matlab tool box.

We also briefly discuss the software programming skill to make speed up the calculation time for implementing the image reconstruction algorithm by using two GPUs. One is for calculation only, and the other is for rendering the graphics. We use the massive threaded parallel processing method by using more than 1,000,000 threads.

9871-9, Session 2

HEVC optimizations for medical environments

Guillermo Fernandez, Alberto del Barrio, Guillermo Botella, Carlos Garcia, Univ. Complutense de Madrid (Spain); Uwe Meyer-Bäse, Anke Meyer-Baese, Florida State Univ. (United States)

HEVC/H.265 is the most interesting and cutting-edge topic in the world of digital video compression, allowing to reduce by half the required bandwidth in comparison with the previous H.264 standard. Telemedicine services and in general any medical video application can benefit from the video encoding advances. However, the HEVC is computationally expensive to implement. In this paper a method for reducing the HEVC complexity in the medical environment is proposed.

The sequences that are typically processed in this context contain several homogeneous regions. Leveraging these regions, it is possible to simplify the HEVC flow while maintaining a high-level quality. In comparison with the H.264 standard, the encoding time is reduced more than 50% on average, with a negligible quality loss. Moreover, the algorithm is straightforward to implement in any hardware platform.

9871-10, Session 2

Image quality guided multispectral image compression

Yufeng Zheng, Alcorn State Univ. (United States); Genshe Chen, Zhonghai Wang, Intelligent Fusion Technology, Inc. (United States); Erik Blasch, Air Force Research Lab. (United States)

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Image compression is necessary for data transportation, which saves both transferring time and storage space. In this paper, we focus on our discussion on lossy compression. There are many standard image formats and corresponding compression algorithms, for examples, JPEG (DCT – discrete cosine transform), JPEG 2000 (DWT – discrete wavelet transform), BPG (better portable graphics) and TIFF (LZW – Lempel-Ziv-Welch). The image quality (IQ) of decompressed image will be measured by numerical metrics such as root mean square error (RMSE), peak signal-to-noise ratio (PSNR), and structural Similarity (SSIM) Index. Given an image and a specified IQ, we will investigate how to select a compression method and its parameters to achieve the expected compression. Our scenario consists of 3 steps. The first step is to compress a set of interested images by varying parameters and compute their IQs for each compression method. The second step is to create several regression models per compression method after analyzing the IQ-measurement versus compression-parameter from a number of compressed images. The third step is to compress the given image with the specified IQ using the selected compression method (JPEG, JPEG2000, BPG, or TIFF) according to the regressed models. The IQ may be specified by a compression ratio (e.g., 100), then we will select the compression method of the highest IQ (SSIM, or PSNR). Or the IQ may be specified by a metric (e.g., SSIM = 0.8, or PSNR = 50), then we will select the compression method of the highest compression ratio. Our preliminary research showed very promising results. The proposed scenario will be tested with both visible (in colors) and thermal (long-wave infrared) images (in gray scales).

9871-11, Session 2

Early breast cancer detection with digital mammograms using Haar-like features and AdaBoost algorithm

Yufeng Zheng, Alcorn State Univ. (United States); Clifford Yang, Alex Merkulov, Malavika Bandari, Univ. of Connecticut Health Ctr. (United States)

The current computer-aided detection (CAD) methods are not sufficiently accurate in detecting masses, especially in dense breasts and/or small masses (typically at early stage of cancers). A mass may not be visually perceived when it is small and/or homogeneous with surrounding tissues in its initial phase. The possible reasons for the limited performance of existing CAD methods are lack of multiscale analysis and unification of variant masses. The speed of CAD analysis is an important concern for field applications. We propose a new CAD system for early mass detection, which extracts simple Haar-like features for fast detection, uses AdaBoost approach for feature selection and classifier training, applies cascading classifiers for reduction of false positives, and utilizes multiscale detection for variant sizes of masses (typically at different cancerous stages). In addition, we will introduce some perception-based models such as luminance masking and contrast masking to breast cancer detection. Specifically, the image brightness will be suppressed per luminance masking and the tissue texture will be unmixed (using independent component analysis [ICA]) per contrast masking. The performance of a CAD system can be measured with true positive rate (TPR) and false positives per image (FPI). We are collecting our own digital mammograms for the proposed research. The proposed CAD system will be initially demonstrated for early mass detection, and then be extended to the detections of architecture distortions and calcifications.

9871-12, Session 2

Medical image segmentation with deformable models on graphics processing units

Anke Meyer-Baese, Florida State Univ. (United States)

We describe the parallel implementation of segmentation algorithms based on a deformable model on graphics processing unit (GPU) mainly with

application to breast cancer detection. The speed-up in segmentation is significant for both the 2D and 3D applications. We demonstrate how GPUs can facilitate simultaneous visualization and segmentation for different shapes of objects.

9871-13, Session 2

A spectral inversion reconstruction algorithm with applications to magnetic resonance imaging

Alfredo Nava-Tudela, John J. Benedetto, Univ. of Maryland, College Park (United States); Alexander Powell, Vanderbilt Univ. (United States); Yang Wang, Hong Kong Univ. of Science and Technology (China)

We present an algorithm to invert spectral data on the Fourier domain to the time/spatial domain that does not rely on regularly spaced samples in the spectral domain. This reconstruction technique is then applied to the problem of magnetic resonance imaging (MRI). The algorithm quantifies results from Beurling's theory of Fourier frames and the underlying concept of balayage.

9871-14, Session 2

Multispectral image fusion for vehicle identification and threat analysis

Yufeng Zheng, Alcorn State Univ. (United States); Erik Blasch, Air Force Research Lab. (United States)

Unauthorized vehicles become an increasing threat to US facilities and locations especially overseas. Vehicle detection is a well-studied area. However, vehicle identification and intension analysis have not been sufficiently investigated. We propose to use multispectral (visible, thermal) images (1) to match the vehicle types with the registered (or authorized) vehicle types; (2) to analyze the vehicle moving patterns, (3) and study methods to utilize open information such as GPS and traffic information. When a vehicle is either permitted to access to the facility, or subjected to further manual inspection (scrutiny), the additional information (e.g., text) can be compared against the imagery features. We will use information fusion (at image, feature, score level) and neural network to increase vehicle matching accuracy. For the vehicle moving patterns, we will classify them as "normal" and "abnormal" by using driving speed, acceleration, stop, zig-zag, etc. The methods would support directions in physical and human-based sensor fusion, patterns of life (POL) analysis, and contextual-enhanced information fusion.

9871-15, Session 2

Computer-aided diagnosis system in breast MRI

Anke Meyer-Baese, Florida State Univ. (United States)

Non-mass enhancing (NME) lesions exhibit a heterogeneous appearance in breast MRI with high variations in kinetic characteristics and typical morphological parameters, and have a lower reported specificity (69%) and sensitivity (75%) than mass-enhancing lesions. Combinations of morphological and temporal BI-RAD descriptors have proven to be insufficient to aid in the automated differential diagnosis of these lesions in contrast-enhanced magnetic resonance imaging (CE-MRI). Newest clinical studies suggest that T2-weighted image sequences and diffusion-weighted imaging (DWI) with quantitative apparent diffusion coefficient (ADC) mapping may provide additional specificity. To translate these findings into an automated diagnosis system, we propose to develop novel descriptors derived from the multiparametric MRI data that will lead to a substantial improvement in diagnostic accuracy and efficiency.

9871-27, Session 2

What smartphone can help the public health? *(Invited Paper)*

Harold H. Szu, Catholic Univ. of America (United States)

We will explore the electrooptic devices embedded with the ubiquitous Smartphone, in order to improve early screening and tracking efficiency of the public healthcare concerns patients (diabetics II, heart attacks, Strokes and Cancers, and Dementia).. Especially, we wish to address a large population of aging WWII baby boomers, about 87 Millions in the US alone over 70 years old. Each Home Alone Seniors (HAS) have their Smartphone together with their insidious health challenge. They need early novelty detection and warning message and tracking picture record to their caretakers. Using Smartphone, we presented the data detecting the Arrhythmia ECG (heart); the dementia EEG (brain); early breast cancers stage I. Furthermore, we wish to suggest a Smartphone persistent surveillance for home alone seniors (HAS). We need to illuminate subject occasionally with a up-shift the transeiver frequency at L-band 1 GHz to the microwave frequency at 2.49 GHz that can penetrate the skin deep for anomaly. Then the system followed with the Smartphone infrared-filtered camera to track the insidious anomaly based on heat capacity changes. Likewise, such a mounted system on a tripod can avoid the precursor of the midnight crisis resulted in a sudden death of HAS.

9871-16, Session 3

Adaptive neurotechnologies: Principles and promise *(Invited Paper)*

Jonathan R. Wolpaw, National Ctr. for Adaptive Neurotechnologies (United States)

Recent recognition that the central nervous system (CNS) changes continually throughout life, and recent development of high-performance hardware and software, provide unprecedented opportunities for real-time adaptive interactions with the CNS that yield new scientific insights and novel diagnostic and therapeutic methods. Adaptive neurotechnologies are systems, protocols, and devices that support these interactions.

We have built a technological infrastructure that supports such adaptive interactions and are using it to create, explore, and exploit three major kinds of interactions:

(1) Operant conditioning of simple spinal cord reflexes ? The simplest spinal reflex pathways can be modified through operant conditioning; and appropriate modifications can improve walking in animals and humans with spinal cord injuries. This work opens a new approach to neurorehabilitation called "targeted neuroplasticity."

(2) Translation of scalp-recorded electroencephalographic (EEG) activity into communication and control outputs ? People can learn to use EEG features to communicate, and even to

control movements in multiple dimensions. A brain-computer interface (BCI) system designed for home use can restore basic communication capacity to people with severe

disabilities. BCIs may also enhance rehabilitation after strokes and in other disorders.

(3) Mapping of and interactions with distributed cortical functions using electrocorticographic (ECoG) activity recorded from the cortical surface ? Analysis methods that take advantage of the high spatiotemporal resolution of ECoG signals provide a new functional mapping system that is a safer and more efficient alternative to stimulation-based mapping prior to brain surgery. ECoG analysis can also elucidate the complex cortical processing underlying sensorimotor functions.

As these examples illustrate, adaptive neurotechnologies can produce new scientific insights, and they can also induce and guide plasticity so as to restore functions impaired by trauma or disease.

9871-17, Session 3

Artificial Neural Networks (ANNS) versus Partial Least Squares (PLS) for spectral interference correction for taking part of the lab to the sample types of applications: an experimental study

Z. Li, University of Waterloo (Canada); Vassili Karanassios, Univ. of Waterloo (Canada)

Spectral overlaps resulting in interference effects are a key problem in analytical atomic spectrometry. To address this problem, medium to high resolution is used for in-the-lab applications. But for taking part of the lab to the sample applications, a portable, small-size spectrometer is required. Smaller size often means more important interference effects. A way of dealing with spectral overlaps is to use Artificial Neural Networks (ANNS). Another way is to use statistical methods such as Partial Least Squares (PLS). In this presentation, these methods will be compared using actual experimental scans and additional parameters and wavelengths over those reported previously.

9871-18, Session 3

Selection of principal components based on Fisher discriminant ratio

Xiangyan Zeng, Masoud Naghedolfeizi, Sanjeev Arora, Nabil? Yousif, Dawit Abera, Fort Valley State Univ. (United States)

Principal component analysis (PCA) transforms a set of possibly correlated variables into uncorrelated variables, and the variance contained in the output data is concentrated in a relatively small number of principal components (variables). It is widely used as a technique of dimension reduction and feature extraction. In dimension reduction, the objective is to use a small number of principal components to represent most variation in the data. The basic idea is to select the components that have large eigenvalues. Different methods of determining the number of principal components have been developed based on minimizing the reconstruction errors. On the other hand, the main purpose of feature extraction is to facilitate pattern recognition and machine learning tasks, such as classification. A small number of uncorrelated features yield better classification performance. Selecting principal components for classification tasks aims for more than dimension reduction. The capability of distinguishing different classes is another major concern. Components that have larger eigenvalues do not necessarily have better distinguishing capabilities.

In this paper, we investigate a strategy of selecting principal components based on the Fisher discriminant ratio. The ratio of between class variance to within class variance is calculated for each component, based on which the principal components are selected. The number of relevant components is determined by the classification accuracy. To alleviate over-fitting which is common when the number of training data is small, we use a cross-validation procedure to select the principal components. Cross-validation has been used for determining the number of principal components in applications, such as data mining. In those cases, however, minimizing the reconstruction errors is the goal. The main objective in this paper is to select the components that have large Fisher discriminant ratios so that adequate class separability is obtained. The leave-one-out cross-validation approach is used. For a set of N training data, in each iteration of cross-validation, PCA is performed on N-1 data and the left-out data is used as validation data. The number of selected components is determined by the classification accuracy of the validation data. The selection method is evaluated by face recognition experiments.

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9871-19, Session 3

Convergence rates of finite difference stochastic approximation algorithms part I: independent sampling

Liyi Dai, U.S. Army Research Office (United States)

Stochastic optimization is a fundamental problem that finds applications in many areas including biological and cognitive sciences. The classical stochastic approximation algorithm for iterative stochastic optimization requires gradient information of the sample object function that is typically difficult to obtain in practice. Recently there has been renewed interests in derivative free approaches to stochastic optimization. In this paper, we examine the rates of convergence for the Kiefer-Wolfowitz algorithm and the mirror descent algorithm, under various updating schemes using finite differences as gradient approximations. The analysis is carried out under a general framework covering a wide range of updating scenarios. It is shown that the convergence of these algorithms can be accelerated by controlling the implementation of the finite differences.

9871-20, Session 3

Convergence rates of finite difference stochastic approximation algorithms part II: implementation via common random numbers

Liyi Dai, U.S. Army Research Office (United States)

Stochastic optimization is a fundamental problem that finds applications in many areas including biological and cognitive sciences. The classical stochastic approximation algorithm for iterative stochastic optimization requires gradient information of the sample object function that is typically difficult to obtain in practice. Recently there has been renewed interests in derivative free approaches to stochastic optimization. In this paper, we examine the rates of convergence for the Kiefer-Wolfowitz algorithm and the mirror descent algorithm, by approximating gradient using finite differences generated through common random numbers. The analysis is carried out under a general framework covering a wide range of updating scenarios. It is shown that the convergence of these algorithms can be accelerated by controlling the implementation of the finite differences. Particularly, it is shown that the rate can be increased to $n^{-2/5}$ in general and to $n^{-1/2}$, the best possible rate of stochastic approximation, in Monte Carlo optimization for a broad class of problems, in the iteration number n .

