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9525-1, Session 1

Ultra-precision optical metrology using highly controlled fiber-based frequency combs *(Invited Paper)*

Kaoru Minoshima, Yoshiaki Nakajima, The Univ. of Electro-Communications (Japan) and Japan Science and Technology Agency (JST), ERATO Intelligent Optical Synthesizer (IOS) (Japan); Guanhao Wu, Tsinghua University (China)

No Abstract Available

9525-2, Session 1

Deterministic phase retrieval employing spherical illumination

Juan Martínez-Carranza, Konstantinos Falaggis, Tomasz Kozacki, Warsaw Univ. of Technology (Poland)

Deterministic Phase Retrieval techniques (DPRTs) have recently emerged as very practical tools for the phase retrieval of non-absorbing specimens [1–3] and are routinely employed over a wide range of wavelengths that go from the optical to the x-ray regime [4–6]. These techniques allow an accurate phase retrieval of the sample under study without disturbing it and with an experimental system of low complexity. Among them, DPRTs based on the Contrast Transfer Function (CTF) and the Transport of Intensity Equation (TIE) have become an interesting solution because they are computationally efficient [7]. Recently, it has been shown that the performance of these two DPRTs can be significantly improved by employing strategies based on unequally spaced defocus planes [8–10]. These strategies are based on the principle that the accuracy for given reconstructed frequency range of the object depends on the separation distance [11]. Thus, for recovering high frequency components we need to capture intensities with small defocus distances and for recovering low frequency components we need to capture intensities with large defocus distances. The exponential plane separation strategy proposed in reference [9] allows recovering a large number of frequency component by employing only a few images. However, due to the significant variation among the defocus distances, the captured intensities can be subject to misalignment errors because of the displacement of the camera. In order to overcome this problem, in this work we propose an optical illumination system for CTF and TIE techniques that allows obtaining the diffraction pattern for a required propagation distance z without mechanical moving element. This illumination system allows capturing the propagated intensities when using unequal plane separation strategy with high precision and without moving the camera. Thus, we will avoid errors due to the mechanical components of the system. With use of this novel illumination system, the sweeping of the object spectrum can be made more accurately improving the performance of the DPRTs. The illumination system will be based on the Koehler system and the employment of the Tunable Liquid Lens (TLL). The TLL will be placed at the position of the condenser lens. This novel configuration allows us to illuminate the object with spherical wavefront where the curvature of the diffracted field can be controlled by the TLL. By employing the Fresnel scaling theorem [12,13], we can relate the captured spherical diffraction pattern with its equivalent plane wave diffraction pattern by finding the effective propagation distance z/M, where M is the geometrical magnification. In this work, it is shown that the values for z and M can be estimated with high accuracy from the TLL parameters. Thus, a high diversity of measured intensities can be captured without displacing the camera. Additionally, these captured intensities have to be interpolated according to its corresponding magnification M in order to have a set of intensities with the same resolution. Finally, the selected DPRTs will be applied to this set of interpolated intensities for reconstructing the phase of the field with high lateral resolution and low phase noise.

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9525-3, Session 1

Digital super-resolution microscopy using example-based algorithm

Shinji Ishikawa, Yoshio Hayasaki, Utsunomiya Univ. (Japan)

The optical microscope image has a limitation of the spatial resolution called the diffraction limit. The resolution is decided by the wavelength of the light source and the numerical aperture NA of the objective lens; in other words, it is difficult to observe and measure subwavelength structures using the standard optical microscope. Thus, observation of nanostructures generally uses the microscopes having highly resolution such as the scanning type electron microscope (SEM) and the atomic force microscope (ATM).

However, in recent years, some super-resolution microscopes that realize a resolution over the diffraction limit, such as the near-field scanning optical microscope (NSOM) and the stimulated emission depletion microscopy (STED) were investigated. Some nanometer scale measurement techniques based on inverse problem solution were developed. The scatterometry can measure parameters of an optical grating such as the shape and composition. The fluorescence imaging one-nanometer scale accuracy (FIONA) technique localizes single-molecule with profile fitting of the diffraction limited point-spread

function, which applies to photoactivated localization microscopy and stochastic optical reconstruction microscopy (PALM/STORM).

In this paper, we investigate a new super-resolution microscopy with a confocal optical setup and example-based super-resolution algorithm developed for enlargement of pixel-based images.

The pixel-based image is most popular expression of two-dimensional image on displays and has also a limitation of the resolution rightfully decided by pitch of pixel that is the Nyquist interval. Consequently, even if the pixel-based image is enlarged and converted to an image having the more pixels using standard pixel interpolation method such as cubic-spline interpolation method, it is introduced blur edges like the microscope image obtained by the optical microscope possessing the magnification beyond the diffraction limit.

On the other hand, super-resolution algorithm for pixel-based image can creates enlarged and sharpening high-resolution image.

The example-based super-resolution algorithm creates super-resolved image using the database which learning the “example” of the relation between high-frequency component and low-resolution component in a lot of high-resolution images divided to the small pixel images such as 5x5 pixel images which are called high-resolution patch and low-resolution patch. This algorithm converts the input low-resolution image to a super-resolved image to reference the low-resolution patches in the database and add the high-resolution patch related the low-resolution patch selected pattern matching method in input image.

We try to apply this example-based super-resolution algorithm to the optical microscope image whose resolution is limited by diffraction limit. Then, the microscope setup is a confocal microscope, but it uses an image sensor instead of the photo detector. The standard confocal microscope obtains a pixel data in microscope image on photo detector. However, our setup can obtain a pixel data or some pixel patch include high-frequency component to compare the captured image by the image sensor to a database, which learns the relations between the transmitted or reflected light field images from samples as high-resolution patch and captured images by the image sensor as low-resolution patch, which are created by using computer simulation.

We examine about the super-resolution effect of created images by the example-based super-resolution microscopy setup and algorithm using computer simulation based on Fourier frequency filtering.

9525-4, Session 1

3D shape metrology of 80 μm deep vias using TSOM method

Ravikiran Attota, HyeongGon Kang, Keana Scott, National Institute of Standards and Technology (United States); Carlos Beitia, CEA-LETI (France)

In this paper we present an aspect of 3D shape metrology of nominally 12 ?m diameter and 80 μm deep through-silicon vias using the non-destructive through-focus scanning optical microscopy (TSOM) method. The TSOM method makes use of the four-dimensional (4-D), through-focus optical image data enabling it to evaluate 3-D shape of any arbitrary shaped target ranging from nanoscale to micro-scale. The 4-D optical data enables the TSOM method to achieve sub-nanometer scale measurement resolution in lateral and vertical directions (i.e. in 3-D). The TSOM method is economical as it requires only a conventional optical microscope, has high-throughput, robust and many properties desirable for nanomanufacturing where 3-D shape metrology is needed, especially as a process monitoring tool. So far we have studied applicability of the TSOM method for metrology of CD, defect, overlay, through-silicon-vias (TSVs), high-aspect-ratio (HAR) targets, nanoparticles, microchannels, MEMS structures, nanoscale steps, buried targets in Si or transparent medium and more. In the current study the TSVs were fabricated using Bosch etch process on a 300 mm wafer. Varied fabrication conditions across the wafer produced TSVs with slightly different shapes in each die. Out of several aspects of 3D shape studied, here we present the method of measuring vertical axis angles of the TSVs with the TSOM method. As expected, the Bosch process generated TSVs with near normal axis. However, we measured angles ranging approximately from 0.01° to 0.5°, resulting in a maximum horizontal bottom displacement of about 700 nm with respect to top, for the 80 ?m deep vias. Measuring angles in different dies located across the wafer produced radially outward bottom displacement signature. However, this needs to be verified using an alternate metrology method, which appears to be challenging.

9525-135, Session 1

3D optical metrology and super-resolution microscopy with structured illumination based on QXGA (2048x1536) resolution

Henning Molsen, Forth Dimension Displays Ltd. (Germany)

3D optical metrology systems and nanoscopy systems using fringe projection or structured light are well established.

Fast binary ferroelectric liquid crystal on silicon (LCoS) spatial light modulator (SLM) based on SXGA (1280x1024, 1.3 Mpixel) resolution is a popular choice for in-line Automated Optical Inspection (AOI) and also suitable for precision mechanical part inspection.

ForthDD’s new QXGA 3.1 Mpixel SLM and structured light specific drive solution for 3D metrology is presented here.

Optical and electrical parameters of the SLM and the printed circuit assembly architecture are detailed.

The presentation also describes optical design examples of the SLM in systems for 3D metrology using amplitude mode in on-axis configuration and off-axis configuration.

The interface solution can be readily used for phase mode applications like nanoscopy with the Pi phase difference of the SLM switching at several kHz for observation of fast processes in living cells.

Optical configuration for phase mode are described.

9525-6, Session 2

Dual spectrally resolved interferometry to improve measurement range

Yong Bum Seo, Byeong Kwon Kim, Ki-Nam Joo, Chosun Univ. (Korea, Republic of)

Spectrally-resolved interferometry (SRI) is an attractive tool to measure a fixed distance without the ambiguity problem which occurs in displacement interferometers. Moreover, SRI is suitable for real-time measurements because it does not need any mechanical/electrical scanning parts opposed to typical white light scanning interferometry. However, SRI has the fundamental limitation in the measurement range caused by the spectral bandwidth of an optical source and the spectral resolution of a spectrometer to detect the spectral interference density. Especially, the minimum range of SRI is determined by the bandwidth of the source and it is approximately a few tens of micrometers when using a LED. Below the minimum range, SRI cannot extract the distance information from the spectral interferogram. In addition, the typical SRI does not give the direction of the target position, which means it only measures the optical path difference between the reference and measurement arms. Due to this characteristic, the measurement range becomes half the whole distance where SRI can detect the spectral interferogram. In this investigation, we propose a simple technique to eliminate the minimum range of SRI and to extend the measurement range twice with the direction of the target position. Instead of using a typical mirror, the combination of a dichroic beam splitter and a mirror is used as a reference and the dual SRI is implemented in the same configuration. When the light from the source is incident to the reference reflecting structure, the light in the short wavelength region is reflected and the other light with long wavelength is transmitted by the dichroic beam splitter. The transmitted light is then reflected by the mirror behind the dichroic beam splitter and both lights can generate their own spectral interferogram. Because the spectrum is divided by the dichroic beam splitter, two reference lights are not interfered each other and dual SRI can measure two distances; (1) distance between dichroic beam splitter and the target and (2) distance between the reference mirror and measurement mirror. Then, the relationship between two distances in dual SRI can determine the direction of the target position. Moreover,

dual SRI can eliminate the minimum measurement range of SRI because one of the distances is always measured even though one distance is below minimum measurement range. In the result, dual SRI can extend the measurement range twice without any blind region. Because of the simplicity and efficiency of this technique, it is expected to be used in various industrial fields.

At this moment, the experiments to verify the proposed concept and evaluate the system performance are ongoing. We will show the optical configuration and experimental results in the presentation.

9525-7, Session 2

Full-field and contact-less topography of nanometric thin films based on multiwavelength interferometry

Pascal Picart, Mokrane Malek, Univ. du Maine (France); Jorge Garcia-Sucerquia, Univ. Nacional de Colombia Sede Medellín (Colombia) and Univ. du Maine (France); Rahma Moalla, Mathieu Edely, Nicolas Delorme, Jean-François Bardeau, Univ. du Maine (France)

Conventional methods for measuring the thickness of thin films, such as spectral reflectance and ellipsometry, usually provide a pointwise measurement. This feature makes the measurement very long for controlling the homogeneity of the whole film and then the spatial resolution is dictated by the mechanical scanning systems. . 2D-detector techniques have been developed to overcome these limitations, such as spectrum-photometric imaging [1] or ellipsometric imaging [2], but they are challenging to implement. An alternative approach is to determine thickness by evaluating the tint in Newton color interferences. This principle has already been applied to semiconductor films [4], magnetic head heights [5], friction phenomena [6], and SiO2layers (minimum 100nm thick) on silicon substrate [7]. However, color interferometry methods have rarely been applied in the industry because they require frequent calibration due to complex relationship (due to lighting and target film structure) between color and thickness. Additionally the periodic behavior of the phenomena that generates a cyclic repetition of colors which constrains the wider application of these methods.

To bypass these difficulties, a Michelson type interferometer was setup such that the light reflected on reference mirror and onto the surface of the thin film produce a flat tint. A color sensor records the tint that is produced in similar way as color interference fringes. Two screens alternately block the beams either from the reference mirror or from the substrate, to record reference intensities for measuring the thickness of the layer. When the screens are removed, the sensor records the interferences at any pixel location. Then, color interferences are approximated by a model based on the measurement of the laser intensities obtained with the reference mirror only. An iterative process leads to unambiguous algorithmic convergence and high accuracy thickness measurement. This method is simple, robust, compact, and single shot. The method does not need for angular scanning over the field of measurement (about 75mm2, limited by the sensor surface). The measurement on the entire surface yields a histogram of the thickness distribution and there is no need for any reference points (e.g. no need to make a groove or a walk on a layer covering a silicon substrate). A thickness measuring performance of 50nm was demonstrated for homogenous polymer films deposited on silicon wafer. Accordingly, this method shows great promise to be implemented at industry level. Set-up and digital image processing are discussed. Notwithstanding the procedure is illustrated with three-color, it can be extended to larger number of wavelength provide the appropriate detector is available.

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9525-8, Session 2

Novel dispersion tolerant interferometry method for accurate measurements of displacement

Adrian Bradu, Michael Maria, Univ. of Kent (United Kingdom); Lasse Leick, NKT Photonics A/S (Denmark); Adrian G. Podoleanu, Univ. of Kent (United Kingdom)

Spectral Domain Interferometry (SDI) can produce axial scanning (A-scan) of a sample with high resolution, high sensitivity and high speed. By performing a Fourier transformation (FT) of the channeled spectrum (CS) delivered by a spectrometer at the interferometer output, the CS modulation is converted into distance measurements. Generally, the spectrometer data is not delivered in equal frequency slots due to the geometry of the spectrometer and the angular dependence of diffraction on wavelength. Therefore, before the FT step, data need to be resampled. The resampling method [1] is limited to interferometers where the dispersion has been compensated for. Several other methods have been also demonstrated to linearize the data, with different degrees of complexity. The better the resampling of data, the more accurate the distance measurements become, as distance measurement is based on linear conversion between the number of peaks in the channeled spectrum and distance. However there are cases where dispersion is difficult to be compensated for, in which case these methods, even when using multiple phase points, cannot deliver perfect linear dependence between the modulation of the CS and distance in the interferometer. This is also a common problem in optical coherence tomography (OCT). Recently, we demonstrated, Master Slave Interferometry (MSI) applied to OCT [2-4]. MSI is based on comparison of CS shapes. Because no FT is needed, there is no need for data resampling. In the present work, we investigate the capability of MSI to be used for more accurate distance measurements than allowed by the conventional FT based SDI methods. To mimic the presence of the dispersion in the system, various lengths of single mode optical fiber were placed in the sample arm of the interferometer. Our experimental results clearly demonstrate that the MSI method can provide accurate A-scans profiles even in the presence of strong dispersion. The axial resolution provided by the MSI technique is immune to dispersion and calibration over the entire axial range. Even for an important chirping of the channelled spectrum created by large dispersion mismatch values, MSI still delivers accurate results. This should find applications not only in measuring distances and thicknesses of layers but also in low cost solutions for sensing. As a demonstration, we measured the thickness of a microscope slide and showed that MSI method delivers more accurate values than the conventional FT method, which fails to provide constant axial resolution along the entire axial range.

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9525-9, Session 2

Phase sensitive computer tomographic measurement using a pixelated phase mask interferometry technique

David I. Serrano-García, Yukitoshi Otani, Utsunomiya Univ. (Japan)

Single shot interferometers, based on polarization phase shifting techniques, are becoming of great interest due to its stability to external vibration and potential implementation in industrial environments. The main property of these interferometers is the capability to obtain the necessary information to retrieve the phase information on a single capture. These systems are commonly based on replication methods like: amplitude/phase gratings, add extra components for getting replicas of the interferograms or by using a pixelated polarizing camera.

A pixelated polarizing camera presents the characteristic of having a special mask aligned with the CCD sensor. This mask is composed by a special pattern where a linear polarizer at different angles is associated with each pixel on the CCD sensor. By taking into account this intrinsic characteristic, phase demodulation algorithms and interferometric systems can be proposed with the final purpose to retrieve the phase information of the sample in a single capture and with a stability to associate with physical properties of the sample.

In this work, we implemented a computed tomographic measurement system based on sensing the introduced phase changes of a transparent sample. The interferometry system is composed by a polarizing Michelson interferometer coupled to a pixelated camera in order to acquire the necessary phase shifted interferograms instantaneously.

By obtaining measurements at different angles of rotation, computed tomographic algorithms can be implemented and inner information of the sample could be retrieved Characteristics and limitations of the implemented system will be explained and experimental results showing inner distribution phase changes of a high temperature torch will be presented.

9525-10, Session 2

Spatial-frequency analysis algorithm for in-situ measurement of wavefront

Qian Liu, Yang Wang, Fang Ji, Jianguo He, China Academy of Engineering Physics (China)

Phase-shifting interferometry (PSI) has achieved widespread use in wavefront measurement due to its high spatial resolution and accuracy. Phase shifting maintains its high accuracy, but meanwhile introduces a drawback that no temporal disturbing is allowed, especially vibration. Phase-shifting error and interference pattern contrast fluctuation are the main error sources for measurement under vibration.

To apply PSI to in-situ measurement, we have proposed an algorithm to detect and suppress phase-shifting error and contrast fluctuation. The principle of the algorithm is that the confused information of spatial-carrier interferogram are separated from each other in spatial-frequency domain. The spectrum of a spatial-carrier interferogram is composed of three components, which are the baseband and positive and negative sidebands. The strength of baseband and sideband implies the pattern contrast. The position and phase angle of the sideband indicates the tilt gradients and translational value of phase shift. Thus, the phase shift error and contrast fluctuation could be extracted in frequency domain. Based on least-squares fittings, a contrast-compensated equation is established to calculate the wavefront phase. The proposed algorithm is verified by computer simulations.

To test the immunity of the proposed algorithm, experiments were carried out on a Fizeau-type interferometer. A pizeoelectric transducer (PZT) was employed to generate sinusoidal displacement to simulate the vibration. The PZT pushed the test mirror and 13 interferograms were collected in each measurement. Then the proposed algorithm was applied to the interferograms subjecting to vibration and wavefront phase was calculated. After unwrapping, the wavefront were reconstructed and compare with the exact value of the wavefront phase. The experimental results show that under vibration of one micron amplitude and 60Hz frequency, the error of wavefront PV value is less than 0.01wave and the 2? repeatability is less than 0.01wave. Quasi-in-situ measurements were conducted at the end. The measurement error is less than 0.005wave.

The proposed algorithm is deterministic and fast. The experimental results show that the proposed algorithm could suppress the errors arising due to vibration. The high accuracy and good repeatability of reconstructed wavefront imply the performance of the proposed algorithm. Meanwhile the algorithm conserves the high resolution ability of traditional PSI. For no hardware is required, the proposed algorithm provides a cost-effective method for wavefront in-situ measurement with PSI.

9525-11, Session 2

Nonlinear interferometry and application for black background tomography

Kamel Mallat, Alain Cornet, Univ. Catholique de Louvain (Belgium); José Luis Fernández, Univ. de Vigo (Spain)

Interferometry is a popular method that uses waves, which are superimposed to extract information about reflective or multilayer surfaces. It has many applications including the measurement of surface profiling, mechanical stress movement, and tomography.

There are two types of interferometry in which the light is used: the first popular one uses linear optic, the second uses nonlinear optic including a type I BBO crystal that generates the Second Harmonic Generation (SHG) and has its major applications in pulse femtosecond characterization.

But when working with multilayer sample, both methods suffer from the problem of low return field from the desired sites of interest within the sample, which leads to a low quality image with not enough contrast sometimes. If we insist on using these methods we can improve these by using numerical algorithms and so try to enhance the contrast and the quality of the images.

The idea of our novel method is to mix in a nonlinear type II crystal, the laser beams from the two arms of a Michelson interferometer. By exploiting the polarization properties of the light, it is possible to make this frequency conversion efficient only to the superposition of the two beams from the reference arm and the one from the desired interface. This can be done by realizing the optical contact, or in other words by setting the position of the reference mirror at equal distance from the beam splitter as the desired interface. Thus, the component of the converted signal comes only from the interference between the experimentally significant beams from the two arms of the interferometer. This allows us to isolate the useful signal component, which contains the tomographic information. Moreover, the frequency conversion permits recording the signal at a visible wavelength (650nm), while the sample is probed in the infrared (1300nm). From an experimental point of view, this is interesting because of the possibilities offered by sensitive detectors in the visible which exceed widely the most sensitive detectors in the infrared.

But the obtained signal contains then no information about the phase, because the pure type II SHG phenomenon excludes interferences; therefore we don't observe any Michelson fringes between the reference arm and the sample arm. Nonlinear and linear fringes can be observed using the type II SHG by turning the crystal around the light propagation axis. This will result in not eliminating completely the auto doubled signal from each arm (background noise); therefore it affects the contrast of the nonlinear fringe. The contrast can be controlled and it is a function of the rotation angle and the delay between the two arms of the interferometer.

A full description of the type II SHG phenomenon is presented, and then a detailed explanation of the theoretical model on how linear and nonlinear fringes can be obtained using second order autocorrelation interferometry, and what the parameters are that affect their contrast. An experimental setup is also presented with experimental results to validate our model.

Finally a no-optical background type II tomographic interferometer, using three waves coupling, is presented.

9525-12, Session 3

Evaluation of polymer matrix homogeneity using functional optical coherence tomography techniques

Marcin R. Strakowski, Michal Trojanowski, Paulina Strakowska, Maciej Kraszewski, Gdansk Univ. of Technology (Poland)

Nanotechnology is one of the most rapidly growing technology, which plays a very important role in today's world. It opens brand new areas of applications in science, medicine, industry and many more. However the success of the nanotechnology is mostly based on high quality of materials engineering. The nanocomposite materials features like strength, conductivity, optical properties, and others, highly depend on nanoparticles material, its size, shape, alignment and dispersion. The quality of the matrix, in which the nanoparticles are deposited, also has a critical influence on the proper behavior of the whole nanocomposite. Therefore, the matrix homogeneity should be tested and taken under control. One of the most widely used in industry are the polymer matrix like Poly(methyl methacrylate) (PMMA) or the wide range of types of polyurethanes, which are in the scope of authors interests. For these materials the quality assessment and testing are based on the manufacturing procedure. It forces to synthesize the polymer materials in exactly the same conditions, which sometimes is difficult to achieve. Therefore, fast, reliable and cheap methods for continuous monitoring of the manufacturing process are still of interests. For this purpose we propose to use an optical coherence tomography methods with functional extensions.

Optical coherence tomography (OCT) is an optical measurement technique for scattering object evaluation and testing. It delivers 2D and 3D images of tested device inner structure, which visualize the surface and subsurface defects and inhomogeneities with micrometer resolution. The OCT measurements are carried out in nondestructive, contactless, and absolutely safe way for the tested object. Therefore, the OCT is readily applied in medical diagnosis especially in ophthalmology and dermatology. Moreover, other applications like optical biopsy for tumor diagnosis or combination of OCT with endoscope are noticed. The high application potential of the OCT makes it an interesting measurement tool for beyond medical applications, as well. With the aid of OCT the scattering materials like ceramics, polymer composites, reinforced composite materials, MEMS, MOEMS devices and many more can be tested and evaluated successfully. The typical OCT system records the intensity of light backscattered from the particular points inside the tested sample. It produces the intensity images, which show up the internal structure of the sample. However, from the beginning of the OCT many new measurement techniques and signal processing methods have been developed in order to expand the range of measurements and OCT applications. Nowadays, one can distinguish several new extensions, which deliver more useful information about the tested device than typical pure OCT system. The main type of them are the Doppler enable OCT (D-OCT), polarization-sensitive OCT (PS-OCT), and spectroscopic OCT (SOCT). All these extensions make the OCT multifunctional ans increase OCT abilities for surface and subsurface defect detection.

Our research is focused on OCT with polarization sensitive and spectroscopic analysis. Till know we present the usefulness of this combination for measurements high birefringent media, as well as thin submicrometer films thickness estimation. In this contribution we are going show the plrizaton sensitive and spectroscopic OCT potential for polymer matrix evaluation. Based on measurement results obtained for PMMA matrix the defects, which can be detected by OCT, will be presented, as well as brief discussion on the usefulness of OCT technique for nanocomposite materials evaluation are going to be carried out.

9525-13, Session 3

The influence of speckle size in OCT for industrial applications

Guy Lamouche, Bruno Gauthier, Marc L. Dufour, National Research Council Canada (Canada)

Speckle is always present in Optical coherence tomography (OCT) images since OCT is a coherent imaging technique. One important characteristic of the speckle field is the speckle size. The speckle size is related to the optics used for illumination and collection. It is also related to the length scale of the scattering structures contained in the sample. When only a few scatterers are contained within the probed volume, the speckle field is partially developed and the speckle size is close to the point-spread function of the optics. For a larger number of scatterers, the speckle field is fully developed, leading to a smaller speckle size. Knowledge of the speckle size is of interest for industrial applications of OCT. It is a factor that limits the scanning speed when a surface can be continuously scanned. With the high measurement rates currently achieved by swept-source OCT systems, it is now possible to scan large samples on a time scale relevant to industrial applications. In order to optimize the scanning strategy, good knowledge of the speckle size is required. In this paper, we discuss the impact of the speckle size in both time-domain OCT and swept-source OCT for industrial applications.

We will first review our previous theoretical and experimental work [1] that describes the variation of the speckle size in relation with the nature of the sample, the sample being characterized the number of scatterers contained within the volume probed by the OCT measurements. We will then present experimental results taken with both time-domain OCT and swept-source OCT for varying scanning speeds. These results will be interpreted in terms of the interplay between the speckle size and the scanning speed.

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9525-14, Session 3

Robust fiber optic flexure sensor exploiting mode coupling in few-mode fiber

Bryan Nelsen, Florian Rudek, Westsächsische Hochschule Zwickau (Germany); Christopher Taudt, Westsächsische Hochschule Zwickau (Germany) and Technische Univ. Dresden (Germany); Tobias Baselt, Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

In the past few years, few-mode fiber (FMF) has become very popular for use in multiplexing telecommunications data over fiber optics. The simplicity of producing FMF and the relative robustness of the optical modes, coupled with the simplicity of reading out the information make this fiber a natural choice for communications. However, little work has been done to take advantage of this type of fiber for sensors.

Multi-mode fiber is extremely sensitive to bending, drastically changing the superposition of occupied modes with even the slightest perturbation in wavelength, temperature, or symmetry. This would make multi-mode fiber useful for a flex sensor, except that the myriad of modes excited in a multi-mode fiber become indistinguishable when using near- and far-field imaging techniques. Extracting exact information on the nature of the perturbation in multi-mode fiber can be difficult. On the other hand, in FMF, the mode coupling is weaker, but still exists, and the superposition of relatively few states (sometimes as little as 3 modes) can be determined using near- and far-field imaging and polarization techniques. This makes FMF a suitable candidate for flex sensing. Fiber flexure sensors are practical in high voltage or high temperature industrial environments where typical electronic flexure sensors would normally fail. Other types of fiber flexure measurements systems, such as Rayleigh back-scattering, are complicated and expensive and often provide a higher-than necessary sensitivity for the task at hand.

Here, we demonstrate the feasibility of using FMF as a mechanism for detecting flexure by exploiting the property that the LP01 mode couples to the LP11 modes when the cylindrical symmetry of the fiber is perturbed. To achieve these results, a single-mode fiber is spliced to the input of the FMF to provide a stable, clean, repeatable coupling to the LP01 mode of the FMF. The FMF was created by using a single mode fiber at a wavelength that was well above the cut-frequency for a single mode fiber (for example, 532 nm propagating down a single mode fiber with a cut-off frequency at 600 nm exhibits few-mode behavior). By launching into the LP01 mode of the FMF and detecting the intensity of

light coupled into the LP11 modes, we determine the amount of flexure the fiber undergoes. In the detection scheme, a linear polarizer is used to eliminate the residual signal from the initial LP01 mode and a spatial filter in the far-field detects either the LP11x or the LP11y modes. Theory predicts that more information about the direction of flexure is contained within the LP11x and the LP11y modes and their relative phases, however, more investigation is required.

9525-16, Session 3

Distributed fiber optic sensor employing phase generate carrier for disturbance detection and location

Haiyan Xu, Hohai Univ. (China); Hongyan Wu, Fudan Univ. (China); Xuewu Zhang, Hohai Univ (China); Zhuo Zhang, Min Li, Hohai Univ. (China)

In recent years, an increasing interest was demonstrated for many applications of the fiber optic sensing technology, such as intruder detection, moving vehicle location, and oil pipeline leakage monitoring, etc. Among all fiber sensor technologies, the interferometric fiber sensor has achieved great development because of its geometric flexibility, high sensitivity, safety and wide dynamic range.

In this paper, a distributed optical fiber sensor based on external modulation with a phase modulator is designed and studied, which committed to solve the problems that exists in the current location technology and to achieve the high-sensitivity and long-distance location. The sensor consists of a line-based white-light interferometers, multiplexed with a broadband light source, interfering unit and sensing fiber by piezoelectric ceramic transducer (PZT) in front of the Faraday Rotation Mirror, which is to elevate the signal produced by interfering of the two lights reflected by the Faraday Rotation Mirror to a high frequency, and other signals remain in the low frequency. Through a high pass filter and phase retrieve circus, a signal, which is proportional to the external disturbance is acquired. Then by means of the interference optical path, the change of light phase is switched to the change of light intensity. After demodulating, the phase shift of interferometric signals can be transformed into spectrum, and the position of the disturbance signals can be measured.The performance of the sensor is examined and compared with the conventional sensor, based on the null frequency of the spectrum of the phase difference generated by the disturbance, through an experimental setup with the total length of sensing fiber up to 30 km.

The accuracy of disturbance positioning with this signal can be largely improved. This method is quite simple and easy to achieve. Theoretical analysis and experimental results show that the sensor is advantageous for easy installation, low location error and flexibility, especially in long-distance perimeter security application.

9525-18, Session 4

Sparsity promoting automatic focusing in digital holography

Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Melania Paturzo, Istituto di Cibernetica Eduardo Caianiello (Italy); Bahram Javidi, Univ. of Connecticut (United States); Paolo A. Netti, Istituto Italiano di Tecnologia (Italy); Pietro Ferraro, Istituto di Cibernetica Eduardo Caianiello (Italy)

One of the most interesting features in digital holography (DH) is the possibility to a posteriori retrieve the focus plane, by simulating a discrete implementation of the diffraction Fresnel propagation integral. This feature makes DH an elective method for several applications, such as 3D tracking, 3D display, quantitative imaging and others. Therefore, an automatic method, able to retrieve the focus distance of an object of interest, is a challenging tasks. Basically, most autofocusing strategies are based on maximization/minimization of a suitable image contrast measure, applied to the amplitude reconstructions of digital holograms varying the reconstruction distance [1]. However most of them present several local extrema points, which could be caused error in the search for the global extreme. A recently published method, based on the Tamura coefficient [2], has the property to have only one extreme in the whole focus range, making it an elective strategy to focus plane detection.

On the other hand, sparsity properties of digital holograms have been investigated for application in compressive holography, permitting the discovery of the sparsest reconstruction plane in which the recovery of digital holograms is suitable. Recent approaches for denoising and phase retrieval are also proposed exploiting the sparsity properties of digital holograms. Thus it can be shown a strong correlation between holograms sparsity and focal plane detection, making a sparsity measure coefficient as a candidate to be used for focus plane calculation. Here we implement different sparsity metrics, that are able to measure a degree of sparsity of reconstructed digital hologram and we investigate their relation with the automatic focusing criterions, highlighting the possibility to use a spartity measure as refocusing metric as well as the contrary, i.e. using image contrast coefficients as sparsity measures [3]. Our analysis will be reported for digital holograms recorded in both lensless and microscope configuration and for both amplitude and pure-phase objects.

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9525-19, Session 4

Holographic position measurements of an optically trapped nanoparticle

Kazufumi Goto, Takumi Yanagawa, Ryosuke Abe, Yoshio Hayasaki, Utsunomiya Univ. (Japan)

Optical tweezers is a well-known technique used to trap and manipulate micro-objects in a liquid. Optical tweezers are used to manipulate gold nanoparticles when the motion, state, and function of a biological system are measured. An optically trapped gold nanoparticle has been used as the probe tip of a near-field optical microscope. The influence of heat on an optically trapped gold nanoparticle has also been discussed. Stable optical trapping of gold particles with diameters ranging from 18 to 254 nm has been demonstrated. To know a structure, movement, mechanical property, and functional property of a target object, a position detection of the optically trapped gold nanoparticle that has an interaction with the object is indispensable. A gold nanoparticle with a diameter of 9.5 nm has been successfully trapped in optical tweezers and detected with a quadrant photodiode (QPD) method.

Use of a camera is effective for measuring optically trapped objects three-dimensionally. A recently developed high-speed camera provides a temporal resolution comparable to that of a QPD. 3D position measurement of trapped particles with a micrometer-order diameter has been demonstrated by using digital holographic microscope (DHM). We have demonstrated position detection of a 200 nm polystyrene particle held in optical tweezers by using low-coherence inline DHM and 3D sub-pixel estimation. Recently we also applied to a gold nanoparticle with a diameter of 60 nm. A holographic method in combination with evanescent illumination and a heterodyne technique has been applied to measure the position of a gold nanoparticle fixed in a polymer on a substrate, allowing position measurement of a 10 nm particle with a high signal-to-noise ratio. A holographic method with a dark-field arrangement for motion measurement of a nanoparticle has been developed. A twilight-field optical arrangement implemented with a low-frequency attenuation filter (LFAF) has also been developed. These methods are effective for the detection of ultra-weak light from a nanoparticle because they can improve the signal-to-noise ratio by controlling straight-through nonscattered light and undesired scattered light.

In this paper, we demonstrate the position measurement of an optically trapped gold nanoparticle using low-coherence inline DHM with a pattern matching method and 3D sub-pixel estimation. The optical tweezers

suppresses the Brownian motion of a gold nanoparticle and controls the position of a gold nanoparticle. The twilight-field method enables us to measure the 3D motion of a gold nanoparticle with a diameter less than 50 nm. This system will be used for topography of a target object with a nanometer resolution; therefore the minimization of the detectable size that decides the spatial resolution is important. This technique will be also applicable to investigate surface chemistry on a solution/solid interface and a laser ablation in solution.

The experimental setup was composed of an optical tweezers and a low-coherence, in-line DHM. In the optical tweezers system, a beam from an Yb-fiber laser with a wavelength of 1070 nm was collimated and focused in a sample solution using a 60? oil-immersion microscope objective lens (OL) with a numerical aperture of NA = 1.25. The irradiation laser power at the sample was calculated as the product of the power measured before introducing the laser beam and the transmittance of the OL. The sample was suspensions of gold nanoparticles (diameter = 40 nm). In the in-line DHM, the light source was a supercontinuum light source (SuperK EXTREME?NKT Photonics). The spectrum was controlled by a filter with the center wavelength of 590 nm and the width of 25 nm. The scattered light from a nanoparticle (the object light) and the straight-through nonscattered light (the reference light) interfered with each other on a cooled charge-coupled device (CCD) image sensor.

A 40 nm gold nanoparticle was successfully trapped by the optical tweezers and measured the three-dimensional positions. The detectable axial region estimated from the 3D motion of the gold nanoparticle was from -300 nm to +900 nm, with the origin at the trapping point. The lower limit was the focal plane of the DHM, and the upper limit was determined by the decrease in fringe visibility caused by the reduction in light intensity due to diffraction. When the laser intensity was 0.39 MW/cm2, the gold nanoparticle moved considerably as a result of Brownian motion, especially in the axial direction, because the axial force was lower than the lateral force. The axial motion was larger in the beam direction, and the gold nanoparticle sometimes went out of the laser focus region in the upward axial direction (the beam direction) beyond the axial detectable region. As the laser intensity was increased, the motion became smaller. When the laser intensity was 8.41 MW/cm2, the gold nanoparticle was almost fixed, and the lateral and axial variations were 6.3 nm and 5.6 nm, respectively.

In conclusion, the 3D motion of 40 nm gold nanoparticles held by optical tweezers in water was measured using a low-coherence in-line DHM by introducing the twilight field method. This is the smallest reported particle whose 3D motion was measured in water. The accuracies were 6.3 nm in the horizontal direction and 5.6 nm in the axial direction, respectively. The twilight field method gave higher contrast of interference fringes. Consequently, the axial resolution was improved as a result of an enlargement of the size of hologram.

9525-20, Session 4

Color holograms synthesis framework for three-dimensional scene reconstruction

Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Marco Leo, Cosimo Distante, Istituto Nazionale di Ottica (Italy); Melania Paturzo, Pietro Ferraro, Istituto di Cibernetica Eduardo Caianiello (Italy)

Digital holography (DH) has the great advantages related to the objects reconstruction process, that can be carried out numerically, by implementing a discrete version of diffraction propagation law. The latter property offers the possibility to envelope numerical methods for different applications, such as multiplexing, compression, denoising, tracking, 3D display and so on.

In particular, applying adaptive transformations on the recorded holograms, the correction of wavefront aberrations, such as tilt and defocus [1], depth of field extension of a tilted objects in both Fourier and Fresnel configurations, and full control of the object's positions and sizes in a 3D volume with high depth-of-focus [2], become feasible. Thanks to the latter, synthesis of 3D holographic scene, combining multiple digital holograms of different objects can be obtained and a realistic 3D display could be performed. Similar approach is already used for Computer Generated Holograms to numerically implement zoom function [3], i.e. without using a zoom lens apparatus. On the other hand, affine transformation method proposed was also used to correct chromatic aberrations in color holography, where digital holograms of the same object are recorded at multiple wavelengths [4]. However, holograms transformation could be introduce artifacts expellee related to the presence of speckle noise. Therefore, a preliminary processing on digital holograms is needed before to apply spatial transformation in order to reduce the noise effect. For this purpose, we prose a complete framework for Coding color three-dimensional scenes and joining different objects by adaptive transformations in DH. We implement two main process: (i) we use a novel speckle reduction method based on Bi-dimensional Empirical Mode Decomposition (BEMD) [5], then (ii) we synthesize 3D scene of different objects, which are recorded with red green and blue wavelengths, with the aim to improve the 3D color holographic reconstructions. We will test the proposed method also for color computer generated holograms (CCGH).

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9525-21, Session 4

Off-axis illumination in object-rotation diffraction tomography for enhanced alignment and resolution

Julianna Kostencka, Tomasz Kozacki, Warsaw Univ. of Technology (Poland)

Optical diffraction tomography (ODT) is a non-invasive method for quantitative measurement of micrometer-sized samples, which over a recent decade proved its great potential in investigation of technical elements [1-3] and in study of biomedical specimens [4-6]. In ODT a series of multiple holograms captured for various illumination directions with respect to a sample is processed using a tomographic reconstruction algorithm. The result of tomographic evaluation is 3D distribution of refractive index or/and absorption coefficient.

Data acquisition in ODT is commonly realized in two ways, either by rotating a sample under fixed illumination and observation directions (object rotation configuration ORC), or by scanning the illumination direction of a fixed sample (illumination scanning configuration ISC). From the purely theoretical standpoint, the ORC configuration is superior to ISC due to larger and more isotropic optical transfer function [7,8]. However, the theoretical maximal resolution of ORC is lower than the maximal resolution, which can be provided with ISC (axial and transverse resolution of ORC dxOR=dzOR=2sin(?/2)/?; transverse resolution of ISC dzIS=2sin(?)/?). Moreover, the quality of tomographic reconstructions in ORC is significantly degraded due to experimental difficulties, including 1) misalignment of the rotation system (error of the rotation step); 2) insufficient accuracy of determination of the rotation axis location.

In this paper we propose a new ODT approach, which provides solution to the all mentioned limitations of ORC. The proposed tomographic approach, besides rotation of a sample in a full angle of 360°, uses simultaneous illumination of a sample from two fixed highly off axis directions. The proposed modification enables 1) an accurate detection of the rotation axis location and precise alignment of tomographic data; 2) enhancement of optical transfer function up to the theoretical limit of ISC. The proposed here marker-free alignment method uses an accurate autofocusing algorithm based on off-axis sample illumination, which was recently developed by Gao [9]. The autofocusing method together with the correlation-based tracking technique enable precise determination of axial and transverse position of the rotation axis and, after application of sine fitting procedure, allow for correction of the angular step error. To take a full advantage of the combined OR-IS tomographic configuration, we apply a diffractive tomographic reconstruction procedure, which takes into account specific illumination conditions of a sample and provides

enhanced resolution of a tomographic 3D image. The utility of the proposed concept is experimentally demonstrated with a tomographic measurement of an optical microtip.

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9525-169, Session 4

Resolution enhancement in phase imaging by using modulated illumination *(Invited Paper)*

Peng Gao, Karlsruhe Institute of Technology (Germany) and Univ. Stuttgart (Germany)

Phase imaging is of fundamental importance for technical and biomedical investigations, since the phase contains the information about the 3D shape and the inner structure of transparent or translucent samples. In this paper we show how resolution enhancement in digital holographic microscopy (DHM) and reference-less phase retrieval approach is obtained by using modulated illumination.

Digital holographic microscopy (DHM) is an important high-precision phase imaging technique. Here the resolution enhancement of DHM based on structured illumination is firstly discussed. Binary phase gratings with different orientations and phase shifts are loaded sequentially on a spatial light modulator (SLM) to generate structured illumination. The object wave under such illumination is holographically recorded. After the waves along different diffraction orders of the structured illuminations are reconstructed, they are combined in the Fourier plane to achieve a synthetic aperture. Thus, an enhancement in spatial resolution is obtained. Compared with other synthetic aperture methods, the proposed method enables to shift different illumination directions without mechanical movement, and enhances the resolution of phase image with high speed and high repeatability.

Resolution improvement of DHM with speckle illumination is also investigated. Speckle fields can be regarded as a combination of plane waves with various illumination directions, and each of them will downshift the spectrum of the object, and the high frequencies of the object can pass through the limited aperture. The resolution enhancement can be obtained through averaging the complex amplitude of the reconstructed object waves under different illuminations. This method requires the spectrum of the speckle illuminations has a uniform distribution, i.e., equal distribution for low and high frequencies. Otherwise, the averaging operation will produce a wrong weighting of the spatial frequencies in the reconstruction. Here an iterative method is used for spectrum synthesis, which has no special requirement on the spectrum property of the speckle field.

Resolution enhancement of reference-less phase retrieval was also implemented by using the modulated illumination. Unlike the DHM which needs an additional reference wave to perform the phase imaging, the phase retrieval method can obtain the phase image in absence of a reference wave. To perform phase imaging and resolution improvement, the random patterns are generated by SLM and are projected to the sample plane; the diffraction patterns of the object wave under these illuminations are recorded by a CCD camera. An iterative method is used to reconstruct the phase from these diffraction patterns and improve the spatial resolution.

9525-22, Session 5

A new class of wide-field objectives for 3D interference microscopy

Peter J. de Groot, James F. Biegen, Zygo Corporation (United States)

For decades interference microscope objectives have been either of the Mirau or the Michelson type, with the rare Linnik double objective for specialized applications. The Michelson dominates at low magnifications (<20X), and is usually assembled from a conventional or long-working distance lens, a beam-spitting prism, and a reference arm assembly jutting out orthogonally to the main axis of the objective. For magnifications below 2X, the Michelson design becomes unwieldy, particularly if the desire is to mount the objective on a turret with other objectives of higher magnification.

We have developed a new interferometer design for interference microscopy to replace the Michelson for wide field of view applications (US Patent 8,045,175). The new design uses partially-transparent, parallel plates coaxial to the optical axis of the lens. A small tilt angle for both plates directs unwanted reflections off axis, where they are blocked by internal apertures, leaving only pure two-beam interference of high contrast, with the zero optical path difference position coincident with the position of best focus. Although the imaging is through tilted plates, the optical design achieves well-controlled lateral chromatic aberration and distortion < 0.1% over the full field. The result is an exceptionally compact design suitable for low magnifications and broadband illumination.

The primary target application is the measurement of technical surfaces using coherence scanning interferometry (CSI). Measurement precision depends on part texture, with best results for optically smooth surfaces. The surface topography repeatability for a single image field on a polished reference artefact is 2 nm for individual CSI measurements and 0.1nm/root(Hz) for continuous averaging using sinusoidal phase shifting interferometry. The same objective using CSI accommodates surfaces that are rough on the scale of optical wavelengths, as well as steep slopes outside of the numerical aperture of the lens, using sensitive signal detection software and oversampling. The resulting scope of application ranges from testing machined metal parts to optical components and semiconductor wafers.

We describe in detail three different versions of the new objective type:

(1) A 1.4X objective with a 12x12mm field that is turret-mountable and parfocal with high-magnification objectives up to 100X. This objective has a 4mm working distance and a numerical aperture of 0.04. This objective is particularly interesting for setups that target fully automated form and roughness measurements on the same platform.

(2) A 1X objective with a 16 mm working distance and 17x17mm field, turret mountable and parfocal with other long-working distance objectives.

(3) A dovetail mount 0.5X objective with a 34x34mm field suitable for high-speed, single field measurements of surface form. Example data for this objective include the parts up to 170mm using automated field stitching.

9525-23, Session 5

Interferometric measuring system for cone inspection on shop-floor level

Till Grübler, Pawel J. Drabarek, Robert Bosch GmbH (Germany)

Small and precise cones are one of the most important functional surfaces for valve seats of today's modern common rail injection systems

for Diesel engines. The quality of the valve seat has a direct impact on fuel consumption and particle emissions and is therefore regarded very closely. Those surfaces are often located inside a small drilling and the typical measuring tasks are angle, roundness, straightness and surface profile e.g. Pt value. Commonly used tactile measuring systems are not able to measure form parameter of such hard-to-access surfaces enough accurate and do not give sufficient information regarding surface quality. We have investigated two concepts of interferometric systems for industrial examination of small-size conical geometries: white-light-interferometer with an endoscopic probe and a special form-measuring-machine with an interferometric stylus ([1], [2]).

We have used a commercial white light interferometer and developed endoscopic probes with a small field of view and with a 360 degree field of view ([3], [4]). Great advantages of white light interferometer systems are the short measuring time and no movement of part during measurement. However endoscopic probes are critical for small and deep drillings, as the optical layout becomes very complex and expensive. For this reason with such an endoscopic probe it is only possible to measure a small area of the cone with very limited information regarded the functional properties of the part.

To increase the universality of small size cone measuring systems, we followed the concept of a special scanning form measuring machine using a single-measuring-point interferometric stylus. The optical system is based on a concept of short coherence heterodyne interferometry working with two wavelengths. It is divided in two subsystems: a modulation interferometer and a small and robust optical probe (stylus) with a diameter of 0.5 mm connected through a single monomode optical fiber. The architecture of the machine is similar to typical form measuring machines. It contains a high precision air bearing, rotatory table and short linear stage. The stage is tilted, that the direction of motion of the stage is parallel to the theoretical shape of the cone to be measured. The part is fixed on the rotary table and the stylus on the linear stage. During measurement the part is rotated and the stylus moves along the line parallel to the cone-shape. The interferometric measuring system collects distance data and the 3D shape of the cone will be generated and presented. Based on the data cloud different parameter will be calculated e.g.: angle, roundness, straightness, Pt value. We have performed first measurements and repeatability tests on the shop floor. Based on standard capability evaluation [5] (Cgk and Cg) we have achieved the following measuring system capabilities: angle T> 0.07°, roundness T>0.3 μm, Pt Value >0.3 μm.

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9525-24, Session 5

Cross-linking characterization of polymers based on their optical dispersion utilizing a white-light interferometer

Christopher Taudt, Tobias Baselt, Westsächsische Hochschule Zwickau (Germany); Gernot Oreski, Polymer Competence Ctr. Leoben GmbH (Austria); Christina Hirschl, Carinthian Tech Research AG (Austria); Edmund Koch, Technische Univ. Dresden (Germany); Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

The increasing usage of polymers in large scale industrial applications such as photovoltaics, semiconductor production or renewable energy production demands a reproducible and stable manufacturing processes. Therefore it is necessary to be able to characterize materials at all stages of the production as well as during the desired operation. With regard to the reliability and long-term stability of crosslinked polymers, the degree of curing is an essential property. It determines the mechanical and optical properties directly after manufacturing and can also be used as an indicator for aging effects due to exposing the polymer to temperature, radiation or humidity during itsoperation.

Known methods to determine the cross-linking state such as differential-scanning caliometry, dynamic mechanical analysis, soxhlet extraction, etc. are rather complex in instrumentation and execution. Besides that, they are not suited for in-process or in-situ measurements. In contrast, this work aims to provide a novel approach which takes these aspects into account. For that purpose, a white-light interferometer based on a supercontinuum light source for combined time and spectrally resolved measurements was set up. In that setup, a polymeric sample is placed in one arm of a Michelson interferometer and the delay is controlled by a piezo-driven translation stage in the other. The recombined interference signal is detected in the spectral domain at distinct postions of the translation stage. Due to the material dispersion of the sample, this signal consists of an oscillation of which the phase is dependent on the refractive index of the sample. Therefore the oscillation shows a clear equalization wavelength for every position of the translation stage, where the derivative of the phase is zero. Using this approach it is possible to record the wavelength dependent time delay in the interferometer which is introduced by the polymeric sample. This information is used to calculate the material dispersion of the sample.

It could be shown that this method is suitable to determine differences in the curing of polymers. In particular the work analyses samples of the widely used encapsulant of photovoltaics modules, ethylene vinyl acetate (EVA). The samples were cross-linked using a lamination technique for different curing times (0 – 20 minutes). By determinating the optical dispersion in the wavelength range of 400 – 1000 nm with the proposed technique it was possible to discriminate the differences in crosslinking for the given curing times. One important feature of this approach is the possibility to perform space resolved measurements of the crosslinking state with μm-resolution. Furthermore the paper discusses the mathematical analysis and processing of measurement data and shows a prototype solution for the fast and automated data aquasition for industrial application.

9525-25, Session 5

Robust vertical scanning white-light interferometry in close-to-machine applications

Stanislav Tereschenko, Peter Lehmann, Pascal Gollor, Peter Kuehnhold, Univ. Kassel (Germany)

Vertical scanning white-light interferometers (SWLIs) measure the 3D-topography of even discontinuous reflective surfaces with nanometer height resolution. During the measurement they perform a so called depth-scan by varying the distance between the interferometer and the measured specimen continuously. During this movement a camera shoots several hundred images at equidistant axial positions. After the measurement the 3D topography is obtained from the captured images by evaluating the intensity of each pixel along the measurement direction.

Due to shorter development times and increasing quality requirements in industries there is a general trend towards analysis of the quality of products during production. Because of the high resolution and short measurement times SWLIs are well suited for such kind of applications. However, vibrations in the production environment caused by running engines will often make the use of today's white-light interferometers difficult or nearly impossible.

We present a novel approach in white-light interferometry which is insensitive to environmental vibrations and can be used in close-to-machine applications for in-situ measurements.

For this purpose we integrated a laser distance interferometer (LDI) with high temporal resolution into the optical path of the white-light interferometer. To demonstrate the feasibility of the concept we use a

Michelson interferometer configuration. Both, the SWLI and the LDI share a part of the optical path comprising the objective lens and the reference mirror. The measure-ment spot of the LDI is within the field of view of the SWLI. So the LDI is able to measure any distance change during the white-light measurement. In order to minimize the influence of the laser light on the white-light measurements we use a NIR laser source and an additional NIR blocking filter in front of the camera of the SWLI. With the knowledge of the real distance changes during the measurement we can compensate for the influence of environmental vibrations on the white-light correlograms. The reconstruction of the white-light interference signals takes place after measurement by reordering the captured images in accordance with their real positions obtained by the LDI. Non-equidistant positions between reordered images can be interpolated in order to achieve compatibility with conventional SWLI envelope and phase evaluation algorithms.

With this system we are able to reconstruct completely distorted and unusable SWLI signals and to determine the 3D topography of the measurement specimen from these reconstructed signals with high accuracy. We demonstrate the feasibility of the method by examples of practical measurements with and without vibrational disturbances.

9525-26, Session 5

Development of a compact low coherence interferometer based on GPGPU for fast microscopic surface measurement on turbine blades

Yinan Li, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

The microscopic surface inspection of engine components is a relevant prerequisite for the aviation maintenance [1] and the optimization of the aerodynamic performance [2]. This paper introduces a high-precision optical measurement system with an optimized small sensor head for the measurement of precision surfaces on a blisk (Blade integrated disk). The non-contact measurement system is based on a low coherence interferometer (LCI). An envelope algorithm to find the central fringe position in the LCI measurement signal is accelerated by the Compute Unified Device Architecture (CUDA) technology, which allows parallel evaluation of the different pixels of camera matrix stacks on independent cores of a General Purpose Graphics Processing Unit (GPGPU). In the future this compact measurement system will be included in an industrial robot based guided system for the automated measurement of Turbine Blades.

The experimental setup of measurement system is based on a conventional Michelson configuration, where the interference pattern can be caused by the different pathlengths between the orthogonal reference and measurement paths. The system uses a deep red light-emitting diode (LED) light source, which outputs high brightness and a low coherence length in nature. In order to reduce the size of the system, the measurement path and the light source path are rotated against the optical axis of the beam splitter by mirror reflectors. A high speed charge coupled device (CCD) camera with 4x telecentric lens used in the system is capable of recording the images at a relatively large focus distance. With the help of a rotatable mirror at the sensor head, the system can further measure an object surface flexibly parallel or orthogonal to the optical axis.

In the measurement procedure, an Arduino microcontroller synchronizes the camera shutter and the fine movement of the piezo stage, which changes the length of the reference path. The observed data stack form the camera is evaluated by a Hilbert-Transform [3] to find the central fringe position in z direction of different camera pixels. In order to accelerate the evaluation algorithms, a program based on CUDA technology is developed, which allows parallel evaluation of data stacks on independent cores of a GPGPU.

As a result, a real measured surface of a worn turbine blade after the removal of the protective layer will be measured with our LCI system. Moreover, in order to reduce the computing time a GPU-based evaluation algorithm for LCI, which runs on NVIDA GPUs via CUDA, is developed. The GPU-algorithm is tested on an Intel i5 CPU with NVIDA GTX970 graphic card. The GPU result is compared with the original CPU-based single-threaded algorithm to show the 60x speedup of computing the Hilbert-Transformation. The advantage of the GPU computing enables the microscopic surface measurement in a short time.

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9525-27, Session 5

White-light interferometry optical fiber sensing for high-accuracy distance measurement in industrial applications

Magnus Lindblom, Acreo Swedish ICT AB (Sweden); Håkan Dahlquist, System 3R International AB (Sweden)

The manufacturing industry has a steady need to improve production yields and product quality. Non-destructive on-line monitoring systems have therefore become a prerequisite for many companies to keep a competitive edge. The steady progress in photonic components in terms of cost-to-performance ratio, maturity and robustness opens new avenues for the commercial deployment of photonic sensor systems in a wide range of industrial applications.

Our concept applies at large to instrumentation for precision manufacturing, where the accuracy required in fabrication is at the sub-micron level. A low-cost sensor solution has been developed to very accurately determine the position of a workpiece in a robotic manufacturing line based on a chuck-pallet positioning system, where the chuck is attached to a machining unit and the pallet holds the workpiece. The chuck-pallet clamping system improves machining precision and reduces set-times for processing when workpieces are moved between different pieces of machining equipment. While the mechanical clamping accuracy is in most cases sufficient, there is a group of emerging applications, including high-precision moulds for optical elements, that requires higher accuracies, on sub-micron level. By integrating an optical fiber into the steel chuck and using non-contact optical techniques, the clamping system is enhanced by measuring the absolute position of the work piece within tens of nanometers.

Our white-light interferomerty fiber optic sensor merely consists of a broad-band light source, a spectrometer and an optical fiber probe. Owing to their small sizes, optical fibers are minimal invasive and can be embedded in a large variety of equipment. The spectral analysis of interferences between light that is reflected by the end-face of the fiber (the reference surface) and light reflected by the target (the signal surface) provides a measurement of the distance between the reference and the signal surfaces. Advantages of whit-light interferometry as a demodulating technique for interferometric signals include access to absolute measurements and high accuracy thanks to advanced algorithms.

Results from lab and field tests will be presented and discussed, as well as advantages, limitations and future possible extensions of the technology.

9525-28, Session 6

Robust speckle metrology for stress measurements outside the lab *(Invited Paper)*

Matias R. Viotti, Armando Albertazzi Gonçalves Jr., Univ. Federal de Santa Catarina (Brazil)

Nowadays, civil structures as for example bridges or buildings as well as mechanical parts belonging to cars, planes, trains, etc. are present in people life solving problems and mainly simplifying life. These structures and mechanical components were designed by considering their application as well as the particular problem to be solved for them. Additionally, the final part must be functional, safe, reliable, competitive,

usable, manufacturable and marketable.

Visual inspection was the first way to evaluate health integrity of a mechanical or civil structure. Nowadays, it continues to be an important, valuable and widely used non-destructive method for the assessment of discontinuities open to the surface of the material. Advances in the area of optics, digital image storage and digital image processing have expanded the field of application of visual inspection. In this case, optical methods can be seen as an extension of this technique since they are used to "monitor" the surface of a material under test and to identify possible anomalies not only on the surface but also below it.

Optical techniques are usually related to laboratory rooms which are places equipped with temperature, humidity and vibration control. These techniques are very suitable for fast measurements due to their non-contact nature and full-field capability. Among them, optical methods based on the speckle phenomenon have had a great development during the last two decades because of the development of digital image processing, cameras, computers, lasers and optical components. Speckle techniques have the advantages cited for optical methods. Additionally, they are adequate for the evaluation of real components without further preparation of the surface and without high time consuming to be analyzed. This paper supplies tools tips and reference parameters to develop interferometers based on the speckle phenomenon to be used outside the laboratory room. Finally, several applications, outside the lab, for the measurement of mechanical and residual stresses are presented. These examples show the high potentiality of speckle metrology as an auxiliary tool for structure integrity assessment.

9525-29, Session 6

Reduction of phase singularities in speckle-shearing interferometry by incoherent averaging of speckle patterns

Klaus Mantel, Max-Planck-Institut für die Physik des Lichts (Germany); Vanusch Nercissian, Norbert Lindlein, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Speckle interferometry is a well established technique for the deformation measurement of rough objects. For most speckle techniques, however, phase singularities appear in the measured phases, impairing the phase unwrapping process. Sophisticated software algorithms have been developed, allowing the calculation of the unwrapped phase despite the presence of singularities. Nevertheless, it would be preferable to apply a physical procedure to reduce the number of phase singularities in the speckle phase fields in the first place. Here, averaging of mutually incoherent speckle fields can be used. When several such speckle fields are incoherently superposed, the intensity statistic is altered; phase singularities, which are associated with locations of zero intensity in the speckle field, become less likely. As a measurement geometry, we chose speckle-shearing interferometry.

To realize an incoherent averaging in speckle-shearing interferometry, however, the shape of the light source has to be matched to the shearing geometry according to the van Cittert-Zernike theorem – then a shear of the wavefront still gives rise to high contrast interference fringes. To this end, we proposed to use a periodic light source for the desired incoherent averaging, in the hope of reducing the number of singularities in the phase fields in turn.

With the help of such a periodic design, spatially extended, incoherent (but monochromatic) light sources may now be used in speckle-shearing interferometry without any significant loss of visibility of the fringes. Apart from its effect on the phase singularities, the influence of coherent noise will be reduced and smoother phase maps are obtained.

During our investigations, it turned out, surprisingly, that the effectiveness of the averaging on the phase singularities depends on the ratio of speckle size and shearing distance. We were able to explain this phenomenon by noting that the phase shifting of an incoherent sum of intensities is equivalent to the addition of certain vector fields associated to these intensities. With the help of this map, it turns out that the phase statistic of the single speckle fields is responsible for the behaviour described above. For a standard speckle field, the phase distribution is constant in the interval [-pi,pi [. However, this changes in speckle-shearing interferometry, where the frequency of occurrence of phase values depends on the ratio of speckle size and shearing distance. A deviation of the phase statistic from the constant one, however, causes a preferred direction in the associated vector fields. The addition of random vector fields with bias makes the preferred direction more pronounced as the averaging proceeds. Eventually, the preferred direction dominates the whole sum vector field, reducing the number of phase singularities in turn.

There is, however, a considerable drawback: As a direction in the vector field gets more and more pronounced, the systematic phase encoding the information about the deformation of the specimen is reduced, too. Incoherent averaging therefore gradually destroys the desired phase information. It can only work if the number of light source points is chosen small enough to ensure a sufficient reduction of the phase singularities, while at the same time preserving the systematic phase within a reasonable tolerance bound.

9525-30, Session 6

Bending stress determination in pipes using a radial in-plane digital speckle pattern interferometer combined with instrumented indentation

Filipe Fontana, Matias R. Viotti, Armando Albertazzi Gonçalves Jr., Univ. Federal de Santa Catarina (Brazil)

This paper presents a modular device based on digital speckle pattern interferometry (DSPI) combined with an instrumented indenter. The system is divided in two modules, the interferometric and the indentation module. The former uses a diffractive optical element (DOE) to obtain radial in-plane sensitivity. This module measures the whole shallow displacement field generated by the indentation print on the surface of the material under testing. The latter module is sized suitably with the interferometric module. The indentation module uses a mechanical/hydraulic scheme to provide the system a high loading capability in a compact module. A piezoelectric loading cell and an inductive transducer are used to simultaneously measure the load applied on the ball indenter and its penetration on the material. For the experimental tests, a bench capable to apply in a specific pipe a very well-known bending moment was used. This bench is mounted with two 12-meters pipes disposed horizontally. A transverse load is applied in the central cross-section of both pipes creating a linear bending moment distribution along the length of the pipes. The load application is made by a hydraulic actuator and measured with a load cell. Strain-gages are also used in a half-bridge configuration to measure the strain in the 8 cross-sections distributed along the pipe length. To perform the experiments, each cross-section was measured by the proposed instrumented indentation system and compared with the strain-gages and load cell measurements. To compute the surface displacement a processing image software is used. The stress calculation in each measured point of the surface is made through an algorithm that uses the displacement curve to calculate a proportional constant for each point in relation with a reference displacement curve. Using the longitudinal stress calculated for each point of the cross section, a mathematical model is used to compute the bending moment, bending stress and the neutral axis orientation. The measurement uncertainty calculated in this work is associated to the curve fitting by using the least-squares method in the mathematical model, the results obtained show an uncertainty level around 20-30% of the measured bending stress. To evaluate the result a chart is used to compare the results of bending stress measurement using the load cell, strain-gages and the instrumented indentation system. Good agreement was found between the computed bending stress using the strain-gages, load cell and the proposed method using the instrumented indentation system.

9525-31, Session 6

Influence of error sources in speckle interferometry using only two speckle patterns

Yasuhiko Arai, Kansai Univ. (Japan); Shunsuke Yokozeki, Jyoukou Applied Optics Lab. (Japan)

Speckle interferometry is one of important deformation measurement methods for an object with rough surfaces. The method has been developed as ESPI(Electronic Speckle Pattern Interferometry) with a high resolution power by using TV-technology and fringe scanning methods. However, because the method uses the general fringe scanning methods, at least three speckle patterns have been usually required for a high resolution power. In order to solve such a problem, the development of fringe analysis that uses as less number of speckle patterns as possible for analyzing deformation information has been strongly hoped. Some technologies based on Duffy's idea have been proposed for solving the problem. Under these technologies, the fringe analysis based on the idea of "difference of phase method", however, has been proposed by processing the information of speckle patterns on each pixel of camera. Therefore, there is a problem which resolution power is strongly influenced by the random noise included in speckle patterns. As the results, it is thought that it is difficult to analyze the deformation in high resolution by these methods. The novel fringe analysis method using a new optical system, which uses a plane wave as the reference beam of the speckle interferometer, was proposed by authors. When the proposed optical system is employed in the fringe analysis, the deformation information and the bias components of the speckle patterns clearly are separated in frequency domain. Therefore, the deformation information can be readily extracted by using Fourier transform. In the fringe analysis processing, a pair of real- and an imaginary-part components concerning the information are extracted. The specklegram can be calculated with a pair of real- and imaginary-part components under the idea of "phase of difference method" in this novel fringe analysis by multiplying these components before and after deformation. Then, the deformation signal can be extracted by an enhanced filtering technology for realizing a high resolution fringe analysis. In this new fringe analysis method, it, however, is known that the measuring accuracy of this method depends on experimental conditions in some experiences. In this paper, the relationship between the measuring accuracy and the measurement conditions of the method is discussed by using experimental results. In particular, the influence of the ratio between the intensity of object and intensity of reference beams, the relationship between the measuring accuracy and the central frequency of the signal, the relationship between the speckle size and the measuring accuracy, the relationship between the quantity of deformation and the measuring accuracy, the setting of the band path width of the filtering of the signal, and so on are discussed. From these discussions, it is confirmed that the S/N ratio of the fringe signal in the analyzing process is the important factor concerning the accuracy. The method that can increase the measuring accuracy by improving the S/N ratio of the fringe signal is also proposed.