9871-21, Session 3

Pre-trained D-CNN models for detecting complex events in unconstrained videos

Joseph P. Robinson, Yun Fu, Northeastern Univ. (United States)

Rapid event detection faces an emergent need to process large videos collections; whether surveillance videos or unconstrained Web videos, the ability to automatically recognize high-level, complex events is a challenging task. Inspired by preexisting methods being complex, computationally demanding, and nearly non-replicable, we designed a simple system that is quick, effective, and carries minimal overhead in terms of memory and storage. Most importantly, our system is clearly described, module in nature, replicable on any Desktop, and demonstrated with extensive experimentation, backed by insightful analysis on several Convolutional Neural Networks (convnets), as stand-alone and fused with others. Using a large corpus of unconstrained, real-world video data, we investigated different pre-trained convnets to detect high-level events each differing in architectures, differing in training data, and differing in the number of outputs. For each convnets, we used 1-fps from all training exemplar to train

one-vs-rest SVMs for each event. To represent videos, frame-level features were fused using a variety of techniques. The best being to max-pool between predetermined shot boundaries, then average-pool to form the final video-level descriptor. Through extensive analysis, several insights were found on using pre-trained convnets as off-the-shelf feature extractors for the task of event detection. Fusing SVMs of different convnets revealed some interesting facts, finding some combinations to be complimentary. It was concluded that no single convnet works best for all events, as some events are more object-driven while others are more scene-based. Our top performance resulted from learning event-dependent weights for different convnets.

9871-22, Session 3

Independent component analysis decomposition of hospital emergency department throughput measures

Qiang He, Mississippi Valley State Univ. (United States); Henry Chu, Univ. of Louisiana at Lafayette (United States)

We present a method adapted from medical sensor data analysis, viz. independent component analysis of electroencephalography data, to health system analysis. Timely and effective care in a hospital emergency department is assessed by throughput measures such as median times patients spent before they were admitted as an inpatient, before they were sent home, before they were seen by a healthcare professional, etc. We consider a set of five such measures collected at 3,086 hospitals distributed across the U.S. One model of the performance of an emergency department is that these correlated throughput measures are linear combinations of some underlying sources. The independent component analysis decomposition of the data set can thus be viewed as transforming a set of performance measures collected at a site to a collection of outputs of spatial filters applied to the whole multi-measure data. The independent component filters produce the maximally spatially independent measure values available in the collected data. We compare the independent component sources with the output of the conventional principal component analysis.

9871-23, Session 3

Radon transform imaging: low-cost video compressive imaging at extreme resolutions

Mohit Gupta, Univ. of Wisconsin-Madison (United States); Jian Wang, Aswin Sankaranarayanan, Carnegie Mellon Univ. (United States)

Most compressive imaging architectures rely on programmable light-modulators to obtain coded linear measurements of a signal. As a consequence, the properties of the light modulator place fundamental limits on the performance and capabilities of the compressive camera. For example, the spatial resolution of the single pixel camera is limited to that of its light modulator, which is seldom greater than 2 megapixels. In this paper, we describe a novel approach to compressive imaging that avoids the use of spatial light modulator. In its place, we use novel cylindrical optics and a rotation gantry to directly sample the Radon transform of the image focused on the sensor plane. We show that the reconstruction problem is identical to sparse tomographic recovery and we can leverage the vast literature in compressive MRI to good effect.

The proposed design has many important advantages over existing compressive cameras. First, we can achieve a resolution of $N \times N$ pixels using a sensor with N photodetectors; hence, with commercially available SWIR line-detectors with 10k pixels, we can achieve spatial resolutions of 100 megapixels, a capability that is unprecedented. Second, our design is scalable more gracefully across wavebands of light since we only require sensors and optics that are optimized for the wavelengths of interest; in

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contrast, spatial light modulators like DMDs require expensive coatings to be effective in non-visible wavebands. Third, we can exploit properties of line-detectors including electronic shutters and pixels with large aspect ratios to optimize light throughput. On the flip side, a drawback of our approach is the need for mechanical components as part of the imaging architecture; we highlight potential solutions to alleviate this.

9871-28, Session 3

Role of diversity in ICA and IVA: theory and applications (*Invited Paper*)

Tülay Adalı, Univ. of Maryland, Baltimore County (United States)

Independent component analysis (ICA) has been the most popular approach for solving the blind source separation problem. Starting from a simple linear mixing model and the assumption of statistical independence, ICA can recover a set of linearly-mixed sources to within a scaling and permutation ambiguity. It has been successfully applied to numerous data analysis problems in areas as diverse as biomedicine, communications, finance, geophysics, and remote sensing.

ICA can be achieved using different types of diversity—statistical property—and as demonstrated in this talk, can be posed to simultaneously account for multiple types of diversity such as higher-order-statistics, sample dependence, non-circularity, and nonstationarity. A recent generalization of ICA, independent vector analysis (IVA), generalizes ICA to multiple data sets and adds the use of one more type of diversity, statistical dependence across the data sets, for jointly achieving independent decomposition of multiple data sets. With the addition of each new diversity type, identification of a broader class of signals become possible, and in the case of IVA, this includes sources that are independent and identically distributed Gaussians.

This talk reviews the fundamentals and properties of ICA and IVA when multiple types of diversity are taken into account, and then asks the question whether diversity plays an important role in practical applications as well. Examples from various domains are presented to argue that in many scenarios it might be worthwhile to jointly account for multiple statistical properties.

9871-24, Session 4

Emerging applications of liquid metals featuring nanoscale surface oxides (*Invited Paper*)

Michael D. Dickey, North Carolina State Univ. (United States)

This talk will discuss work in our group to pattern and actuate liquid metals for stretchable, reconfigurable, and soft electronics. The metal is an alloy of gallium. These alloys are noted for their low viscosity, low toxicity, and negligible volatility. Despite the large surface tension of the metal, it can be molded into non-spherical 2D and 3D shapes due to the presence of an ultra-thin (~3 nm thick) oxide skin that forms on its surface. The metal can be patterned by injection into microchannels or by direct-write techniques. Because it is a liquid, the metal is extremely soft and flows in response to stress to retain electrical continuity under extreme deformation. By embedding the metal into elastomeric substrates, it is possible to form soft electrodes and optical components, stretchable antennas, and ultra-stretchable wires that maintain metallic conductivity up to ~800% strain. The ability of the oxide to reform instantaneously also allows the metal to self-heal in response to damage. In addition, the ability to remove the oxide electrochemically provides a new means to control the shape of the metal for reconfigurable and transient electronics. We show that the oxide is one of the best surfactants ever reported and can tune the surface tension of the metal over an unprecedented range by using electrochemical reactions at the surface of the metal. In addition, nanoparticles of the metal can be

utilized as nanomedicine and to create soft circuit boards that can be drawn by hand.

9871-25, Session 4

Analysis of geographical variations of healthcare providers performance using the empirical mode decomposition

Michael A. Pratt, Henry Chu, Univ. of Louisiana at Lafayette (United States)

Performance of healthcare providers such as hospitals varies from one locale to another. Our goal is to study whether there is a geographical pattern of performance using metrics reported from over 3,000 hospitals distributed across the U.S.

Empirical mode decomposition (EMD) is an effective analysis tool for nonlinear and non-stationary signals. It decomposes a data sequence into a series of intrinsic mode functions (IMFs) along with a residue sequence that represents the trend. Each IMF has zero local mean and has exactly one zero crossing between any two consecutive local extrema. An IMF can be used to assess the instantaneous frequency. Reconstruction of a signal using the residue and those IMFs of the lower frequency can reveal the underlying pattern of the signal without undue influence of the higher frequency fluctuations of the data.

We used a space-filling curve to turn a set of performance metrics distributed irregularly across the two-dimensional planet surface into a one-dimensional sequence. The EMD decomposed a set of hospital emergency department median waiting times into 9 IMFs along with a residue. We used the residue and the lower frequency IMFs to reconstruct a sequence with fewer fluctuations.

The sequence was transformed back to a two-dimensional map to reveal the geographical variations.

9871-26, Session 4

Proteomic data analysis of Gliom stem-like cells

Anke Meyer-Baese, Florida State Univ. (United States)

Glioma stem-like cells (GSCs) are known to be radio- and chemo-resistant and self-duplicate. The analysis of proteomic data plays an important role in therapeutic solutions. A collection of 35 GSC lines at the protein level is analyzed based on label-free quantitative proteomics. Several unsupervised clustering algorithms are used to classify these cell lines based on proteomic profiles. The results identify the most relevant molecules for treatment of gliomas.

9871-29, Session 4

Smartphone system design for earthquake nowcast

Jerry Wu, The George Washington Univ. (United States); Harold H. Szu, U.S. Army RDECOM CERDEC NVESD (United States)

Smartphones and mobile devices, widespread in use, can form a distributed computing network and function as an Earthquake Now-cast System (ENS). Our goal is to utilize the existing built-in sensors of commercial Smartphones or mobile devices as a network to detect an earthquake. In addition, the detected information from volunteer devices are gathered and sent to a central analysis server that estimates from a minimal set of received ground-motion parameters, when an earthquake has occurred. The customized earthquake Now-cast could be transmitted back to users and

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subscribers through our Earthquake Now-cast System. We found that the speed of an electronic warning travels faster than the earthquake shaking does.

system to quickly and reliably identify the precursors that precede every earthquake. When a precursor is detected and is expected to be followed by a major earthquake, the sensor system will analyze and determine the magnitude of the earthquake. This newly proposed 3D MEMS sensor can provide P-waves, S-waves, and surface waves along with timing measurements to a data processing unit. The out coming date is processed and filtered continuously in order to remove noise and other disturbances and determine an earthquake pattern. Our goal is to reliably initiate an alarm before the arrival of the destructive waves.

9871-30, Session 4

Smartphone big data analysis

Hong Yu, Capitol Tech Univ. (United States); Harold H. Szu, The Catholic Univ. of America (United States)

Smartphone augmented with IMU sensor can generate billion byte vector time series Earthquake data easily. The worst is that each phone has its own intrinsic vibration, noise and provide imprecise origin of Earthquakes without sync. We design local cellular tower Natural Intelligence Associative Memory signal processing from thousands vector times series matrix memory for all the mobile phone users. The consistent data will be piece wisely sent from a tower to another to USGS data center where fusion with USGS local seismic stations and integration further with NASA satellite gravity data. The novelty detection will Now-cast the early warning of the imminent Earthquake.

9871-31, Session 4

Smart sensing surveillance video system

Charles C. Hsu, Trident Systems Inc. (United States); Harold H. Szu, The Catholic Univ. of America (United States)

Unattended ground sensors (UGS) network has been widely used in remote battlefield, tactical, and civilian applications including border surveillance, special force operations, airfield protection, perimeter and building protection, etc. The UGS network would be more effective if equipped with visual understanding capabilities to detect, analyze, and recognize objects, track motions, and predict intentions. In this paper, a highly-distributed, fault-tolerant, and energy-efficient Semantic Mesh of Intelligence Sensors (SMIS) System is presented to efficiently provide 24/7 and all-weather security operations in a situation management environment. The SMIS nodes with EO/IR cameras can provide applicable advanced on-board digital image processing capabilities to detect and track the specific objects. The imaging detection operations include unattended object detection, human feature and behavior detection, and configurable alert triggers, etc. In the SMIS system, all the nodes are connected with a robust, reconfigurable, LPI/LPD (Low Probability of Intercept/ Low Probability of Detect) wireless mesh network. This SMIS network can provide an ad-hoc, Advanced Encryption Standard (AES) encryption mesh network and capability to relay network information, communicate and pass situational awareness and messages. In addition, the SMIS creates Service Oriented Architecture such that remote applications can interact with the SMIS network and use the specific presentation methods. The SMIS capabilities and technologies have great potential for both military and civilian applications, enabling highly effective security support tools for improving surveillance activities in densely crowded environments. It would be directly applicable to solutions for emergency response personnel, law enforcement, and other homeland security missions, as well as in applications requiring the interoperation of sensor networks with handheld or body-worn interface devices.

9871-32, Session 4

MEMS 3D sensor for application on earthquakes early detection

Jerry Wu, The George Washington Univ. (United States); Harold H. Szu, The Catholic Univ. of America (United States)

This paper presents a 3D Microelectromechanical systems (MEMS) sensor

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9872-15, Session PWed

Modeling of systems wireless data transmission based on antenna arrays in underwater acoustic channels

Valentin Fedosov, Anna Lomakina, Andrey Legin, Southern Federal Univ. (Russian Federation); Viacheslav V. Voronin, Don State Technical Univ. (Russian Federation)

Due to the growing popularity of wireless technologies to them increased requirements for increasing bandwidth and reducing the likelihood of errors in the transmitted message. The article presents adaptive algorithm for wireless data communication for underwater acoustic channel. The purpose of this article is to find methods and algorithms for solving the problem of increasing capacity and maintenance of wireless speaker channel in a multipath propagation, using technologies such as MIMO and OFDM. MIMO technology is used for underwater acoustic communications recently to increase the data rate for channels with bandwidth - limited. In this article we will discuss methods of implementing the acoustic communication channel based on the spatio-temporal signals where spatial multiplexing by using technology OFDM. The efficiency of adaptive algorithm used with the technology of MIMO-OFDM is analyzed. Bit error probability for various system configurations MIMO-OFDM was calculated. The results indicate that for high throughput using high-frequency signals, it is necessary to increase the number of items of receiving and transmitting antenna array. Examined dependences prove the effectiveness of the developed adaptive algorithm. Its application decreases the probability of erroneous reception and therefore increases the channel capacity. This is due to orientation of the transmitting and receiving antenna arrays along the path of the signal with highest power, thereby reducing the influence of noise on the signal. Thus the effectiveness of the reception is increased through the usage of spatial filtering under complex conditions of electro-magnetic wave propagation in underwater acoustic channel.