9525-32, Session 6

A calibration method of self-referencing interferometry based on maximum likelihood estimation

Chen Zhang, Dahai Li, Mengyang Li, Kewei E, Guangrao Guo, Sichuan Univ. (China)

Interferometer is used widely to test the surface of optical elements. Removing the reference wavefront and system errors is necessary to improve the precision of measurement. There have been proposed several methods to achieve the absolute measurement, such as the three-flat method and N position method. These methods are only appropriate for non-self-referencing interferometer like Fizeau. For self-referencing interferometer (SRI), the iteration method are usually used to extract and reconstruct the wavefront under test without considering the system errors.

In this paper, an absolute measurement method in terms of maximum likelihood estimation is presented, which can be used to calibrate the SRI system. As an example of SRI, the cyclic radial shearing interferometer(CRSI) is used to prove the result of the simulation experiment. Not only the phase difference wavefront but also the system errors obtained at the same time from the interferogram. In order to separate the system errors from the total wavefront, only need three wavefronts by three different positions of tested element. The first wavefront is the original wavefront, the second wavefront is obtained by rotating the tested element 10° for separating the non-rotational symmetry, the third wavefront is obtained by shifting the tested element 1 pixel for separating the rotational symmetry. The three wavefronts are the sample data used to establish the maximum likelihood function, and Zernike polynomials used to represent the wavefronts. Zernike coefficients of the phase difference wavefront and system errors are the unknown parameters which need to be estimated. Maximizing the logarithmic of the likelihood function is equivalent to minimize the exponential of the likelihood function. The Zernike coefficients can be solved by using least square method. Through this method, the system errors can be reconstructed and separated from the total wavefront.

The results of the simulation experiment are shown the original and reconstructed wavefront of the phase difference and the system errors, respectively. And the difference between the reconstruction and the original 37 terms Zernike coefficients of wavefront of the phase difference and the system errors, respectively. The residual of the phase difference and the system errors are about 10-14. So the difference between original and reconstruction can be ignored. The result proves that using the maximum likelihood method to calibrate the SRI system is effective and feasibility.

9525-33, Session 7

Multiplex acquisition approach for high speed 3D measurements with a chromatic confocal microscope

Miro Taphanel, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany); Ralf Zink, Robert Bosch GmbH (Germany); Thomas Längle, Fraunhofer IOSB (Germany) and Fraunhofer IOSB (Germany); Jürgen Beyerer, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

Optical 3D measurement equipment is on its way from laboratory to the production line. The challenge is to significantly speed-up the measurement speed. A combination of the chromatic confocal measurement principle with a multispectral camera is well suited for this task. The involved multispectral camera replaces the normally used spectrometer. This reduces the amount of pixel data from about 512 pixels per 3D measurement to 6 or even less. As consequence the measurement speed is no longer limited by the pixel data readout time, but by the available light.

In this research a high speed chromatic confocal linescan sensor was build up. The data acquisition allows for 294 million 3D measurement points per second, which outperforms all known optical 3D sensors in acquisition speed. Due to the limited amount of light, the current maximum measurement speed is limited by the necessary integration time. However, replacing the LEDs by a supercontinuum laser could be a technical solution.

A special multiplex acquisition approach was developed to realize a high speed multispectral camera with six channels. Instead of spectral filtering in front of the camera, the illumination was filtered and multiplexed. Normally, this reduces the measurement speed by six compared to the linescan frame rate. The new proposed acquisition technique does not suffer from this problem and allows measurement speeds as high as the camera frame rate.

Instead of one camera line, six adjacent lines of a monochrome full frame sensor are used as region of interest. The multiplexed illumination is synchronized with the camera and the movement of the scanning table. If the object moved the projected distance of one pixel, the LED is changed and a new frame of 6 by 2300 Pixel is acquired. By resorting the data, it is possible to retrieve the color information of all six illumination situations. The benefit of this approach is that the object can continuously be scanned. Furthermore, the 3D measurement rate and the frame rate of the camera are equal. As drawback changed illumination situations must be considered. The assignment of the pixel position and color is periodically changing. If this is not correctly compensated, artefacts are visible.

The article describes the developed high speed chromatic confocal measurement principle in detail, with a special focus on the multiplex acquisition approach. Experimental results are presented to evaluate the influences of the multiplex approach to the measurement uncertainty. Preliminary results show that this acquisition approach tends to artefacts which will be investigated, too. Furthermore, an adapted signal processing is proposed, which tackle these artefacts.

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9525-34, Session 7

Multi-scale roughness measurement of cementitious materials using different optical profilers and window resizing analysis

Paul C. Montgomery, Fabien Salzenstein, Gianto Gianto, Univ. de Strasbourg (France); Komla Apedo, ICube (France); Nicolas Serres, Institut National des Sciences Appliquées de Strasbourg (France); Christophe Fond, Univ. de Strasbourg (France); Françoise Feugeas, Institut National des Sciences Appliquées de Strasbourg (France)

In the development of new eco-cements for ecologically friendly construction, precise knowledge of the surface structure of the material is necessary when considering how it reacts to living matter.

The porosity, surface structure and chemical nature of the material can influence the bioreceptivity of the surface and the aptitude or not of environmental micro-organisms to form biofilms. Such films are the source of biocontamination that can lead to a degradation in the structural properties over time. Accurate measurement of surface roughness and topography are therefore important to help in the understanding of this interaction. Optical profilers are well adapted to the quantifying of large surface roughness (RT <30 μm) and porosity typical of cementitious material surfaces [1]. The use of optical probes makes these techniques more rapid for areal measurements and better able to cope with high roughness compared with stylus and near field techniques which require lower scanning speeds to avoid tip damage. In addition, near field probe profilers are severely limited in depth range on such samples.

Any given surface profiler typically has specific range limits in terms of axial and lateral resolution and field of view. These performance limits can lead to different roughness values according to the type of optical profiler used to make the measurement [2]. In the present work, unpolished and polished cement paste samples have been measured with two different systems [3]. The first one is interference microscopy, or Coherence Scanning Interferometry (CSI) as it is known, in which a white light interference pattern is scanned over the depth of the roughness to be measured [1]. A camera captures a series of successive XY images as a function of Z and signal processing along Z is performed to determine the height of the surface at each pixel in the image. The second one, Scanning Confocal Microscopy (SCM), makes use of chromatic aberration of the optical pen over Z to measure surface height at a point. The probe is scanned over XY to build up the complete surface topography.

In order to be able to compare the results of roughness measurement from both techniques, the method of window re-sizing, more commonly used in tribology and fracture mechanics [4], has been used for calculating the average roughness parameters at different scales [3]. This technique uses successively larger sized sliding XY windows to calculate the roughness parameters from the XYZ data matrix. A graphical plot of the roughness parameters as a function of the window size indicates the variation with increasing scale. Plotting the results of the measurements made on the same sample from different profilers allows the comparison between the different systems. The initial results obtained show a successful overlap of the results for the unpolished samples (Figure 1(a)) and a slight separation for the polished samples (Figure 1(b)). These results show the validity of the measurements by both techniques for certain roughness regimes and sample types and the existence of differences in the measurements on other types of sample due to variations in instrument performance and the introduction of instrument specific artefacts in the data. They also demonstrate the usefulness of the window resizing technique for analysing surface roughness data at different scales and coming from different types of profilers.

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9525-36, Session 7

Surface topography measurement based on color images processing in white light interferometry

Tong Guo, Yue Gu, Jinping Chen, Xing Fu, Xiaotang Hu, Tianjin Univ. (China)

Microstructure surface topography is a key aspect of micro-nano measuring research for it has an obvious influence on the performance and the quality of devices. Scanning white light interferometry, as a non-contact optical method, is widely used in measuring and calibrating microstructures ranging from nanometer scale to micrometer scale for it has several advantages, such as high precision, non-damaged and high efficiency. A color CCD camera, rather than a black-and-white CCD camera, can be utilized to acquire white light interference images, which could obtain RGB channels information. In this paper, RGB phase-crossing method was proposed to accomplish surface topography measurement. Based on acquired color interference images, wavelet transform method was employed to calculate phase value of corresponding channel in each scanning position. Then zero-optical-path-difference positions were accurately determined via a constructed evaluation function and the least square method. Besides, relevant simulations were performed to verify RGB phase-crossing method. Meanwhile, the results showed that the accuracy was higher via color images than gray images in RGB phase-crossing method.

9525-163, Session 7

Calibration of z-axis linearity for arbitrary optical topography measuring instruments

Matthias Eifler, Jörg Seewig, Julian Hering, Georg von Freymann, Technische Univ. Kaiserslautern (Germany)

According to the increasing use of optical topography measurement devices within the field of geometrical product specification, numerous approaches for calibration guidelines regarding these instruments were developed in the past years, of which some have already been standardised by now. The calibration of the height axis is an essential part of these procedures. A state of the art technology for the calibration of the z-axis, precisely its linearity and amplification, is the use of step height artefacts. However it is also well-known in the literature that a proper calibration of the z-axis requires numerous step heights at different positions within the measurement range. Calibrating the linearity with one or just a few different heights is not sufficient as todays optical devices exhibit height uncertainties within the nanometre range. The measurement result of a step height depends on many parameters, such as the position within the measurement range. Another issue is that step height artefacts are artificial surface structures, that are not related to later performed measurement tasks. In order to overcome this shortcomings, new approaches for the calibration have to be developed.

In our paper, we propose a new approach for calibration artefacts which is based on the 3D-Abbott-Curve. It is shown that with the 3D-Abbott-Curve, which can be calculated by sorting all topography values in a descending order, it is possible to image certain characteristics of the

surface. Another improvement towards conventional artefacts is the use of real geometric structures. As the requirements for calibration and measurement procedures are steadily increasing, new geometries that are based on actual measured surfaces should be used for a more accurate calibration. Based on this considerations, an algorithm is introduced which transforms the measurement data of an arbitrary surface in a way that it can be used as a measurement artefact for the z-axis. In order to achieve a calibration of as many height values as possible, a linear 3D-Abbott-Curve is the aim of this transformation. With this linear 3D-Abbott-Curve, the entire measurement range of the z-axis can be calibrated almost continuously. The method works both for profiles and topographies. In order to consider effects of the manufacturing, measuring and evaluation process an iterative approach is chosen. The mathematical impact of many processes can be calculated with morphological signal processing. A surface for the transformation can be chosen according to the future application. The artefact is manufactured with 3D laser lithography and can be applied for different types of topography measurement devices, e.g. white light interferometers or confocal microscopes.

The manufactured artefact is characterised with different optical measurement devices and an according calibration routine is suggested. This calibration routine can calibrate the entire z-axis-range within one measurement and can therefore minimize the required effort for this task. With this results it is as well possible to locate potential linearity deviations and to adjust the z-axis. Results of different optical measurement principles are compared in order to evaluate the capabilities of the newly designed measurement artefac

9525-5, Session PS

Small angle X-ray sacatterometry for overlay measurement

Deh-Ming Shyu, Industrial Technology Research Institute (Taiwan); Joseph Kline, Daniel F. Sunday, Wen-li Wu, National Institute of Standards and Technology (United States)

As integrated circuit feature size continues to shrink, precise positioning and alignment during fabrication are important in manufacturing accurate patterns. According to ITRS (International Technology Roadmap for Semiconductors) 2013 Update-Metrology, the wafer minimum overlay control is planned to be 4.4 nm at the 22 nm node, and widespread impact of double patterning techniques is expected to drive it down to around 1.0 nm. The tightened to tolerance for overlay indicates the need for acceleration of improvements in overlay metrology.

Several metrologies are used in the overlay measurement. Optical imaging metrology are commonly thought to face challenges for nano-scale overlay measurement. However, the resolution is limited by the optical diffraction limit and optical aberration. Another metrology is the optical scatterometry, the overlaid linear gratings are used as the alignment key. A polarized beam is projected on the overlay grating and the intensity of diffraction beams from the overlay grating is measured. After data analysis, the overlay value could be obtained. The resolution of optical scatterometry is limited by the wavelength of light source. Currently, the visible or deep ultraviolet light soured are used in the optical scatterometer. However, it is hard to achieve the requirement of overlay control below 1.0 nm. Critical dimension small angle x-ray scattering (CD-SAXS) proposed by National Institute of Standards and Technology (NIST) has been used for three-dimension measurement of fin field-effect transistor (FinFET) structur lately. The scattered X-ray fom target are collected and analyze to determine line width, pitch, sidewall angle, line width roughness and other structure parameters with nano-scale resolution.

The resolution of small angle x-ray scatterometry is superior than deep-ultraviolet scatterometry. In this paper, we use the method of small angle x-ray scattering and the x-ray source of Advanced Photon Source (APS) at Argonne National Laboratory (ANL) in Chicago to measure the overlay target. We produce a series of overlay target with the same structure but different overlay value. The rigorous coupled-wave analysis (RCWA) and small angel scatter theorem are used to analyze the measured signals, and we can obtain the three dimension struecture and overlay value. In this paper, we can know the x-ray scatterometry is the powerful tool in the metrology of semiconductor process.

9525-15, Session PS

Fibre optic pressure sensor using a microstructured POF

Oskar Arrizabalaga, Gaizka Durana, Univ. del País Vasco (Spain)

Although telecommunications area was the primary field of application of optical fibres, nowadays fibre applications have broadened to many other areas of interest. Optical sensing is one of the fields that makes extensive use of the physical aspects of light propagation in optical fibres [1]. To date, most of the research has been focused on the development of intensity-based POF sensors, for which multimode POFs offer great advantages, such as high coupling efficiency or high numerical aperture, over their glass counterparts. However, properties such as the polarisation state of light and its high sensitivity to external perturbations has not been sufficiently exploited in POFs since the light becomes highly depolarised after travelling a small length of fibre. However, microstructured POFs (mPOFs) [3] make it possible to have control over the polarisation of the light and to use it for sensing purposes, e.g. for pressure or mechanical stress sensing.

We consider as starting point the results reported in [4], where the fundamentals for one type of pressure sensing were established based on the mechanism of stress-induced birefringence in a single-mode mPOF (SM mPOF) using a mechanical piece with serrated edges. Based on those results, we make one step forward and analyse the effect that a variable number of edges would have on the ability to distinguish between different pressure levels. Additionally, the polarimeter at the end of the mPOF used to analyse the polarisation state of the output light is substituted by a linear polariser and a photodiode in order to make simpler the experimental set-up

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9525-46, Session PS

Wafer warpage characterization measurement with modified fringe reflection method

Po-Yi Chang, Yi-Sha Ku, Industrial Technology Research Institute (Taiwan)

Wafer warpage is one of the most challenging problem in three-dimensional stacking integration processes which has been studied and analyzed by considering different factors such as CTE mismatch, residual stress, and ground wafer thickness. The stress issue is one of the root causes leading to process and device failure such as delamination, cracking, within wafer uniformity, and defect density increasing. Therefore, it is critical to measure the wafer warp before and after any stacking process.

Full field optics methods, such as interferometer, fringe reflection method, CGS interferometer have been widely adopted for measuring out-of-plane deformation of a wafer. We have developed a wafer level warpage measurement system by a whole field fringe reflection method using phase shift algorithm. A set of periodic fringe patterns are projected onto the wafer surface and the reflection fringe images are recorded by a CCD camera. The fringe patterns are deformed due to the slope variation of the wafer surface. By analyzing the fringe shift, the wafer surface slope variation and 3D surface profile including tiny dimples and dents on a wafer can be reconstructed. The resolution is enhanced by an order of

magnitude if the phase shifting setup and subsequent algorithms are employed.

In this work, we have used an optical mirror as a reference flat plane and the reflected fringe images are recorded. However, the shape measurement error will be occurred due to the height differences between the wafer surface and the optical mirror surface. The 0.1 mm height difference will cause about 1.3 μm warpage error due to our estimation. The way to avoid the shape measurement error is to move the wafer surface to the same height of the optical mirror surface by using the optical sensors, such as laser triangular method or chromatic sensor. This way will make the fringe reflection system more costly and complicated. Therefore, we develop a compensation algorithm to calibrate the fringe reflection system without any moving part and eliminate the shape error. Experimental results show that the accuracy of warpage measurement is less than 2 μm for 4-inch and 6-in sapphire wafers after applying compensation algorithm.

9525-79, Session PS

Application of high-accuracy laser Doppler velocimeter in self-contained navigation

Gao Chunfeng, Wei Guo, National Univ. of Defense Technology (China); Zhou Jian, Wang Qi, National University of Defense technology (China); Xingwu Long, National Univ. of Defense Technology (China)

The basic composition and measuring principle of Laser Doppler Velocimeter (LDV) are discussed, and the superiority of LDV been the external velocity observation system of the SINS is analyzed. For study of the RLG inertial navigation system and the LDV which is self-developed by our own department, the feasibility of SINS/LDV composite system is proved, and vehicle navigation tests have been conducted. Taking the CGPS as reference, the results show that the maximum positioning error of SINS/LDV composite system is 6 meters in one hour test while the maximum positioning error of pure SINS reaches 1130 meters. Results show that the SINS/LDV composite system can effectively inhibits the time accumulated navigation errors, and the high accuracy self-contained navigation can be realized.

9525-80, Session PS

Design of photonics crystal fiber sensors for bio-medical applications

Santosh Kumar, DIT Univ. (India); Akanksha Bisht, Ashish Bisht, Gurdeep Singh, DIT University (India); Angela Amphawan, Univ. Utara Malaysia (Malaysia)

Photonic Crystal Fibers (PCFs) have special structures and offer a number of novel design options, such as very large or very small mode areas, high numerical aperture, guidance of light in air, and novel dispersion properties. PCFs have become an attractive field for the researchers and they are trying to work on these to get their properties applied in dispersion related applications, sensing applications and much more. PCFs sensors are widely used in bio-medical applications. The sensitivity and performance of sensors are enhanced due to novel applications of PCFs.

9525-82, Session PS

Dimensional field testing of an optical measurement system in a long-span suspension bridge

Luis F. Lages Martins, Nacional de Engenharia Civil (Portugal); José Manuel N. V. Rebordão, Univ. de Lisboa (Portugal); Álvaro S. Ribeiro, Nacional de Engenharia Civil (Portugal)

This paper describes the field testing activity performed in a long-span suspension bridge – the 25th of April Bridge (P25A), in Lisbon (Portugal), with a 1012 meters main span – regarding the application of an optical system for displacement measurement of its central section. In this type of large-scale structures, the use of GNSS systems or microwave interferometric radars is compromised by the multi-path effect of the electromagnetic signal in the bridge's stiffness beam metallic components, which affects their measurement accuracy. Optical systems allow overcoming this restriction, sharing the same advantages ? non-contact and long-distance measurement in real-time, and continuous dimensional observation in a short or long-term scenario ? although being operationally vulnerable to atmospheric attenuation by heavy fog or rain.

The paper presents the displacement results for the main span central section, obtained by an optical system with a high focal length camera (600 mm) rigidly attached to the lower surface of the bridge stiffness beam and orientated towards the tower foundation where a measurement referential ? composed by four active LED targets with known world coordinates ? was installed. Based on the camera's intrinsic parameters (focal length and principal point coordinates obtained in a previous geometrical testing by the diffraction optical element method) and the targets world (quantified by previous dimensional testing) and image coordinates (by digital image processing), the camera projection centre (which in this approach represents the bridge's spatial position) was calculated through a non-linear optimization process.

Maximum displacement values in the transverse and vertical directions are presented for two operational scenarios (with road traffic and with or without rail traffic). Special attention is given to the camera aperture and exposure time in order to prevent the blurring effect on the targets image caused by train circulation (high vertical displacement in a short period of time). The optical system shows high vertical measurement sensitivity since the corresponding displacement recorded allows identifying small changes namely due to the transition of carriages of the train and to estimate the speed and the longitudinal position over the bridge. The vertical displacements are discussed and compared with results of historic static loading tests and current available strain records for the main span central section.

The field activities also included the in situ calibration of the optical system using a reference standard prototype, previously tested and characterized in a metrological laboratory and traceable to SI primary standards. Calibration tests were performed in different Seasons (Summer and Winter) in order to assess the impact of environmental variables in the deviations found between displacement readings and reference values. A static observation condition within the vertical plane of the measurement configuration was defined for this purpose, with the camera installed in the P25A anchorage and the targets in the tower foundation. The same experimental setup was also used to study the effect of beam wandering due to thermal gradients in the optical propagation path and to validate correction models for the vertical refraction systematic effect on the world coordinates of the targets. Measurement uncertainties are also presented and discussed, namely, regarding the use of a Monte Carlo method and the identification of the major uncertainty components.

9525-83, Session PS

Principal component analysis based carrier removal approach for Fourier transform profilometry

Shijie Feng, Qian Chen, Chao Zuo, Nanjing Univ. of Science and Technology (China)

Fringe projection profilometry has been widely employed for shape measurement in recent years. In a generalized fringe projection measuring system, a fringe pattern is projected to the measured object and from another view a camera is used to capture the pattern modulated by the object surface. Then the profile can be retrieved through a fringe analysis method. There are a number of techniques to analyze the captured fringe pattern and generally they can be categorized into two classes. The first class based on the phase-shifting algorithm always requires at least three fringe patterns to reconstruct a 3D profile. By contrast, the second class dependant on Fourier transform needs only one frame to retrieve the contour of a measured scene. With the rapid advance in the digital projection and imaging system, more and more interests have been attached to the surface measurement of moving or deforming object.

Because the Fourier transform profilometry (FTP) is insensitive to the movement or deformation, it has been adopted extensively in dynamic measurements. In FTP, through Fourier transform, filtering and inverse Fourier transform, a phase map including object phase and carrier phase is obtained. To acquire the object phase from the map, it is necessary to remove the unwanted carrier phase.

To deal with the issue of the carrier, a number of approaches have been developed. Takeda et al. suggested that the carrier can be removed by a spectral translation in frequency domain because a spectrum shift of is equivalent to a phase subtraction of in spatial domain. It is easy to be implemented and is robust if the captured stripes are equally spaced. However, for a generalized fringe projection set-up, the light beam is cast divergently onto the measured object which results in unequally distributed fringes across the measured scene. Therefore, a constant spectrum shift will be insufficient to eliminate the variant (nonlinear) carrier. Thus to cope with this issue, in their following work they proposed a method that requires respective measurements of the object and the reference plane. Then the effect of the carrier can be eliminated by subtracting the reference from the object phase map. Although this method is robust, it requires two measurements thus may be not very convenient to be implemented. After that, Chen et al. developed a technique in which a polynomial function is used to describe the nonlinear carrier. Then Zhang et al. presented a similar approach using the Zernike polynomials to represent the carrier. Both of the methods can effectively address the nonlinear carrier issue. However, in these two techniques data points need to be selected from the reference plane for the estimation of the polynomial coefficients, thus increasing human interventions.

Here, we introduce the principal component analysis (PCA) into our work aiming at removing the carrier in FTP for the divergent illumination measuring system. As aforementioned, the spectral translation enables the elimination of the linear carrier and retains the nonlinear one. In our method, thus, the PCA is carried out to study the remaining nonlinear carrier phase. We find that the first dominant component of the exponential form of the phase map can describe the concerned nonlinear carrier phase. Therefore, we extract the first dominant component which is a rank one matrix and use the product of two singular vectors derived from the nonlinear carrier function to fit it. Finally, the fitted first dominant component is employed to compensate the nonlinear carrier phase left by the spectral translation. The proposed method has several advantages. Firstly, it is fully automatic and demands less human intervention because no data points need to be collected from the reference plane in advance. Then, it is efficient as only a single fringe pattern is required to remove the nonlinear carrier phase, which indicates its applicability to the measurement of moving objects. Lastly, the image distortion correction is performed on the captured fringe pattern, thus reducing the measurement error. Our experiments verify that the proposed technique is able to remove the carrier phase effectively in both static and dynamic measurements.

9525-84, Session PS

Transparent layer thickness measurement using low-coherence interference microscopy

Peter Kuehnhold, Univ. Kassel (Germany); Anton Nolvi, Univ. of Helsinki (Finland); Stanislav Tereschenko, Univ. Kassel (Germany); Ivan Kassamakov, Edward Hæggström, Univ. of Helsinki (Finland); Peter Lehmann, Univ. Kassel (Germany)

Vertical scanning white-light or low-coherence interferometry (SWLI) can measure the thickness of transparent layers. A single layer on a substrate creates two interferometric signals, one from the top surface and one from the layer-substrate interface. Appropriate signal analysis depends on the overlap of the two signals and therefore on the layer thickness. Here we assume the layer thickness to exceed 2 μm. Consequently the signal separation along the depth axis permits analyzing both signals individually. However, even in this case two different effects have to be accounted for when the envelope position of the signals are determined. First, the envelope width of a SWLI signal is limited by the temporal coherence of the light source. Second, this width is also limited by the depth of focus of the microscope objective. This is called spatial coherence gating [1].

Two extreme situations exist: If a light source of very low coherence, e.g. a halogen bulb is used together with an objective lens of low numerical aperture (NA), the first limitation holds and the optical path length difference between the two signals from the two interfaces is measured.

On the other hand, if a light source of high temporal coherence (low bandwidth) is used in combination with a high NA objective, the depth of focus limits the width of the envelope of the resulting signals. Due to refraction at the top surface, the focus length inside the layer increases leading to a reduced apparent height difference between the two SWLI signal envelopes.

We study these effects using a known layer thickness standard made by the PTB [2] featuring two transparent polymer layers of nominal thickness of 4.1 and 2.2 μm. It is demonstrated that both low temporal coherence and low NA of 0.13, or high temporal coherence (FWHM 10 nm) and high NA of 0.7, can be used to determine the layer thickness. However, if lateral resolution is unimportant the first option provides larger separation of the SWLI signals, easier bias correction, and finally higher accuracy. Nevertheless, if high accuracy and lateral resolution are required, a layer whose thickness is known from e.g. a tactile measurement, can be used to calibrate the interference microscope. Such calibration permits determining the layer thickness with a SWLI microscope that features high NA and low bandwidth illumination.

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9525-85, Session PS

Dynamic goniometer for industrial applications

Elena Ivashchenko, Petr Pavlov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation)

Laser goniometer has obvious advantages in calibration of angle encoders operating in dynamic mode. Nevertheless it cannot meet all dynamic range requirements, which are applicable to state-of-the-industry encoders. Dynamic range can be enlarged using ring laser and optical encoder together. Standard of plane angle unit is an example of this technology in Russia.

Problems of construction, research methods and results of examinations are presented in the talk.

Dynamic goniometer is based on optical encoder with holographic scale of 4”/pulse resolution. Increasing of resolution down to 0.01”/pulse is provided by time interpolation. Dynamic goniometer is built using the air bearing, optical encoder and contactless rotor motor mounted on the rotor of goniometer. The developed data sampling circuit board makes it possible to sample 1500 byte data with the speed of over at least 1MHz. Interferometric null-indicator was included in the dynamic goniometer to ensure traceability from plane angle standard.

The ring laser, mounted on air bearing rotor, was used for the optical encoder uncertainty investigation. Research methodology included phase-time and reversible methods. Phase-time method eliminates the ring lasers uncertainty, caused by the instability of rotation speed, as well as the ring lasers bias instability. Reversible method is that changing the direction of rotation of the ring laser, eliminates systematic uncertainty caused by the external magnetic field.

Method of examination of dynamic goniometers random uncertainty (DGRU-method) was used for error source estimation. DGRU-method is applicable for examination of optical encoders with more then one detecting heads. It makes it possible to estimate its potential uncertainty and the dole of the encoders uncertainty as a part of the overall goniometer uncertainty. The research has shown, that the main sources of encoders’ error as a part of goniometer error sources are the white noise, angle quantization and sinusoidal noise.

To ensure traceability from plane angle the standard dynamic goniometer’s metrological research was carried out using the echelon polygon and interferometric null-indicator. The research had shown the dynamic goniometer applicability for calibration of the precise encoders.

9525-86, Session PS

3D structure stitching method for MEMS nondestructive detection with low overlap rate

Long Ma, Dan Wang, Hong Yan Zhang, Yi Fan Niu, Civil Aviation Univ. of China (China); Tong Guo, Tianjin Univ. (China); Li Hua Lei, Shanghai Institute of Measurement and Testing Technology (China)

With the development of precision detection technology, the contradictions among its testing resolution, range and efficiency are becoming more and more prominent. In order to solve the problem of large scope testing for MEMS non-destructive detection, in this paper, a 3-D structure stitching method with high robustness and low overlap rate is presented. Since MEMS (Microelectromechanical Systems) devices often contain a large number of similar or array structures, especially in the microscopic field of view, this similarity is likely to produce erroneous matched points. Hence the area for the feature point extraction is designated within the overlap region in the first step based on the experimental configuration and relative displacement of two adjacent structures in order to reduce the possibility of incorrect matching and increase the processing efficiency. Assuming that P is the pixel length along the horizontal direction of the structure to be stitched and p is the pixel equivalent size, the relationship between relative horizontal displacement L of two adjacent structures and the overlap rate a can be written as (P-L/p)/P=a. The next key step in stitching is feature point extraction and matching. Because of the high similarity or unobvious features of some MEMS devices, it is inadequate to use SIFT(Scale-Invariant Feature Transform)algorithm for feature point extraction and matching which may cause the mismatch of feature points. Within the designated feature point extraction sector, combining with SIFT algorithm, the matched points searching area is optimized according to the uncertainty of the profiler and therefore the matched points could be obtained with high reliability. By assuming that (x1,y1) and (x2,y2) is a matched points pair and (Lx,Ly) is the relative displacement along horizontal or longitudinal direction of two adjacent structures, (rx,ry) defines the searching area along horizontal or longitudinal direction. This area optimization formulas are expressed as x1+ Lx - rx≤x2≤x1+ Lx+ rx and y1+ Ly- ry≤y2≤y1+ Ly+ ry. However, with high resolution measurement process of MEMS, measurement environment disturbance during the test can be directly reflected in the measurement results. Therefore, the initial stitching of adjacent structures will show some mismatch inevitably. In the last step, based on the regional continuity of the overlap area, this mismatch is corrected by a correction matrix with STLS(Scaled Total Least Squares)algorithm. This paper makes a series of experiments to evaluate the capacity of the new algorithm. Two adjacent resonator structures with array features whose region is 512 pixel ? 512 pixel are tested and the overlap rate is 6 %. Meanwhile, a stitched result comparison for these two adjacent structures between the proposed method and the commercial profiler which requests the overlap rate varying from 10 % to 25 % is carried out to verify the performance of this introduced method. To be specific, the overlap rate for the commercial profiler is set to 25 % in the experiment and one can still observe the mismatch and deformation between the stitched structure whereas the low overlap rate stitching is successfully obtained by the introduced algorithm. The experiments show that for MEMS non-destructive detection, this new 3-D stitching method with low overlap rate is effective for the micro-structures with similar and unobvious features when the overlap rate is down to 6 %. The testing accuracy and efficiency are greatly improved with the proposed algorithm.

9525-87, Session PS

Analysis of adaptive laser scanning optical system with focus-tunable components

Petr Pokorný, Antonin Mikš, Jiří Novák, Pavel Novák, Czech Technical Univ. in Prague (Czech Republic)

Three-dimensional optical scanners are devices which enable performing fast, very precise and non-contact measurement of a studied subject or modifying the target. Areas of application of 3D optical scanners are in civil engineering, mechanical engineering, mining engineering, geodesy, architecture, medicine, culture, scanning optical microscopy, and many others. In all above-mentioned fields the adaptability of measurement devices is an important issue.

A three-dimensional optical scanner usually comprises of a laser source, an optical or opto-mechanical laser beam-steering device, a photodetector, and a control and evaluation system. A beam of light, which is coming from the source of radiation, is transformed by an optical system, deflected by a beam-steering device to an accurately determined direction, and it impinges on the measured object. After the reflection from the object, a part of the diffused light, which returns back through the optical system, is detected by the photodetector. Then, one can determine the spatial coordinates of the object point. A distance between the scanner and the point of interest is usually calculated from the modulation of light waves or from the counted pulses.

As obvious, the principle of the optical scanner is based on the determination of the laser beam spot position on the measured object. A disadvantage of the present state is that the parameters of laser scanners cannot be continuously and adaptively changed, which is a limitation of the field of application. On the other hand, there exist various active optical elements (tunable-focus lenses, deformable mirrors, spatial light modulators) that start to appear commercially on the market in the last few years, which may be implemented into optical systems of laser scanners. Such laser scanners will enable to adaptively change their properties, which is very promising for future applications of scanners. Such active components make possible to design new types of scanners providing that a size and a shape of the laser beam spot can be changed in a continuous way. Moreover, this is possible in an arbitrary distance from the measuring device which is impossible with current state-of-the-art laser scanners. Consequently, the adaptive laser scanners could have a wider field of application than the current types of scanners.

This work presents a primary analysis of an adaptive laser scanner based on two-mirror mirror beam-steering device and focus-tunable components (lenses with tunable focal length). It is proposed an optical scheme of an adaptive laser scanner, which can focus the laser beam in a continuous way to a required spatial position using the lens with tunable focal length. This work focuses on a detailed analysis of the active optical or opto-mechanical components (e.g. focus-tunable lenses) mounted in the optical systems of laser scanners. The algebraic formulas are derived for ray tracing different configuration of the scanning optical system and one can calculate angles of scanner mirrors and required focal length of the tunable-focus component provided that the position of the focused beam in 3D space is given with a required tolerance. Computer simulations of the proposed system are performed using MATLAB.

9525-88, Session PS

3D structure stitching method for MEMS nondestructive detection with large scope and low overlap rate

Long Ma, Dan Wang, Hong Yan Zhang, Yi Fan Niu, Civil Aviation Univ. of China (China); Tong Guo, Tianjin Univ. (China); Li Hua Lei, Shanghai Institute of Measurement and Testing Technology (China)

No Abstract Available.

9525-89, Session PS

Spatial filtering velocimeter for vehicle navigation with extended measurement range

Xin He, Jian Zhou, Xiaoming Nie, Xingwu Long, National Univ. of Defense Technology (China)

The idea of using spatial filtering velocimeter is proposed to provide accurate velocity information for vehicle autonomous navigation system. The presented spatial filtering velocimeter is based on a CMOS

linear image sensor, which is employed both as a photodetector and as a differential spatial filter. The sampling rate of the signal is just the frame rate of the image sensor, so the maximum measurable velocity is restricted by the frame rate. The measurement range can be adjusted by changing the optical magnification of the imaging system, but it is complicated to realize. In this paper a new method of frequency shifting is put forward to extend the measurement range for high speeds measurement of vehicle. The spatial filtering operation is fully performed in a field programmable gate array (FPGA). As a result, the method of frequency shifting is easy to realize and the value of shifting frequency is changeable even during measurement. Theoretical analysis shows that the frequency of output signal can be reduced and the measurement range can be doubled by this method when the shifting direction is set the same with that of image velocity. The approach of fast Fourier transform (FFT) is employed to obtain the power spectra of the spatially filtered signals. Because of limited frequency resolution of FFT, a frequency spectrum correction algorithm, called energy centrobaric correction, is used to improve the frequency resolution. The correction accuracy energy centrobaric correction is analyzed. Experiments are carried out to measure the moving surface of a conveyor belt, which is wound around a cylinder and the table top of a rotary table. The rate stability of the rotary table is better than 10-5 measured over one revolution. The experimental results show that the maximum measurable velocity is about 800deg/s, about 2.513m/s, without frequency shifting, 1600deg/s with frequency shifting, when the frame rate of the image is about 8117 Hz. Therefore, the measurement range is doubled by the method of frequency shifting. To verify the feasibility of the SFV instrument for vehicle, experiments were carried out to measure the vehicle velocity simultaneously using both the designed SFV and a laser Doppler velocimeter (LDV). The measurement results of the presented SFV are coincident with that of the LDV, but with bigger fluctuation. To conclude, the velocimeter using spatial filtering method has the advantage of low cost, and can satisfy the requirements of non-contact, real-time velocity measurement of moving surfaces. Therefore, it has the potential of application to vehicular autonomous navigation.

9525-90, Session PS

Precision inspection of micro-components flatness by Moiré interferometry

Saïd Meguellati, Univ. Ferhat Abbas de Sétif (Algeria)

The automation, speed and precision in the quality control of surface shape require the development of control methods suitable for this purpose. The technique proposed in this paper provides a quality control components surface flatness by non-destructive and contactless way, with high resolution and increased sensitivity. The control is done in real time and instantaneously on all inspected surface. The accuracy of components geometry is the one of parameters which influences precision of the function. Moiré topography is full-field optical technique in which the shape of object surfaces is measured by means of geometric interference between two identical line gratings. The technique has found various applications in diverse fields, from biomedical to industrial and scientific applications. In many industrial metrology applications, contactless and non-destructive shape measurement is a desirable tool for, quality control and contour mapping. This method of optical scanning presented in this paper is used for precision measurement deformation in shape or absolute forms in comparison with a reference component form, of optical or mechanical components, on surfaces that are of the order of few mm2 and more. The principle of the method is to project the image of the source grating to palpate optically surface to be inspected, after reflection; the image of the source grating is printed by the object topography and is then projected onto the plane of reference grating for generate moiré fringe for defects detection. The optical device used allows a significant dimensional surface magnification of up to 1000 times the area inspected for micro-surfaces, which allows easy processing and reaches an exceptional nanometric imprecision of measurements. According to the measurement principle, the sensitivity for displacement measurement using moiré technique depends on the frequency grating, for increase the detection resolution. This measurement technique can be used advantageously to measure the deformations generated by the production process or constraints on functional parts and the influence of these variations on the function. The optical device and optical principle, on which it is based, can be used for automated inspection of industrially produced goods. It can also be used for dimensional control when, for example, to quantify the error as to whether a piece is good or rubbish. It then suffices to compare a figure of moiré fringes with another previously recorded from a piece considered standard; which saves time, money and accuracy. This optical device control has advantageous features allows non-destructive and contactless testing, real time speed inspection and measurement; possibility of image tracking in motion analysis and surface deformation, high spatial resolution and high sensitivity may vary depending of the importance of defects to be measured.

9525-91, Session PS

Method of increasing the working distance of optical-electronic autocollimator

Igor A. Konyakhin, Anastasia A. Moiseeva, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

High-precision measurements of angles are one of the most important operations in instrument and mechanical engineering. Autocollimation measurement method is the most promising and convenient method, since the measurement is carried out in a contactless manner, and the error is very small. An important task in improving the autocollimators is to increase the working distance autocollimation measurements. This is especially true for the nondestructive testing and fault detection.

Dual-axis optical-electronic autocollimators are effective to solve the problems of measurement of the angular position of objects. Such autocollimators allow you to control the position of the object relative to two axes that are perpendicular to the optical axis of the autocollimator (collimation axes). The analysis was performed on dual-axis autocollimators, which presents on the market today. Devices of firms Optrotech (Russia), Taylor Hobson (USA), Möller-Wedel and Trioptics (Germany) were considered. All considered autocollimators are equipped with special software. Working with the devices is performed through a personal computer. Electronic autocollimators allow you to automate, stabilize and accelerate the process of readout.

Optical-electronic autocollimation system includes autocollimator, mounted on the fixed base, and a controlling reflection element, placed on inspected object.

The stationary XYZ coordinate system is specified by the autocollimator. The axis OZ coincides with its optical axis, passing through the rear nodal point of the lens and the center of the matrix analyzer. The XOY plane is parallel to the plane of the matrix analyzer, and the OX and OY axes, respectively, are parallel to the rows and columns of the matrix analyzer.

The mobile coordinate system X1Y1Z1 is associated with a reflection element, which is placed on inspected object. The axes of the coordinate system X1Y1Z1 are parallel to the axes of the coordinate system XYZ when the initial position of the inspected object.

When the reflection element rotates, the reflected beams are deflected from its original direction. Thus, position of image on the matrix analyzer is changed.

Autocollimators of considered firms are used together with a flat mirror, which is mounted on the controlled object. The working distance of the autocollimator with a flat mirror does not exceed 5 meters. One of the reasons is significant displacement of the reflected beam in the plane of the aperture of the lens in the presence of both angles of rotation about two collimation axes.

In this paper view reflector in the form of a quadrangular pyramid, which allows to increase the working distance. Its characteristic feature is an opposite faces to form one working surface and for this reason, the parallel beam incident on the refracting face in the reflection, is divided into two beams, each of which generates a corresponding equivalent right-angle prism.

During the rotation of the quadrangular pyramid-shaped reflector relative to one axis, each reflected beam in the plane of the aperture of the lens will move only along the orthogonal axis. According to another coordinate position of the beam will not change. As a result of mathematical modeling it was found that the diameter of the lens for receiving the two beams will be in sqrt(2) less than the diameter of the lens for receiving

a beam reflected from the flat mirror, if rotation angles are same. This allows you to increase the working distance of the autocollimator simple replacement reflecting the controlling element in sqrt(2).

9525-92, Session PS

The threshold sensitivity of the molecular condensation nuclei detector

Vladimir D. Kuptsov, Saint-Petersburg State Polytechnical Univ. (Russian Federation); Vadim Y. Katelevsky, Neorganika (Russian Federation); Vladimir P. Valyukhov, Saint-Petersburg State Polytechnical Univ. (Russian Federation)

Molecular condensation nuclei (MCN) method is used in production engineering and process monitoring and relates to optical metrology methods of measuring the concentrations of various contaminants in the environment. Ultra high sensitivity of MCN method to a class of substances is determined by measuring the optical scattering aerosol particles, at the centers of which are located the detectable impurities molecules. This article investigates the influence of MCN manifestations coefficient (ratio of the concentration of aerosol particles to the concentration of molecules detectable impurities) on the sensitivity of the MCN detector. The MCN method is based on the application of various physico-chemical processes to the flow of a gas containing impurities. As a result of these processes aerosol particle that are about 10^6 times larger than the original molecule of the impurity are produced. The ability of the aerosol particle to scatter incident light also increases ~10^14÷10^16 times compared with the original molecule and the aerosol particle with the molecule of the impurity in the center is easily detected by light scattering inside a photometer. By measuring of the light scattering intensity is determined concentration of chemical impurities in the air. An application nephelometric optical metrology scheme of light scattering by aerosol particles ensures stable operation of reliable and flexible measuring systems. Light scattering by aerosol particles is calculated on the basis of the Mie's theory as aerosol particle sizes comparable to the wavelength of the optical radiation. The experimental results are shown for detectable impurities of metal carbonyls. The technical characteristics of metal carbonyls gas analyzers and their use in the inspection of large-scale objects ?r? presented. Gas analyzers based on the MCN method find application in industries with the possibility of highly toxic emissions into the atmosphere (carbonyl technology of metal coatings and products, destruction of chemical weapons, etc.), as well as during storage and transportation of toxic substances. There are some perspective areas of use MCN detector: prevention of illegal use of dangerous substances, revealing of their origin and leakage paths by means of marking with special non-radioactive chemical compounds; investigation of large-scale atmospheric circulation with the help of marking substances; nondestructive inspection for highly efficient filters with indicating agent concentration and for the inspection of the devices of high level tightness (heat-exchangers of fast nuclear reactors).

9525-93, Session PS

Special electronic distance meter calibration for precise engineering surveying industrial applications

Jaroslav Braun, Martin Stroner, Rudolf Urban, Czech Technical Univ. in Prague (Czech Republic)

All surveying instruments and their measurements suffer from some errors. To refine the measurement results, it is necessary to use procedures restricting influence of the instrument errors on the measured values or to implement numerical corrections. In precise engineering surveying industrial applications the precision of the distances is a key parameter limiting the resulting precision of the determined values (coordinates, etc.), because the measurements are usually realized on relatively short distance up to 50 m and the precision of the measured horizontal directions and zenith angles are significantly more accurate.

To determine the size of systematic and random errors of the measured distances tests were made with the idea of the suppression of the random error by the averaging of the repeating measurement, and reducing systematic errors influence by identifying their absolute size on the absolute baseline.

To determine the magnitude of the errors and standard deviations of measurements of distance meters of total stations EDM (Electronic Distance Meter) baselines are used. These EDM baselines are realized as outdoor or laboratory, for precise short distance measurement with its demanded precision only laboratory baselines are useful.

The lengths of the laboratory baselines are 20 m - 50 m. Classical laboratory baseline consists of a rail and the interferometer (standard deviation of the measured distance by the interferometer is 1.5 ppm ? D) and is used for the determining of the difference of the relative distance measured by the interferometer and by the distance meter (usually build in total station today). The absolute deviations of the measured distance are not determined there. The outdoor baselines (length usually more than 1 km) are usually made up of pillars with forced centerings with precisely known distance, and therefore can be used for absolute deviations determination, but on only a few distances.

In geodetic laboratory at the Faculty of Civil Engineering CTU in Prague was realized EDM baseline combining both types of baselines, having stabilized points with forced centerings and with distances determined with extra high precision. The 16 concrete pillars with forced centerings were set up and the absolute distances between the points were determined with a standard deviation of 0.02 millimetre using a Leica Absolute Tracker AT401. The baseline was built for testing of the distance meters of total stations, the actual lengths between the pillars ("true values") are compared with the measured lengths.

The EDM measurement repeatability and stability of the systematic errors over time was successfully tested first, different instruments were used based on the different measurement principles and different nominal measurement precision, namely Trimble S6 HP, Topcon GPT-7501, Leica TC1202 and Trimble M3. Observed systematic errors were found to be fairly stable in time (under the same conditions). To determine the size of systematic errors influencing the measurement of distances different from those between the pillars, the traditional interferometric baseline was used (at Geodatisches Institut, TU Dresden, Germany). Relative deviations representing a particular device were obtained from the experiment (highly different for different instrument and also different for different instruments of the same producer, type and production series) and these deviations were transformed (shifted) to absolute ones with use of the absolute deviations previously determined on the absolute baseline. The shift was determined by a weighted average using a robust L1-norm.

A Fourier Transform (FFT) was performed on the final data and the parameters of the correction function were determined (amplitude, phase shifts, the frequency of the main features of which consists course error EDM).

For any measured distance (up to the length of the testing baseline, i.e. 38.6 m) there are two ways to determine the size of the error correction of the distance meter: Firstly by the interpolation on the raw data, or secondly using correction function.

The quality of this calibration and correction procedure was tested on three instruments (Trimble S6 HP, Topcon GPT-7501, Trimble M3), experimentally using Leica Absolute Tracker AT401 in three characteristic intervals (5 m - 6 m, 12 m – 13 m, 19 m – 20 m) with total number of the measured distances 141. The standard deviation of the measured distances was reduced by the correction procedure from significant to less than 0.6 mm. In case of Topcon GPT-7501 it is the nominal standard deviation of 2 mm, achieved (without corrections) 2.8 mm and after corrections 0.55 mm; in case of Trimble M3 is nominal standard deviation of 3 mm, achieved (without corrections) 1.1 mm and after corrections 0.58 mm; and finally in case of Trimble S6 is nominal standard deviation of 1 mm, achieved (without corrections) 1.2 mm and after corrections 0.51 mm.

Proposed procedure of the calibration and correction is in our opinion very suitable for increasing the precision of the electronic distance measurement and allows the use of the common surveying instrument to achieve uncommonly high precision.

9525-94, Session PS

Dynamic processing of intefrerometric fringes parameters using stochastic algorithms: recent developments

Maxim A. Volynsky, Igor P. Gurov, Pavel S. Skakov, Petr A. Ermolaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Peculiarities of stochastic algorithms with application to analysis of interferometric fringes parameters are considered and discussed. Examples of practical application of recurrent algorithms to dynamic signal processing are presented.

Interferometric technique is widely used in measurement of structure and optical properties of different objects including industrial inspection, material science, biomedical application ets. (see, for example, [1, 2]). Parameters of interfererometric signals contain useful information about an investigated object. High accuracy, noise-immunity and signal processing speed play important role in practical application of interferometric systems.

A few widely used fringe processing method is well-known such as Fourier transform (FT) method [3-4]. The FT method is based on processing of interference fringes in frequency domain using comparably time-consuming integral transformation. It was suggested [5-7] and investigated in detail in last decade [8-12] new approach to interference fringe analysis based on recurrent calculations. In this approach, fringe processing is carried out using recurrent algorithms, in which fringe signal value is predicted to a following discretization step utilizing full information available before this step, and fringe signal prediction error is used for step-by-step dynamic update of the fringe parameters. Several versions of the recurrent fringe processing, in particular, in the form of Markov nonlinear filtering (MNLF) [5], extended Kalman filtering (EKF) [8-10] including second order EKF [13], unscented Kalman filtering (UKF) [12, 14, 15] and sequential Monte Carlo (SMC) method [16] were successfully applied to interference fringe analysis in rough surface profilometry and optical coherence tomoghraphy [8-9], in processing of 2-D fringe patterns [11].

To compare noise-immunity and computational properties of the algorithms experimentally, they were applied to process the modeled low-coherence fringe signals with Gaussian envelope. The MNLF error histogram is close to the UKF histogram. Opposite, the EKF error histogram is wider with respect to the two other histograms. It means that the MNLF and UKF algorithms provide less RMS error and higher accuracy with respect to the EKF algorithm. The numerical estimates of the normalized RMS error (using error histograms) were 0.030 for MNLF, 0.071 for EKF and 0.036 for UKF (for equivalent filtering realization).

There was calculated a quantity of elementary computational primitives as well as averaged computational primitive speed for each algorithm to compare computational properties of the algorithms. The EKF algorithm has the highest speed, however, as it was mentioned above, provides lower accuracy. The matrix multiplications are the most time consuming calculations in the MNLF. In the UKF, numerous matrix additions and subtractions are used to calculate statistics through the number of sigma-vectors, it is why the UKF algorithm is slower with respect to the two other algorithms.

Properties of the SMC method are very specific: the algorithm not assume to noise elimination, but immunity to not fully correct process model is characteristic side. Computational complexity of SMC method was compare with properties of EKF (like typical case of Kalman-type algorithms). It is shown that processing time of one discrete-time sample of the signal by Kalman-type algorithm increases polynomially with sizes of parameters vector and observation vector. Processing time of one discrete-time sample of the signal by SMC method depends linearly both on sizes of parameters vector and observation vector, and on the number of generated random vectors. Experimental results of processing time measurement are compared and discussed.

In the research, basics of recurrent computational algorithms applied to fringe analysis are considered, and examples of practical use of the algorithms are presented in details.

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9525-99, Session PS

Algorithm for recognition and measurement position of pitches on invar scale with submicron accuracy

Oleg U. Lashmanov, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Accurate position measurement systems are critical for many high end computerized numerical control (CNC) machines. Such systems controls position of CNC. For solving this problem laser interferometers are widely used.

Laser interferometers can achieve submicron accuracy. However it operate in strict conditions and very sensitive for air tract near laser beam, if theirs air turbulence result error of the measurement will be increased up to tens of microns. Another way to solve problem of positioning CNC tool is to use optical encoder. Such encoders frequently based on scale with pitches.

Main requirement for such systems are accuracy and time of measurement, therefore image processing are often performed by FPGA or DSP. This article will describe image processing algorithm for detecting and measuring pitch position on invar scale.

A “shadow” method was implemented: pith images on a CCD sensor are formed by the lens focused at the front surface of scale; the laser module lights up the scale through a beam-splitting cube by a parallel beam. Further dark pitch images on a light scale are detected and analyzed to estimate the encoder position. The optical scheme uses two beams from

the pitch:

• Parallel beam from the laser module that is directly reflected by the scale mirror surface. The lens forms a defocus cross-section of this beam on the detector that acts as the light background.

• Divergent beam from the pitch edges. The edges scatter the beam to arbitrary direction; the lens conjugates the scale surface with the detector, so shape images of pitch edges could be achieved. The sharper the edges the better conditions for the pitch image detection and calculation algorithms could be achieved.

For measure position of pith image processing algorithm is used, it can be divided into two parts: preprocessing and processing. Preprocessing part take grayscale image and perform inversion (measurement part is based on centroid). As we can see all pitches are vertical with small error caused by adjustment inaccuracy. For reducing influence of this error image has been summed by columns.

For recognition of pitch used two threshold criteria. Both of thresholds are based on sliding average, window width of this average is approximately 3 pitches width in pixels, and equal 70 pixels. Lower threshold half of average and upper threshold is 1.3 from average. Algorithm recognizes pitch when there are four sequential triggers:

- Rising edge on lower threshold
- Rising edge on upper threshold
- Falling edge on upper threshold
- Falling edge on lower threshold

Recognition step performs with pixel accuracy, and for reducing measurement error algorithm performs next step based on centroid.

After pitch recognition in window between first (m position) and last trigger (n position) occurs perform calculation of pitch result position. Calculations based on 1-d centroid.

This algorithm performs measurement with error near 0.07 pixels.

9525-101, Session PS

Electrooptic converter to control linear displacements of the large structures of the buildings and facilities

Aleksandr S. Vasilev, Igor A. Konyakhin, Alexander N. Timofeev, Oleg U. Lashmanov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Fedor V. Molev, OAO Avangard (Russian Federation)

The paper analyzes the construction matters and metrological parameters of the electrooptic converter to control linear displacements of the large structures of the buildings and facilities.

The task is especially important for the modern industrial environment that is determined by the large number of the constructed and designed large ground facilities both industrial and common urban: stadia, water parks, multi-storey residential areas. Provision of the faultless functioning of the facilities under the conditions of the natural and operational loads is an important social and technical task. These circumstances determine relevance of the research and development of the accidents prevention integrated systems based on the geo-technical sensors of the foundations and load bearings structures deformation.

The converter includes the base module, the processing module and a set of the reference marks. The base module is the main unit of the system, it includes the receiving optical system and the photodetector array that realizes the instrument coordinate system that controls the mark coordinates in the space. The base module is located in the basement of the structure or in the points intended for observation of the facility setting. The reference marks are installed in the “central” and “critical” points of the structures, information on their location allows to describe behavior of the entire facility. The system is based on the modular circuit which permits to combine several converters into the distributed measuring network. The converter is intended for operation in the outdoors in the temperature range -60...+40??.

The converter performs the multi-point control of the spatial position of the reference active marks rigidly tied with the structure elements. Optical system of the base module forms the image of the reference marks on the matrix-based CMOS photodevice that converts the input optical emission into digital electrical signal. The resulting digital image is transmitted to the processing unit where it is analyzed by the digital processing algorithm realizing the functions of the image mark detection against a complex background and determination of its location in the converter coordinates system.

The methods of the frame-to-frame difference, adaptive threshold filtration, binarization and objects search by the tied areas to detect the marks against accidental contrast background is the basis of the algorithm. After reference mark detection and classification its spatial position shall be identified on the basis of the energy centre calculation method. The entire algorithm is performed during one image reading stage and is based on the FPGA.

The developed and manufactured converter experimental model was tested in laboratory conditions at the metrological bench at the distance between the base module and the mark 50±0.2 m. The static characteristic was read during the experiment of the reference mark displacement at the pitch of 5 mm in the horizontal and vertical directions for the displacement range 400 mm. The preset displacements value was controlled by the laser tracker API Radian 50. The converter experimental model error not exceeding ±0.5 mm was obtained in the result of the experiment.

9525-102, Session PS

High-speed and long-time FBG interrogation system using wavelength swept laser

Tatsuya Yamaguchi, Yukitaka Shinoda, Nihon Univ. (Japan)

The purpose of this research is the development of a system for fabricating high-speed and long-time measurements of wide-band vibration using fiber Bragg gratings (FBG) to perform structural health monitoring of aircraft and other structures in use. Taking advantage of the property that an FBG-reflected wavelength is proportional to strain, placing FBGs with different Bragg wavelengths at different points in the optical fiber enables multipoint strain measurement.

In this research, we developed a real-time FBG-reflected-wavelength measurement system using a wavelength swept laser for high-speed and long-time monitoring of wide-band vibration in a structure. Using a wavelength swept laser with a wavelength-swept frequency of 10 kHz and a data acquisition system with sampling frequency set to 20 MHz, this system can perform real-time measurement of reflected wavelengths from a multipoint FBG with different Bragg wavelengths at a temporal resolution of 0.1 ms. The authors also constructed a database system for managing the data obtained from high-speed and long-time measurement. This database system manages data using a relational database and transfers information on FBG-reflected wavelengths obtained from this measurement system via the local network. Users can access this database to perform strain analysis based on FBG reflected wavelengths.

An experiment was performed using a 1.55?m-band wavelength swept laser of operating with a wavelength-swept frequency of 10 kHz. The reflected light from a multipoint FBG was detected and the reflected wavelengths were calculated every 0.1 ms. The standard deviation of the FBG reflected wavelengths measured by this system was under 2?10-3 nm. Furthermore, on measuring reflected wavelengths from a multipoint FBG at a temporal resolution of 0.1 ms over several hours, it was shown that this measurement system could also monitor instantaneously applied high-speed vibrations.

9525-103, Session PS

Electronic speckle pattern interferometry for fracture expansion in nuclear graphite based on PDE image processing methods

Chen Tang, Junjiang Zhang, Chen Sun, Yonggang Su, Tianjin Univ. (China); Kai Leung Su, The Univ. of Hong Kong (Hong Kong, China)

Electronic speckle pattern interferometry (ESPI) as a well-known technique for the measurement of deformation fields of the object surface, has been extensively investigated and widely used in numerous fields for its simple optic devices and its resistance ability to environment noise.

Nuclear graphite, characterized by excellent mechanical performance under high temperature, large neutron scattering cross-section, small neutron absorption cross-section, low mass number and high atomic density per unit volume, has been widely used as moderating and reflecting materials. However, due to severe neutron irradiation under high temperature, nuclear graphite is prone to deteriorate, resulting in massive microscopic flaws and even cracks under large stress in the later period of its service life. Thus, the safety of nuclear power station is threatened. It is indispensable, therefore, to understand the fracture behavior of nuclear graphite to provide reference to structural integrity and safety analysis of nuclear graphite members in reactors.

In this paper, we investigated the fracture expansion in nuclear graphite based on PDE image processing methods. We used the second-order oriented partial differential equations filtering model (SOOPDE) to denoise speckle noise, then used the oriented gradient vector fields for to obtain skeletons. The full-field displacement of fractured nuclear graphite and the location of the crack tip were lastly measured under various loading conditions.

9525-104, Session PS

Oil film interferometry technique for skin friction measurement in subsonic and supersonic flows

Wei Wang, Chang Zhao, Minglei Yuan, Ke Wang, China Academy of Aerospace Aerodynamics (China)

Even small reductions in skin friction drag should provide important design tradeoffs including: significant resizing options for new aircraft designs, increased range capability without increased take-off gross weight, increased speed and productivity, and reduced fuel volume and cost. Lots of researches have been done to reduce skin friction drag and improve aerodynamic efficiency. The first to do is to measure skin friction accurately.

The oil-film interferometric technique has been used to measure skin friction for the last 30 years in one form or another. The technique has relative ease of implementation and the solid theoretical underpinning which could provide spatial qualitative as well as quantitative information without interfering with the flow.

In this project, the oil-film interferometry (OFI) skin friction technique is described and applied to subsonic and supersonic flows in the tunnels at CAAA (China Academy of Aerospace Aerodynamics). The details for applying the technique are discussed. Results are shown for tests that illustrate the oil-film's good ability to measure the skin friction.

The technique works on the principle that oil applied to an aerodynamic surface will flow and thin due to shear As time goes on the oil becomes thin to the point that interference patterns known as fringes (illuminated by monochromatic light) will be spaced far enough apart to be visible in the oil. The shear is then determined from the oil's thinning rate using thin film lubrication theory.

Details of Setup

1 Test Surface

The first step is to prepare the test surface so that it is optically smooth and partially reflective. The interference is a result of the reflected light from the test surface interfering with the light from the air–oil interface (Fig. 2). Investigation and experiments contrastapproves that, the easiest approach is to apply thin sheets of Mylar with black pigment and adhesive backing to the test surface. The self-adhesive back makes it easy to apply, and it strongly adheres to the surface. The combination of Mylar (index of refraction of 1.67) and black pigment embedded in the Mylar provides a partially reflective surface that reflects light with about the same intensity as does the air–oil interface.

2 Oil Procedure

Silicon oil is used as the oil due to its good clarity and vaporizes not readily. Silicon oil in viscosities of 5-100,000 cS is provided on the market. The choice of viscosity is based on tunnel run time, dynamic pressure, and desired displacement between adjacent interference patterns (or commonly called fringes) at the end of the test. The oil patches (line segments, drops, smudges, etc.) should be spaced far enough apart so that one oil-flow patch does not significantly run into another patch.

3 Light Disposal

The oil should be illuminated with as nearly a monochromatic light source as possible. Low-pressure sodium bulbs are used, which emit at a single wavelength, (actually a closely spaced doublet), =589 nm and =589.6 nm.

Unlike other forms of flow visualization in which a point light source is usually adequate, the oil film interferometry requires an expansive (extended) light source, i.e., light emitted from a wide range of positions. To overcome this problem, in our experiments ,the entire wind tunnel top and side walls have been used as a reflector (with walls painted white), with the camera positioned on the overhead window's (small non-painted) viewing hole.

OFI experiment in Subsonic Flow?20m/s?

Oil was applied in a line approximately normal to the stream directions in a small opening-mouth wind tunnel. As the tunnel was running, fringes appeared and the spacing between "fringes" gradually broaden. Skin friction could be determined from the two images acquired at different time after the tunnel achieved the desired test condition (plus an additional image of the ruler). From the images, the spacing between interference bands of light and dark (known as the "fringe" spacing) was measured with the aide of MATLAB.

OFI experiment in Supersonic Flow

The tunnel was run at Mach 2. The pressure and temperature were measured at the same time. We get interference fringes cleary.

9525-105, Session PS

Design for measurement of the polarization state of light based on division of wave front

Hongwen Gao, Shaanxi Open Univ. (China); Chunmin Zhang, Xi'an Jiaotong Univ. (China)

The polarization of light is a physical phenomenon. Polarizing light coming from an aim is full of rich of its information. There are a few methods to describe the polarization state of light, whereas the method of the Stokes vector is the convenient one. Azzam, Matchko, and others introduced many photoelectric detectors that are employed to measure the Stokes vector of light, and Tyo, et al. reviewed passive imaging polarimetry for remote sensing applications. There are mainly two kinds of methods to measure the polarization state of light: light modulation method and division of wave one. Usually a beam of incident light passes through a sequence of optical elements (such as polarizers, wave plates, and rotators) and the emergent light intensity is measured by a linear photoelectric detector. The measurements of light intensity can be repeated for different (at least four) discrete settings of the analyzing optics and the detected signals are mathematically analyzed to extract the Stokes vector that characterizes the polarization state of light. Other distinct techniques for the Stokes vector measurement employ division of amplitude, division of wave front, or division of aperture of light. All the previously described photopolarimeters usually require polarizing optical elements, such as wave retarders and polarizers.

A design for simultaneously measuring the polarization state of light based on division of wave front is presented. An incident light beam is divided by a composite beam splitter into four branches. The four branches of light are detected by four different independent detecting units respectively. The measured signal values from the four detecting units are used to form a signal vector. The instrument matrix of the system is obtained by calibration experiment. The Stokes vector describing the polarization state of an incident light is obtained by the matrix calculation by using the signal vector and the instrument matrix. The calculated result for an incident light is in good agreement with the measurement one.

In the Stokes vector method, the four elements of the Stokes vector are four real number parameters denoted by s0, s1, s2, and s3 that describe a certain polarization state of light. This method involves four light intensity measurements, using four distinct optical configurations. Each measurement corresponds to the intensity of a light beam after

it has passed through each of four different optical elements. The four parameters of the Stokes vector are derived from these four measured intensities.

The design mainly includes five parts: an optics-aligning part, a beam-splitting part, an optics-analyzing part, a light-detecting part and a signal-processing part. The alignment part is composed of two groups of lenses of L1 and L2. The beam-splitting part is a composite beam splitter (CBS), which is composed of four same corner cube prisms and used to divide a beam of light into four equal branches. The four prisms are adhibited together with their undersides outsiding. The cross section of the CBS that is perpendicular to the optical axis of the system is a square. The optics-analyzing part is composed of four composite filters F0, F1, F2, and F3. Each of the filters includes a quarter-wave plate and a polarizer. The four filters are used to modulate the lights for obtaining the elements of the Stokes vector. The light-detecting part is consists of four same photoelectric detectors D0, D1, D2, and D3. These detectors are used to detect the light intensities emitting on them and convert the light signals into electric signals for processing. The signal-processing part includes a computer and corresponding hardware and software. The four filters and the four detectors form four independent detecting units, respectively. The four detecting units are designed symmetrically around the optical axis of the system.

In the design, the calibration method by experiment is a simple way to confirm some technical data of an instrument system than the theoretical calculation. If the experiment is designed elaborately and proper care is taken, the error of the experimental result may be very small comparing with the ideal value, but the amount of the calculation for confirming the instrument matrix of the system is greatly decreased.