9872-16, Session PWed

Development of thunderstorm monitoring technologies and algorithms by integration of radar, sensors and satellite images

Aida Adzhieva, Kabardino-Balkarian State Agricultural Univ. (Russian Federation); Vitaliy Shapovalov, High-Mountain Geophysical Institute (Russian Federation)

In the context of rising of natural disasters and catastrophes frequency it is necessary to develop methods and tools to ensure safe living conditions. The effectiveness of preventive measures are greatly depended on the quality and lead time of the natural phenomena forecast, which is based on the amount of knowledge about natural hazards, their causes, manifestations, and impact. To prevent natural disasters it is necessary to have the complete and comprehensive information of the spread and severity of natural processes that can act within the defined territory. For these purposes the automated workplace of mining, analysis and archiving of radar, satellite, thunderstorm and terrestrial (automatic weather station) weather information was made.

The combination and aggregation of data from different sources of meteorological data provide the growing of system informativeness. The

satellite data represent the global cloud region in the visible and infrared ranges, but have an uncertainty in terms of weather events and the large time interval between the two periods of measurements, which complicates the usage of this information for very short range forecasts of weather phenomena. Thunderstorm and radar data provide the detection of weather phenomena and their localization on the background of the global pattern of cloudiness in the region and have a low measurement period of rapid processes such as hail, thunderstorms, rainfall, squalls, tornadoes. The improved algorithms for recognition of dangerous weather phenomena based on the complex analysis of the incoming physical information using the mathematical apparatus of image sensing were developed.

9872-1, Session 1

Towards the exploitation of formal methods for information fusion

Joachim Clemens, Robert Wille, Kerstin Schill, Univ. Bremen (Germany)

When (autonomous) systems have to act in or interact with an environment, a suitable representation of it is required. In the past decades, many different representation forms – especially spacial ones – have been proposed and even more information fusion techniques were developed in order to build these representations from multiple information sources. However, most of these algorithms do not exploit the full potential of the available information. This is caused by the fact that they are not able to handle the full complexity of all possible solutions compatible with the information and that they rely on restrictive assumptions (i.e. independencies) in order to make the computation feasible. In this work, a new methodology is proposed that utilizes formal methods, in particular solvers for Pseudo-Boolean Optimization, to drop some of these assumptions. In order to illustrate the ideas, information fusion based on belief functions and occupancy grid maps are considered. It is shown that this approach allows for considering dependencies among multiple cells and thus significantly reduces the uncertainty in the resulting representation.

9872-2, Session 1

Semantic segmentation of multispectral overhead imagery

Lakshman Prasad, Kari Sentz, Paul A. Pope, Los Alamos National Lab. (United States)

Land cover classification uses multispectral pixel information to separate image regions into categories. Image segmentation seeks to separate image regions into objects and features based on spectral and spatial image properties. However, making sense of complex imagery typically requires identifying image regions that are often a heterogeneous mixture of categories and features that constitute functional semantic units such as industrial, residential, or commercial areas. This requires leveraging both spectral classification and feature extraction synergistically to synthesize such complex but meaningful image units.

We present a graphical model for extracting such semantically cohesive regions. We employ an initial hierarchical segmentation of images into features represented as nodes of an attributed graph that represents feature properties as well as their contextual interactions with other features. This provides a machine-learning framework to group spectrally and structurally

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diverse features, which are nevertheless semantically cohesive, based on user-driven identifications of features and their contextual relationships in the graph. We present graphical machine-learning algorithms that utilize intrinsic properties, such as color, shape, and scale of segmented features as well as extrinsic properties such as neighborhood interactions with other features in terms of subgraphs and hierarchical memberships to both disambiguate feature identity and qualify feature category based on context. User interaction with and labeling of initially segmented and categorized image feature graph will be used to learn feature (node) and regional (subgraph) ontologies and to identify other similar semantic units. The variability among semantically similar units is modeled in terms of probabilities on vertices and edges.

9872-3, Session 1

Optimal Rotation Sequences for Active Perception

David Nakath, Carsten Rachuy, Joachim Clemens, Univ. Bremen (Germany); Kerstin Schill, University of Bremen (Germany)

One major objective of autonomous systems navigating in dynamic environments is gathering information needed for self localization, decision making, and path planning. To account for this, systems are usually equipped with multiple types of sensors.

As these sensors often have a limited field of view and a fixed orientation, the task of active perception breaks down to the problem of calculating alignment sequences which maximize the information gain regarding both required and expected measurements. Action sequences then have to be generated that rotate the system according to the calculated optimal rotation patterns.

In this paper we present an approach for calculating these sequences for an autonomous system equipped with multiple sensors.

We use a particle filter for multi-sensor fusion and state estimation. The planning task is modeled as a Markov decision process (MDP), where the system decides in each step, what actions to perform next. The optimal control policy, which provides the best action depending on the current estimated state, maximizes the expected cumulative reward. This is computed from the expected information gain of all sensors over time using value iteration. The algorithm is applied to a manifold representation of the joint space of rotation and time.

We show the performance of the approach in a spacecraft navigation scenario where the information gain is changing over time, caused by the dynamic environment and the continuous movement of the spacecraft. Rotation is independent from translation. In an outlook we discuss the applicability to more general cases including rotatable sensors.

9872-4, Session 1

The USGS requirements, capabilities and analysis for earth observations project

Greg Snyder, Peter J. Doucette, Zhuoting Wu, Bruce Quirk, Gregory L. Stensaas, Carolyn Vadhais, U.S. Geological Survey (United States)

The United States Geological Survey (USGS) Land Remote Sensing (LRS) Program is partnering with Federal agencies to document the uses of and requirements for Earth observation data, and develop an analytical infrastructure to map these requirements to a range of Earth observing systems that can support applications that require single or multi-sensor fusion solutions. This paper will describe the LRS Requirements Analysis and Capabilities for Earth Observations (RCA-EO) project components and uses. Uses include the ability to simultaneously evaluate the actual or expected performance of remote sensing capabilities and products, from land to space, to address science and operational applications in hazards,

natural resource, climate, and land use change. Also discussed will be the RCA-EO information infrastructure, being jointly developed by the USGS and the National Oceanic and Atmospheric Administration, and supporting the President's Office of Science and Technology Policy, Earth Observation Assessment 2016. Sample RCA-EO analysis outputs will be shown in the decision-making context of their use by LRS to more effectively manage and evolve its products and services to meet user needs. The future of RCA-EO is also expected to play a role in the design of future Landsat missions, and other potential sensor developments for key applications in the civil community.

9872-5, Session 2

Visualization to support identification, exploitation and fusion of data and information delivered from heterogeneous sources in intelligence, surveillance and reconnaissance

Kavyashree Jamboti, Ralf Eck, Gunther Grasmann, Daniel Haferkorn, Achim Kuwertz, Florian van de Camp, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

In ISR (Intelligence, Surveillance and Reconnaissance), heterogeneous sources deliver data and information having spatial and temporal relations. Real time and non-real time data created for various purposes, present in different formats has to be exploited and fused. The Coalition Shared Database (CSD) concept makes the interoperable sharing of ISR data and information possible. The concept itself and a technical approach for it were developed within the multinational projects CAESAR, MAJIC and MAJIC 2 and tested in coalition exercises. The interfaces of software systems providing access to CSD data must allow the user to intuitively use the system and form a substantial part with regard to user acceptance. We present different systems and approaches designed and developed to access CSD data that can locate and present the data to the user based on his specific demands. Visualization forms an important part of these systems which share the common challenge of representing data and information with spatial and temporal attributes. The visualization of data and information has to be designed in a manner that it supports efficient access, discovery and optionally, additional processing (such as filtering and sorting). Given the large amount of data and information that may be available, visualization taking into account their quality and inherent uncertainty is an additional challenge. This publication provides an overview of the described approaches and systems with a specific focus on new research results regarding visualization of data and information with temporal and spatial relations.

9872-6, Session 2

PASES: Combining radar and video sensing for improved pedestrian safety

David B. Chenault, Richard Edmondson, Jonathan B. Hanks, Polaris Sensor Technologies, Inc. (United States)

Polaris Sensor Technologies reports on the development of Pedestrian Automated System for Enforcement and Safety (PASES), a radar and video based system used to monitor vehicle and pedestrian traffic with the intent of improving pedestrian safety. Data is fused from a system of multiple sensors and multiple sensor modalities to identify vehicular violations of pedestrian right of way. A focus was placed on the selection of low cost COTS sensors to make the system more widely available to state and local DOTs with limited budgets. Applications include automated enforcement, adaptive traffic control, and improved intersection and crosswalk design based on high quality data available for traffic engineering. We discuss early results with high fidelity sensors, and the performance trades made in

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order to make the system affordable. A discussion of the system processing architecture is included which highlights the treatment of each sensor data type, and the means of combining the processed data products into state information related to traffic incidents involving vehicles and pedestrians.

9872-7, Session 2

Progress in using collaborative brain computer interfaces to improve target detection

Kyongsik Yun, Adrian Stoica, Jet Propulsion Lab. (United States)

Combining the information from brain signals (EEG) of multiple subjects observing images with targets and non-targets results in improved target detection accuracy compared to that of a single subject.

We used an EEG dataset by Delorme et al. 2003. In his reported experiment and dataset the EEGs were recorded with 32-channel Neuroscan device (Cz referenced, 1,000Hz sampling frequency) while the 14 subjects (7 females, 7 males) performed go/no-go categorization task on natural photos presented for a short duration (20ms) – for a total of 25 trials, each series consists of 50 target images (animal) and 50 non-target images (non-animal) – subjects were given 1,000ms to respond. The stimulus onset asynchrony was 2,000ms plus or minus a random delay of 200ms.

First, the two evoked responses between the target (animal) and distractor images were compared -the task was to make a “go” response with the target images. P300 response was significantly higher in the target images than in the distractor images (FDR multiple comparisons correction <0.05). Second, we calculated and compared the classification accuracy using one, two, and three EEG signals. We applied linear support vector machine with 5-fold cross validation. Overall accuracy of three brains prediction (89.3%) and two brains prediction (88.7%) were higher than one brain prediction (79.4%). These results show promise for building collaborative BCI systems that combine the power of multiple brains in providing faster and more accurate target detection.

9872-8, Session 3

On the development of interferometric SAR signal processing algorithms for terrestrial biomass estimation

Tracee L. Jamison, Rafael F. Rincon, NASA Goddard Space Flight Ctr. (United States)

Terrestrial biomass, which is the woody mass per unit area, ecosystem structure including height and density, need to be quantified on a global scale and with meaningful frequency to account for changes from both natural and human-induced disturbances (Fatoyinbo et al, 2012). High sampling rates are necessary to meet bandwidth requirements for the instrument to operate in a high resolution science mode with resolution up to 0.75 meters (up to 200 MHz). This requires custom FPGA-based DSP receiver core designs. This paper discusses the concept and hardware implementation of the SAR Signal Processing techniques for Terrestrial Biomass Estimation using a model-based Simulink design approach. This SAR algorithm utilizes an FPGA-based architecture to implement digital in-phase and quadrature (I/Q) demodulation, beamforming, and range and azimuth compression.

9872-9, Session 3

Evaluation of the use of laser scanning to create key models for 3D printing separate from and augmenting visible light sensing

Jeremy Straub, Scott Kerlin, Univ. of North Dakota (United States)

The illicit creation of 3D printed keys is problematic as it can allow a would-be intruder nearly undetectable access to a secure facility. Keys produced in this way lack a mechanism to allow their creation to be tracked back to a particular key holder, thus making it difficult to determine who conducted a breach (absent other relevant information). Prior work has discussed how keys can be created using visible light sensing, from afar. This paper builds on this prior work relating to the creation of replica keys using visible light by evaluating the comparative utility of keys produced with visible light imaging only, laser scanning and the combination of both visible light imaging and laser scanning.

Specifically, the quality of the model produced using a structured laser scanning approach is compared to the quality of a model produced using a similarly robust (fixed camera, positioned key) visible light sensing approach. These models are compared in terms of the utility of the key, as measured by its ability to open the corresponding lock.

The paper then considers the effect of multiple types of obfuscating treatments and techniques on the three (optical, laser scanning, and combined optical / laser scanning) approaches. The use of multi-mode obfuscation is also considered. Also discussed is the comparative ease of the three approaches. The paper concludes with a discussion of the future of keyed locks, the security of multi-mode facility access mechanism and the role of keys as a prospective component in a multi-mode system.

9872-10, Session 3

In-drilling alignment scheme for borehole assembly trajectory tracking over a wireless ad hoc network

Emmanuel Odei-Lartey, Univ. Siegen (Germany); Klaus Hartmann, Zess Univ. Siegen (Germany)

In this in-drilling alignment scheme, by virtue of mechanical limitations, communication network architecture and telemetry framework constraints, the rotary optical encoder is physically located at the well head above ground always and provides the reference angular position measurement update. At periodic intervals, reference measurement information from the external rotary optical encoder is made available to update or reset the yaw angle error on each node. This is done sequentially until the final measurement update in the sensor node is done. Each node has an integrated IMU and runs the navigation machination algorithm and an extended kalman filter (EKF)-based signal processing for estimating or keeping track of the yaw angle during the drilling process. The top node obtains the reference yaw angle measurement update information from the rotary optical encoder. It then makes an optimal prediction of the attitude angles at each time step during the data outage period until the next transmission window. At that point, it transmits its current optimal yaw angle prediction to the next node as reference measurement update information. During this transmission, its time-stamp and angular velocity are also sent to enable for measurement update adjustments to be made at the receiving node. This process repeats sequentially over all connected nodes until the final update is made at the main sensor node. This process and measurement model enables for accurate tracking of the yaw angle of the main sensor unit mounted on the outer surface of the inner tube of the lowest drill tube, just above the drill monitor and at a fixed radial distance from the reference center position.

9872-11, Session 3

Health state awareness of helicopter blades using an artificial neural network strategy

Andrew Lee, Univ. of Maryland, Baltimore County (United States); Ed Habtour, U.S. Army Research Lab. (United States); Stephen A. Gadsden, Univ. of Maryland, Baltimore County (United States)

Structural health prognostics and diagnosis strategies can be classified as either model or signal-based. Artificial neural network strategies are popular signal-based techniques. In this paper, helicopter blades are utilized to study the sensitivity of artificial neural network to structural fatigue. The experimental setup consists of a scale aluminum helicopter blade exposed to transverse vibratory excitation at the hub using a single axis electrodynamic shaker. The intent of this study is to optimize an algorithm for processing high-dimensional data while retaining important information content in an effort to select input features and weights, as well as health parameters, for training a neural network. Data from accelerometers and piezoelectric transducers is collected from a known system designated as healthy. Structural damage will be introduced to different blades, which they will be designated as unhealthy. A variety of different tests will be performed to track the evolution and severity of the damage. A number of damage detection and diagnosis strategies will be implemented. Future work will look at utilizing the detection information as part of a hierarchical control system in order to mitigate structural damage and fatigue. The proposed approach may eliminate massive data storage on board of an aircraft through retaining relevant information only. The control system can then employ the relevant information to intelligently reconfigure adaptive maneuvers to avoid harmful regimes, thus, extending the life of the aircraft.