The system based on division of wave front is available for measurement of the polarization state of light despite the light is completely polarized, partially polarized, or un-polarized. It is especially suitable to the circumstances that the light is very dim and quickly changed. The method of the measurement described in this paper can be realized under the present scientific techniques and experimental conditions. The system enables us to realize the real time measurement for light in practice. We expect that the methods and techniques used in this system can be applied to measure and acquire more useful information of objects in more fields at scientific research and engineering.

9525-106, Session PS

Robust phase-shifting holography with high spatial resolution

Igor A. Shevkunov, Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

This paper evaluates a simplified method of implementation of phase shifting holography with use of a rotating plane-parallel plate. As a rule, a piezo-mechanical translation stage is used to move one of the mirrors in the reference arm of the experimental setup with nanometer resolution. Thereby it changes the optical path length of the light for creation a phase shift between exposures. Here we considered a simple and reliable method of phase delay: a rotation of a plane-parallel plate around its axis changes the optical path length in the reference beam. For the appearance of very thick carrier fringes, we incline the reference beam at the small angle. The measurement of intensity variation in the individual pixel of the registration matrix during rotation provides a feedback for adjusting the precise phase shift. An emerged slope of the wavefront can be corrected numerically during reconstruction.

The dependence of the phase reconstruction quality from the angle between the reference and object beams was investigated. The differences between in-line phase shifting and off-axis holography methods discussed. A clear advantage of the phase shifting method over the off-axis holography is the high spatial resolution. Another advantage is the simplicity of calculations procedure, so it is possible to compensate the time spent on the registration of additional holograms due to faster computing.

9525-107, Session PS

Influence of video compression on the measurement error of the television system

Alena Sotnik, Sergey N. Yarishev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Valeriy Korotaev, ITMO University (Russian Federation)

Video data require a very large memory capacity. Optimal ratio quality / volume video encoding method is one of the most actual problem due to the urgent need to transfer large amounts of video over various networks. The technology of digital TV signal compression reduces the amount of data used for video stream representation. Video compression allows effective reduce the stream required for transmission and storage. It is important to take into account the uncertainties caused by compression of the video signal in the case of television measuring systems using.

There are a lot digital compression methods. The aim of proposed work is research of video compression influence on the measurement error in television systems.

Measurement error of the object parameter is the main characteristic of television measuring systems. Accuracy characterizes the difference between the measured value abd the actual parameter value. Errors caused by the optical system can be selected as a source of error in the television systems measurements. Method of the received video signal processing is also a source of error.

Presence of error leads to large distortions in case of compression with constant data stream rate. Presence of errors increases the amount of data required to transmit or record an image frame in case of constant quality.

The purpose of the intra-coding is reducing of the spatial redundancy within a frame (or field) of television image. This redundancy caused by the strong correlation between the elements of the image. It is possible to convert an array of image samples into a matrix of coefficients that are not correlated with each other, if one can find corresponding orthogonal transformation. It is possible to apply entropy coding to these uncorrelated coefficients and achieve a reduction in the digital stream. One can select such transformation that most of the matrix coefficients will be almost zero for typical images . Excluding these zero coefficients also possible reducing of the digital stream. Discrete cosine transformation is most widely used among possible orthogonal transformation.

Errors of television measuring systems and data compression protocols analyzed In this paper. The main characteristics of measuring systems and detected sources of their error detected. The most effective methods of video compression are determined. The influence of video compression error on television measuring systems was researched. Obtained results will increase the accuracy of the measuring systems.

In television image quality measuring system reduces distortion identical distortion in analog systems and specific distortions resulting from the process of coding / decoding digital video signal and errors in the transmission channel. By the distortions associated with encoding / decoding signal include quantization noise, reducing resolution, mosaic effect, “mosquito” effect edging on sharp drops brightness, blur colors, false patterns, the effect of “dirty window” and other defects. The size of video compression algorithms used in television measuring systems based on the image encoding with intra- and inter prediction individual fragments. The process of encoding / decoding image is non-linear in space and in time, because the quality of the playback of a movie at the reception depends on the pre- and post-history of a random, from the preceding and succeeding tracks, which can lead to distortion of the inadequacy of the sub-picture and a corresponding measuring signal.

9525-108, Session PS

Evaluation of interference fringe parameters using sequential Monte Carlo method

Petr A. Ermolaev, Maxim A. Volynsky, Pavel S. Skakov,

National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Non-invasive high-resolution optical investigation methods are demanded in many fields, as material science, microbiology, medicine, metrology and others. Interferometric methods are most precise among other optical methods and traditionally used for objects inspection [1].

Individual parameters of signals, which are registering in interferometric systems, contain useful information about structure of investigated objects. It is necessary to use high-speed and high-accurate methods for obtaining this information. These signals may be affected by different types of noise that makes it difficult to recover useful information about the object.

Conventional signals processing methods based on Fourier transform are not allow obtaining individual parameters of signals as amplitude or phase and do not take into account available a priori information about signals formation and stochastic characteristics of noise. These methods do not always provide the required processing speed, because the use of discrete FT requires all samples of processing signal.

The use of recurrent algorithms of dynamic parameters estimation [2–3] is another approach to interferometric data processing. These algorithms use representation of interferometric signal as output of dynamic system that allows taking into account a priori information about signal formation and estimating of individual parameters of signal on every discrete time signal sample in the step-by-step mode. This fact is also allows increasing of speed of data processing that is important for creation of practical interferometric systems.

The recent researches interferometric data processing algorithms based on state-space approach consider so-called Kalman-type algorithms, such as extended Kalman filter [4] and unscented Kalman filter [5]. These algorithms are not robust in case of high uncertainty about the a priori form of the equations described dynamic system which is representing interferometric system. The sequential Monte Carlo (SMC) method [6] is an alternative approach to dynamic estimation of parameters of non-linear dynamic systems, which has not been researched in relation to the interferometric data processing.

The SMC method is based on statistical approximation of probability density of signal parameters distribution on every discrete time signal sample. In the simplest case the approximation is implemented by selection vectors of parameters which are best satisfied the observations from a set of randomly generated vectors. It is possible to change input parameters of the algorithm, such as count of randomly generated vectors, selection rule, starting probability density etc. for precision tuning of data processing in accordance with the requirements of the solving problem and available a priori information. This fact allows using of SMC method for data processing in many types of interferometric systems.

The SMC method was tested in some applications, such as data processing in system of biomedical tissues testing based on optical coherence tomography technique and solving problem of phase unwrapping.

In this research, the algorithm for dynamic estimation of parameters of interferometric signals by SMC method is considered. The influence of input parameters on estimation error value is analyzed. On the basis of simulation results for the considered class of signals, it is recommended to select 30% of the generated vectors number. The increase of the generated vectors number over 150 does not give significant improvement of the obtained estimates quality.

Results of experimental signals processing by SMC method are presented and discussed. It is shown that these results are matching with results which were obtained by other processing methods.

The computational complexity of this algorithm is estimated. The possibility of implementation using parallel computations is discussed.

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9525-109, Session PS

Fast inspection of bulk and surface defects of large aperture optics in high power lasers

Yuanan Zhao, Guohang Hu, Shijie Liu, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

Laser induced damage for nanosecond pulse duration was attributed to the existence of defects. The growth and polishing, as well as coating deposition, may induce versatile kinds of defects, including dig, scratch and inclusions. It is special important to get the information of the defects, such as size and location, which is the basis to know the origin the defects and figure out effective measures to improve it. It is quite easy to get the information of the defects with high resolution, but it is time-consuming and is not suitable for fast inspection of the large aperture (hundreds of millimeters). In this work, on-the-fly scattering image capture technique was employed to realize fast inspection of large aperture optics. A green laser was employed as illumination source to enhance and enlarge the image of the defects. A special lens with two variable slits was designed to distinguish the scattering light from the defects on surface or inside the bulk. The witness can be raster scanned driving by a stepper motor through the stationary illumination laser and digital camera. The field of view is about 2.8mm?1.6mm, and the speed to scan the witness is about 10cm/s. The resolution of this on-the-fly imaging is ~?m order. The results of several kinds of typical optics were demonstrated.

9525-110, Session PS

Enhanced adjustment methods for optical rotary encoders

Nikolai V. Smirnov, Svjatoslav M. Latyev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); René Theska, Technische Univ. Ilmenau (Germany)

Rotary encoders are used for angular measurements in a wide and growing number of devices and machines. The accuracy of rotary encoders is highly influential to the positioning accuracy of movements in the workspace. The applications of rotary encoders in the industry enabled a breakthrough in the degree of automation of production processes, productivity and product quality. That is why rotary encoders have high requirements on accuracy and operating speed thus generating high requirements on adjustment and subsequent control of rotary encoders.

The encoder operation accuracy is significantly dependent on the alignment of the center of the optical grating and the center of rotation. Fundamental errors of optical rotary encoders based on the circular pattern, are eccentricity and none uniform steps of the optical grid especially at the working tracks. Eccentricity is a mismatch of the centre of the circular optical pattern and the mechanical axis of rotation.

This paper is dedicated to methods for the improvement of the accuracy of optical rotary encoders, to accuracy characteristics control as well as to error compensation methods. Error minimization methods are analyzed.

Centering of the radial grating is commonly done by the use of a check mark as a reference in form of a circle applied in the same operation.

Alignment is usually executed by use of a measuring microscope by a worker or an aligning automatic device of high efficiency. State of the art techniques have a number of substantial disadvantages. The residual centering error is dependent on the resolution of the microscope, the quality of the rotary bearing as well as on the roundness of the circle mark and displacements relative to the radial grating. Moreover, the

circular centering mark alignment cannot compensate for the influence of the first harmonic of cyclic error of the radial grating. A centering set up for rotary encoders with two diametrically opposed reading heads has been developed that avoids all mentioned errors. The analog signals of both reading heads are displayed at an oscilloscope. The sensitivity of the described centering technique is very high due to electrical signal amplification at the screen of a digital oscilloscope and due to the high sensitivity of the human eye.

Besides centering, amplitude balance and phasing of the reading signals of the photo receivers are aligned as part of the encoder assembly process. Signal amplitude balance is usually achieved by alignment of incident light fluxes or by the alignment of resistors in the power-supply circuit. Phasing can be achieved by adjustment of photo receivers.

Once the adjustment has been finished, it is necessary to control the accuracy of the assembled device. The accuracy of the encoder under test is measured by comparing the operation with a reference rotary encoder. For this purpose, the shafts of the tested and the reference encoder need to be connected with a coupling. The shafts are than synchronously rotated and the rotation conversion codes of both encoder shafts are compared.

Angular axial and radial misalignments of the two shafts of the fixed encoders as well as deformations are causing errors transmitted by the commonly used rigid coupling from one shaft to the other. These errors often exceed those generated by the encoder under test itself. It is quite problematic to consider their impact to the overall process accuracy. For that reason, the shafts of the reference and the test encoder must be carefully aligned. This makes the test process more complicated increases the necessary working effort and reduces the validity of the obtained results.

In order to eliminate these errors, a special coupling device was designed. This device represents a four-bar linkage parallelogram mechanism with ball joints. The rotational axis of the bar linkage is orthogonal to the parallelogram mechanism plane. The design provides a connection between the encoder under test and a fixed point that is free of over constraints. This coupling mechanism is purely blocking the rotation and compensates for all other five degrees of freedom. Furthermore the setup is equipped with an automatically controlled autocollimator for an algorithmic correction of the measurement results based on the error mapping of the optical rotary encoder. The resulting error is calculated by a PC and can be describe as a difference between angle values derived from tested and reference encoders and corrections of the autocollimator for each selected position.

The described experimental setup allows the calibration of optical rotary encoders in an unlimited number of control points. It compensates error influences of the coupling of the encoder under test and the reference encoder. This increases significantly the accuracy of the calibration.

Based on the described theoretical and applied studies the realization of the suggested set up in form of a device for alignment and test of rotary encoders seems to be reasonable. The ongoing work will be focused on the development and optimization of an appropriate design.

9525-111, Session PS

Investigation on measurement of mid-frequency wavefront error for large optics in high-power laser system

Shijie Liu, Chunxiang Jin, You Zhou, Yunbo Bai, Yuanan Zhao, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

With the wide application of modern computer controlled small tools to the fine polishing process for various optical components, the periodic structures induced by the small tools with defined traces are not avoidable on the manufactured surface profile. These periodic waviness errors (so called mid-frequency wavefront error) with a certain amplitude will scatter the illumination light and are very harmful to the image performance in the optical system. Especially for the optics applied in the high-power laser system, these mid-frequency wavefront errors will intensify the nonlinear self focus effects, which would split the light beam and create filamentation effects. Therefore, how to accurately measure the mid-frequency wavefront error is very important to provide the feedback to the manufacturing process and thus improve the quality of optics.

Previous studies have reported how to use the phase-shift Fizeau interferometer to measure the reflected or transmitted wavefront of optical components and extract the mid-frequency wavefront information based on Fourier transform filtering technique. However, most of these studies focused on the large flat optics regardless of spherical and aspherical optics. Moreover, how to reduce the various effects on the measurement of mid-frequency wavefront error with the RMS specification of <=1.8nm is still blank in the existing literatures as far as we know. In this paper, we extend the measurement method of mid-frequency wavefront error to spherical and aspherical components. Some influence factors like the system error of interferometer, environment variation, surface parallelism of optics, polarizations of interferometer illumination, and the wavefront distribution of optics are analyzed in detail. Some optimized measurement strategies for different kinds of optics are suggested. Finally, experimental measurements on flat optics, spherical and aspherical optics are performed to testify the suggested measurement methods, respectively.

9525-112, Session PS

Phase disturbing speckle suppressing method in fiber metrology under coherent illumination

Weimin Sun, Yunxiang Yan, Jing Wang, Hongyuan Fu, He Tian, Yongjun Liu, Harbin Engineering Univ. (China)

Laser is the most important light source in optical metrology. The measures usually have to suffer the poor image quality because the coherent speckles. When we use multimode fibers to guide laser light, the output spot from the fiber contain speckles. The more modes is transmitted in the fibers, the more speckle spots could be obtained in the output spots.

A phase-disturbing speckle-suppressing method is proposed to enhance the image quality. The principle of this method is that introduce of random modulation into the phase of the laser beam will lead to random speckle pattern. Under a certain exposure time, these random speckle pattern will be average. After dozens of millisecond, the contrast of the speckle could be reduced dramatically.

We chose laser as the light source when we tested the focal-ratio-degradation test of astronomical fibers, because we can focus laser beam to a small point to control the import position in the incident ends of the large-core LAMOST fibers. When we wanted to fit the output spot from the fibers to a circle Gaussian-like curve, we found it is impossible because the serious speckles. We tried average dozens of images, but we found the speckle image was stables. So we tried to modify the speckle image by introducing phase disturbing system. We changed phase of different fiber guide modes, so the output speckle changed accordingly.

Both random-phase-plate-disturbing system and fiber disturbing system was established and tested. The random-phase-plate-disturbing system is to set a vibrating random-phase-plate against the output end of the tested fiber. The fiber disturbing system is to set the vibrating device in the middle of the fiber. Under different vibration frequency we compared the contrast of speckle patterns. We set different exposure time of the CCD camera to check the effects.

For the random-phase-plate-disturbing system, the exposure time should be long enough, for example 30 ms, to guarantee enough different patterns could be collected to suppress the contrast of the speckle and get good Gauss-like pattern. We compared the effects under 10, 100 to 1000 ms exposure time. 100ms is long enough for good image quality.

For the fiber disturbing system, we compared three kinds of fibers with different core-diameters, 10, 125 and 320 microns. We found that 70 Hz is the optimized vibration frequency for all fibers.

The introduction of the phase modulation could dramatically suppress the speckle under coherent illumination. The measurement accuracy could be enhanced according to the speckle suppression.

9525-113, Session PS

Generalized phase-shifting algorithms: error analysis

Gastón A. Ayubi, Univ. de la República (Uruguay)

Phase-shifting (PS) is a well-established technique for phase retrieval in interferometry (and three-dimensional [3D] profiling by fringe projection) that requires a series of intensity measurements with known or unknown phase-steps.

The required intensity measurements I_k(x , y) (with k =1,2 , ... , N) are given by

I_k(x , y)= I_0(x , y)[1+ K (x , y) cos (?(x , y)+?_k)] , (1)

where (x , y) are Cartesian coordinates, I_0(x , y) is the mean intensity, K(x , y) is thecontrast, ?(x , y) is the phase to be retrieved, and ? k are phase-steps.

In practice, the acquired images differ from (1) because several causes . Some error sources are phase shift errors (miscalibration of the phase shifter, nonlinearity and hysteresis of the phase shifter), detector nonlinearities, deviations of the intensity distribution in the fringes from a sinusoid and additive noise.

Recently, we developed a new method for generating algorithms with N arbitrarily spaced phase steps [1]. The objective of this work is find some conditions for this PS algorithm to minimize the error in the reconstructed phase.

In the literature there are a lot of PS algorithms that reduce the impact of the different error sources, but the mayor part of this algorithms works with equispaced images. Our generalized phase-shifting algorithm works with arbitrarily spaced images, so new conditions are required to reduce the impact of images affected by the different error sources.

We will discuss how to avoid the error produced by the previously mentioned factors.

Simulations of some deduced PS algorithms will be presented.

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9525-114, Session PS

Testing techniques for large aspheric primary mirrors in grinding

Yongqian Wu, Gaofeng Wu, Yundong Zhang, Institute of Optics and Electronics (China)

Large primary mirrors are key optical components in astronomical telescopes. The size, surface profile and quality of the primary mirror determine the imaging resolution and detection capability of the telescope. However, there are many difficulties in the measurement of large primary mirror in the fabrication process, especially in grinding.

In grinding process, the surface accuracy of large grinding mirror should be below 1um and the visible interferometer cannot be used due to the rough surface. The questions to be solved are how to test the large ground mirror in reasonable time and how to reduce the measuring error in the range of the visible interferometry. At present, the coordinate machine is usually used. However, it is very difficult to reach such accuracy when the aperture is larger than 2 meters. A high-precision far-infrared interferometer and IR compensator are presented here.

The wavelength of the interferometer is 10.6?m. At this wavelength, the grinding surface is optical “smooth”. The measurement rage of the interferometer reaches more than 30μm and the measuring error (RMS) is less than 0.05μm. Since IR radiation is invisible, it is very difficult to align the primary mirror or the interferometer. For some novel methods are used here, the alignment is more convenient and the efficiency of measurement is greatly improved. The interferometer we designed can fulfill the testing of grinding primary mirror.

The IR compensator is an optical system of large spherical aberration. It can guide the grinding process and determine the results of the large primary mirror in grinding. But it has intrinsic localization of stringent tolerance. There is a possibility that the IR compensator could be flawed, resulting in the final shape of the optic being incorrect. The two methods of accurate testing of the compensator are presented. The errors of the compensator would have been discovered and corrected .

The experiment is shown and it proves the efficiency of the far-infrared interferometer for the testing of large aspheric primary mirror in grinding process. It can significantly improve the test precision.

9525-115, Session PS

Uncertainty reduction of light spot angular position estimation in optical measurement system based on quadrant photodiode

Evgeni G. Lebedko, Kirill V. Trifonov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Systems based on quadrant photodiode can be used for solving different angular position measurement tasks. But such systems have accuracy problems. Solving these accuracy problems makes systems based on quadrant photodiode applicable for different industrial inspection processes such as positioning and pointing systems and interferometer experiments. For example angular drift in a laser beam can be a serious concern in interferometer experiments where anomalous fringe shifts can be caused by such drift.

The main purpose of this research is analysis of errors caused by change in slope angle of static characteristic of optical angular position measurement system based on quadrant photodiode and development of methods for the static characteristic stabilization.

Change in slope angle of the static characteristic is based on changes in magnitude of the received signal and object angular size, zonal dependent aberrations, e.g. coma, and mismatch of the receiving channels for each coordinate under temperature and time influence.

Analysis of errors caused by the change in slope of the static characteristic was performed by computer simulation. Two types of sensor were compared. The difference between these two types is that the first type uses of the normalized signal magnitude and the second one uses unnormalized magnitude.

In this work we show that in the case of unnormalized signals, the change in signal magnitude results in significant error of object angular position estimation. In the case of signal fluctuations the main error of the system is determined by change in signal magnitude. This problem can be solved by using normalized signals. In the case of object displacement within the system’s field of view, coma has the most significant influence on the slope of the static characteristic. The change of object angular size has great influence for both types of sensors as well. In the case of mismatch of the sensitivity of the receiving channels there are both changes in static characteristic slope and its axial displacement which can result in rough measurement errors.

Changes in static characteristic slope caused by described effects are graphically illustrated in this paper. The methods of the stabilization of static characteristic are proposed as well. Also illustration of digital interpulse sensitivity adjustment scheme of the receiving channels is shown in this work.

The conducted analysis of the error of angular position measurement and proposed methods for static characteristic stabilization give opportunity to significantly increase precision of object angular position measurements in optical electronic devices for different industrial applications.

9525-116, Session PS

An approach to defect inspection for packing presswork with virtual orientation points and threshold template image

Xiangyang Hao, Songlin Liu, Zhao Fulai, Lixing Jiang,

Zhengzhou Institute of Surveying and Mapping (China)

With the development of market economy, the consumers and manufacturers require industrial products with higher and higher quality. The packing presswork is an important factor of industrial product, especially for the luxury commodities as cigarettes and cosmetics. The fine packing presswork usually needs several procedures during its production, in which defects may be brought to the product and consequently negatively influence on the quality of packing presswork. In order to ensure the packing presswork to be qualified, the products should be inspected and unqualified one be picked out piece by piece with the visual inspection method, which has such advantages as no-touch inspection, high efficiency and automation. The possible defects can be classified into two categories as defects that appear only in local areas and defects that may appear anywhere in the presswork according to the defect position. Because the second sort of defect has the characteristics of undetermined position, shape and size, its visual inspection involves the detection in the whole area and usually needs more time for the inspection. The study of this paper will concentrate on the inspection strategy and algorithm for the second sort of defect.

Visual inspection of packing presswork mainly consists of steps as image registration, defect detection and defect discrimination. The registration between inspected image and reference image is the foundation and premise of visual inspection. The corners of packing presswork are not directly utilized for image registration because they are usually not sharp enough to find the precise position. In order to realize the rapid, reliable and accurate image registration, a registration method based on virtual orientation points is put forward. Although a piece of packing presswork is irregular in shape instead of a rectangle after the procedure of cutting, its outline still consists of straight line segments. A pair of original orientation points is firstly acquired for each side of its outline by searching from borders of the image and computing the color or intensity difference between object and background. With the help of these original orientation points, four virtual precise orientation points can be obtained by calculating the intersect points of perpendicular straight lines. The registration parameters are finally acquired according to bilinear model with the virtual orientation points. In this way, the precision of registration between inspected image and reference image can reach to 0.01 pixels.

Generally, defect inspection is implemented by comparing the inspected image with reference image after image registration. Since the second sort of defect is lack of fixed position, shape, size and color, three measures are taken to improve the inspection effect during the design of inspection algorithms. Firstly, as the packing presswork may consist of various designed patterns and backgrounds with different colors, while the defect emerged in different position on the packing presswork has different influence on the quality of final product, therefore different inspected areas usually need to be inspected with different thresholds of color difference. For this reason, the concept of threshold template image is put forward. Each pixel of threshold template image, which can be generated in advance, records a threshold value correspondent to the reference image. Thus the inspection involves three images, i.e. reference image, inspected image and threshold template image. Secondly, for the registration error still exists to some extent, the color difference is calculated by comparing each pixel with the adjacent pixels of its correspondent pixel on reference image. In this way, false defects resulted from registration error can be effectively avoided. Thirdly, in order to enhance the inspection efficiency, the strategy of image pyramid is applied in the inspection algorithm. The defect detection is carried out firstly on image with decreased resolution. Once a defect pixel is detected, the original inspected image is used. In light with the methods described in this paper, visual inspection software for cigarette packing presswork is developed. A large amount experiments show that the related algorithm is effective to such defects as stains, scratches, creases and damages and it takes about 32 milliseconds on average to inspect a piece of cigarette packing presswork.

9525-117, Session PS

Short wavelengths active bichromatic pulsed pyrometer for solids and liquids designed for measurements in harsh environments

Lorris Navello, Univ. Paris Ouest Nanterre La Défense (France); Jeremy Lebedinsky, Lasur SARL (France); Julien Pierre Offret, Bruno Serio, Tanguy Davin, Univ. Paris Ouest Nanterre La Défense (France); Yannick Bailly, Univ. de Technologie de Belfort-Montbéliard (France); Philippe J. L. Hervé, Univ. Paris Ouest Nanterre La Défense (France)

Optical thermometry methods such as radiation pyrometer or thermo-reflectivity sensors are well suited to measure temperature of moving targets at high temperature when non-intrusive temperature measurements are necessary. If the emissivity factor is known, for a transparent environment, passive optical methods such as thermography or pyrometry are very interesting because they allow a non-intrusive measurement.

But emissivity variation is the most serious problem encountered in the application of radiation thermometry in industrial processes. Indeed, the knowledge of this factor is critical for determining the actual temperature of a surface from the analysis of the thermal radiation in a wavelength band.

When the object to be measured is placed in harsh environments, such passive optical methods are greatly disturbed by the presence of an optically absorbing medium such as smoke, soot or water vapor. It is also distorted for objects located in very hot environments emitting intense interfering radiation during high-energy processes. In particular, measurements within walls of industrials furnaces or in the vicinity of flames such as those produced by a turbojet engine are especially made complicated. Consequently, high accuracy pyrometry in hostile industrial environment under conditions in which emissivity of the measured target changes with processing conditions cannot be obtained with conventional spectral radiation thermometer without using compensation algorithms.

Active bichromatic pulsed pyrometer allows to overcome these drawbacks by taking some precautions about the choice of its working wavelength values.

In this study, an active bichromatic radiometric method for measuring the temperature of solid or liquid surfaces in harsh environments is presented. The method is based on a localized thermal excitation using a pulsed laser source in the infrared range. The temperature of the measured target is then locally modulated by the photon flux. The temperature range is correlated with the laser amplitude and frequency excitation. This periodical excitation allows a synchronous detection to extract the signal embedded in a noise up to 10^6 times superior. A specific optical system has been designed to collect the radiation emitted by the excited surface at two wavelength bands in both the visible and near infrared range. At high temperature, working at short wavelengths offers a large sensitivity range and minimizes the error due to variations in emissivity with the wavelength. The measurement system collects the radiation emitted by the object at a distance from a few meters up to dozens of meters depending on the configuration of the optical system used.

The purpose of this study is to present the principle of the measurement method, the optical wavelength separation system, the telemetry apparatus and the signal detecting and demodulation processing required to determine the temperature of the measured object.

The theoretical and experimental studies of the sensitivity are compared and the precision of the new temperature sensor device (around 20°C to 1500°C) is presented as well as its calibration.

Finally, to illustrate the performance of the equipment, particularly under harsh environments in terms of ambient temperature, noise, vibration and smokes, results obtained for the characterization of the temperature of a wall of both the outlet nozzle of an aircraft propeller and an industrial furnace are presented.

9525-118, Session PS

Sapphire fiber optic sensor for hot flow temperature analysis

Wei Wang, Yuanhong Wang, Minglei Yuan, China Academy of Aerospace Aerodynamics (China)

In many high temperature processes, it is important to have accurate knowledge of temperature. This is true for processes such as materials processing in the metal and glass industries, and is equally true in the measurement of turbine inlet temperatures in jet engines and in stationary gas turbine power plants. However, the maximum temperatures in these processes can reach as high as above 2000°C, and the environments are always chemical corrosive or strong electromagnetic. Ordinary thermocouples cannot meet the requirements for stable and accurate operation in such high temperature applications. Optical-based temperature measurement systems have several advantages, including the ability to withstand high temperatures and immunity from electrical noise due to their all-dielectric construction.

The sapphire fiber-optic temperature sensor based on Black-Body radiation law, is a new technique of high-temperature measurement in extreme environment, which combines techniques of radiometric thermometry and optical-based temperature measurement. In the paper, a system is established and tested.

The blackbody probe is formed of a single crystal sapphire rod divided into a waveguide region and a cavity region which is the key to achieve high temperature measurement. Yttria-stabilized zirconia which can be used at temperature in excess of 2300°C is selected as the cavity ceramic material. A thin film has been coated on a 450-μm single crystal sapphire fiber by plasma spray used as the blackbody source. Optical signal from the black body radiating cavity was conducted along the sapphire fiber to a low temperature fiber. The light output from the low temperature fiber passed through a notch filter and was detected by a detection system based on an InGaAs photodiode and then collected and processed by computer. The temperature was determined from the output voltage signal of photodiode at particular wavelengths(λ=830nm) easily isolated with the notch filter using the Planck relationship.

Tests were performed at the temperature range from 400°C to 1600°C using spirit lamp and butane gas gun as the heat sources: It was found that when measuring the temperature of spirit lamp flame, the voltage signal was too small to be detected due to the black body radiation intensity is weak below 800°C, so the sensor is not suit for the temperature measurement below 800°C. But at high temperature region of 800~1600°C, the test data achieved high consistency with the thermocouple results measured at the same heat point over the butane gas gun.

The design of interface system of optical fiber system and wind tunnel is another important part to realize long-life high temperature test. Design of sensor mechanical protection interface system with Solid Ramjet Engine Ground Test afterburning chamber as the application object, measuring the temperature of a medium to high temperature air staged combustion chamber. The choice of tungsten alloy for the sensor housing materials, its melting point is as high as 3410°C. High melting point, high temperature transpiration characteristics of tungsten copper alloy can endure as high as 2000°C use. As the temperature of the device interface and external support part is lower, stainless steel material is selected, easy processing and low cost.

In conclusion, the plasma sprayed ceramic blackbody cavity endures through the high temperature environment, which is also satisfying the rigour requirements such as chemically stable and well-bonded with the fiber body. The black body results of this study demonstrate that the plasma sprayed ceramic thin film is suitable for sapphire fiber cladding for high temperature applications. The tests approved that the sapphire fiber-optic temperature sensor based on Black-Body radiation law has high sensitivity and is suitable for 800~1600°C temperature measurement.

9525-119, Session PS

Determination of the refractive index of particles by using wavelength immersion matching technique

Ilpo O. Niskanen, Univ. of Oulu (Finland)

The measurement of the refractive index is widely applied to control the quality of products, to verify raw materials such as detection of particle concentration, purity, chemical identification of species and density. The refractive index of materials has been investigated using various devices for a long time in the science. Ellipsometry and interferometry are also useful optical techniques for determining the refractive index of solid materials, but these are rather expensive devices and require good sample quality. Unfortunately, there is no rigorous scattering theory currently that would provide accurate refractive index of a particle with irregular shape and volume in a suspension. However, immersion methods is independent on the shape and size of a particle, and the measurement of refractive index is relatively easy and fast to perform. Refractive index can be measured by a number of different immersion techniques including liquid variation, temperature variation and wavelength variation methods. Recently we have developed optical measurement methods, devices and analyzing methods of refractive index of micro- and nanoparticles using the idea of light dispersion of a suspension where solid particles are embedded in an immersion liquid [1,2]. The wavelength matching technique is based on that immersion liquid and particle have differential intrinsic dispersion n(?) characteristics. The refractive indices of the immersion liquid and a particle may equal at certain wavelength ?. This condition can be observed from the transmission spectrum and particularly from the spectral location of the maximum transmittance. In such an ideal case the light scattering intensity in a suspension would be zero and thus the light transmittance through the suspension would be 100%. The wavelength matching method is quite economic because a small liquid volume is needed and it is easier and faster way to determine the refractive index and purity of particles.

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9525-120, Session PS

Optical detection of microorganisms dispersed in pure water

Ayata Takami, Takeshi Ishiyama, Toyohashi Univ. of Technology (Japan)

Because microorganism testing in foods is essential to prevent food poisoning, food poisoning is generally caused by microorganisms. The flow cytometry technique is one technique to detect microorganisms using light. However, the flow cytometry is complicated and very expensive. Therefore, we have developed a detection system that is inexpensive and is simpler than flow cytometry.

In this work, we constructed above detection system and the transmitted and scattered light were detected to polystyrene particles and microorganisms which were dispersed in pure water. The polystyrene particles were used as previous step for detection of microorganisms existing in foods. From these results, we evaluated the measurement limit of the detector by using intensity of transmitted and scattered light.

Figure 1 shows a schematic diagram of the experimental system constructed in this study. The radiated light from the He-Ne laser (05-LHR-171, Melles Griot) was irradiated to a glass cell where sample solutions were dispensed. The transmitted light was detected by the PIN photodiode (S3071, Hamamatsu photonics). The scattered light was detected by the photomultiplier tube (H10722-20, Hamamatsu photonics) which was set at 90°.