9872-12, Session 4

Progress in building a cognitive vision system

D. Paul Benjamin, Pace Univ (United States); Hong Yue, Pace Univ. (United States)

We are building a cognitive vision system for mobile robots that works in a manner similar to the human vision system, using saccadic, vergence and pursuit movements to extract information from visual input. At each fixation, the system builds a 3D model of a small region, combining information about distance, shape, texture and motion to create a local dynamic spatial model. These local 3D models are composed to create an overall 3D model of the robot and its environment. This approach turns the computer vision problem into a search problem whose goal is the acquisition of sufficient spatial understanding for the robot to succeed at its tasks.

The research hypothesis of this work is that the movements of the robot's cameras are only those that are necessary to build a sufficiently accurate world model for the robot's current goals. For example, if the goal is to navigate through a room, the model needs to contain any obstacles that would be encountered, giving their approximate positions and sizes. Other information does not need to be rendered into the virtual world, so this approach trades model accuracy for speed.

We describe progress over the past year.

9872-13, Session 4

Automating the collection and processing of large stereo image databases for benchmarking visual homing algorithms

Luca Del Signore, Fordham Univ. (United States); Damian M. Lyons, Fordham Univ (United States)

Visual Homing is a robot navigation method, inspired by the behavior of insects returning to a visually learned location (e.g., a nest), that compares an image of a goal location with a current image and calculates the proper vector needed to arrive at the goal location [1]. Homing with Stereovision (HSV) is an enhanced visual homing algorithm developed by Nirmal & Lyons [2] [3] that uses a stereo camera to calculate and fuse depth information with appearance based homing information or greater accuracy. Nirmal & Lyons [2] show, using 200 indoor trials with two Pioneer 3-AT robots, that this approach yields better performance than calculating depth using visual scale information [4]. However, it is difficult to conduct large numbers of physical trials of visual homing due to the physical difficulties of powering the robot for long periods, moving in to many different test locations and measuring the final placements accurately. We here propose an approach for and initial results from a system for collecting and storing large stereo image databases to be used for extensive testing of visual homing algorithms in simulation.

In the proposed approach, stereo imagery is collected for a test site at each node on a regular grid of nodes and is annotated with the location of the node. The resolution of the grid is a parameter to the collection process. At each node, a set of visual and disparity images are stored, each pair annotated with the orientation of the camera at which the stereo image was taken. The number of image pairs is also a parameter to the process. The entire data set for a test site can then be used to quickly and effectively run homing simulations.

Data collection is automated as follows. A grid resolution and origin is decided upon. The robot is manually position at the origin and collects the dataset for the first node. An IR LED is manually positioned to point at the robot collinear with the first grid row. A second IR LED is manually positioned to point at the robot collinear with the first grid column. Once data has been collected at a node, the row and/or column LED is manually moved to the next row and/or column. The robot then moves to occupy a position centered on both LEDs at which point it collects the data for the next node. This approach minimizes the amount of manual work necessary for data collection while maintaining good grid position accuracy.

To run a homing simulation, the visual homing algorithm is modified as follows. Any position of the robot p is modeled as a 2D location on the test site grid $p = (i, j)$. When the robot moves to a new location p' , its position is modelled as the closest grid location to p' . When the algorithm requests a stereo image at any location p , instead of querying the stereocamera for the image, the algorithm looks up the dataset for grid location p . It then selects the stereo imagery that was taken at the orientation closest to the current robot orientation and processes this as if it came from the camera. This allows the visual homing algorithm to move between the nodes on the grid until the homing termination criterion is met.

Initial results are presented here for indoor and outdoor datasets. The benefit of this approach is that it facilitates easy extensive testing. The initial testing of HSV consisted of 200 physical trials. Results are presented here for 2000 simulated trials.

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9872-14, Session 4

Mobile robot and mobile manipulator research towards ASTM F45 developments

Roger V. Bostelman, Tsai H. Hong, National Institute of Standards and Technology (United States); Steven Legowik, Robotic Research, LLC (United States)

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United States and European safety standards have evolved to protect workers near Automatic Guided Vehicles (AGV's). However, performance standards for AGV's and mobile robots have only recently begun development. Similarly, safety and performance of these industrial vehicles with onboard equipment, such as robot arms, are beginning to evolve. ASTM F45 Driverless Automatic Guided Industrial Vehicle standard has been making progress towards, first defining AGVs and mobile robots, among many other terms, in a terminology working document that is near the ballot stage. For example, the terms 'AGV' and 'mobile robot' are being replaced by 'Automatic, Automated, and Autonomous-unmanned ground vehicle (A-UGV)', describing levels of autonomy for these vehicles.

Some test methods being developed at the National Institute of Standards and Technology (NIST) are in navigation and docking, including both vehicle and vehicle with onboard equipment docking. Navigation test methods for defined areas, such as within barriers or along pedestrian paths, are now being considered, developed, and reduced to practice. Performance measurements demonstrated that a need for vehicle users and manufacturers to understand the extent of vehicle divergence from planned paths and that test methods should be developed that are inexpensive and easily replicated for their use. Similarly, NIST is developing test methods for vehicle docking with facility equipment. An apparatus was developed that can test performance of any vehicle type and for measuring performance of vehicles with onboard robot arms, typically called mobile manipulators. The paper will detail both vehicle and vehicle with onboard equipment performance measurement research and results.

Conference 9873: Quantum Information and Computation IX

Wednesday - Thursday 20–21 April 2016

Part of Proceedings of SPIE Vol. 9873 Quantum Information and Computation IX

9873-1, Session 1

Spontaneous parametric down conversion with a depleted pump as an analogue for black hole evaporation/particle production

Paul M. Alsing, Michael L. Fanto, Air Force Research Lab. (United States)

In this work we argue that black hole evaporation/particle production has a very close analogy to the laboratory process of spontaneous parametric down conversion, when the pump is allowed to deplete. We present an analytical formulation of the recent one-shot decoupling model that was numerically analyzed in Bradler and Adami [arXiv:1505.0284]. We compute the resulting “Page Information” curves, which describe the rate at which information escapes from the black hole as it evaporates, for the reduced density matrices for the evaporating black hole internal degrees of freedom, and emitted Hawking radiation pairs entangled across the horizon. This work extends the trilinear Hamiltonian model for black hole evaporation/particle production recently investigated by the first author in *Class. Quant. Grav* 32, 075010 (2015) [arXiv:1408.4491].

9873-2, Session 1

Higher-order spontaneous parametric down-conversion with back-propagating idler using submicron poled KTP waveguide

Mark Bashkansky, Marcel W. Pruessner, Igor Vurgaftman, U.S. Naval Research Lab. (United States); Mijin Kim, John F. Reintjes, Sotera Defense Solutions, Inc. (United States); Philip R. Battle, Tony D. Roberts, AdvR, Inc. (United States)

Spontaneous parametric downconversion (SPDC) using periodically poled nonlinear optical crystals under the quasi-phase-matching (QPM) condition has found wide use in quantum optics. It was demonstrated [1] that using one-dimensional waveguides in crystals results in higher efficiencies and a better coupling to single-mode fibers. Under typical operating conditions, phase matching dictates the bandwidth of the SPDC to be of the order of <1 nm. This occurs because the co-propagating signal and idler photons are entangled, and an increase of the signal wave-vector is compensated by a decrease of the idler wave-vector. Often, it is desirable to obtain a considerably reduced bandwidth, which is possible when the signal and idler are counter-propagating, and the changes in the wave-vector with frequency are additive. The condition for counter-propagating QPM requires domain inversion on the wavelength scale. It is sometimes believed [2] that domain inversion is limited to scales exceeding a few microns. However, it was demonstrated that sub-micron poled inversion regions can be created in bulk crystals [3]. In this work, we show that SPDC with submicron poling is possible in one-dimensional KTP-based waveguides. We compare our experimental results with theoretical predictions.

[1] M. Fiorentino et al., “Spontaneous parametric down-conversion in periodically poled KTP waveguides and bulk crystals”, *Optics Express* 15(12) 7479 (2007).

[2] P. B. Dixon et al., “Spectral engineering by Gaussian phase-matching for quantum photonics”, *Optics Express* 21(5) 5879 (2013).

[3] C. Canalias et al., “Backward quasi-phase-matched second-harmonic generation in submicrometer periodically poled flux-grown KTiOPO₄”, *Appl. Phys. Lett.* 86, 181105 (2005).

9873-3, Session 1

Efficiently heralded silicon ring resonator photon-pair source

Jeffrey A. Steidle, Rochester Institute of Technology (United States); Michael L. Fanto, Christopher C. Tison, Air Force Research Lab. (United States); Zihao Wang, Rochester Institute of Technology (United States); Paul M. Alsing, Air Force Research Lab. (United States); Stefan F. Preble, Rochester Institute of Technology (United States)

Here we present results on a silicon ring resonator photon pair source with a high heralding efficiency. Previous sources suffered from an effective 50% loss because, in order to generate the photons, the pump must be able to couple into the resonator – which is an effective loss channel. However, in practice the pump power can be traded off and as a result the heralding efficiency can be dramatically increased. We found theoretically that the heralding efficiency should increase by a factor of ~ 3.75 with a $10\times$ increase in the required pump power. Here this was demonstrated experimentally by varying the gap between the input waveguide and the ring while maintaining a constant drop port gap. The ring ($R = 18.5\mu\text{m}$, $W = 500\text{nm}$, and $H = 220\text{nm}$) was pumped by a tunable laser ($\sim 1550\text{nm}$). The non-degenerate photons, produced via spontaneous four wave mixing, left the ring and coupled to fiber where they were filtered symmetrically about the pump. Coincidence counts were collected for all possible photon path combinations (through and drop port) and the ratio of drop port coincidences to the sum of the drop port and cross term coincidences (one photon from the drop port and one from the through port) was calculated. With a 350nm pump waveguide gap (2.33 times larger than the drop port gap) we confirmed our theoretical predictions, with an observed $\sim 3.49\times$ improvement in heralding efficiency (94% of correlated photons coupled out of the drop port). These results will enable high performance quantum computing and communication systems.

9873-5, Session 1

Gaussian quadrature inference for continuous-variable quantum key distribution

Laszlo Gyongyosi, Sandor Imre, Budapest Univ. of Technology and Economics (Hungary)

We propose the Gaussian quadrature inference (GQI) method for multicarrier continuous-variable quantum key distribution (CVQKD). A multicarrier CVQKD protocol utilizes Gaussian subcarrier quantum continuous variables (CV) for information transmission. The GQI framework provides a minimal error estimate of the quadratures of the CV quantum states from the discrete, measured noisy subcarrier variables. GQI utilizes the fundamentals of regularization theory and statistical information processing. We characterize GQI for multicarrier CVQKD, and define a method for the statistical modeling and processing of noisy Gaussian subcarrier quadratures. We demonstrate the results through the adaptive multicarrier quadrature division (AMQD) scheme. We define direct GQI (DGQI), and prove that it achieves a theoretical minimal magnitude error. We introduce the terms statistical secret key rate and statistical private classical information, which quantities are derived purely by the statistical functions of GQI. We prove the secret key rate formulas for a multiple access multicarrier CVQKD via the AMQD-MQA (multiuser quadrature allocation) scheme. The GQI and DGQI frameworks can be established in an arbitrary CVQKD protocol and measurement setting, and are implementable

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by standard low-complexity statistical functions, which is particularly convenient for an experimental CVQKD scenario.

9873-6, Session 2

Precise microwave frequency electric field sensing with Rydberg atoms

Daniel T. Stack, The MITRE Corp. (United States); Paul D. Kunz, U.S. Army Research Lab. (United States); David H. Meyer, Univ. of Maryland, College Park (United States) and U.S. Army Research Lab. (United States); Neal E. Solmeyer, U.S. Army Research Lab. (United States)

Atoms form the basis of precise measurement for many quantities (time, acceleration, rotation, magnetic field, etc.). Measurements of microwave frequency electric-fields by traditional methods have limited sensitivity and can be difficult to calibrate properly. Highly-excited (Rydberg) neutral atoms have very large electric-dipole moments and many dipole allowed transitions in the range of 1-500GHz. It is possible to sensitively probe the electric field in this range using the combination of two quantum interference phenomena: electromagnetically induced transparency and the Autler-Townes effect. This technique allows for very sensitive field amplitude, polarization, and subwavelength imaging measurements. These quantities can be extracted by measuring properties of a probe laser beam as it passes through a warm rubidium vapor cell.

Thus far, Rydberg microwave electrometry has relied upon the absorption of the probe laser. We report on our use of polarization rotation, which corresponds to the real part of the susceptibility, for measuring the properties of microwave frequency electric fields. Our simulations show that when a magnetic field is present and directed along the optical propagation direction a polarization rotation signal exists and can be used for microwave electrometry. The central advantage in using the polarization rotation rather than absorption is that common mode laser noise is eliminated leading to a potentially dramatic increase in signal-to-noise ratio.

9873-7, Session 2

Quantum sensing with spatially-engineered beams

Stephen P. Pappas, Daniel T. Stack, The MITRE Corp. (United States); Colin Lualdi, Princeton Univ. (United States); Yaakov S. Weinstein, Gerald N. Gilbert, The MITRE Corp. (United States)

Remote quantum sensing with photonic states has been extensively explored, starting with work by Boto et al. to use NOON states to enhance resolution for lithography. To date, all proposed methods suffer from extreme sensitivity to loss: entangled n-photon states suffer from higher order exponential loss than classical states since all entangled photons must remain unperturbed.

In non-turbulent realistic atmospheres the loss processes consist of direct absorption and diffraction/scattering. The latter consists of Mie and Rayleigh processes. Limited diffraction beams (LDBs) diffract significantly less than conventional beams and reconstruct their shape around scatterers. The structure of Mie scattering hints LDBs might counteract loss, potentially enhancing flux on target.

We report on progress to measure the scattering properties of LDBs containing single and biphoton states (i.e. $|n=2\rangle$ Fock states) in simulated atmosphere. We measure the angular distribution of coherent states scattering off polystyrene microspheres in aqueous suspension and observe that the results are consistent with Mie scattering theory. We also compare the flux through a circular aperture for LDBs to non-LDBs for both weak coherent states and biphotons states. The LDBs are created at the target using a phase-only Spatial Light Modulator, lenses, and polarization optics. The weak coherent states originate from a pulsed laser at 785 nm, and the

biphoton states are generated via spontaneous parametric down-conversion from 400 nm pump light to wavelength degenerate photon pairs at 800 nm.

9873-9, Session 2

Developments in quantum repeaters

Gerald N. Gilbert, The MITRE Corp. (United States)

Quantum repeaters will be needed in order for many suggested applications of quantum information science to become practical technologies of use outside of the laboratory. Quantum repeaters were first proposed many years ago, and a variety of different, prospective implementations have been presented since their initial suggestion. In this talk we present the latest aspects of research in this area being carried out under MITRE's program in quantum information science.

9873-10, Session 2

A proposed optical test for Popper's challenge to quantum mechanics

John F. Reintjes, Sotera Defense Solutions, Inc. (United States); Mark Bashkansky, U.S. Naval Research Lab. (United States)

Popper proposed a test involving the role of observer knowledge in the Copenhagen interpretation of quantum mechanics[1]. Popper's experiment predicted that the spread in momentum of one of two entangled particles from a point source would increase because of knowledge gained about its position as a result of a measurement that localized the position of the second particle even if there was no physical interaction with the first particle. Many authors have concluded that quantum mechanics does not predict the behavior Popper described and therefore his experiment does not provide the test he proposed. We have similarly demonstrated[2] that a published optical realization[3] likewise does not provide the test proposed by Popper. Here we describe an alternative geometry using entangled ghost imaging with signal-idler photon pairs from a spontaneous parametric downconverter that does exhibit the behavior Popper ascribed to quantum mechanics. This system then confronts us with the issues that affect quantum state preparation, entanglement and the results of projective measurements. We provide an explanation of our predicted behavior in terms of the mode properties of the entangled biphoton that do not involve observer knowledge as a causative agent as asserted by Popper.

[1] Popper K. R. "Postscript to the Logic of Scientific Discovery" Totowa, New Jersey: Rowman and Littlefield, 1982

[2] J. Reintjes & Mark Bashkansky (2015): Considerations on an optical test of Popper's experiment, Journal of Modern Optics, DOI: 10.1080/09500340.2015.1063723

[3] Y. Shih and Y-H Kim, Fortschr. Phys 48 (2000) 5-7, 463-471

9873-11, Session 2

Application of a Lyot filter plate in discreet frequency entanglement

Reinhard Erdmann, Advanced Automation Corp. (United States); David Hughes, Air Force Research Lab. (United States)

Non-degenerate frequency entanglement has been reported in a recent experiments based on SFWM in a Fiber [1]. The original observation [2] by L. Mandel entailed post selection from a spectrally broadband state, while later approaches entailed non-unitary projection to the required state. We report on the use of a novel component design [3] based on Lyot filter principles, which overcomes the losses of the prior works, and exhibits no intrinsic loss for any detectable photons. The configuration, requiring only

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two components, apart from source & detectors, can serve dual uses;

- 1) De-multiplex strong classical signals for multi-user network routing
- 2) Exchange the entanglement in entangled photon pairs.

The entangled parameters, photon polarization or discrete frequency, are manifested in measurements made by remotely located users. This makes the system suitable, in principle, for efficient QKD protocols based on frequency entangled photon pairs, when appropriate interferometric monitoring is included. These are significantly more robust to distortion effects in fiber propagation than those based on polarization entanglement.

1. Z. Ou and L. Mandel "Observation of Spatial Quantum Beating with Separated Photodetectors" Phys. Rev. Lett. 61, 54 (1988)
2. A. Zeilinger et al "Discrete Tunable Color Entanglement" Phys Rev Lett, 103, 253601(2009)
3. US Patent 658050509B1, 7400448 Optical Physics Corp (2008); Richard Hutchin, "Hyperspectral Lyot Filter Assembly."

9873-22, Session 2

Programmable multi-node quantum network design and simulation

Venkat Dasari, U.S. Army Research Lab. (United States);
Ronald J. Sadlier, Ryan Prout, Brian Williams, Travis S. Humble, Oak Ridge National Lab. (United States)

A quantum network is realized by devices responsible for encoding and decoding, transmitting and receiving, repeating and routing quantum information. Quantum metadata specifies attributes needed by the network to accommodate specific uses of the quantum channel. This is classical information that moves through the network and characterizing how applications intend to make of the quantum network. Each type of network device may have different metadata requirements, e.g., a router versus a transmitter, but the metadata should be consistent across devices of the same type. In this contribution, we address the inclusion of quantum metadata using the SDN paradigm by showing compatibility with the OpenFlow protocol. We investigate how quantum networks can be built using SDN principles and how the OpenFlow protocol can be extended to account for metadata specific to quantum networks. Because of its programmability and compatibility with management of optical networks, OpenFlow is highly suitable to control the new attributes defining the quantum channels that carry metadata between various quantum devices. We build on this compatibility by designing models of the devices, including hosts and switches, needed to implement a quantum network. We then use numerical simulation alongside explicit classical networking to mimic the behavior of a switched quantum network performing super-dense coding. We implement quantum-classical communication protocols, including metadata exchanges, and we use numerical simulations that include noisy quantum transmissions. We present details of the quantum network simulator as well as the software infrastructure that can be easily extended for use in experimental test beds.

9873-12, Session 3

Do quantum strategies always win?

Colin Benjamin, Namit Anand, National Institute of Science Education and Research (India)

In a seminal paper, Meyer [David Meyer, Phys. Rev. Lett. 82, 1052 (1999)] described the advantages of quantum game theory by looking at the classical penny flip game. A player using a quantum strategy can win against a classical player almost 100% of the time. Here we make a slight modification to the quantum game, with the two players sharing an entangled state to begin with. We then analyze two different scenarios, first in which quantum player makes unitary transformations to his qubit while the classical player uses a pure strategy of either flipping or not flipping the state of his qubit. In this case the quantum player always wins against the

classical player. In the second scenario we have the quantum player making similar unitary transformations while the classical player makes use of a mixed strategy wherein he either flips or not with some probability "p". We show that in the second scenario, 100% win record of a quantum player is drastically reduced and for a particular probability "p" the classical player can even win against the quantum player. This is of possible relevance to the field of quantum computation as we show that in this quantum game of preserving versus destroying entanglement a particular classical algorithm can beat the quantum algorithm.

Reference: Namit Anand and Colin Benjamin, arXiv:1412.7399v3, Quantum information Processing (2015), DOI:10.1007/s11128-015-1105-y

9873-13, Session 3

The effects of number scaling on entangled states in quantum mechanics

Paul Benioff, Argonne National Lab. (United States)

My interest in working towards a coherent theory of mathematics and physics together is based on use of space and time dependent number scaling and of fiber bundles to describe physical and geometric quantities. These uses have their origin in gauge theories. Number scaling is an extension to scalars of the basis choice freedom in vector spaces in gauge theories. Fiber bundles are a useful framework for describing gauge theories.

This talk has two goals. One is to briefly summarize a detailed description of number scaling, and the other is to use fiber bundles to describe entangled states in quantum mechanics. The description of number scaling begins with a discretely well ordered set, S. The additive and multiplicative identity axioms are used to assign natural number values to the elements of S or to subsets of S. The freedom of assignment of the number value "1" to elements of S introduces scaling. This assignment freedom is extended to linearly ordered sets for integers, pairs of integers as rational numbers, convergent sequences of rational numbers as real numbers, and pairs of real numbers as complex numbers.

Using fiber bundles to describe n particle entangled quantum states requires assigning each bundle fiber to an n tuple of space locations. Similarly the description of the number scaling field must be expanded to describe the field as a function of n tuples of space locations. These extensions and their application to multiparticle quantum mechanics will be summarized.

9873-14, Session 3

Braiding with Majorana fermions

Louis H. Kauffman, Univ. of Illinois at Chicago (United States); Samuel J. Lomonaco Jr., Univ. of Maryland, Baltimore County (United States)

The purpose of this talk is to begin with diagrams from quantum processes such that individual diagrams represent unitary transformations, and to discuss how such elements can be interconnected to produce global unitary quantum processes. Many examples are available of idealized devices so interconnected such as discussions of Mach-Zehnder interferometers or Mermin machines, or indeed the ubiquitous circuit diagrams for quantum computers. There are categorical ways to insure the unitarity of such compositions, but many thought experiments go beyond these categorical methods and we shall discuss the success and limitations of such excursions. By working with this analysis we contact many issues in the modeling of quantum processes including finite approximations of Feynman integrals and the role of three dimensional space itself in the organization of quantum processes. We concentrate on specific examples from both graph theoretic and category theoretic formulations in relation to thought experiments involving interference and entanglement.

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9873-15, Session 3

Formal verification of communication protocols using quantized horn clauses

Radhakrishnan Balu, U.S. Army Research Lab. (United States)

We work in the settings of a canonical quantum probability space constructed from a classical probability space of Herbrand interpretations. Quantized Horn clauses are constructed as Hermitian operators on the resulting separable Hilbert space. The Boolean and non-Boolean lattices underlying the quantum logic of Horn clauses are characterized. Several algorithms and communication protocols are described in this language that is Turing-computable and based on constructive logic. Quantum measurements are incorporated in the theorem proving process that will interpret the language constructs. Open issues in the design of a theorem prover are identified.

9873-16, Session 3

Topological quantum computation from the 3-dimensional bordism 2-category

Juan F. Ospina, Univ. EAFIT (Colombia)

A great part of the mathematical foundations of topological quantum computation is given by the theory of modular categories which provides a description of the topological phases of matter such as anyon systems. In the near future the anyonic engineering will provide the anyonic devices from which the topological quantum computers will be constructed. From other side the string anyons are interesting topological phases of matter which can be described using mathematical constructions such as Frobenius algebras and open-closed string topological quantum field theories which are based on cobordism categories. Recently was proposed that is possible to obtain representations of cobordism categories using modular categories. In the present work, the modular categories resulting as representations of the 3-dimensional bordism 2-category are used with the aim to construct a new model of topological quantum computation. Such new model is named "Sanyon Topological Quantum Computation" and it is theoretically performed by evolving non-abelian string- anyons (sanyons) using the Loop Braid Group and the open-closed cobordism category. The output of the computation uniquely depends on how the sanyons have been braided by the Loop Braid Group and operated by the generators of the cobordism category. Small disturbances do not unravel the loop braids and the cobordisms, making the computation resistant to errors and decoherence.

9873-17, Session 3

Mermin's machine and the GHZ paradox

Samuel J. Lomonaco Jr., Univ. of Maryland, Baltimore County (United States); Louis H. Kauffman, Univ. of Illinois at Chicago (United States)

We illustrate the many subtleties involved in the quantum control of distributed quantum systems via Mermin's machine and the Greenberger Horne Zeilinger (GHZ) paradox.

9873-8, Session 4

Quantum hyper-entanglement and angular spectrum decomposition applied to sensors

James F. Smith III, U.S. Naval Research Lab. (United States)

Hyper-entanglement with an emphasis on mode type is used to extend a previously developed atmospheric imaging system. Angular spectrum expansions combined with second quantization formalism permits many different mode types to be considered using a common formalism. Fundamental Gaussian, standard Hermite-Gaussian, standard Laguerre-Gaussian, and Bessel modes are developed. Hyper-entanglement refers to entanglement in more than one degree of freedom, e.g. polarization, energy-time and orbital angular momentum. The system functions at optical or infrared frequencies. Only the signal photon propagates in the atmosphere, the ancilla photon is retained within the detector. This results in loss being essentially classical, giving rise to stronger forms of entanglement. A simple atomic physics based model of the scattering target is developed. This model permits the derivation in closed form of the loss coefficient for photons with a given mode type scattering from the target. Signal loss models for propagation, transmission, detection, and scattering are developed and applied. The probability of detection of photonic orbital angular momentum is considered in terms of random media theory. A model of generation and detection efficiencies for the different degrees of freedom and the implications for signal to noise ratio (SNR), signal to interference ratio, the quantum Cramer-Rao lower bound, the quantum Chernoff bound, the measurement time and the maximum detection range of the system are provided in closed form. Techniques for further enhancing the system's SNR and resolution through adaptive optics are discussed. The formalism permits random noise and entangled or non-entangled sources of interference to be modeled.

9873-18, Session 4

Improving ancilla states for fault tolerant quantum computation

Yaakov S. Weinstein, The MITRE Corp. (United States)

I determine the amount of improvement in output state fidelity after many gates as a function of ancilla state fidelity. Specifically, I simulate gates and syndrome measurements of information encoded into the $[[7,1,3]]$ quantum error correction code and determine the output state fidelity as a function of the accuracy with which Shor states (for syndrome measurements) and magic states (to implement T-gates) are constructed. I also analyze the improvement in fidelity seen after application of a T-gate and the results of applying syndrome measurements only after numerous gates have been implemented. The goal of these simulations is to determine what protocols should be optimized to maximize overall accuracy and how best to utilize resources such as qubits and time.

9873-19, Session 4

Nondestructive measurement of light propagation in optical nanofibers

Fredrik K. Fatemi, U.S. Army Research Lab. (United States); Jonathan E. Hoffman, Joint Quantum Institute (United States); Guy Beadie, U.S. Naval Research Lab. (United States); Pablo Solano, Steven L. Rolston, Luis A. Orozco, Joint Quantum Institute (United States)

Optical nanofibers provide a practical method for connecting photonic equipment to atomic systems. Atoms trapped in the evanescent field of these nanofibers can interact strongly with propagating photons, and a number of experiments have investigated a rich array of phenomena even when the nanofiber supports only a single spatial mode. These traps can also be tailored by using higher-order modes, but this requires nondestructive evaluation and control of the propagating modes.

In this work, we describe and compare two techniques for the nondestructive visualization of light propagation in optical nanofibers supporting the first excited family of modes. In the first technique, we image Rayleigh scattered light through the side of the nanofiber. This approach enables us to rapidly analyze propagation throughout the entire nanofiber,

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including the tapered region where the propagation undergoes a transition from core-cladding guidance to cladding-air guidance. In the second technique, we use near-field imaging to directly measure the evanescent fields. This technique provides immunity from scattered light and very high spatial resolution (< 1 micron), offering the ability to measure beat frequencies between all allowed modes in the nanofiber. By measuring beat frequencies, we can determine the nanofiber radius with sub-nanometer precision using only optical fields. Our results are compared with measurements made using scanning electron microscopy.