Table. 1. The details of the polystyrene particles and the microorganisms

Particle diameter (μm) Product number Manufacturer

30 6602799 Beckman Coulter

1.6 4016A Thermo Fisher Scientific

5.3 (BioBall:

Aspergillus brasiliensis) 410106 Sysmex biomerieux

The details of the polystyrene particles and the microorganisms used are summarized in Table 1. The diameters of the polystyrene particles are almost the same as those of the microorganism colonies (approximately 50 μm in diameter) and the individual microorganisms (approximately 1 μm in diameter). The polystyrene particles and microorganisms were dispersed in pure water with various concentrations. The aqueous solutions were injected into the test cell, and the transmitted and scattered light was detected using the experimental system. Incidentally, BioBall's average particle diameter was evaluated using optical microscope (BX51, OLYMPUS). The result was 5.3 μm.

Figure 2 shows the transmitted light intensity as a function of the particle concentration, where the transmitted light intensity was normalized with respect to that for pure water. The transmitted light intensity decreased with increasing particle concentration (Fig. 2). In addition, the threshold concentrations for the decay of the transmitted light intensity increased as the particle diameters decreased. In general, the transmitted light intensity I is given by[1]

I=I_0 exp(-Q_ext NL) (1)

where I0 is intensity of light source, Qext is the extinction cross-section per particle, N is the particle concentration and L is the optical path length. By fitting Fig. 2 using equation (1), Qext was evaluated and is shown in Fig. 4. Incidentally, Qext is given by

Q_ext=Q_scat+Q_abs ?????? (2)

where Qscat is scattering cross section and Qabs is absorption cross section.

Fig. 2. Normalized transmitted light intensity for various concentrations and particle diameters of polystyrene particles and BioBalls

Figure 3a, 3b and 3c shows measurement results of the scattered light intensity. The scattered light intensity was proportional to the particle concentration (Fig. 3a, 3b and 3c). Moreover, the detection limits of particle concentrations were 64 mL-1 for the 30-μm-diameter polystyrene particle, 3.2?103 mL-1 for the 1.6-μm-diameter polystyrene particle and 2.0?102 mL-1 for the BioBall. Next, the scattered light intensities at 90° were divided by the particle concentrations and the scattered light intensity per particle at 90° (Iscat) was obtained. The estimated Iscat is shown in Fig. 5.

The change trend of Qext of the BioBall corresponded to the change trend of the polystyrene particles (Fig. 4). Iscat of the BioBall was stronger than that of the polystyrene particles (Fig. 5). From these results, the Qext of the polystyrene particles and the microorganisms were almost the same. However, the Iscat of the microorganisms was bigger than the Iscat of the polystyrene particles. Therefore, the detection of the microorganisms was easier than the polystyrene particles, at measurement of scattered light.

However, this system cannot be distinguished the microorganisms from the food residue when we inspect the foods at this stage. The future problem is distinction between the microorganisms and the food residue.

9525-121, Session PS

Integration of an intensity-modulated optical fiber temperature sensor into ceramic coating obtained by wire flame thermal spray

Duo Yi, Univ. de Technologie de Belfort-Montbeliard (France); Pièrre Pfeiffer, Univ. de Strasbourg (France); Bruno Serio, Univ. Paris Ouest Nanterre La Défense (France); Sophie Costil, Univ. de Technologie de Belfort-Montbéliard (France)

Temperature sensors working at several hundreds of degrees are key components for Structured Health Monitoring (SHM) in the industrial applications, the detected in-situ temperature information are vital for optimization of system elaboration conditions as well as following structural monitoring services. Optical fiber sensors like Fabry-Perot sensors, Bragg Grating sensors are of great interests and have been widely applied in the industrial and military applications, they can realize measurements with high sensibility and resolution. However, they stand for also high expenses and complicated data processing techniques. When compared to these sensors above, the intensity-modulated optical fiber sensor owns many particular advantages due to its relatively low cost, simple structure and principle. Moreover, it can offer various designs based on different application purposes. At present, the application field of this kind of sensor is primarily related to the measurement of stress, strain and deformation, there is not much applications about temperature sensing directly since the optical fiber itself has a low sensitivity to the temperature variation (thermal expansion coefficient: 5.5?(10)^(-7) /?, thermo-optic coefficient: 1?(10)^(-5) /?), which introduce the main objective of this work.

Although a large number of fiber optic sensors have been developed, the applications in the material science are still observed to proceed slowly especially in the mechanical and thermal fields, for example, the mechanic attachment applications. Currently, the mechanic attachment technologies can be divided mainly into three parts: mechanical brackets, ceramic adhesives and thermal spray. Thermal spray has been developed greatly in the recently years for applications of cavitation erosion, corrosion, wear, weld, repair, etc. It can be used to manufacture various dense multi-layer coatings with high reliability, practicality and diversity. This is particularly true for the ceramic spray coating, which could provide durable protection and high temperature resistance under optimized manufacturing conditions.

Nowadays, the multi-layers structure embedding optical fiber sensors has been received growing interest since it can be used to monitor various useful internal structure information. This work mainly concentrates on the feasibility of intensity-modulated optical fiber sensor integrated into ceramic coating and the temperature detection based on the optical intensity variation. The sensor consists of two cleaved optical fibers separated by an air cap and aligned with a capillary tube. The elaboration principle of intensity-modulated optical fiber sensor is firstly explained. A thermal modeling is then built up in order to evaluate the effect of temperature on the deformations of the optical fiber sensor which finally lead to the intensity variation during the thermal test. Next, static temperature dependence test is done in order to analyze the relationship between the temperature variation and the optical intensity variation. Finally, the first results of the thermal response test as well as the repeatability test of this embedding optical fiber temperature sensor are discussed.

9525-122, Session PS

Measurement of concentration of sugar in solutions with laser speckle decorrelation

Swapnil Mahajan, Vismay Trivedi, Vani K. Chhaniwal, The Maharaja Sayajirao Univ. of Baroda (India); Mahendrakumar P. Prajapati, P D Pandya Mahila Commerce College (India); Zeev Zalevsky, Bar-Ilan Univ. (Israel); Bahram Javidi, Univ. of Connecticut (United States); Arun Anand, The Maharaja Sayajirao Univ. of Baroda (India)

Measurement of rotation of plane of polarization of linearly polarized light can provide information about the concentration of the optically active system with which it interacts. In the case of substances containing sugar, accurate measurement of rotation of the linear polarization state can provide accurate information on the concentration of sugar in the material. Measurement of sugar levels is important in many areas ranging from blood sugar level measurement in body fluids to measurement of sugar concentrations in juices and other beverages. But in many of these cases, the changes introduced to the state of polarization considering a sample of practical proportion is low and the measurement of low optical rotations becomes necessary. So methods with higher sensitivity, accuracy and resolution need to be developed for the measurement of low optical rotations. Here we describe the development of a compact, low cost, field portable, device for rotation sensing leading to sugar concentration measurements, using speckle de-correlation technique. The developed device measures rotations by determining the changes occurring to a speckle pattern generated by a laser beam passing through the medium under investigation.

The device consists of a sample chamber made up of microscope slide having a volume of 5mmX5mmX10mm. An off the shelf diode laser module was mounted a short distance from the chamber. Beam from the laser was polarized using a commercially available dichroic sheet. Laser beam was allowed to pass along the longer dimension of the sample cell. A ground glass diffuser was pasted on the exit face of the cell to convert the laser beam into volume speckle field. This speckle pattern is recorded by a webcam sensor placed at a distance from the diffuser such that the sampling criterion is taken care. Since the transmittance and the reflectance of the incident beam depends upon the angle of incidence of the electric field of the light beam, the complex amplitude of the laser beam at the output face of the diffuser changes with polarization. So a change in the state of polarization changes the resulting speckle field. The device was calibrated by using sugar solutions of different concentrations. Speckle decorrelation was computed by comparing the resulting speckle pattern to the speckle pattern generated when the chamber was filled with distilled de-ionized water, which is called as the reference speckle pattern. This quantity can then be related to the rotation angle or the sugar concentration, since they are related linearly. The developed device was used to measure of small sugar concentrations using the calibration plot. The calculated sensitivity of the technique was 0.007/mg/ml, the resolution was 0.9mg/ml and precision was 0.6mg/ml. This paper discusses in detail the development of the device as well as the obtained experimental results.

9525-123, Session PS

Precise angular position measurement of a point source in an optoelectronic system with CCD arrays upon a single readout

Evgeny G. Lebedko, Elena Zvereva, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The purpose of this article is to examine the method of angular position measuring of a point source by means of angle - time - code transformation and to determine a random error of measurement under optimal and quasi-optimal linear filtering of signals at the CCD arrays output upon a single information readout.

This work introduces an optoelectronic system circuit with stretched CCD arrays and a point of reference for angular position measuring. In this case the arrays have images projections of both the reference point source and the target point source, whose angular position is measured with high precision. From the CCD array output the signals arrive at an optimal (or apt) linear filter, and then to the signal peak position detection circuit, which provides the minimum error due to noise impact. Pulse edges, corresponding to the signals maximum, make a time interval filled with high-frequency counting pulses. The number of pulses in this interval will correspond to the measured angular position of the target point source.

In terms of the statistical decision theory this work analyses random errors given the signals spectral function that, in turn, accounts for the transfer function of the optical system and the CCD array as an image analyzer. This article also presents analysis of how measurement accuracy depends on frequency of information readout from the CCD-arrays for different values of signal-to-noise ratio.

Error analysis of the proposed optoelectronic circuits showed that measurements can be made upon a single readout with an accuracy of 0.01 and even 0,001 pixels.

9525-124, Session PS

Cost effective spectral sensor solutions for hand held and field applications

Edgar Reetz, Martin Correns, Technische Univ. Ilmenau (Germany); Gunther Notni, Technische Univ. Ilmenau (Germany)

Optical spectroscopy is without doubt one of the most important non-contact measurement principles. It's being used in a wide range of applications from bio-medical to industrial fields. One recent trend is to miniaturize spectral sensors to address new areas of application. With the exception of colorimetry no real low-cost high-volume applications have been addressed yet. In the authors opinion there are two reasons. The state of art in miniaturized spectral sensors has:

- lack of robustness for operation in challenging environments, and
- high cost for whole measurement systems.

Today three major technologies for the miniaturization are in pursuit to reach the goal of robust and low-cost spectral sensors. With micro mechanical systems (MEMS) it is possible to build small FT-spectrometers with production methods used for integrated circuits. With modern interference filter technologies it is possible to create highly stable fine structured spectral filter array systems. And lastly classic diffraction grating optics are optimized in size and system integration to create competitive results.

All of these approaches leave one important influence out of the cost calculation: The spectral sensor itself is only a small part of a fully operational measurement system. After all, very few applications require spectra as a result, most need a value for a specific parameter, i.e. substance property. Additionally most of these concepts neglect the fact, that in hand held or mobile operation of a spectral sensor the environmental conditions change drastically. An unmonitored single channel spectrum will very likely be prone to strong systematic measurement errors. This situation is even worse when natural light sources are used directly.

The proposed new concept is to optically couple a spectroscopic optical system to a smart phone, in contrast to an electrically (i.e. USB) or wireless (BT, WiFi) coupled external spectrometer. One advantage is to get computing power and connectivity at very low cost. Another is getting the photoelectric sensor for free as it is already integrated. Comparable sensor modules are practically impossible to obtain separately at the same price point. One would argue that the pixel quality of a smart phone camera is much worse than that of an industrial grade image sensor. That is true, but the investment in research and development of those consumer modules is much higher than in conventional industrial products. The smart phone cameras are improved faster than others. So the technological gap is decreasing with every year passing.

Another aspect of our new approach is to use an imaging diffraction grating to resolve several channels. As there already is a matrix sensor integrated, it is sensible to use it to detect multiple spectra at a time. The biggest advantage is not higher throughput but redundancy. With the extra channels online calibration, light source control and environmental monitoring suddenly are possible without extra cost. With these additional monitoring features robustness can be greatly improved.

We will present a functional model based on an Android smartphone with an optically coupled imaging diffraction grating and an 11-channel fiber optics, including embedded image processing methods to acquire the spectra from the smartphone camera.

9525-125, Session PS

Integration of an autonomous optical sensor system in the machining area of milling centers

Marc Preißler, Mathias Schellhorn, Rolf Hoffmann, Gunther Notni, Technische Univ. Ilmenau (Germany)

Companies in the material processing industry are exposed to increased pressure from competition. The requirements in quality are rising in higher dimensions and the manufacturing accuracy getting even smaller. At the same time productivity must be increased or may not be affected at least. These requirements of sophisticated quality control and a simultaneous reduction of cycle times are only to comply through integration of new technologies and improvement of degree in automation.

A suitable approach is the integration of quality control in the ongoing manufacturing process. This paper discusses the possibilities for integrated quality control in CNC milling machines. As state of the art milling machines have tactile sensors as integrated metrology equipment for the determination of the work piece position or manual selective probing. Possible conclusions must be calculated by the operator itself. At once the procedure takes a long time to complete.

At this point a process-integrated, automated measurement system which is fully integrated in the CNC machine flow to early enable the detection of quality deviation would be helpful and should be content to this approach.

For these the technology is optical measuring during the cutting process in the machining area before removing work piece from clamping. Non-contact measurements with image processing sensors have significant benefits for data acquisition in rapidity and a high grade of flexibility. New effective measurement strategies can be developed in effect of the quality controlling in the machining area. These includes classical geometric measurement applications from optical 2D but also options for 3D measurement tasks like determining roughness or other typical image processing applications.

This paper presents the challenges for the implementation of an optical sensor system in the machining area of milling centers. Primarily a suitable location in the machining area must be found and an associated strategy has to be developed. The integrated optical image sensor system should be protect against impurity and does not derogate in his functionality. For this purpose the optical sensor system can be load via the HSK (hollow shank taper) interface from the tool magazine. Furthermore strategies and solutions for non-existent interfaces in the roughness machining area are to evaluate. That means a possibility to supplying all electric sensor components with power, an interface to control the optical sensor system and an interface for the transmission of image data to a control unit. For the full integration as a quality control loop, the results must eventually feed into the machine control. Thus a further interface between measurement program and a machine control is necessary.

Another major field of research exists in the optical components. Especially the illumination, image sensor and lens are selected and adaptable for the measurement tasks after the considerations of the above-mentioned basic requirements.

CNC machines have high-precision positioning systems in order to maintain the required manufacturing tolerances. The innovation is to integrate advanced measuring systems in the machining area of milling machines and to lift the fusion of both technologies to a new level.

The presented research provides a suitable solution to make the CNC manufacture more efficient. Quality controls of the work piece can be executed within the CNC process and potential post processing can be performed simultaneously.

9525-126, Session PS

Quantifying height of machined steps on copper disk using Fourier domain short coherence interferometer

Risto Montonen, Helsinki Institute of Physics (Finland) and Univ. of Helsinki (Finland); Ivan Kassamakov, Edward Haeggström, Univ. of Helsinki (Finland); Kenneth Österberg, Helsinki Institute of Physics (Finland)

The internal shape and alignment of accelerating structures (AS) is crucial for efficient collider operation in the future compact linear collider (CLIC) [1]. Here we apply Fourier domain short coherence interferometry (FDSCI) to measure the height of ultra-precisely machined steps (surface roughness RA ≤ 25 nm, flatness ≤ 1 μm) on an oxygen-free electronic (OFE) copper disk. This is a first step towards a quality assurance tester for CLIC. LED light (λ0 = 655 nm, Δλ = 22 nm) illuminates the copper disk and a glass slide that provides a reference reflection. The light reflected back is coupled into a visible range spectrometer (Ocean Optics, HR2000+) that captures the spectral interferogram constructed from the copper disk reflection and glass slide rear surface reflection. A-scans revealing the optical distance (OT) between the copper disk and glass slide are extracted from spectral interferograms using a non-uniform inverse fast Fourier transform [2]. Calibration of the FDSCI is taken into account by calculating the corrected OT using a correction function C, OTcorr = OT – C. The geometric distance is obtained by complementing the corrected optical distance data with the refractive index of the ambient air [3]. A step height profile is then achieved by scanning the copper disk across the FDSCI probing beam. The proposed research relies on our recent work to calibrate the FDSCI for absolute dimension measurements by comparing the optical thickness of two Check Line CPS-100 thickness standards and three Schott D 263 M cover slips. During the calibration we extracted a correction function C = 0.017OT – 0.1 with a system uncertainty of (6.2·10^(-3)·OT + 2.3) μm, where OT is the interferometer reading in units of μm, with 95% confidence across the 240 μm optical measurement.

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9525-127, Session PS

The research of the nonexcluded air control error component using the optical-electronic system based on the dispersion method

Ivan S. Nekrylov, Alexandr N. Timofeev, Sergey N. Yarishev, Anton V. Nikulin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Nowadays there is a tendency of tightening the accuracy requirements for optical-electronic systems working in the field of geodesic engineering measurements, occurring in the open space. The analysis conducted has shown that the most influencing errors are connected with the influence of an air tract. Nowadays there is not any general theory that could completely describe the character of an air tract influence on electromagnetic radiation, particularly belonging to the optical range. Among all the known solutions to this problem requested to use the method based on dispersion of the optical radiation passing through the air tract. The proposition of this system is to measure the coordinate difference between the energy centers of two source images differing in the wavelength. The difference between the refraction indexes provides the different character of radiation passing through the same nonuniformities of the air tract. The displacement of the image energy center is connected with a refraction index random spatial rearrangement. Using the photoreceiver with the Bayer filter allows to measure the difference between the images from two color channels (red and blue) using some possibilities of an image processing. The research conducted has shown that the coordinate error of a retroreflector position, determined by the influence of a vertical temperature gradient, is inversely proportional to the squared distance between the retroreflector and the radiation source. Even if the vertical temperature gradient is less than 0,005°C/m the error reaches the value is about 1,2 mm for a distance of 100 m. In this paper requested to explore a non-excluded error component of this system produced by the influence of the air turbulent parameters fluctuations and an inaccuracy of a vertical temperature gradient definition. A vertical temperature gradient definition error defines by the selecting of wavelengths ?_1 and ?_2, that defines the refraction indexes of the air tract n_1 and n_2, an image position error and some receiver parameters. To explore the error components requested to operate with receiver parameters and some possibilities of the image processing. A set of measurements has proved the difference of 0.5 pix between energy centers of LED image without air temperature gradient between different colors (RMS error is about 0.02 pix at 1000 frames). At 2.5 m distance and 0.02°C/m gradient the shift of blue and red image at 19 pix was recorded with a stable difference between them at 0.2 pix. The non-excluded error component is 0,05 of image displacement.

9525-128, Session PS

The definition of the railway position control error in the plane and profile using the optical-electronic system

Anton V. Nikulin, Alexsandr N. Timofeev, Ivan S. Nekrylov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Continuous development of the high-speed railway traffic causes some accuracy requirements to be higher, especially for a railway placing. For modern technologies of a railway service using it's absolute coordinates the perspective way is to create a special anchor network. Using the optical-electronic system that works with the anchor network it is possible to get the information about the position of the railway with a measurement error not more than 1,5 mm. The system works with a velocity of a railway machine is about 10 kmph even if the weather conditions are quite rough. Sush systems can give the information about the position of the railway in the plane, profile and at the level relative the anchor network independent of one another. The perspective way to comply the requirement for accuracy and the range of control is to use an adaptive optical-electronic system based on some possibilities of a computer vision. The analysis conducted has shown that the most influencing errors are connected with the definition of the distance between receiving channels and the velocity of the railway machine. The relations obtained for a random component of the system error which is determined by the anchor coordinate error on a matrix field. Experiment research shows that the threshold value of the main error doesn't exceed the defined error value. Test of the system with the Duomatic 09-32 railway machine using the trajectories analysis of information from nonsynchronized matrix receivers shown the decrease of the results variation produced by the motion blur of the anchow image. At the range of 5 m and the velocity of 3,3 mps the error value is 0,15 mm in profile and 0,82 mm in the plane. It is shown that using the dispersion method allows to decrease the vertical temperature gradient of the air tract.

9525-129, Session PS

Aberration influence on accuracy of angle measurements by means of autocollimator

Yuri V. Filatov, Roman A. Larichev, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation)

Autocollimators are the most common optical devices used in high precision angle metrology nowadays. They are included in measurement setups for angle standards calibration with accuracy better than 0,1 arc sec. Comparison measurements held by few national metrology laboratories with angle polygon as a transfer standard have shown that results achieved with different measuring setups and (or) different autocollimator models may not correspond with each other. With measuring accuracies declared not worse than 0,1 arcsec the disagreement have reached value of 0,3 arcsec.

A few reasons for this disagreement have been proposed assuming that angle polygon has been transferred between laboratories properly. These are: non-flatness of reflecting surface, aberrations of autocollimator imaging system, mutual misalignment of reflecting surface and autocollimator and reflecting surface edge effects. In this paper authors suggest investigation of listed factors influence from the wave theory of light point of view. Except the effects that are brought by edges of reflecting surface as they are of random character and hard to explore.

Non-flatness of reflecting surface and imperfections in autocollimator imaging system are regarded through aberrations they bring to wavefront travelling through aggregate optical system consisting of autocollimator and reflecting surface. All aberrations are presented in terms of Zernike polynomials. Orthonormality of Zernike polynomials allow to examine aberrations presented by different polynomials separately.

Aberration influence on angle measurement is calculated from lateral shift that aberrations impose to illumination centroid of reticle imaged on the focal plane of the autocollimator objective. The only aberrations that can cause such shift are tilt and coma of all orders. Taking in account that tilt is parameter being measured, coma is the aberration that will be considered. Coma of each order causes lateral shift of illumination centroid linearly dependent on the value of aberration itself.

In case of ideal autocollimator and reflecting surface wavefront travelling between them is flat. Presuming that aberrations of optical system can be brought to one plane, autocollimator aberrations will be regarded in the plane of its exit pupil as a distribution of phase shift. Non-flat reflecting surface also brings a phase shift to flat wavefront being reflected. Thus aberrations brought by autocollimator and reflecting surface are of additive character.

Turning back to angle measurements involving angle polygon it can be said that aberrations of autocollimator do not affect results of measurement of angle between two faces. Angular offsets caused by autocollimator aberrations when measuring different polygon faces will be annihilated due to additive character of aberrations and linear dependency of its influence on measured angle.

The influence of aberration caused by topography of reflecting faces and their alignment respectively to autocollimators optical axis can be estimated simultaneously by expanding the phase shift in terms of Zernike polynomials for autocollimator's circular exit pupil. Also the expansion shouldn't be calculated for all terms but those that represent coma of different orders. Report contains results of numeral estimations of angle errors with different parameters of measurements.

9525-130, Session PS

Measurement of in-plane rotation angle by sampling Moiré technique

Soheila Javadianvarjovi, Amirkabir Univ. of Technology (Iran, Islamic Republic of); Khosro Madanipour, Amirkabir Univ. (Iran, Islamic Republic of)

The precise angle measurement is an important issue in optical metrology. Because of simple optical equipment, high sensitivity and accuracy, non-contact, fast responsibility and reliability, Moiré measurement technique has found many applications in different fields of industry and science. Moiré fringes are formed by superimposition of two periodic patterns. Also, it can be formed in sampling devices and techniques. This phenomena is occurred in under-sampling process. The under-sampling can be caused by software and hardware in imaging systems the resulting from image processing and optics respectively. An array detector has discrete and periodic structure. This structure can cause a moiré effect in an image of periodic pattern, if it is used appropriate optics. The sampling moiré is a simple, compact and fast approaches for deformation, stress and displacement measurements and topography.

The sampling moiré forms when under-sampling decreases under the Nyquist criterion, that is: required sampling interval (pixel size) to perfectly reconstruct an image which must be at least twice the maximum frequency measured.

In this work, we present a simple, reliable and precise technique for measurement in-plane rotation angle by sampling moiré method. Moiré fringes are produced by superimposing of two periodic pattern which one of the grating is the image of one specified grating by (po) pitch that formed on the array of detector and other grating is detector array by the pixel size pitch (pr). A magnification of imaging system has basic role in this technique. The moiré pattern arises, if the magnification is less than 1 somewhat the pitch of the image of grating be the order of the pixel size. Thus image of grating and consequently moiré pitch depend on distance of the grating to optics of the detector. Moiré pattern is formed on array detector in the interval of the grating distance. In this interval moiré angle varies with the grating angle variation. In a certain distance the moiré pitch is infinite. If the grating distance close to infinite position of the moiré pitch, moiré angle variation has high inclination in small changes of grating angle. Therefore small rotation of grating induces big rotation of moiré.

The sampling moiré set up is simply implemented by a CMOS camera, lens, grating, and rotation stage. The pixel size of CMOS camera, focal length of camera lens and pitch of the gratin are 4.3 ?m, 18mm and 50?m respectively. The grating mounts on the rotation stage and is rotated on it. The angle variation of moiré is captured by the camera and processed by MATLAB software. Results of image processing show that angle variation in order of arc-second is detectable by this technique.

9525-131, Session PS

Monitoring of deep-sea industrial facilities using fiber optic cable

Valery V. Korotaev, Victor M. Denisov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Joel J. P. C. Rodrigues, Instituto de Telecomunicações (Portugal) and Univ. of Beira Interior (Portugal); Mariya G. Serikova, Andrey V. Timofeev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Monitoring of offshore zones in order to control the condition of underwater industrial objects and facilities represents an important problem for which no effective solution has been found. However, as the number and technical complexity of such facilities are increasing, the risks of emergencies and accidents that may lead to serious environmental damage, multiply. This kind of structures shall, first of all, include the main pipelines pumping oil and gas products, equipment for exploration and production of oil and gas. In this work we have discussed the results of research that were carried out in order to create the monitoring system that is continuous in time and space, which provides reliable measurements of the such objects' condition.

In this work general requirements for the monitoring system have been developed. Analysis thereof showed that, judging by a number of certain criteria, the best combination of parameters and characteristics is provided by application of the fiber optic sensor (FOS) laid in the immediate vicinity of the object of monitoring.

In the process of research and modeling, in the conditions of specially-designed test site, the fiber optic shieldless cable of standard G.652 was chosen. This cable is loosely lying on the bottom or is placed in the near-bottom area. FOS is connected to the coherent semiconductor laser with wavelength of 1550 nm. While in pulsed mode, laser generates infrared radiation (pulse width: 20 300 ns, repetition interval: 20-100 ns), which spreads within optical fiber.

Probing impulses pass through the inhomogeneity of optical fiber and undergo Rayleigh scattering. This gives an opportunity to register the result of chaotic interference of Rayleigh scattering, strictly corresponding to certain FOS areas. These products of chaotic interference are called speckle patterns. Influence of hydroacoustic waves coming on the FOS surface from remote sources of acoustic emission changes local refractive index of the fiber. Due to this effect, the change in the spectral – energetic composition of the speckle patterns can be recognized at the receiving part and transmitted to a datacenter.

Dynamic spectral analysis of speckle patterns corresponding to the different periods of the FOS sensing can effectively solve the problem of detecting sources of acoustic emission, evaluation of their coordinates and classification of source type.

One coherent laser is capable to serving a FOS up to 40 km. Frequency range of processed elastic waves from sources of acoustic emission lays in the interval [0, 1000 Hz]. By FOS length reduction, frequency of probing may be increased, which would enhance the upper limit of the analyzed frequency range, which in turn would significantly improve quality of acoustic sources' classification.

As a result of the research applied to method of seismic activity analysis in the extended objects' location area, study of properties vibration-sensitive monomode fiber was carried out. During the experiments, optical fiber was placed on the bottom of the lake at a distance of ~20 m from the object. The results confirmed high application efficiency of optical fiber which has proved to be a reliable sensor for such application.

9525-132, Session PS

Wavelength dependency of the Total Integrated Scattering (TIS) method in surface roughness measurements

Sepehr Razi, Iran Univ. of Science and Technology (Iran, Islamic Republic of); Khosro Madanipour, Amirkabir Univ. of Technology (Iran, Islamic Republic of); Mahmoud Mollabashi, Iran Univ. of Science and Technology (Iran, Islamic Republic of)

In many cases a material success or failure in a particular application is in a direct relation with its surface conditions. One of the most important and effective characteristics in this regard is the surface irregularities such as roughness. Roughness which is a feature of all surfaces is in fact a measure of the statistical deviation in the distribution of surface topography. The statistical parameter which is used frequently for roughness is Root Mean Square (RMS) height. Roughness has an important role in modern technology. It can directly affect the surface thermal and electrical conductivity, surface reflectivity, wettability and lots of other physical Specifications. So its measurement is one of the essential quality control processes.

There are some common methods for the calculation or measurement of the surface irregularities from which the DEKTAK profilometer, Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) are utilized more. Contact Stylus type measurements are widely used for surface roughness inspections, but they lack lateral resolution due to the tip geometry. On the other hand they may also cause surface damage due to the possible high forces exerted on the surface. Optical techniques which are mainly based on Total Integrated Scattering (TIS), Angular Distribution (AD), interferometery and speckle pattern recognitions also offer quick measurement of surface features without the surface contact or damage.

In this paper, we use Total Integrated Scattering (TIS) method to extract the roughness characteristics of the surfaces. In general because of the simple instrumentation it is more convenient to employ TIS for the surface roughness measurements of the diffusive samples. 316L stainless steel samples that were laser irradiated in specified conditions are selected for the investigation. Here based on the TIS technique a simple set-up using instrumentations such as a low intensity laser, integrating sphere, silicon detector and appropriate optical elements is used to determine the RMS roughness in different wavelengths of probe lasers.

Roughness for any surface is depending to the probe light wavelength and angle. For this purpose the dependency of the measured RMS roughness to the incident laser wavelength is investigated widely using different lasers from UV (?=355 nm) up to the IR (?=980 nm) wavelengths. STM microscopy is also assessed to evaluate the accuracy of the determined RMS values. Then finally the appropriate wavelength and conditions applicable for the different roughness intervals are determined and discussed.

9525-134, Session PS

Roughness measurement of nanofiber webs by using of light scattering technique

Masoumeh Taghizadeh, Khosro Madanipour, Masoud Latifi, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

The applications of nanofibers include of nano-catalysts, tissue scaffolds, protective clothing, filtration and nano electronics. In various applications such as tissue engineering, filtration, catalysts and drug delivery, nanofiber surface roughness or Porous structure are advantages. It has been shown that the surface roughness influence on cell attachment. nanofiber surface roughness is very impressive in applications such as scaffolds, membrane filtration and general applications where adhesion and wettability properties of matter. Also, in the membrane, one of the important properties of the surface is roughness, that has great influence on the adhesion and internal mass transfer. Increaseing surface roughness, enhances wettability hydrophilic layer, while increasing the roughness of the surface layer reduces the wetting layer is hydrophobic.

Conventional methods for measuring textile surface roughness are contact methods. But because of the delicacy of nanofiber, that is not a good method to measure surface roughness of nanofibers. The atomic force microscopes AFM(especially in non-contact mode)are the usual instrument for measuring surface roughness of web nanofibers. Optical methods for surface roughness measuring of textiles can be used as the Non-contact and Non-destructive techniques .

In this study, surface roughness of polyacrylonitrile nanofiber webs

are measured by laser beam scattering. The statistical parameter for roughness is the root-mean-square (RMS) ?q . The Beckmann equations are used for roughness measurement. Therefore, surface roughness can be achieved by measurement of the incident light intensity and the intensity of light scattered in two different angles. For roughness measurement, polyacrylonitrile nanofiber webs are prepared in solution concentrations of 10, 12, 14 and 16 weight percent. SEM images of the sample were prepared and distribution of the diameter was obtained by imageJ software. The results show, with increasing concentration of the polymer solution, nanofiber diameter increasing in 150-450 nm.

In measurement set up, a He-Ne laser beam with 633 nm wavelength at three angles is irradiated on sample. Two angles of 30° and 45° are selected for measurement. Distribution of scattered light is captured by a CCD camera in specular direction. Images are analyzed by MATLAB software and the intensity profiles of scattered light are measured. By measurement of intensity profile in two angles, two equations are found and roughness parameter are evaluated by Beckman formula. The results of this method show that increasing the nanofiber diameter enhance the surface roughness of webs.

9525-136, Session PS

The choice of marks for systems with noncontact position control

Valery V. Korotaev, Maksim A. Kleshchenok, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Optical-electronic methods and means for the contactless control of the position of objects relative to the linear base are relevant in many areas of technology. This is because the non-contact, distance and the ability to fully automate the processes of measurement combined with high speed makes extensive to use of optical - electronic systems (OES) for the active control of the spatial position of objects (disposition). Of particular interest for this class of systems is called invariant optical-electronic system for alignment control (OESAC).