9873-20, Session 4

Symbols of a cosmic order

John M. Myers, Harvard Univ. (United States); Frederick H. Madjid, Consultant (United States)

Quantum theory separates evidence from explanations: the Born trace rule implies that for any given evidence there are always an infinite number of inequivalent explanations in terms of quantum states and operators, so choosing an explanation takes a guess. The generation of evidence at a laboratory bench draws on previously guessed explanations, for example as coded into the computers controlling feedback loops, so that guesses at the blackboard enter physical activity on the bench.

Previously we introduced the notion of a “live clock” that consists of a computer stepped through a cycle of phases by an adjustable clock. In this report we recognize integers as the mathematical structure appropriate to expressing distinctions visible on the bench. To this end we represent a live clock mathematically by a set of ticks, postulating that each tick of a live clock is named by an integer. Without assuming a spacetime manifold with a metric tensor field, we explore a pre-geometric mathematical structure consisting of partial functions from integers to integers. The ideas behind this structure are:

- (1) to name successive ticks of a live clock by successive integers; and
- (2) to express a signal from a live clock A to a live clock B by a partial function relating the integer name of a tick of A at the transmission of a signal to the integer name of a tick of B at the receipt of a signal.

A variety of relations among such partial functions has physical implications and invites mathematical exploration.

9873-21, Session 4

Active quantum walk: A framework for quantum walks under adiabatic quantum evolution

Nan Wu, Fangmin Song, Nanjing Univ. (China); Xiangdong Li, New York City College of Technology (United States)

We study a new methodology for quantum-walk (QW) based algorithms. Different from the passive quantum walk, which drives a walker in the QW procedure, the new framework that we developed allows the walker to walk with adiabatic quantum evolution in an active way. This can be helpful for us to develop new quantum-walk based searching or optimizing algorithms.

Conference 9874: Remotely Sensed Data Compression, Communications, and Processing XII

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9874-1, Session 1

A terrain-based comparison of chaos modulation in acoustic wireless sensor networks

Dasola A. Oluge, Henry Leung, Univ. of Calgary (Canada)

The operating environment, in which wireless sensor networks are deployed to function, has a significant impact on the network performance. This is due to the inherent non-ideal channel conditions present in the operating environment such as multipath, noise and propagation delays. However, most simulations ignore these non-idealities thus yielding very optimistic results.

Hence, this paper incorporates channel non-idealities such as multipath into a simulated wireless sensor network, and evaluates the effect on network performance in different terrains.

Given their inherent wideband characteristic which makes them robust to non-ideal conditions such as multipath, chaos-based modulation schemes are a possible alternative to conventional spread spectrum techniques. By incorporating these non-ideal conditions, and evaluating network performance when deployed in non-terrestrial terrains such as deep space Martian exploration or underwater acoustic localization, this paper contributes a more realistic simulation framework of the sensor network performance using the metrics of throughput and end-end delay. Furthermore, a comparison of the results when different chaos modulation schemes are applied in different terrains is presented.

9874-2, Session 1

Geometric convex cone volume analysis

Hsiao-Chi Li, Chein-I Chang, Univ. of Maryland, Baltimore County (United States)

Convexity is a major concept used to design and develop endmember finding algorithms. For abundance unconstrained techniques, Pixel Purity Index (PPI) and Automatic Target Generation Process (ATGP) which use Orthogonal Projection (OP) as a criterion, are commonly used method. For abundance partially constrained techniques, Convex Cone Analysis is generally preferred which makes use of convex cones to impose Abundance Non-negativity Constraint (ANC). For abundance fully constrained N-FINDR and Simplex Growing Algorithm (SGA) are most popular methods which use simplex volume as a criterion to impose ANC and Abundance Sum-to-one Constraint (ASC). This paper develops a Geometric Convex Cone Volume Analysis (GCCVA) which projects a convex cone orthogonally on a hyperplane so that the simplex volume obtained by fully abundance constrained method such as N-FINDR and SGA can be shown to be actually a product of the volume of its base obtained by GCCVA multiplied by its height obtained by ATGP. Accordingly, SGA can be viewed as an algorithm combining GCCVA and ATGP in one-shot operation.

9874-3, Session 1

Spectral restoration for hyperspectral images

Zihui Tan, Guorui Jia, Huijie Zhao, BeiHang Univ. (China)

Traditional Wiener filtering has been widely used to restore single-band

images. However, it has not been discussed yet how to specially use Wiener filtering to get a spectral restoration effect for a 3-Dimensional hyperspectral image. Modeling the measured spectrum to be the result of a convolution with the Spectral Response Function (SRF) and noise-adding process, a method to apply spectral Wiener filtering to hyperspectral images is proposed. Spectral Wiener filtering aims to get an optimal estimation of real spectrum which considers the effect of both noise and SRF. For doing this, the spectral signal-to-noise ratio (SNR) is calculated using a decorrelation method. In an experiment based on simulated hyperspectral image cube, spectral Wiener filtering in a pixel by pixel way achieved an increase of 6.67% in the average depth of spectral signature, relative to spatial Wiener filtering band by band. However the spectral filter corresponds to an increase of 2.23% in gray-scale difference around the edge, which is 21.39% less than that of spatial filter. The results suggest that spatial and spectral degradation of hyper-spectral image are inter-coupled, both of spatial and spectral Wiener filter have restoration effects on both spatial signature and spectral signature, but have a better increase on corresponding aspects. Spatial Wiener filter is more suitable to restore single-band images and spectral Wiener filter is more suitable to restore spectrum. A method that combines spatial and spectral degradation to restore three dimension data simultaneously is our future work.

9874-4, Session 1

Performance tuning Fu-Liou-Gu longwave radiative transfer scheme on Intel Xeon Phi

Jarno Mielikainen, Bormin Huang, Hung-Lung A. Huang, Univ. of Wisconsin-Madison (United States)

Next-generation mesoscale numerical weather prediction system, the Weather Research and Forecasting (WRF) model, is a designed for dual use for forecasting and research. WRF offers multiple physics options that can be combined in any way. One of the physics options is radiance computation. The major source for energy for the earth's climate is solar radiation. Thus, it is imperative to accurately model horizontal and vertical distribution of the heating. Goddard solar radiative transfer model includes the absorption due to water vapor, ozone, oxygen, carbon dioxide, clouds and aerosols. The model computes the interactions among the absorption and scattering by clouds, aerosols, molecules and surface. Finally, fluxes are integrated over the entire longwave spectrum. In this paper, we present our results of optimizing the Goddard longwave radiative transfer scheme on Intel Many Integrated Core Architecture (MIC) hardware. The Intel Xeon Phi coprocessor is the first product based on Intel MIC architecture, and it consists of up to 61 cores connected by a high performance on-die bidirectional interconnect. The coprocessor supports all important Intel development tools. Thus, the development environment is familiar one to a vast number of CPU developers. Although, getting a maximum performance out of MICs will require using some novel optimization techniques. Those optimization techniques are discussed in this paper.

9874-5, Session 1

Optimizing the Fu-Liou-Gu shortwave radiation scheme for Intel many integrated core (MIC) architecture

Jarno Mielikainen, Bormin Huang, Hung-Lung A. Huang, Univ. of Wisconsin-Madison (United States)

Intel Many Integrated Core (MIC) architecture ushers in a new era of

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supercomputing speed, performance, and compatibility. It allows the developers to run code at trillions of calculations per second using the familiar programming model. In this paper, we present our results of optimizing the Fu-Liou-Gu shortwave radiation scheme on Intel Many Integrated Core Architecture (MIC) hardware. The Intel Xeon Phi coprocessor is the first product based on Intel MIC architecture, and it consists of up to 61 cores connected by a high performance on-die bidirectional interconnect. The co-processor supports all important Intel development tools. Thus, the development environment is familiar one to a vast number of CPU developers. Although, getting a maximum performance out of Xeon Phi will require using some novel optimization techniques. Those optimization techniques are discussed in this paper.

9874-6, Session 2

Unsupervised hyperspectral unmixing using compressive sensing

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Recently, the concept of Compressive Sensing (CS) has been investigated for HU. It is known that two properties defining CS are sparsity and incoherence. Interestingly, only the property of sparsity has been used for this purpose. This paper explores the use of both properties in UHU where sparsity is used to determine the value of p and incoherence is used to find distinct signatures to best represent the data for HU. The idea of using CS is based on the fact that signatures used for UHU must be sparse enough by choosing the value of p as small as possible, while their correlation must be also incoherent as much as possible. Since sparsity has been well studied for HU in the literature and incoherence has not been factored into HU, this paper takes this challenging issue by looking into how incoherence plays its role in HU. Most specifically, the concept of incoherence is re-interpreted by principle of orthogonality and an Orthogonal Subspace Projection (OSP)-based criterion is further to measure the degree of incoherence. In other words, a desired signature should be the one which has maximal magnitude in the orthogonal subspace complement to the space linearly spanned by other signatures. In order to evaluate the proposed UHU technique experiments are designed and conducted to compare other existing UHU techniques for demonstration.

9874-8, Session 2

Semi-supervised hyperspectral unmixing approach based on nonnegative matrix factorization

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Non-negative matrix factorization (NMF) has been introduced into the field of hyperspectral unmixing in the last ten years. Though NMF-based approaches have been widely accepted by researchers, the assumptions in them may not always fit for the characteristics of real ground objectives, which will cause the incorrect results and restrict the applications for these approaches. This paper proposes a novel semi-supervised NMF model, in which the ground truth information is introduced such as partial known endmembers from ground measurement. The relationship between the known and unknown endmembers are explored. The distance function is designed to describe the relationship and introduced into the NMF model. In this way, SSNMF could use the known endmembers to help estimating the unknown endmembers, so that accurate and robust results can be obtained. The proposed algorithm was compared with NMFupk, which also considered partial known endmembers, using extensive synthetic data and real hyperspectral data. The experiments show that the proposed algorithm can give a better performance.

9874-9, Session 2

Spectral unmixing using the extended minimum class variance support vector machines

Xiaofeng Li, Northeast Institute of Geography and Agroecology (China); Xiuping Jia, The Univ. of New South Wales (Australia); Ligu Wang, Harbin Engineering Univ. (China); Kai Zhao, Northeast Institute of Geography and Agroecology (China)

To address the within-class spectral variability of endmembers, several spectral unmixing techniques using multiple endmembers for each class have been developed. Then some uncertainty is introduced due to the model overlap and fraction overlap of spectral mixture analysis (SMA). The spectral unmixing resolution (SUR) based on the extended support vector machines (eSVM) has been proposed to characterize the uncertainty, which indicates that if SUR is decreased then the uncertainty of SMA can be reduced, and the unmixing accuracy may be improved. Moreover, it is an effective way for decreasing the SUR to reduce the within-class variances and increase the between-class variances. In this study, a minimum class variance SVMis extended (e_MCVSVM) to decrease SUR and perform the linear SMA, which can maximize effectively the between-class scatter while minimizing the within-class scatter. Experimental results indicates that e_MCVSVM algorithm performed better in the unmixing accuracy and the computation speed than the other algorithms (e.g., FCLS, EM bundles) whether in linearly separable or non-separable cases. This new proposed approach advances the linear SMA with faster and higher accuracy based on the SVM after SUR was characterized effectively.

9874-7, Session PWed

Region-based collaborative sparse unmixing of hyperspectral imagery

Jiaojiao Li, Xidian Univ. (China); Qian Du, Mississippi State Univ. (United States); Yunsong Li, Xidian Univ. (China)

Sparse unmixing (SU) has been investigated to select a small number of endmembers from a large spectral library, which is a pixel-based technique. In image-based collaborative sparse unmixing (CSU) techniques, pixels are forced to select the same small set of endmembers if possible. In reality, the same small set of endmembers may be responsible for pixel construction within a homogeneous area. For an entire image, the endmember sets are often different. So, in this paper, we propose a region-based collaborative sparse unmixing (RCSU) algorithm, and the region may include nonlocal areas as long as they belong to the same type of homogeneous segments. Experimental results show that the overall performance of the proposed RCSU algorithm is better than that of image-based CSU or pixel-based SU.

9874-20, Session PWed

Perceptual video compression based on separate static and dynamic texture synthesis

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This paper presents original framework for perceptual video coding. It is based on robust texture segmentation and classification scheme and different synthesis techniques applied to static and dynamic textures. During the coding stage we divide GOP(group of pictures) into the set of disjoint segments, labeled as: structural information, static texture and dynamic texture. To provide robust segmentation results we propose a

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novel CNN(convolutional neural network)-based space-time descriptor and multilabel graph cut optimization technique. Video segments marked as structural information are coded by traditional hybrid video coding scheme and segments marked as texture are partially dropped. At the decoder side we restore missing parts of the video sequence by texture synthesis. We implemented our method into H.265/HEVC reference implementation HM 16.1. Evaluation of our approach on several test sequences has shown that it is superior to existing techniques both in perceived visual quality and compression rate.

9874-29, Session PWed

The improved method for estimating soil surface temperature covered by snow using passive microwave data in Heilongjiang province of China

Xingming Zheng, Xiaofeng Li, Northeast Institute of Geography and Agroecology (China); Lingjia Gu, Jilin Univ. (China); Kai Zhao, Northeast Institute of Geography and Agroecology (China)

Soil surface temperature is an important indicator of global temperature change and a key input parameter in retrieving land surface variables by remote sensing technique. Due to the shelter in thermal infrared band and the scattering in microwave band of snow, soil temperature covered by snow is difficult to be inferred from remote sensing data. This paper attempts to retrieve soil surface temperature covered by snow in Heilongjiang province of China from the special sensor microwave/imager (SSM/I) brightness temperature. This paper incorporates snow discrimination method and brightness temperature modification method into the scheme of soil surface temperature estimation, and the effect of snow on estimated soil surface temperature has been weakened. The results shows that the root mean square error (RMSE) of estimated T_s decrease from 17.5K to 5.7K for crop areas, and from 32.7K to 3.8K for forest areas. The method in this paper greatly improves the accuracy of estimated soil surface temperature under snow conditions, and it needs no auxiliary information. Thus, this method is very suitable for soil temperature estimation for large scale and contributes to determine the state of soil freezing and thawing.

9874-30, Session PWed

Unmixing Method of Passive Microwave Data Based on the Land/Water Surface Type Classification

Ruizhi Ren, Lingjia Gu, Jilin Univ. (China)

Passive microwave remote sensing is often used to observe microwave emission features from the surface of the Earth under most weather conditions, however, the main drawback of microwave remote sensing data is the extremely low spatial resolution as compared with data from spectral remote sensing. An effective unmixing method of passive microwave data based on the Land/Water surface type classification is proposed in the paper. Northeast China is selected as the study area in the research. Firstly, the observation areas are divided into the two surface types using the MODIS spectral remote sensing data, including water surface type and land surface type. Furthermore, an unmixing model of passive microwave data is built according to the brightness temperature characteristics of the two surface types. Through solving the underdetermined system of equations, the component brightness temperature values of water and land are retrieved from the mixed passive microwave data separately. Given the brightness temperature and the spatial position distribution of the two components, the spatial resolution of passive microwave data can be improved. Through comparative analysis of brightness temperature values derived from unmixing MWRI data and AMSR-E data, the proposed unmixing method can obtain preferable results for spatial resolution improvement of passive microwave data.

9874-31, Session PWed

Snow Cover Identification of Saline-alkali Land in the Western Jilin Province of China based on MWRI Data

Mingbo Sun, Lingjia Gu, Ruizhi Ren, Jilin Univ. (China)

The western Jilin Province of China has obvious salinization problem. Meanwhile, it belongs to a typical snow-covered area of China. In this paper, the western Jilin Province is selected as the study area and divided into the four land surface types, including grassland, farmland, slight saline-alkali land, moderate and severe saline-alkali land. The main research focuses on the analysis of the snow depth covered on the four land surface types. Based on the five years' FY3B MWRI data from 2011 to 2015, the changes of snow depth on the four land surface types are analyzed. The pure MWRI pixels of the four land surface types are extracted from the study area. Furthermore, a decision tree method of snow identification is designed to distinguish different snow cover conditions. After using the proposed decision tree method, the Chang's algorithm is applied to retrieve snow depth for the pure MWRI pixels. The snow depth retrieval equation for each type is given by adjusting the retrieval coefficients. Finally, the snow depth of each MWRI pixel is estimated from the sum of snow depth values from each land surface type algorithm, weighted by the percentage of the land surface type within each MWRI pixel. This research is used to retrieve the snow depth in the western Jilin Province of China and provides important information to study snow depth in saline-alkali land area.

9874-32, Session PWed

A Linear Signal Transmission System Calibration Method of wideband GPR

Bin Wu, Kai Zhao, Xiaofeng Li, Xingming Zheng, Northeast Institute of Geography and Agroecology (China); Lingjia Gu, Jilin Univ. (China)

In VHF pulse Ground Penetrating Radar(GPR), the radar echo arrives receiver through antenna and transmission line circuit, so the reflection coefficient at the end of the transmission line is different from the real reflection coefficient of the media at antenna interface. The pulse GPR receiver is a wideband system that can't be described by traditional narrowband transmission line model. Since the GPR transmission line circuit is a linear system, linear transformation method can be used. So a GPR receiver transmission line calibration method based on transmission line theory is proposed, which combine the reflection coefficients of theory calculation at antenna interface and measuring by network analyzer, using the least square method, to calibrate the transfer function of transmission line circuit of the GPR receiver. This calibration method can be used in quantitative inversion of media by GPR. When getting the reflection coefficient at the end of the transmission line, the real reflection coefficient of the media at the antenna interface can be finally obtained.

9874-33, Session PWed

Morphological hyperspectral target detection

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Target detection is one of the most fundamental and important tasks in hyperspectral data processing. There are a lot of matched filter methods for target detection, but most of them only use the spectral information and process one single pixel at a time, ignoring the spatial information that is also important. To separate target pixel and background pixel, matched filter anomaly method usually generate a background distribution model, and then project each pixel in the hyperspectral image to this distribution model

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to highlight the anomaly pixels as targets, because target pixels will have large projection length than any other pixels. In this way, the background model used is very important, that it should have the good represent of the background pixels. Unfortunately, targets can't be separated with the background pixels that have similar spectral with them, and in some situation, target spatial information can be specified by human knowledge, such as size and distribution, these information are commonly ignored, conduct to high false alarm rate. In this paper, we proposed a method with morphological processing that not only use spectral information, also spatial information to distinguish the target that has different spatial feature with background.

9874-34, Session PWed

A nonlinear spectral unmixing method for abundance retrieval of mineral mixtures

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Minerals are generally present as intimate mixtures. The spectra of intimate mixtures are complex function of abundance, grain size, and optical constants et.al, making the linear model inapplicable. In this paper, we presented a nonlinear unmixing method by combining Shkuratov model (SK99) and Hapke model (H81) to unmix mineral mixtures. SK99 model is invertible, the imaginary index of refraction k of the surface material can be calculated if the n , S , q are available. However, it is difficult apply SK99 model in large scope because of its computation complexity. The reflectance r of semi-infinite medium of regolith particles scatters is a function of single scattering albedo (SSA) and was given by Hapke (1981). The SSA obtained from H81 and SK99 is quite good agreement. For obtaining the abundances of mineral endmembers, we constructed a look-up table (LUT) in the following steps: First, the optical constants were derived based on the invertibility of SK99 model and then single scattering albedos of endmembers were computed. Second, the approximation of multiple scattering was derived by the Chandrasekhar H-function. Finally, LUT was constructed using H81 model and RMSE was calculated to find the best match between the reflectance of mixtures and LUT. We used the laboratory mineral mixtures to verify the accuracy of abundance estimation. The result shows that RMSEs are less than 1% and the absolute errors of abundance retrieval are within 5%. The presented method can retrieve mineral abundance effectively and rapidly. It will be a potential method for mineral mapping quantitatively by hyperspectral images on the earth and planetary surfaces.

9874-35, Session PWed

Real time progressive hyperspectral remote sensing detection methods for crop pest and diseases

Taixia Wu, Lifu Zhang, Bo Peng, Hongming Zhang, Institute of Remote Sensing and Digital Earth (China)

Crop pests and diseases is one of major agricultural disasters, which have caused heavy losses in agricultural production each year. Hyperspectral remote sensing technology is one of the most advanced and effective method for monitoring crop pests and diseases. However, Hyperspectral facing serial problems such as low degree of automation of data processing and poor timeliness of information extraction. It resulting we cannot respond quickly to crop pests and diseases in a critical period, and missed the best time for quantitative spraying control on a fixed point. In this study, we take the crop pests and diseases as research point and breakthrough,

using a self-development line scanning VNIR field imaging spectrometer. Take the advantage of the progressive obtain image characteristics of the push-broom hyperspectral remote sensor, a synchronous real-time progressive hyperspectral algorithms and models will development. Namely, the object's information will get row by row just after the data obtained. It will greatly improve operating time and efficiency under the same detection accuracy. This may solve the poor timeliness problem when we using hyperspectral remote sensing for crop pests and diseases detection. Furthermore, this method will provide a common way for time-sensitive industrial applications, such as environment, disaster. It may providing methods and technical reserves for the development of real-time detection satellite technology.

9874-10, Session 3

Two-stage compression of hyperspectral images with enhanced classification performance

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Most compression methods for hyperspectral images have been optimized to minimize mean squared errors. However, this kind of compression method may fail to capture all the discriminant information of hyperspectral images since features which are important for classification may not be high in signal energy. Such discriminant information is very important if hyperspectral images are to be used to distinguish among classes. In order to address this problem, we propose a two-stage compression method for hyperspectral images with encoding residual discriminant information. In the proposed method, we first apply a compression method to hyperspectral images, producing compressed image data. From the compressed image data, we produce reconstructed images. Then we generate residual images by subtracting the reconstructed images from the original images. We also apply a feature extraction method to the original images, which produces a set of feature vectors. By applying these feature vectors to the residual images, we generate discriminant feature images which provide the discriminant information missed by the compression method. Thus, in the proposed method, these discriminant feature images are also encoded. Experiments using AVIRIS data show promising performance. The proposed method provides better compression efficiency and improved classification accuracy than existing compression methods.

9874-11, Session 3

Spectral decorrelation of hyperspectral imagery using fractional wavelet transform

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Hyperspectral data is composed of a set of correlated band images. In order to efficiently compress the hyperspectral imagery, this inherent correlation may be exploited by means of spectral decorrelators. In this paper, a fractional wavelet transform based method is introduced for spectral decorrelation of hyperspectral data. As opposed to regular wavelet transform which decomposes a given signal into two equal-length sub-signals, fractional wavelet transform is carried out by decomposing the signal corresponding to the spectral content into two sub-signals with different lengths.

Sub-signal lengths are adapted to data to achieve a better spectral decorrelation. Performance results pertaining to AVIRIS datasets are presented in comparison with existing regular wavelet decomposition based compression methods.

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9874-12, Session 3

**Compact high performance spectrometers
using computational imaging**

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Compressive sensing technology can theoretically be used to develop low cost compact spectrometers with the performance of larger and more expensive systems. Indeed, compressive sensing for spectroscopic systems has been previously demonstrated using coded aperture techniques, wherein a mask is placed between the grating and a charge coupled device (CCD) and multiple measurements are collected with different masks. Although proven effective for some spectroscopic sensing paradigms (e.g. Raman), this approach requires that the signal being measured is static between shots (low noise and minimal signal fluctuation). Many spectroscopic techniques applicable to remote sensing are inherently noisy and thus coded aperture compressed sensing will likely not be effective. This work explores an alternative approach to compressed sensing that allows for reconstruction of a high resolution spectrum in sensing paradigms featuring significant signal fluctuations between measurements. This is accomplished through relatively minor changes to the spectrometer hardware together with custom super-resolution algorithms. Current results indicate that a potential overall reduction in CCD size of up to a factor of 4 can be attained without a loss of resolution. This reduction can result in significant improvements in cost, size, and weight of spectrometers incorporating the technology.

9874-13, Session 3

**Hyperspectral band selection using
compressive sensing**

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Compressive Sensing (CS) has received considerable interest in recent years. This paper develops a new approach to Band Selection (BS) using two key CS concepts, sparsity and incoherence. These concepts can resolve two major issues arising in BS, determining the number of bands p , and choosing the subset of p bands from the data. Interestingly, the first issue, determination of the value of p , can be re-formulated as the sparsity issue of CS and the second issue, finding a desired set of p bands, can be re-cast as the incoherence issue of CS. Since the number of bands to be selected must be as few as possible, the sparsity plays its role in determining the smallest number of bands. This approach provides an alternative technique to the established Virtual Dimensionality (VD). On the other hand, since the selected bands must also have minimal correlation, the principle of orthogonality widely used in the mean squared error estimation theory can be used to account for incoherence. In other words, we can select a band that has the maximal leakage into the space linear spanned by previously selected bands. In order to evaluate the effectiveness of the proposed approach experiments were conducted and compared to existing BS techniques for demonstration.

9874-14, Session 3

**Compressed imagery detection rate
through map seeking circuit (MSC) pattern
recognition**

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LLC (United States)

Images were compressed using open-source compression algorithms to an almost unrecognizable object. Original and compressed images were

processed with Map Seeking Circuit (MSC) pattern recognition, showing the same target detection rates. Location precision and target aspect were degraded for the highest compression rates.

Automatically recognizing objects in imagery has become necessary in today's information overload. Remote sensors collect volumes of imagery, and compress the data for transfer and storage. Researching the effect of compression techniques on spatial object recognition algorithms assists in optimizing target detection and identification while reducing data transfer and storage requirements.

Object recognition in the compressed domain has potential of saving storage and processing time. But the selection of the compression technique needs to be optimal for the pattern recognition algorithm feature extraction. The Map Seeking Circuits (MSC) object detection is based on finding the edges within the imagery and correlating the patterns with the object of interest. MSC is a biologically-inspired algorithm developed by David Arathorn [1]. MSC was found to be successful in recognizing three dimensional objects in imagery with reasonable computational complexity [2]. MSC can easily be run on a laptop, using a template derived from 3D target models.

We present promising results that indicate a significantly compressed image generates the same detection rate and object location through MSC.

References:

[1] David Arathorn, "Map Seeking Circuits in Visual Cognition, A Computational Mechanism for Biological and Machine Vision," Stanford Press, 2002

[2] Patricia Murphy, Pedro Rodriguez, Cameron Peterson, "Detection and recognition of 3D targets in panchromatic gray scale imagery using a biologically inspired algorithm", Applied Imagery Pattern Recognition Workshop (AIPRW), IEEE 14-16 Oct. 2009

9874-15, Session 3

**An integral design strategy combining
optical system and image processing to
obtain high resolution images**

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University (China)

In this paper, an integral design that combines optical system with image processing is introduced. Traditional imaging methods often separate the two technical procedures of optical system design and imaging processing, in which the first stage is to optimize the lens subsystem using an optical measure of performance and the second stage is to optimize the image processing subsystem, resulting in the failures to exploit opportunities for efficient cooperation between the optical and digital elements. Therefore, we introduce an innovative approach to combine the merit function during optical design with the constraint conditions of image processing algorithms together. Specifically, an optical imaging system with low resolution is designed to collect the image signals which are indispensable for imaging processing, while the ultimate goal is to obtain high resolution images from the final system. Then, in order to optimize the global performance of the whole system, we utilize the user defined optimization capability of the ZEMAX software to achieve the trade-off state between the optical design and the image processing. The results show that, although the modulation transfer function (MTF) of the optical imaging systems is not the best, it can provide image signals that are more suitable for image processing. In conclusion, this integral design of optical system and image processing can decrease redundant data greatly, improve the effectiveness of image signals remarkably, and actualize cost reduction and high resolution images simultaneously.