Because such systems allow preventing (warn) technological disasters, the urgency of the problem increases in proportion to the technical progress of all mankind, to prevent the recurrence of tragedies have occurred, for example, the Bhopal disaster (1984), the Chernobyl disaster (1986), the Sayano-Shushenskaya power station accident (2009), pipeline spill in Israel (2014), which served as the impetus for the development of systems of this trend.

Invariant devices - devices that are insensitive to external mechanical impacts (insensitive to changing external conditions) that do not require prior verification or verification before starting work, always ready for use and guarantee the required accuracy of control. The use of a single planar photodetector matrix fields for the analysis of the representations of natural and specially created spatial distributions of informative features of the object of control are widely used for the implementation of robotic tasks in machine vision. In this case, the application of computer vision algorithms, in combination with the properties of optical systems, enables to implement invariant to environmental influences and changes the distance of the OES for alignment control.

This class of systems allows to register transverse displacement with an accuracy of tens of microns, changes in the distance of several tens of meters and the range of transverse displacements of a dozen millimeters. Special interest is to use of the application of the autoreflection schemes for alignment control with the control elements like different types of reflectors.

When using the reflectors in geodesy, systems, road safety, security systems, gas analyzers, and meters visibility range and so on, very often, the incident radiation flux on reflector is generated by transmitting optical system, which consists of a collimating lens and emitting area. Since the entrance pupil of the optical system is located in the same plane as the exit pupil transmitting optical system, when the energy calculation it is necessary to know the distribution of irradiance (illuminance) on the plane, which is the exit pupil of the transmission system. This paper analyses the influence of geometrical and optical parameters of reflectors emitting area, a collimating lens for illumination at points on the plane of the exit pupil transmitting optical system. Is the expression describing the dependence of the components of the basic error from the design parameters in the automatic reflection of the OES scheme with retroreflector in the form of a matrix field of corner cube prism or reflective coatings. For distances up to 20 meters estimated value of the random component of the basic alignment errors in each of the recorded direction in laboratory conditions. Formulated approach to optimize data format to minimize the processing time measuring information and requirements errors. Estimates of energy efficiency schemes with duplex and matrix retroreflector for semiconductor emitters.

9525-137, Session PS

Improving the resolution in phase-shifting Gabor holography by CCD shift

Luis Granero-Montagud, Vicente Micó, Univ. de València (Spain); Zeev Zalevsky, Bar-Ilan Univ. (Israel); Javier García, Univ. de València (Spain); Bahram Javidi, University of Connecticut (United States)

Holography dates back to the year when Dennis Gabor reported on a method to avoid spherical aberration and to improve image quality in electron microscopy. Essentially, Gabor's architecture proposes an in-line configuration where two beams interfere at the recording plane. One beam is the imaging beam caused by sample's diffraction and the other one is the reference beam incoming from the non-diffracted light passing through the sample. Both beams interfere in propagation and the resulting light distribution is recorded on a photographic film. Finally, the reconstruction is obtained by illuminating the film with a reconstruction wave identical to the reference wave that was used in the recording process. This two-step holographic method was pioneer but suffered from three major drawbacks: the reconstructed image is affected by coherent noise, the twin image problem of holography that also affects the final image quality, and a restricted sample range (weak diffraction assumption) for preserving the holographic behaviour of the method.

Nowadays, most of those drawbacks have been overcome and new capabilities have been added due to the replacement of the classical recording media (photographic plate) by digital sensors (CCD and CMOS cameras). Thus, digital in-line holography (DIH as the digital version of Gabor's holography) has been validated with coherent noise reduction by the use of partially coherent light sources while the sample's weak diffraction assumption can also be beaten by abandoning the Gabor in-line layout and externally reinserted the reference beam at the recording plane in an angle (off-axis geometry) on both classical and digital versions.

But in the Gabor' regime, holography is restricted to weak diffraction assumptions because otherwise, diffraction prevents an accurate recovery of the object's complex wavefront. We have proposed a modified Gabor-like setup to extend the Gabor's concept to any sample provided that it will be non-diffusive and with twin image elimination [V. Micó, J. García, Z. Zalevsky, and B. Javidi, Opt. Lett. 34, 1492-1494 (2009)]. Such configuration proposes the insertion of a condenser lens and a spatial light modulator (SLM) into the classical Gabor configuration. Thus, the phase-shifting procedure is introduced by the SLM that modulates the central spot (DC term) in an intermediate plane (plane where the condenser lens focuses the incident plane wave). However, the resolution of the final image becomes limited as consequence of the additional elements introduced in the experimental setup.

In this contribution, we present an experimental approach to overcome such limitation and improve final image resolution. We use the phase-shifting Gabor configuration while the CCD camera is shifted to different off-axis positions in order to capture a bigger portion of the diffracted wavefront. Thus, once the whole image set is recorded and digitally processed for each camera's position, we merge the resulting band-pass images into one image by assembling a synthetic aperture. Finally, a superresolved image is recovered by Fourier transformation of the information contained in the generated synthetic aperture. Experimental results are provided using a USAF resolution test target and validating our concepts for a gain in resolution of close to 2.

9525-138, Session PS

Rapid detection of delamination areas in laminated structural elements by means of optically monitored strain solitons

Irina V. Semenova, Ioffe Physical-Technical Institute (Russian Federation); Andrey V. Belashov, Ioffe Physical-Technical Institute (Russian Federation) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Galina V. Dreiden, Ioffe Physical-Technical Institute (Russian Federation); Nickolai V. Petrov, ITMO University (Russian Federation); Alexander M. Samsonov, Ioffe Physical-Technical Institute (Russian Federation)

Laminated structural elements made of polymeric composite materials find wide applications in modern industry, most notably in construction, aerospace and automotive sectors. As we have previously shown (see e.g. [1] and references therein) glassy polymers and composites on the base of polymeric matrices are materials allowing formation and propagation of strain solitary waves. Bulk strain soliton is a long non-linear localized traveling wave, which, under certain conditions, can be formed in a solid waveguide from an initial pulse. Being formed, the soliton propagates along the homogeneous waveguide with almost no change of amplitude, shape and velocity. In inhomogeneous waveguides soliton parameters vary depending upon the nature and characteristics of inhomogeneities.

The soliton behavior in laminated bonded and delaminated waveguides made of glassy polymers and polymeric composite materials exhibits specific features depending upon a variety of factors, including characteristics of an adhesive and even the number of layers in the laminated structure. The observed phenomena include formation of soliton trains in the delaminated area with the number of secondary solitons depending upon the number of layers; formation of radiating solitons in the case of viscous, rubber-like adhesives etc. More complicated wave patterns are generated if layers in a laminated waveguide are made of different materials. While a unified soliton is formed in a bonded area, in the delaminated area separate solitons propagate in layers, with different velocities that are characteristic for each material. This effect provides an immediate evidence of the delamination existence and its location.

We demonstrate the differences in soliton behavior in bonded and delaminated layered waveguides made of glassy polymers and composites and discuss the soliton feasibility as a

reliable tool for fast delamination detection in lengthy laminated structures. The application of solitons is attractive since it is the only bulk elastic wave which does not decay much even at long distances.

In our experiments solitons are recorded by means of holographic technique, that allows one to obtain in a single shot a complete wave pattern in the waveguide within the area of several centimeters in diameter. The technique provides information on the soliton amplitude, shape, width and velocity and allows one to monitor the formation of complex wave patterns due to soliton propagation into a delamination area. The holographic interferogram processing is performed by means of the recently suggested approach utilizing algorithms of the off-axis digital holography (e.g. [2]). The advantages of the approach are discussed.

Note that while being worked out the suggested methodology may be functional with more simple optical techniques, such as beam deflection method etc.

1. G.V.Dreiden, A.M.Samsonov, I.V.Semenova. Evolution of bulk strain solitons in long polymeric waveguides. Tech. Phys., 53, 5, 540-546, 2008.

2. M. Liebling, T. Blu, and M. Unser, “Complex-wave retrieval from a single off-axis hologram,” J. Opt. Soc. Am. A, 21, 367–377, 2004.

9525-139, Session PS

Diffusivity measurement using compact low cost field portable device based on light deflection

Vani K. Chhaniwal, Swapnil Mahajan, Vismay Trivedi, Arun Anand, The Maharaja Sayajirao Univ. of Baroda (India)

Imaging and measurement of diffusion process in binary liquid solutions is a challenging and interesting problem. Diffusion of liquid solutions happens due to movement of molecules owing to their thermal energies when they come under the influence of concentration gradient. Diffusion is a process that pervades fields as diverse as chemical engineering, biology, pollution control, separation of isotopes, etc. Diffusivity is the most important parameter of a diffusing liquid solution. For example, knowledge of diffusivity is necessary for the design of chemical equipment and for mass transfer studies. Optical techniques provide one of the best means to image diffusion in transparent liquid mixtures and to measure their diffusion coefficient. The optical methods used to image diffusion process ranges from conventional interferometry to highly accurate holographic interferometry. Digital variations of conventional and holographic interferometric methods have been used for this purpose. Especially, the method involving digital holography is used to compare the wavefronts passing through the solution under investigation at two instances of time and can directly yield the diffusion coefficient. But implementation of interferometeric techniques usually requires the superposition of two wavefronts, one passing through the diffusing medium and the other acting as the reference wavefront. This necessitates the use of laser source, vibration isolation system to tune out the mechanical noise, and accurate adjustment of beam ratios for high contrast fringes. Interference techniques need optical elements for the splitting and combining of laser beams making them unwieldy and expensive. So their implementation in an industrial environment becomes difficult and also their field portability is reduced. Development of compact, easy to implement, easy to use and inexpensive devices, for imaging and quantification of the diffusion process, which does not require the stringent optical conditions of interferometric techniques, becomes crucial. Here we discuss the development of a non-interferometric, cheap and easy to use device to measure diffusion coefficients of transparent binary liquid solutions. The device is based on the principle that, light gets deflected when it encounters a region of varying refractive index. The deflection of the light depends upon the gradient of refractive index and hence on the diffusion coefficient of the solution. The device consists of a white light source, an experimental cell contacting the diffusing solutions, a line pattern pasted on the experimental cell and a webcam to image bending of the line pattern. Inhouse developed software automatically processes the imaged line patterns. The image processing involves thresholding, skeletalization and fitting of the skeltalized line pattern to yield the deflection of the line pattern from a reference pattern. The measured deflection of the line pattern at different time instances is used to measure the diffusion coefficient of the solution. The developed device was tested on several solutions to determine their diffusion coefficients. The measured diffusivity values varied by less than 1%, with the values of diffusivity reported in literature.

9525-140, Session PS

GPUs benchmarking in subpixel image registration algorithm

Martin Sanz, Univ. de València (Spain); Jose Angel Picazo-Bueno, Univ de València (Spain); Vicente Micó, Univ. de València (Spain); Carlos Ferrerira, Univ de València (Spain); Luis Granero, Univ. de Valencia (Spain); Javier Garcia, Univ. de València (Spain)

Image registration techniques are used among different scientific fields, like medical imaging or optical metrology. The straightest way to calculate shifting between two images is using the cross correlation, based on FFT to minimize the computing time, taking the highest value of this correlation image. Despite this technique is very fast, shifting

resolution is given in whole pixels which cannot be enough for certain applications. To achieve better results we have to go over other solutions. First possibility, easy to implement, is to interpolate both images, as much as the desired resolution we want to get, and apply the same technique described before, but the memory needed by the system is significantly higher. To avoid memory consuming we are implementing a subpixel shifting method based on FFT. With the original images, without resampling, subpixel shifting can be achieved multiplying its discrete Fourier transform by a linear phase. Using different slopes for this linear phase will give us a different shifting. There is no high memory consumption, but it is high time consuming method because checking a concrete shifting means new calculations. This fact makes the algorithm highly parallelizable, being very suitable for high performance computing systems. GPU (Graphics Processing Unit) accelerated computing became very popular more than ten years ago because they have hundreds of computational cores in a reasonable cheap card. GPUs are perfect for parallel algorithms which are independent between calculations, taking advantage of the full number of cores that GPU has. Even more, you can use more than one GPU, making it scalable, or buying a new generation GPUs which are exclusively dedicated to processing.

In our case, we are going to register the shifting between two images, doing the first approach by FFT based correlation, and later doing the subpixel approach using the technique described before. As we are going to calculate the correlation value for all the positions we want to check, this will be considered as 'brute force' method. So we will present a benchmark of the algorithm consisting on a first approach (pixel resolution) and then do subpixel resolution approaching, decreasing the shifting step in every loop achieving a high resolution in few steps. The computer implementation method described before will be supported both in CPU and GPU. This program will be executed in three different computers, workstation and laptops, without using the GPU and using it. At the end, we will present the results of the computation, with different kind of CPUs and GPUs, checking the accuracy of the method, and the time consumed in each computer, discussing the advantages, disadvantages, bottlenecks, learning curve and helper libraries of the use of GPUs.

9525-141, Session PS

Remote sensing of temperature and concentration profiles of a gas jet by coupling infrared emission spectroscopy and LIDAR for characterization of aircraft engine exhaust

Julien Pierre Offret, Univ. Paris Ouest Nanterre La Défense (France); Jeremy Lebedinsky, Lasur SARL (France); Lorris Navello, Vincent Pina, Bruno Serio, Univ. Paris Ouest Nanterre La Défense (France); Yannick Bailly, Univ. de Technologie de Belfort-Montbéliard (France); Philippe J. L. Hervé, Univ. Paris Ouest Nanterre La Défense (France)

To enhance engine performances, a better understanding of mechanisms governing combustion reactions is necessary. Since the performances are improved with the combustion chamber temperature increase, large emission of NOx gas is produced. Indeed, as soon as the temperature rises locally beyond 1700°C, NOx emission appears. Thus, reducing NOx engine emission has become a very important issue as it was proved to be the first leading cause of acid rains and participates to the greenhouse effect. Combustion processes are inhomogeneous and current characterization techniques are inadequate. For instance, intrusive methods like thermocouples cannot be used for temperatures above 2200°C. Remote sensing such as LIDAR (Light Detection And Ranging) methods, based on Rayleigh scattering measurement and processing, has the advantage of providing temperature profiles along a laser line but is not enough accurate because of the ignorance of the mixture gas constituent. Radiation emission is very sensible to the temperature and to a lesser extent to gas concentrations. But the signal is integrated along the gas column line sighting. For LIDAR, spatial resolution is defined by either the laser pulse duration or the camera response time. The method presented in this study is based on the use of a 30ps YAG laser and a Streak camera of 2ps resolution time to measure the gas temperature. Since photons travel a round trip, a spatial resolution of about 5 mm can be obtained from this resolution of time (30 ps). The maximum temperature can be computed from the emission measurement along an axis perpendicular to the flame propagation axis by reversing the radiative transfer equation. Knowing the maximum temperature, concentration profiles of CO2 or H2O can be evaluated. The species analyzed depend on the studied spectral line emission range, between 2380 and 2400 cm-1 for CO2 for instance. The radiative transfer equation inversion is a difficult problem to resolve since it depends on the gas column transmittance, the wall luminance, the luminance of each discrete element and finally, the transmittance between each discrete element and the observation point. The purpose of this study is to develop a method combining the interests of LIDAR and emission spectroscopy for high-speed temperature and concentration measurements. It has been carried out using backscattering measurements along the laser beam illumination and emission measurements centered on the CO2 or H2O absorption lines. The paper will present the application of this accurate method to measure temperature and concentration (H2O or CO2) profiles along a laser line in order to characterize small turbojet exhaust gas. The used model combining measurements from both LIDAR and radiation emission will be presented. It has been applied to compute temperature and concentration profiles along the laser line for a small turbojet exhaust gas. The complex algorithm process used to solve the radiative transfer equation will be introduced. Results have shown that the temperatures measured with this method were very close to the ones measured with a thermocouple moved inside the jet.

9525-142, Session PS

Experimental measurement of group velocity dispersion during operation in cladding-pumped large-mode-area Yb-doped fibers

Tobias Baselt, Christopher Taudt, Westsächsische Hochschule Zwickau (Germany); Andrés-Fabián Lasagni, Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS (Germany); Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

Ever higher output power of fiber lasers leads to growing requirements on the fibers used. The increasing intensity of light in the fiber core is compensated by enlargement of the doped core. The guiding properties of the optical fiber are significantly affected and must be very accurately defined. This leads to significant deviations of the guiding properties of the optical fiber during laser operation due to absorption and thermal effects. In particular, the Group-velocity dispersion characteristics are thereby affected. The change in the dispersion curve in Yb-doped large mode-area double-clad fibers is usually simulated or measured indirectly. In particular, to know the change in Group-velocity dispersion during operation is important for the development of high power fiber laser systems. In an effort to gather such knowledge, this paper presents the results of dispersion characterization measurements using ytterbium-doped large mode area double-clad fibers cladding pumped at a wavelength of 915 nm. The measurement of the Group-velocity dispersion in the emission range of the ytterbium-doped fibers (950 nm to 1150 nm) allows a direct measurement of fiber propagation characteristics. The sample is part of a Mach-Zehnder interferometer and is pumped by a laser diode (? = 915 nm). Using dichroic mirrors, the radiation of a supercontinuum light source is coupled into the fiber sample. Various types of large mode-area fibers were examined under different operating conditions of the Laser setup.

Group-velocity dispersion characteristics of several large mode-area double-clad fibers with various launching pump laser power levels were systematically analyzed. The dispersion parameters for different fiber designs and various doping levels are investigated over a broad spectral range in the emission area of Yb-doped fiber samples for controlled sets of operating parameters. The experiment utilizes a supercontinuum source developed within this laboratory as well as a Mach-Zehnder interferometer with a dual-channel spectral-detection system sensitive to wavelengths from 0.95 ?m to 1.75 ?m. Temporally resolved spectrograms recorded at distinct delay positions enable the detection of interference fringes for the equalization-wavelength. By applying a Sellmeier

polynomial fit to the wavelength dependent differential group-delay function, the group-velocity dispersion can be derived. The measured Yb-doped large mode-area fibers show a variation of the doping concentration between 0.7 mass percent to 3 mass percent of ytterbium. The measurement of the Yb-doped large mode-area fiber with or without optical load on the sample during the measurement was examined.

9525-143, Session PS

Optic-electronic system for measuring the three-dimensional angular deformation of pipe sections at large constructions

Igor A. Konyakhin, Van Phong Hoang, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Yury Artemenko, P.N. Lebedev Physical Institute (Russian Federation); Renpu Li, Andrey A. Smekhov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The inspection of large-scale objects in industry, science and power generation calls for the high-precision measurements of angular deformations.

It is necessary to measure three-dimension deformations of the pipe or tube units at industry constructions. These angular deformations are pitch, yaw and torsion angles.

For example there are three-dimension deformations of support tube of main mirror at a radiotelescope. Reasons of deformations are the construction weight and the temperature influence. The angular deformations of support tube vary over a range from 6 to 30 minutes of arc. As result the direction of a parabolic main mirror axis after setting in elevation and in azimuth is not equal to accuracy angular values. Therefore it is necessary to realize the special system to measure and correct the angular deformation of the mirror tube support.

Optic-electronic autocollimators for non-contact angular measurements are used effectively.

However production-type autocollimators have principal disadvantages for measurements of three-dimension angular deformations.

At first, the autocollimator with the mirror as reflector measures only two tilt angles: yaw and pitch for rather small range. The measurement of torsion angle is impossible.

The second disadvantage of the production-type autocollimators with mirror as reflector is the short work distance L between autocollimator and reflector. The cause is the large value of conversion coefficient as the proportionality factor between the angle U?of rotation of the reflector and the angle u of the deviation of the reflected beam, which value for mirror is Q = 2. As result at the non-long distance the reflected beam after rotation of mirror can not return into the objective of autocollimator. For example, for a measured angular displacement up to 20 minutes of arc and diameter of the receiving objective of the autocollimator equal to 50 mm, the working distance L is less than 4 m, which is insufficient for measuring the deformations of the main mirror support tube with long as 15 meters. The method to increase the work distance is to decrease the value Q of the conversion coefficient of the reflector.

The autocollimator for measuring the yaw, pitch and torsion angle deformations at long work distance is researched.

Disadvantages of existing autocollimators can be avoided by using of the special optical reflector with sensitivity to the torsion rotations and small conversion coefficient for pitch and yaw angle rotations.

The offered reflector is the trihedral composition of three mirrors 1,2,3. Geometric parameters of the reflector are following: the angle 1-2 between sides 1,2 is 90°- d1, angle 2-3 between sides 2,3 is 90°- d2 and angle 3-1 between sides 3,1 is 90°- d3. Values d1, d2, d3 are not more than 1 degrees. The necessary relations between values d1, d2, d3 are roots of nonlinear equations.

The reflector divides the incident beam to three pairs of reflected beams. The reflected beams form six images in the photoreceiver matrix of the autocollimator. Two central images are used for measuring the pitch and yaw angles with conversion coefficient Q = 0.1.

The pair of peripheral images gets the sensitive to the torsion angle.

The experimental setup of the autocollimator for the measure three angular deformations is designed.

The main parameters are: infrared emission diode by power 40 mWt as sources of radiation; the objective by the focal length 450 mm, the CMOS matrix receiver by type Micron MT9P401 2592*1944 pixels and one pixel size (2.2*2.2) micrometers as image analyzer.

The experimental measuring error of the yaw, pitch and torsion angles is 10 seconds of arc at the region 1 degrees for the work distance 12 meters.

9525-144, Session PS

Parallelism measurement of plane glass at oblique incidence by interferometers

Yi Yang, Huan Ren, China Academy of Engineering Physics (China)

Parallelism is an important parameter of plane glass and the huge power solid-stat lasers such as NIF etc contains many large rectangular plane glasses with slight wedge angle. The parallelism of these glasses should be measured at full aperture. To realize high measurement accuracy, this parameter of these glasses is tested by interferometers. Parallelism measurement is often done at 0°incidence by interferometers, so the size of large rectangular plane glasses is limited to the interferometer aperture. Subaperture stitching is a well known method which could enlarge the size of testing aperture, but the positioning inaccuracy bring much error and the algorithm should be improved, and also, subaperture stitching testing take too much time. If position a plane glass at a oblique incidence angle then measure the parallelism of it by interferometers, the parallelism of the glass could be obtained at full aperture, but this result is quite different from the result obtained at 0°incidence angle. And if a same plane glass is positioned at a same incidence angle but is rotated left or right either, the testing results of parallelism may not be the same. In this paper, a new method is presented for parallelism measurement that plane glasses are measured at oblique incident angle. This method is based on refraction law, and the parallelism testing modeling is built by MATLAB. In this modeling, the emergence direction of the testing beam light at different incidence angle and with different glass rotation could be calculated, the direction of tilt could also be obtained, and the optical path difference between different testing angles could be attained too. With the 3 factors mentioned above, the relation equation of the results of parallelism with different testing incidence angle could be figured out. So those rectangular plane glasses could be qualified at different incidence angle, the results of parallelism could be converted to the results obtained at 0°incidence angle---that means the dimension of sample measured at horizontal direction is enlarged, those rectangular plane glasses could be evaluated on some angle at full aperture using a smaller aperture interferometer. This method will not take anymore equipment nor extra measuring time. In this paper, a same plane glass is measured at 0° angle and at other angles in experiment , and the testing results are compared with each other. The error source of this method is discussed, and the ways to avoid these errors are also pointed out.

9525-145, Session PS

Optical-electronic system for real-time position control of roof's supporting structure

Sergey V. Mikheev, Igor A. Koniakahine, Oleg Barsukov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The paper reports the results of computing and phisical modeling of measurement optical-electronic system for real-time position control of extended objects with an active tags. We proposed an original method for solving systems of differential equations to calculate the coordinates of the objects. We create the physical model of this system for controlling the position of the pool's roof.

During the construction and operation of extensive engineering facilities is particularly important task of monitoring their spatial position in real time. This task is often complicated by variable external conditions, fluctuations in ambient temperature, humidity, wind speed, level of background illumination, etc.

To solve these problems, we can use the optical-electronic systems based on triangulation scheme, they have undoubted advantages: high accuracy, simplicity and cheapness. There is the resection method, built on a single triangulation scheme with a “made base” chosen for controlling the position of the supporting structure elements of the pool’s roof .

The elements of the bearing structure of the roof with a certain step are fitting out by several active targets bases of three infrared LEDs. Targets radiation is captured by two or more cameras installed in order to see all the targets. The structural system consists of active targets on the test object, the lens, the matrix analyzer, the coupler and the computer, allowing you to measure linear and angular displacement of the object.

The coordinates calculations of this method occurs in several stages: the first stage is finding the coordinates of the centers of gravity of the spot image targets on the matrix analyzer, in the second stage - solving the system of equations, which associates the position of the targets in the space and their images on the matrix analyzer.

The result of solving the system of equations are six parameters: three angular coordinates of the object, three linear coordinates. In the General case the system of equations does not have an analytical solution but can be solved numerically by iteration method.

The solution is to find the Jacobian matrix, which consists of a set of derivatives of the six functions, which describe the behavior of the system when the angular and linear displacements, on 6 variables. Next, we need to find the inverse matrix to the Jacobian matrix.

The calculation continues until the difference between the roots computed from k and k+1 step, becomes sufficiently small. At zero cycle solutions of the equations necessary to determine the initial values of the roots, this can be done by taking the limits of measurement. In practice, to solve this system missing less than 20 cycles of iteration.

The proposed optical-electronic system has a simple structure to measure the full spatial position of a floating object, we developed an original algorithm for determining the six spatial coordinates. The results of the experiments with the layout of the optical-electronic system confirmed the possibility of implementing high-precision system for 6DOF measuring the spatial position of the object.

9525-146, Session PS

Autocollimating systems for roll angle measurement of large-scale object deformation

Tatyana V. Turgalieva, Igor A. Konyakhin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Autocollimating systems are used for angle position controlling of large-scale objects, such as, oil and gas pipelines, radio telescope elements. Such systems include opto-electronic autocollimator mounted on fixed reference point of controlled object and mirror-prism control element placed on angle position control point. Generally, it is required to measure rotation angles relative to three orthogonal axes, one of which coincideswith the optical axis of autocollimator (roll axis), and the other two are orthogonal to it (collimation axes). Rotation angles relative to the mentioned axes are called roll and collimation angles respectively.

Analysis of general algorithm of autocollimation measurements shown the influence of collimation components on the roll angle measurement, which leads to increasing of measurement errors of this angle coordinate. For this reason, research of autocollimating systems for roll angle measurement is the most interesting.

In the previously discussed scheme of thee coordinate autocollimator with increased sensitivity of roll angle measurement the tetrahedral reflector, which has the deviation ? from 90° in two dihedral angles between reflecting sides, was chosen as a control element. The incident optical beam which is going along the axis of the autocollimator is divided into two pairs of beams due to reflection from the control element. One of these pairs can be used for roll angle measurement. Both beams in the pair for roll angle measurement have an angle ? with the autocollimator objective axis, which is equal to transmission coefficient between angle of rotation of the control element at the roll angle and deviation of the reflected beam from its initial direction. This angle ? determines the sensitivity of roll angle measurements. Increasing of sensitivity of the angle ? for a standard autocollimator with a small field angle is provided by re-reflection from a flat mirror. Thus, the beam reflected from the tetrahedral reflector passes through the receiving objective and comes back to the tetrahedral reflector after reflection from the mirror. After second reflection from tetrahedral reflector the image of the mark is formed in the focal plane of the autocollimator objective. Collimation angles are measured by second image of the mark which is obtained by reflection of the part of incident beam from tetrahedral reflector frontal edge as from autocollimation mirror.

Analysis of precise equations for orts of the reflected beams in the presence of the object rotation revealed that the roll angle measurement with methodical error, which can be caused by the influence of one of the collimation angles. For this reason, for increasing accuracy of roll angle measurement needs to measure the influencing collimation angle before it and introduce the correction.

For realizing the precise roll angle measurement and at the same time increasing sensitivity is proposed the scheme autocollimator with re-reflection when incident beam and reflected from tetrahedral reflector beam symmetrically orientated relative to the roll axis on opposite sides. Incident beam and reflected from tetrahedral reflector beam have an angle ?/2 with roll axis. Thus, the beam reflected from the tetrahedral reflector passes through the receiving objective and reflecting from the mirror comes back to the tetrahedral reflector. After the second reflection from tetrahedral reflector the image of the mark is formed in the focal plane of the autocollimator objective. Passing the same way beam reflected from the front edge of tetrahedral reflector as from autocollimation mirror are formed at analyzer second image of the mark.

For two proposed schemes of the system the total error of roll angle measurement was modeled. Considered the difference of the results in solutions direct tasks of determination coordinates image of the mark at the analyzer by specified object rotations and inverse task of determination object angle position by image of the mark at the analyzer when presence rotation of the object at the collimation angle, matrix analyzer noise and deviation optical element parameters from nominal.

The results of the research shown that the modeling of rotation angle measured range up to 2.5 deg. maximum of the relative methodical error is about 14% for scheme with increased sensitivity roll angle measurement. For the second system scheme the methodical error decreases drastically and for the same range of rotation angles no more than 0.5%.

These benefits are determined the preference of using symmetrical scheme of the three coordinate autocollimators with increased sensitivity of roll angle measurement.

9525-147, Session PS

Analysis of Fourier-based digital microscopy holography systems for retrieval of phase objects

Alfonso Padilla-Vivanco, Martin Hernández-Romo, Carina Toxqui-Quitl, Univ. Politécnica de Tulancingo (Mexico)

This work is based in two papers previously presented:

1) Martín Hernández-Romo, Alfonso Padilla-Vivanco, Myung K Kim, Carina Toxqui-Quitl, “Phase retrieval of microscope objects using the Wavelet-Gabor transform method from holographic filters,” SPIE Proceedings, vol. 9192, September (2014).

2) A. Padilla-Vivanco, R. Farías-Díaz, C. Toxqui-Quitl, and J. Valdiviezo-Navarro “Diffractive and sampling effects in Fourier holographic filters using spatial light modulators,” Applications of digital image processing XXV, SPIE, vol. 8499, August (2012)

Our interest is to continue working in new interferometric setups in the context of industrial applications.

9525-148, Session PS

Measurement of plasma parameter in Dielectric Barrier Discharge (DBD) by Moiré deflectometry technique

Fatemeh Salimi Meidanshahi, Mahfanavar Co. (Iran, Islamic Republic of); Khosro Madanipour, Amirkabir Univ. of Technology (Iran, Islamic Republic of); Babak shokri, Shahid Beheshti Univ. (Iran, Islamic Republic of); Mohammad Reza Khani, Hamid Razavi Borzoki, Shahid Beheshti University (Iran, Islamic Republic of)

In recent years, the non-equilibrium atmospheric plasmas have been applied in different industry and such as petroleum, polymer and textile industries because of low price, simplicity and no need to vacuum equipment. This kind of plasma can be used to produce ozone, processing of polymers, destruction of air pollution gasses, UV ray producing and catalyst purification. The dielectric barrier discharge reactors are the simplest and most widely used non-equilibrium atmospheric plasma. Measurement and characterization of the plasma parameters can be useful for different applications.

One of the best ways to measure the plasma are the optical techniques. Interferometric methods require high mechanical stability and precision optical instruments. They are very sensitive to vibrations and environmental noises. In high gradient refractive index the methods are inefficient. Schileren, shadowgraphy and moiré deflectometery are the more appropriate for high gradients.

In this paper it is shown that the refractive index and electron density distribution of atmospheric Dielectric Barrier Discharge plasmas can be measured by Moiré deflectometry. In experimental set up, for producing the DBD plasma, two stainless steel electrodes in atmosphere are connected to the high voltage potential and a quartz plate as a dielectric barrier is placed between the electrodes. This plate prevent to transform of the plasma discharge to arc plasma. An expanded and collimated He-Ne laser as a probe beam is illuminated to the plasma. The refractive gradient in plasma distribution lead to deflection of probe and Moiré fringe deformation in Talbot-Moiré deflectometer. Fringe analysis is used to calculate moiré deflection and so evaluate refractive index in different points of environment. By Sa-Ha equation and considering the first ionization, the dependence of refractive index and electrons, ions and molecules number densities in this atmospheric plasma are obtained. By knowing this relation between plasma parameters, the spatial distributions of the plasma properties are evaluated. This technique is simple, precise and efficient for plasma characterization and can be used for diagnosing other axial symmetric plasmas.