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9874-16, Session 4

Progressive band processing of fast iterative pixel purity index

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Fast Iterative Pixel Purity Index (FIPPI) was previously developed to address two major issues arising in PPI which are the use of skewers whose number must be determined by a priori and inconsistent final results which cannot be re-produced. Recently, a new concept has been developed for hyperspectral data communication according to Band SeQuential (BSQ) acquisition format in such a way that bands can be collected band by band. By virtue of BSQ users are able to develop Progressive Band Processing (PBP) for hyperspectral imaging algorithms so that data analysts can observe progressive profiles of inter-band changes among bands. Its advantages have been justified in several applications, anomaly detection, constrained energy minimization, automatic target generation process, orthogonal subspace projection, PPI, etc. This paper further extends PBP to FIPPI. The idea to implement PBP-FIPPI is to use two loops specified by skewers and bands to process FIPPI. Depending upon which one is implemented in the outer loop two different versions of PBP-FIPPI can be designed. When the outer loop is iterated band by band, it is called to be called Progressive Band Processing of FIPPI (PBP-FIPPI). When the outer loop is iterated by growing skewers, it is called Progressive Skewer Processing of FIPPI (PSP-FIPPI). Interestingly, both versions provide different insights into the design of FIPPI but produce close results.

9874-17, Session 4

Real time hyperspectral anomaly detection via band-interleaved by line

Hsiao-Chi Li, Chein-I Chang, Univ. of Maryland, Baltimore County (United States)

Anomaly detection is one of most fundamental tasks in hyperspectral data exploitation. Since anomalies are generally unknown and unexpected, their detection must be carried out without prior knowledge. Most importantly, when anomalies are weak and moving as time goes on real time processing of anomaly detection becomes immense in detecting these anomalous targets. Due to hyperspectral sensor design two major formats are used for data acquisition in real time. One is real-time sample processing which collects data in two different fashions, Band-interleaved by Pixel/Sample (BIP/BIS) sample-by-sample and Band-Interleaved-by-Line (BIL) line-by-line. Another is real-time band processing which follows the Band Sequential (BSQ) format to collect the data. Recently, anomaly detection using both BIP/BIS and BSQ has been reported in the literature. Since a hyperspectral imaging sensor generally collects the data in a pushbroom manner, the BIL format is preferred to BIP/BIS. But it is interesting to note that AD using BIL has not been explored and investigated in the past mainly because it was expected that AD using BIL may perform similarly to AD using BIP/BIS. This paper shows otherwise due to the fact that the covariance/correlation matrix used by an anomaly detector has significant impact on the detectability of anomalies. It has been shown that anomaly detection is heavily determined by the ratio of anomalies to be detected to the image size that forms the covariance/correlation matrix. So, when AD using BIL is implemented, the information of covariance/correlation matrix provided BIL is different from that provided by BIP/BIS. As a result, it is anticipated that AD using BIL may result different performance from AD using BIP/BIS.

9874-18, Session 4

Progressive anomaly detection in medical data using vital sign signals

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Vital Sign Signals (VSSs) have been widely used for medical data analysis. One classic approach is to use Logistic Regression Model (LRM) to describe data to be analyzed. There are two challenging issues from this approach. One is how many VSSs needed to be used in the model since there are many VSSs can be used for this purpose. Another is that once the number of VSSs is determined, the follow-up issue what these VSSs are. Up to date these two issues are resolved by empirical selection. This paper addresses these two issues from a hyperspectral imaging perspective. If we view a patient with collected different vital sign signals as a pixel vector in hyperspectral image, then each vital sign signal can be considered as a particular band. In light of this interpretation each VSS can be ranked by band prioritization commonly used by band selection in hyperspectral imaging. In order to resolve the issue of how many VSSs should be used for data analysis we further develop a Progressive Band Processing of Anomaly Detection (PBPAD) which allows users to detect anomalies in medical data using prioritized VSSs one after another so that data changes between bands can be dictated by profiles provided by PBPAD. As a result, there is no need of determining the number of VSSs as well as which VSS should be used because all VSSs are used in their prioritized orders. To demonstrate the utility of PBPAD in medical data analysis anomaly detection is implemented as PBP to find anomalies which correspond to abnormal patients. The data to be used for experiments are data collected in University of Maryland, School of Medicine, Shock Trauma Center (STC). The results will be evaluated by the results obtained by Logistic Regression Model (LRM).

9874-19, Session 4

Automated morphological analysis of human sperms cells according to WHO standards using image and vision algorithms

Waqas Hussain, Saqib Mehmood, Air Univ. (Pakistan)

Currently, we have at least one million hospitals all over the world but none of them have an application catering to sperm morphology. Microscopic evaluation of human sperm quality is a basic requirement of any diagnostic fertility service, assisted conception (IVF) center or pathology laboratory. Human Sperm is evaluated in terms of three key features, namely concentration (sperm count), motility (sperm speed) and morphology (individual sperm shape). Conventional manual microscopic analysis of sperm samples is time consuming (1-2 hours) and lacks accuracy and reproducibility in many IVF centers.

Motility and concentration are handled with variable degrees of efficiency (Tomlinson et al 2010) but morphological or individual sperm health and abnormality detection is still missing from the automated software tools. The manual testing for morphology in labs according to world health organization (WHO) standards is labelled flawed by the andrology and fertility researchers due to the following problems:

1. A dye has to be injected in the immobilized sample so the microscope can pick the sperms heads well at 1000x magnifications using oil immersion. The dye may transform the natural morphological characteristics of the original cells.
2. Too much time has to be consumed as 1000x magnification means looking at only a couple of sperms per slide. Moreover, if we follow WHO standards at least 200 sperms have to be analyzed, so a lot of frames from the microscope have to be taken and processed.

I propose a sophisticated solution which analyses the immobilized sperms at 200x magnification without injecting a dye in. Main objectives are:

To analyze sperms samples at lower magnifications to get more sperms in the image and save time

To write image processing and computer graphics algorithms to detect sperms without theinjection of chemical dye which messes with their natural

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morphology.

Automatically divide the sperm in 3 major parts namely head , mid-piece and tail

Find the head abnormalities using machine learning techniques

Find the neck and tail defects using tracking algorithms and some structural analysis techniques mentioned in a Bioinformatics paper (Naeem et al 2011)

9874-21, Session 5

Remote logo detection using angle-distance histograms

Sungwook Youn, Sangwook Baek, Seongyoun Woo, Chulhee Lee, Yonsei Univ. (Korea, Republic of)

As more terminals and machines are equipped with cameras, computer vision technologies can significantly enhance product applications and create new markets. Among various pattern recognition problems, logo recognition is rather special. Acceptable performance is possible in many application areas. As a result, automatic logo recognition has drawn great interests from the industry and academy. Logo can convey store information to nearby pedestrians. Logo recognition for a vehicle or autonomous moving machines such as drones or robots can be used as a landmark. Logos often appear in images/videos of real-world indoor or outdoor scenes superimposed on objects of any geometry. They may undergo perspective transformations and deformations, be often corrupted by noise or lighting effects, or partially occluded. In this paper, we propose an angle-distance histogram, which we use to develop a logo detection algorithm that is robust against size-variations and rotation. First, we find candidate logo regions based on primary color information. The centroid is calculated for homogeneous regions. Then, for all boundary pixels of the region, distances and angles of the centroid are calculated. Using these two features (distance and angle), we can generate an angle-distance histogram. Since we normalize the distance, this histogram is size-invariant. The proposed method also use shape information and color characteristics. Experiments show promising results.

9874-22, Session 5

Hyperspectral Analysis Approach to Prioritizing Vital Sign Signals for Medical Data

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When medical data are collected there are many Vital Sign Signals (VSSs) that can be used for data analysis. From a hyperspectral imaging perspective, we can consider a patient with different vital sign signals as a pixel vector in hyperspectral image and each vital sign signal as a particular band. In light of this interpretation this paper develops two new concepts of prioritization of VSSs. One is Orthogonal Subspace Projection Residual (OSPR), which measures the residual of a VSS in the orthogonal complement subspace to the space linearly spanned by the remaining VSSs. Another is to construct a histogram for each of VSSs that can be used as a means of ranking VSSs according to a certain criterion for optimality. Several measures are proposed to be used as criteria for VSS prioritization, which are variance, entropy and Kullbak-Leibler (KL) information measure. The VSS prioritization can then be used as to form Logistic Regression model (LRM). In order to determine how many VSSs should be used a recently developed concept, called Virtual Dimensionality (VD) can be used for this purpose. To demonstrate the utility of VSS prioritization data collected in University of Maryland, School of Medicine, Shock Trauma Center (STC) was used for experiments.

9874-23, Session 5

Lesion detection in magnetic resonance brain images by hyperspectral imaging algorithms

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Magnetic Resonance (MR) images can be considered as multispectral images so that MR imaging can be processed by multispectral imaging techniques such as maximum likelihood classification. Unfortunately, most multispectral imaging techniques are not particularly designed for target detection. On the other hand, hyperspectral imaging is primarily developed to address subpixel detection, mixed pixel classification for which multispectral imaging is generally not effective. This paper takes advantages of hyperspectral imaging techniques to develop target detection algorithms to find lesions in MR brain images. Since MR images are collected by only three image sequences, T1, T2 and PD, if a hyperspectral imaging technique is used to process MR images it suffers from the issue of insufficient dimensionality. To address this issue, two approaches to nonlinear dimensionality expansion are proposed, nonlinear correlation expansion and nonlinear band ratio expansion. Once dimensionality is expanded hyperspectral imaging algorithms are readily applied. The hyperspectral detection algorithm to be investigated for lesion detection in MR brain is the well-known subpixel target detection algorithm, called Constrained Energy Minimization (CEM). In order to demonstrate the effectiveness of proposed CEM in lesion detection, synthetic images provided by BrainWeb and real images are used for experiments where 3D Receiver Operating Characteristic (ROC) analysis is used to evaluate their detection performance.

9874-24, Session 5

Imbalanced data classification using reduced multivariate polynomial

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Automatic classification has been widely applied to various real life problems, such as pedestrian detection, face recognition and handwritten digit recognition. For most of these real life problems, class population is not uniformly distributed or even extremely biased to a certain class, which is known as a majority class. In this case, applying conventional classifiers that simply maximize the classification accuracy may lead to a situation that most samples are classified as the majority class. However, it may not be true that the samples of minority classes (classes with a smaller number of samples) have less significance simply because they are fewer in number. Moreover, there are some cases that minority samples may have higher importance. For example, when diagnosing a certain disease or detecting a certain target, the minority class may be most important.

In this paper, a weighted reduced multivariate polynomial (Weighted RM) is proposed for imbalanced data classification. When there is a large variation in numbers of available class samples, conventional classifiers may classify most samples as majority classes to maximize the classification accuracy, which may not be desirable in some applications. Thus, when there is a huge imbalance in class populations, an additional algorithm may be required to address the class imbalance problem when the classification performance of minority classes is important. We propose to use weighted ridge regression for class imbalanced data classification. Experimental results with the UCI database show improved classification performance of minority classes.

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9874-25, Session 5

Discriminant power analyses of non-linear dimension expansion methods

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With the successful development of learning algorithms, various classification algorithms have been successfully applied to different pattern recognition problems. In particular, non-linear classifiers that can define arbitrary decision boundaries have showed most promising performance. Most non-linear classification methods can be viewed as non-linear dimension expansion followed by a linear classifier. For example, the support vector machine (SVM) expands the dimension using various kernels and classifies the data in the expanded space using a linear SVM. In case of the extreme learning machine (ELM) or neural networks, the dimension is expanded by hidden neurons and the final layer can be viewed as linear classification. In this paper, we analyze the discriminant powers of five non-linear classifiers, which include reduced multivariate polynomial (RM), radial basis function (RBF) kernel, sigmoid kernel, polynomial kernel and ELM. We compared their discriminating power using the UCI databases. In order to compare the discriminating power of each dimension expansion method, the ridge regression is applied as a linear classifier to the five methods. Analyses of discriminating powers of non-linear dimension expansions are presented along with a possible way to improve class separability in non-linear classifiers

9874-26, Session 5

An algorithm of remotely sensed hyperspectral image fusion based on spectral unmixing and feature reconstruction

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Hyperspectral remote sensing plays an important role in a wide variety of fields. However, its rapid progress has been constrained due to its low spatial resolution. Data fusion of hyperspectral and other multi-source data has become one of the effective ways to solve this problem. However, most of the data fusion algorithms are insufficient in spectral feature-preserving. Therefore, this paper probes into the spatial resolution improvement of hyperspectral image, based on the research of hyperspectral fusion theory, spectral mixing theory and the correlation theory of ground object features on different spectral resolution scales. A hyperspectral and multispectral image fusion algorithm named SISU was proposed to improve the spatial resolution of hyperspectral image by the auxiliary multispectral images. This algorithm can take advantage of the NMF spectral unmixing method to unmix the spectral information of hyperspectral and multispectral data, so as to get the feature type of each pixel on high spatial scale. And then, the linear spectral characteristic reconstruction method is used to reconstruct the hyperspectral information from the multispectral image pixel by pixel, based on the endmember type of each multispectral pixel. The proposed algorithms were verified by experiments, and the fusion results based on the algorithms were evaluated. The result showed that the spatial information of the fused data by SISU was significantly improved and the spectral characteristics of different objects are preserved well, which can effectively solve the problem of spatial resolution shortage of hyperspectral data.

9874-27, Session 5

Parallel computing the WRF MM5 similarity surface layer scheme on Intel Xeon Phi coprocessor

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The surface layer is the layer in which a turbulent fluid is affected mostly by interaction with a solid surface or with a surface between gas and liquid. The physical simulation of surface layer has been included in the weather research and forecast (WRF) model for weather prediction. The surface layer calculates friction velocities and exchange coefficients that are responsible for the computation of the surface heat and moisture fluxes. There are a few surface layer schemes in WRF, and the MM5 similarity surface layer is one of the schemes. The structure of the WRF model has fine-grained data parallelism, which is easy to be exploited by vector processors for enhancing the computing performance. In this work, we will demonstrate a programming effort on the parallel development of the MM5 scheme with Intel Xeon Phi coprocessor.

9874-28, Session 5

Implementation of the WRF Monin-Obukhov-Janjic surface layer scheme via Intel many integrated cores

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The weather research and forecast (WRF) model has been widely used for weather prediction. The surface layer plays an important role in part of the physical simulation in WRF. The surface heat and moisture fluxes are provided in the surface layer scheme through the calculation of the surface friction velocities and exchange coefficients. Monin-Obukhov-Janjic (MOJ) is one surface layer scheme in WRF, where it uses a parameterization approach to handle the viscous sub-layer. In the past almost 50 years, the softwares developed for weather prediction have received benefits from increasing processor power. Because of the fine-grained data parallelism built in WRF, it is suitable to parallelize the MOJ scheme for computing performance. In this work, we will present how we improve the performance of the MOJ scheme via Intel Many Integrated Cores.

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