9525-149, Session PS

Research and development objectives for the spectral coherence tomography

Dmitriy I. Yegorov, National Research Univ. of ITMO (Russian Federation); E. A. Tsyganok, National Research Univ. of Informational Technologies, Mechanics and Optics (Russian Federation)

Optical coherence tomography - a non-destructive method for studying the cross-sectional tissue, carried out on the basis of an interference microscope scheme Academician VP Linnik. Axial movement of the mirror in the reference arm (mechanical scanning) is regulated by the depth of penetration into the test object, and the interference pattern determines the reflectivity of the point cut. The disadvantage of this method is the low scanning speed of the object.

Increasing the scan rate can be achieved by the use of spectral scanning, which is carried out using a tunable laser radiation and the lens chromatism equal to the depth of the scan in the object arm of the interferometer.

One of the tasks of the spectral coherence tomography is a research and calculation channel object lens of the microscope working with lasers with tunable wavelength (investigated spectral ranges 0,8-1,0mkm and 1,26-1,36mkm). The study shows the impossibility of using glass as the only element of the optical system of the microscope objective for the spectral range 1,26-1,36mkm. Chromatism determined by the ratio of the focal length of the lens and the dispersion coefficient of glass. Abbe number of glasses for different groups in a given spectral range lies within the 350-500 that for small lens focal lengths of 16mm and 32mm forced to use a large number of optical glass with huge powers. Maximum “depth of immersion”, which can be achieved by using glass - 0.5mm. The study considered the task of using kinoform lens as a power lens element. Also it is shown the properties of a kinoform aberration and the impossibility of its using as a single component of the microscope objective. As the result of research aberration properties of kinoform it was obtained method of calculating the hybrid lens object channel interference microscope, consisting of a kinoform lens and parts.

The main difficulty in manufacture of the calculated channel microscope object lens undoubtedly causes kinoform. It represents a phase diffraction grating with variable pitch. Frequency lines kinoform for different focal lengths and a particular spectral range (within the terms of reference) may be from 40 to 200 lines / mm. The study tested the possibility of not using a kinoform lenses operating in the spectral range 0,8-1,0mkm.

The study of the dispersion coefficients in the spectral range of glasses 0,8-1,0mkm was chosen pair fluorite - zinc selenide. If the value of the Abbe numbers (261.7 and 43, respectively) in the range of relative optical power in contact lenses are small (of the order of 1.67 and -0.67, respectively) which makes it possible to use them for chromaticity position 0.7 in the air at the focal a distance of 32mm.

In addition to research and calculation of the lens of the microscope lens object channel was calculated compensator lens (meniscus lens) required for quality control of the assembly of the lens. Taking into account that the adjustment assembly and quality control is carried out visually, you can not use glasses group ICS, not transparent in the visible range. For quality control of the assembly it is advisable to use a laser because of its monochromatic radiation (the use of white light is impossible because of the presence of chromatism 1mm). Compensation meniscus lens is corrected for the presence of coma and spherical aberration.

The main results of the study are: a study of the dispersion properties of glasses and crystals in the near-infrared region of the spectrum, to investigate the possibility to solve the problem using only lens components, research aberration properties of kinoform, derivation of the formulas and relationships between parametric coefficients kinoform lens and the optical power values of the aberrations of the third and higher order to investigate the possibility to use the kinoform as the main and the only element of the lens object channel interference microscope, a design procedure of obtaining hybrid lens consisting of a kinoform lens and parts, research and calculation of object lenses with a given value of chromaticity position in the medium for the spectral region 0.8 -1.0 mm, study and calculation of the reference channel of the microscope lens, the calculation of expansion joints for the control assembly and adjustment of lenses in the light of the laser. All lenses have calculated the diffraction image quality, simple and technologically possible to manufacture.

9525-150, Session PS

The TiO2 nanoparticles concentration assessment in polymer matrix using OCT technique.

Michal Trojanowski, Maciej Kraszewski, Marcin R. Strakowski, Paulina Strakowska, Gdansk Univ. of Technology (Poland)

Filling the polymer materials with nanoparticle dopants allows to modify the original material features such as strength, optical properties, chemical permeability. Obtaining the desired properties requires a very precise control of nanoparticle concentration inside the polymer matrix. Therefore, measurement of the nanoparticle concentration is crucial in nanocomposite materials manufacturing. The known measurement methods, such as electron microscopy, allows to determine the particle concentration accurately but they are invasive and require special sample treatment. Moreover they allow to analyse only small volume of the manufactured material. Therefore, there is a need for a non-invasive measurement method allowing for fast evaluation of particle concentration inside the large volumes of the composite material.

Here we propose application of the optical coherence tomography (OCT)

for non-invasive evaluation of nanoparticle concentration inside a polymer matrix, which can be applied relatively cheap and easily. OCT is an optical imaging method based on low-coherence interferometry, which allows to visualize inner structure of light scattering objects. The resolution of OCT systems varies in range from 1 ?m to 20 ?m. In many cases this resolution is not sufficient for direct measurement of nanoparticle concentration, therefore indirect approach is necessary.

In this research we have imaged the poly meta-methyl acrylate (PMMA) matrices doped with spherical titanium dioxide (TiO2) nanoparticles with known concentrations using the OCT system with axial and lateral resolution of 15 ?m. The particles concentration was varying from 0.1% to 0.5% V/V. The diameter of the particles were below 100 nm (specified by a manufacturer – Sigma Aldrich). All of prepared samples were created in the same manufacturing process giving repeatable properties of PMMA matrix. We have tested various algorithms of OCT image analysis in order to determine the TiO2 particles concentration. The approaches based on measurement of light scattering coefficient inside the material, analysis of statistical properties of the OCT image and direct counting of the particles in the image have been implemented. As an additional reference method for evaluating quality of given samples, optical microscope was used. It allowed to detect agglomerated nanoparticles inside polymer matrix and confirm uniformity of surface layer.

The applied OCT systems allows to perform tomographic imaging with the rate of 20000 axial scans per second. This makes analysis of samples with surface area of 1 cm2 in the real-time and without the need for special sample preparation what is significant advantage over the electron microscopy imaging. In addition used system works in the near infra-red spectrum giving it capability to analyse objects opaque in VIS spectrum.

The conducted research indicates that the OCT imaging has a potential to become an useful tool in nanocomposite materials manufacturing as it allows to evaluate concentration of nanoparticles inside the polymer matrix on-site and in the real-time. With this method we hope to reduce the end cost of manufactured nanocomposite materials.

Future work will be conducted to further expand OCT capabilities as an measurement technique for nanocomposite materials. New materials will be analysed with higher concentrations of nanodopants and smaller diameter. Also new types of nanoparticles with higher scattering properties will be analysed.

9525-151, Session PS

Application of Fresnel diffraction from a 2D array of reflective disks in optical profilometry of a flat surface

Ahmad Darudi, Pegah Asgari, Yousef Pourvais, Univ. of Zanjan (Iran, Islamic Republic of)

Interferometry, holography and moiré techniques are of well-known methods in optical testing and quality control processes. Recently, Fresnel diffraction from a phase step has introduced as a method for precise measurement of thickness and refractive index (M. Amiri and M.T. Tavassoly, Optics Communications, V.272, N.2, 2007). Whenever a part of an optical wave-front experiences a sharp change in its phase, Fresnel diffraction becomes appreciable. Sharp phase variation occurs as a wave-front reflects from a step or passes through a transparent medium with abrupt change in thickness or refractive index. It has been shown that the visibility of Fresnel diffraction near the phase step is a function of phase variation at step. The idea was also used for 1D surface profilometry as well.

In this paper, the Fresnel diffraction from an array of 2-D phase-steps has been applied for surface profilometry of a high reflective optical flat surface. An array of circular disks are coated on a glass plate and placed in front of the test surface in which the coated surface is facing it. A parallel laser beam is reflecting from the disks and test surface that makes Fresnel diffraction patterns around the disks. The visibility variations of diffraction pattern around the disks are traced that are a measure of surface height variations. The higher density of the disks, the higher resolution of the sampling. But there is a limitation for decreasing the size of the disks. This paper presents the theoretical and experimental results of the new method. It is sown that the method is reliable, precise and less sensitive to the environmental conditions.

9525-152, Session PS

Optical coherence tomography for ceramic tableware inspection

Maciej Kraszewski, Michal Trojanowski, Marcin R. Strakowski, Gdansk Univ. of Technology (Poland)

The ceramic tableware products are composed of a ceramic base (the potsherd) covered by the glossy enamel layer. Imperfections of the manufacturing process leads to defects in the enamel layer such as holes or inclusions of a foreign materials. Such a defects significantly reduce value of the final product and even make it not suitable for sales. Fast and noninvasive methods allowing to image the enamel structure would be useful in optimization and evaluation of the tableware manufacturing process. In this research we propose application of optical coherence tomography (OCT) as an efficient method of tableware enamel inspection. OCT is an imaging technique based on the optical low-coherence interferometry. It allows for nondestructive visualization of inner structure of light scattering materials in visible and infrared wavelength regimes. It was proven useful in various industrial or medical applications. Here we show the usage of OCT images for evaluation of the tableware parameters: the enamel thickness uniformity, concentration of foreign inclusions and size of holes.

We present the applied OCT system with the tunable laser source allowing for imaging with rate of 20 000 of axial scans per second and resolution of 15 ?m. The available resolution is sufficient for observation of even small inclusions inside the enamel layer of the final ceramic product. Moreover, the system allows to analyze the polarization state of the light backscattered from the examined object. In case of tableware ceramics this provides additional imaging modality that makes the images more readable.

The processing of the enamel layer consist on three parts:

(a) Image distortion reduction: Since OCT imaging is based on time-of-flight measurement of the light backscattered from the inner structure of the examined object, the variation in object refractive index as well as non-uniform thickness of the object layers cause image distortion making the imaging hard to interpret by a non-trained operator. The most important problem in case of the tableware ceramic is a distortion of the enamel-potsherd boundary line. However, on the OCT image this distortion appears to be caused by the non-uniform thickness of the potsherd, but in reality it is caused by a variation in the enamel layer thickness. Here we propose the algorithm that compares images of the continuous and non-continuous parts of the enamel layer a in order to determine its refractive index and reduce image distortions. Such a reduction makes the image more readable and easier to interpret.

(b) Evaluation of thickness and uniformity of the enamel layer: After the image distortion reduction the thickness of the enamel layer is measured using the edge detection algorithm. The concentration of foreign inclusions is measured using the peak detection algorithm.

(c) Automatic detection and diameter measurement of holes in the enamel layer.

The applied image processing algorithms allows for fast, quantitative evaluation of the final tableware product without the need of a highly trained operator. The presented results indicates that the OCT may become an useful tool for tableware ceramics evaluation allowing to improve the manufacturing process and reduce the number of faulty products. In particular, the developed evaluation method may be useful in determination of the causes of enamel defect that may lie in the potsherd layer produced in an early stage of the tableware manufacturing.

9525-153, Session PS

A two-wavelength digital microscopy holography system based on a Mach-Zender interferometer

Martin Hernandez-Romo, Alfonso Padilla-Vivanco, Carina Toxqui-Quitl, Univ. Politécnica de Tulancingo (Mexico)

This paper is a continuation of the results recently obtained in:

1. Martín Hernández-Romo, Alfonso Padilla-Vivanco, Myung K Kim, Carina

Toxqui-Quitl, "Phase retrieval of microscope objects using the Wavelet-Gabor transform method from holographic filters," SPIE Proceedings, vol. 9192, September (2014)

9525-154, Session PS

Light scattering and transmission measurement using digital imaging for online analysis of constituents in milk

Pranay Jain, Sanjay E. Sarma, Massachusetts Institute of Technology (United States)

Milk is an emulsion of fat globules and casein micelles dispersed in an aqueous medium with dissolved lactose, whey proteins and minerals. Quantitative analysis of these constituents is important in various stages of the dairy supply chain for process control and quality assurance. Analysis of raw milk in essential in the early stages of production for eliminating abnormal milk prior to pooling and for managing cattle feed and health. Online instruments can help reduce human errors in measurement and are required for application in automatic milking systems at the farm level. However, the presence of multiple particle types, in wide size ranges, and varying concentrations significantly complicates analysis. Fat globules in raw milk have an average spherical diameter ranging from 5 – 10 ?m, which is reduced by homogenization to below 1 ?m in processed milk. Casein micelles have an average spherical diameter ranging from 100 – 400 nm. Laboratory instruments like FTIR spectrometers hence require homogenization and dilution of samples before analysis. Field instruments like nephelometers and turbidimeters, used for estimating fat content, further require addition of chelating agents like EDTA to eliminate turbidity caused by casein micelles. Current instruments are therefore not suitable for online constituent analysis, especially of raw milk.

Recent work on developing instruments has focused on optical measurements using UV/VIS spectrophotometry for deducing fat, protein and lactose concentrations. UV/VIS spectrum is especially attractive because of the low-cost of silicon photodetectors sensitive to 400 – 1100 nm wavelengths. Reflection and scattering of light are dominant interactions between the dispersed phase and incident UV/VIS radiation due to the comparable particle sizes and wavelengths. Absorption is the dominant interaction between the aqueous dispersion medium and incident radiation. Use of digital imaging for capturing scattered and transmitted radiation has been discussed in literature. Varying particle size and concentration has been shown to generate perceivable impact on captured digital images. Although the method is promising, the relations between particle sizes and concentrations, and captured images are not well understood.

This paper presents an analysis of the use of digital imaging for estimating fat and protein concentrations in milk by comparing results obtained from experiments and from analytical modeling. For the experiments, milk samples with varying constituent size and concentrations are prepared using raw milk from milch animals. Reference globule sizes are estimated from microscope images and concentrations are estimated using standard FT-IR instruments. Multiple LEDs with known emission spectra are used as discrete light sources to individually illuminate a sample contained in a transparent flow-through channel. The resultant images are captured using a CMOS camera. The captured images are processed to estimate relative transmittance and scattering at different wavelengths. These multiple data points are calibrated with reference fat and protein concentrations using partial least squares regression. Inferences are drawn based on obtained results and compared with expected outcomes based on a Lorenz-Mie Scattering model.

9525-155, Session PS

Applying of digital signal processing to optical equisignal zone system

Anton A. Maraev, Aleksandr N. Timofeev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Vadim F. Gusarov, ITMO University (Russian Federation)

Means of optical-electronic remote control are widely used in industry, construction, geodesy, etc. They enable to achieve high performance and accuracy while positioning objects under control at large distance. There are instruments based on optical equisignal zone which can perform this task.

Such a system contains a searchlight forming the base plane, and a receiver, which determines its position relative to the base plane. The base plane is created by two light sources (e.g. LEDs) modulated with different frequencies. Their fluxes are condensed on the edge of a splitting prism, thus halves of the original sources compose one light source on the edge. The prism reflects these fluxes in the same direction. Thus, two fields of irradiance divided by the base plane are formed in the plane of the sensor. The difference between fluxes coming on the plane of the sensor (so-called differential flux) results in the signal of the receiver, indicating the direction the receiver is to move. The receiver is attached to an object under control and the object is kept in a required position.

In a common system of this type the position of the base plane is analyzed on a photodiode. In our work we propose to use a CMOS as a sensor to define the position of the base plane. It would enlarge the functionality of the system. First, the processing algorithm can be adapted to the change in the state of the air path. Second, CMOS enables to define more geometric parameters, for instance, not only lateral displacement but also tilt of the CMOS relative to the searchlight. Third, the system in this implementation has better sensitivity to lateral displacement than its ancestor with a photodiode as receiver that leads to increase of accuracy of positioning.

Two ways of defining of the base plane position on a CMOS are proposed. One of them implies comparison of the level of the signal from irradiance of the same pixels in the two fields of irradiance. In this way the position of equisignal zone is defined by the number of the CMOS element where the level of the signals is equal in both fields.

The second way imitates work of the photodiode. In this case, the position of the equisignal zone is found by equality of the energy of two irradiance fields received by the CMOS. Here two fields of irradiance are scanned by a window and the signal level in two fields is measured not element by element but as a sum of energy levels received by scanning window of known size or by the whole receiver. The result of the study shows that the error of positioning is dependent on the size of the scanning window.

9525-156, Session PS

System for deflection measurements of floating dry docks

Alexey A. Gorbachev, Anton V. Pantyushin, Mariya G. Serikova, Valery V. Korotaev, Aleksandr N. Timofeev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Inspection of large-scale objects in general and deflection control of industrial structures in particular are very important fields where robustness and accuracy of automated measurements can never be overestimated. One of particular examples of this type of applications is deflection control of floating dry docks. This type of structures is created in order to build and maintain ships. A typical length of the docks differs from 100 to 200 meters while its' height and width may exceed 25 m. It is obvious that this structure experiences heavy loads both from its own weight and from a ship, which is gradually floating into the dock. It leads to deformations, namely deflection, that can cause severe damage and losses when critical value is exceeded. Typically floating docks have a system of ballast tanks in order to compensate the deformations. But for correct work of the compensation system a current magnitude of deflection has to be accurately measured.

In this work general requirements for deflection control systems were discussed. Analysis of different types of measuring systems was also conducted. It was shown that the best combination of characteristics for dock deflection control is provided by optical-electronic system based on image acquisition and measurements.

Based on research and modeling results an image-based control system was developed and tested both on specially-designed setup and in real infrastructure of a floating dock. The system contains two measurement channels observing opposite directions of the dock. It also includes set of reference marks, an industrial computer and a display. Each channel

contains CMOS camera with long focal-length lens. Reference marks are implemented as IR LED arrays with 940 nm working wavelength for better performance within bad weather conditions (e.g. fog, rain, high humidity etc.). In special section of the paper we also discuss developed approaches for accuracy improvement under heavy environmental conditions.

Experiments were conducted on specially-designed setup (in the middle of 40 m optical trace a base unit with 2 channels was mounted, while reference marks were placed at each side of the track and 500-mm motorized stages was used for linear shift of the marks in perpendicular direction to the trace). We also tested the system at a real floating dock under increased humidity and fog conditions. Experimental results confirmed that chosen scheme provides accurate (estimated error is no more than 2 mm for 100 m dock) measurements and also shows good resistance against complex clutter and weather conditions.

9525-157, Session PS

360-degree three-dimensional shape measurement system: applications in oil industry

Carlos Ricardo Contreras Pico, Univ. Industrial de Santander (Colombia) and Univ. Santo Tomás (Colombia); Javier R. Arciniegas, Jaime Enrique Meneses Fonseca, Univ. Industrial de Santander (Colombia)

The oil industry is in evolution constant, especially in Colombia, with the objective to improve the environmental security and the performance of the hydrocarbons transport systems. The new technologies, implemented for the secondary extraction of the petroleum, produce acceleration in the failure mechanisms of the conventional metallic pipes which are used to transport hydrocarbons; this cause an increment in the damages that generate economic losses, environmental affectations and expensive investments with the objective to recover affected zones. A new technology in pipes elaborated with non-metallic materials has been converted in an alternative for industry, because it provides installation easy, good mechanical resistance, resistance to the internal and external corrosion and less pressure losses.

In the last seventy years the plastic has been the material more utilized in the fabrication of diverse pipes, this technology was introduced six years ago by the oil industry in Colombia, this has provided a rapid solution to the demanding environmental normative that this industry confronts and it has facilitated a reduction significant in maintenance costs.

Three-dimensional shape measurement is a subject that consistently produces high scientific interest and provides information for medical, industrial and investigative applications, among others. Techniques to identify faults that may affect the integrity of metal pipes have been developed in the oil industry. However, in the case of non-metallic pipes, such techniques are not yet consolidated or are under development. In this paper, it is proposed to implement a 360-degree three-dimensional reconstruction system for applications in superficial inspection of non-metallic piping for the hydrocarbons transport. The system is formed by a CCD camera, a video-projector and a laptop and it is based on fringe projection technique. System functionality is evidenced by evaluating the quality of three-dimensional reconstructions obtained, which allow observing the failures and defects on the study object surface.

9525-158, Session PS

360-degree three-dimensional digitization of human torso by using multiples projection-acquisition systems

Carlos Ricardo Contreras Pico, Univ. Industrial de Santander (Colombia) and Univ. Santo Tomás (Colombia); Jaime Enrique Meneses Fonseca, Univ. Industrial de Santander (Colombia)

The first three-dimensional (3D) full body scanners appeared on the market in the late twentieth century. These systems were quite bulky, expensive (several hundred thousand dollars) and had resolutions on the order of millimeters. Technology has improved in the last decade; this has allowed the development of systems with better resolutions, more compact and economical. Currently, 3D scanners using various techniques in order to scan regions of the human body are made. The main techniques that are implemented include linear laser triangulation, structured light modules, systems formed by two or more cameras, and millimeter wave systems, mainly. A system based on the technique of linear laser triangulation, is essentially a structured light module, however, usually is not classified as such because it is not as fast as those that project a light pattern that covers entire surface of the object to be reconstructed. A structured light module projects a light pattern onto the object to be scanned, from deformation of pattern is possible to obtain the 3D coordinates of the points are located on the object surface. This pattern may consist of points, stripes, or other light pattern. The advantage of a structured light module is the speed with which can scan. In order to avoid interference between the projected patterns, systems formed by several structured light modules do not work in parallel, this work in series. However such systems are so fast that can be used for scans in real time at 200 Hz.

A structured light module generally consists of a projector, used to project the pattern, a digital camera, which is used to acquire the distorted pattern, and an additional RGB camera to record the actual color of the scene or object scanned. The projected light pattern can be formed of multiple colors, however those projected in gray levels, or near infrared are the most used.

Daanen et al made a review of the main systems of 3D reconstruction that are on the market, its resolutions and costs vary. Among these are those developed by the company Artec (www.artec3d.com) offering systems that can be combined with the purpose of obtaining the 360-degree three-dimensional reconstruction of human torso; and 4D-Dynamics (www.4ddynamics.com), which company offers systems that can be combined in order to obtain the 360-degree three-dimensional reconstruction of the complete human body. The main applications of such systems are in medicine and the entertainment industry.

On the other hand, in the field of medicine esthetic has been developed a set of non-invasive techniques to mold the body, such as Blepharoplasty, Mastoplasty, and Lipoaspiration, among others. At present, non-invasive therapeutic procedures are applied: Mesotherapy, Vacuum Therapy or Endermologie and Ultrasonic Hydrolipoclasia, etc., by using a set of modeler systems with high technology, which permit to obtain esthetic results that are demonstrated qualitatively. Many authors conclude that although the results are demonstrated qualitatively, there are not appropriate studies that verify quantitatively and locally the volume variations from objective and precise measurements. As consequence of this situation, the companies that manufacture systems to treatment and specialized academies in the matter, restrict your participation in the market and they reduce the competitiveness of your products front to others procedures.

In this paper the development of a system to digitize the human torso is shown. The system has been developed in order to evaluate, primarily, the effectiveness of the therapeutic methods mentioned above; however, the applications of such a system would be multiple in various fields. The system consists of four projection-acquisition modules and it is based on the fringe projection technique and the phase shifting algorithm. The calibration procedure, which is implemented to determine the transformations that allow to locate the point clouds, which are acquired by each of the systems, in a single coordinate system is carried out from the digitization of a control object, in this case a parallelepiped.

9525-159, Session PS

Evaluation of focal length of a lens using the Lau effect

Mohammad Abolhassani, Arak Univ. (Iran, Islamic Republic of)

Conventional Lau setup is composed of two gratings in tandem, a lens that is followed by the two gratings, a light source, and an observation plane. In the setup a light source illuminates the first grating as source grating. Lines of the gratings are parallel with each other and period of the first grating is assumed to be a multiple integer of the one for the second grating, diffracting grating. Observation plane is located at focal

plane of the lens.

Well-defined fringes appear at observation plane when separation distance between the two gratings is equal to a multiple integer of an elementary distance, z¬L. The elementary distance is a function of light wavelength, λ, and period of the diffracting grating, p; z¬L=p2/(2 λ).

With a very narrow slits source grating and a binary diffracting grating all orders of Lau fringes will be binary. When the opening ratio of the diffracting grating is equal to 0.5, odd orders convert to a uniform intensity; that is no fringes appear. A little dislocation causes appearance of a fringe system. If the opening ratio slightly different with 0.5, very thin dark fringes appear in odd orders. In these situations locations of the diffracting grating for odd orders can be determined precisely. Therefore, in this case odd orders are suitable for measurement of unknown measurable quantities.

If the observation plane is not at focal plane of the lens, the Lau fringes are produced when the gratings separations, z, have values other than the ones that should be in the conventional setup. The separation distances, z, is a function of, in addition to the aforementioned parameters, focal length of the lens, f, separation distance between the lens and the diffracting, grating, d, separation distance between the lens and observation plane, D, and Lau fringes order, ν.

In an experiment for a fixed order ν, variation of D can be measured as a function of z. By fitting a curve with known functional form and unknown parameters, to be determined, to experimental data the unknown parameters can be determined. These parameters are focal length of the lens, and positions of its principal planes.

On the other hand period of the Lau fringes is a function of the mentioned parameter. That is by measuring this period in every stage some additional data can be achieved. These data help to evaluate unknown parameters more precisely.

9525-160, Session PS

Potential use of the characteristic Raman lines of toluene (C7H8) as a reference on the spectral analysis of fuel blends

Valentin Ortega Clavero, Andreas Weber, Werner W. Schröder, Dan Curticapean, Hochschule Offenburg (Germany)

We report the use of the Raman spectral information of the chemical compound toluene C7H8 as a reference on the analysis of laboratory-prepared and commercially acquired gasoline-ethanol blends. The rate behavior of the characteristic Raman lines of toluene and gasoline has enabled the approximated quantification of this additive in commercial gasoline-ethanol mixtures. This rate behavior has been obtained from the Raman spectra of gasoline-ethanol blends with different proportions of toluene.

All these Raman spectra have been collected by using a self-designed, frequency precise and low-cost Fourier-transform Raman spectrometer (FT-Raman spectrometer) prototype. This FT-Raman prototype has helped to accurately confirm the frequency position of the main characteristic Raman lines of toluene present on the different gasoline-ethanol samples analyzed at smaller proportions than those commonly found in commercial gasoline-ethanol blends. The frequency accuracy validation has been performed by analyzing the same set of toluene samples with two additional state-of-the-art commercial FT-Raman devices. Additionally, the spectral information has been contrasted, with highly-correlated coefficients as a result, with the values of the standard Raman spectrum of toluene.

9525-162, Session PS

Monitoring industrial facilities using principles of integration of fiber classifier and local sensor networks

Valery V. Korotaev, Victor M. Denisov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Joel J. P. C. Rodrigues, Instituto de Telecomunicações (Portugal) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Mariya G. Serikova, Andrey V. Timofeev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Increased complexity of the engineering structures, higher human impact on the natural environment inevitably lead to the growing number of natural emergencies and technogenic disasters. One of the most effective ways to solve this problem is to create a system for continuous monitoring of the potentially dangerous objects. Analysis of changes in the structures, ground and communications allows proper assessment of possible emergencies at any time point.

As a part of this work, we have discussed the experience of creating the integrated monitoring systems used to control the hazardous industrial facilities with significant extent. These objects include railways, pipelines, communications systems, bridges and tunnels.

In the recent years, in order to conduct monitoring of the extended objects, method based on use of optical fiber has been widely used. This method relies on a property of high vibration sensitivity of infrared radiation propagating in the optical fiber. The fiber is placed next to the controlled object. A semiconductor low-power laser is used as a source of coherent radiation. This sensor can be considered in monitoring tasks as a spatially-continuous receiver of seismoacoustic signals. However, based on our experience, we are convinced that use of fiber optic sensor only does not provide the required functional completeness.

Practical tasks of industrial monitoring require a monitoring system to provide simultaneous solution of the following tasks: 1) monitoring the condition of the local areas, including structural elements, soils, and grounds; and 2) monitoring the condition of extended objects and classification of the external disturbances. The first task group is to be solved by applying a set of discrete sensors. The second group requires application of spatially-extended sensors which may include optical fiber. With these requirements in mind, studies aimed to integrate fiber classifier and local segments of sensor networks into a single system, have been conducted.

In this system, the optical fiber is used for solving the technological traffic monitoring problem, the condition of the railroad bed. The sensors included in the network allow monitoring the condition of structures designed to protect the railway from falling rocks and landslides. The integrated monitoring system provides for proper control over the road section up to forty kilometers long. The system's structure includes fiber optic cable, a group of segments of the sensor network attached thereto, and a single control center that hosts the radiation source, the receiver of the reflected optical signals, and networks' control device. Number of the connected sensor networks is not restricted by the optical fiber which in this case acts as a parallel communication channel. The number of connected sensor networks has no restrictions imposed on the optical fiber, which in this case plays the role of a parallel link.

As a result of the conducted research, the architecture of integrated monitoring system was developed, fiber–optic classifier has been designed and tested, sensor networks including vibration, breakage, shock, decline sensors, have been created and tested. The study of algorithms for multimodal classifier for object condition monitoring was also performed. The study has confirmed feasibility of the predictive (adaptive) monitoring. This allows increasing frequency of information retrieval in the periods when observed structures experience the highest external impacts. Furthermore, measurement frequency control can also be performed depending on the seismic activity or due to the existing climatic factors. In natural conditions, assessment of an object's condition can be done 1 - 2 times a day. In the face of ever increasing external perturbations, such assessment may be generated 1 - 2 times per minute and even more often. This may significantly increase the effectiveness of the monitoring system and, at the same time, reduce the operational costs thereof.

9525-164, Session PS

Length characterization of a piezoelectric actuator travel with a mode-locked femtosecond laser

Lenka Pravdova, Adam Lešundák, Václav Hucl, Martin Cížek, Bretislav Mikel, Jan Hrabina, Šimon Rerucha, Onddej Cíp, Josef Lazar, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

The development of absolute distance measurement methods have been enabled by new kind of lasers, special digital signal processing electronics, algorithms and new materials for optics. The phenomenon of the mode-lock of the femtosecond pulse laser increased a number of potential applications with distance surveying where that stable generator of very short and periodically repeated coherent pulses can be used.

The main aim of the work is a description of precise measuring method with absolute scale which is able to determine the length of unknown distance with direct traceability to a time standard. The principle of the method is based on a passive optical cavity with mirrors keeping measured distance, in our case a piezoelectric actuator. Time spacing of short femtosecond pulses generated by mode-locked laser is optically phase locked to the cavity free spectral range. A value of the repetition frequency of the laser determines the measured distance. The exact value of the frequency/period of the femtosecond pulse train is detected by a frequency counter. The counting gate of the counter is synchronized with a highly stable oscillator disciplined by H-maser or GPS received signal from atomic clocks. The work shows methods how to overcome problems with dispersive optics in the passive cavity and a way of phase lock of the femtosecond laser repetition rate to free spectral range of the cavity. This measuring technique is demonstrated on length characterization of the piezoelectric transducer which belongs to ultra-precise positioning actuators.

9525-165, Session PS

Preparation of optical frequency references based on gas filled hollow core photonics crystal fibers

Miroslava Hola, Bretislav Mikel, Jan Hrabina, Josef Lazar, Ondrej Cíp, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

This work is oriented towards our research in the field of splicing and ending of optical frequency references based on hollow core photonics crystal fibers (HC-PCF). This type of references is very promising optical element to replacing classic bulky absorption cells for laser frequency stabilization. We prepared and present methods of splicing HC-PCF to standard telecommunication fiber by fiber splicer. A special care was taken to optimize the splicer setting and to obtain a splice with minimal optical losses between HC-PCF and SMF. The prepared fiber cell was closed at one side by connecting to SMF and second fiber end was placed into the vacuum chamber with the help of vaccum-tightened connection. We present our first results from filling of HC-PCF in our vacuum chamber with the acetylene absorption gas and we report a prepared method for closing of unfinished side of fiber outside of the chamber.

9525-166, Session PS

Industrial interferometry systems for multi-axis measurement

Jindrich Oulehla, Miroslava Hola, Jan Hrabina, Josef Lazar, Ondrej Cíp, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic); Miloslav Vychodil, Petr Sedlár, Milan Provaznik, Meopta - optika, s.r.o. (Czech Republic)

We report on the results of the common collaborative project of applied research where the Institute of Scfientific Instruments (ISI) of the Academy of Sciences of the Czech Republic and a company Meopta – optika joined their effort in development of high-precision interferometric systems for dimensional metrology and nanometrology. This research exploits previous results in the field of laser standards of optical frequencies and the methodology of interferometric metrology of length together with detection systems of interference signals and their processing at the ISI and the production technology of precise optical components at Meopta – optika.

The main aim of the project is a design of a complex interferometric measuring system in a form of a prototype serving as a master for further production. It concept is a modular family of components configurable for various arrangements primarily for multi-axis measurements in nanotechnology and surface inspection. Within this project we developed a compact, solid-state frequency stabilized laser referenced to iodine transitions and technology of iodine cells for laser frequency stabilization. A fundamental setup of the laser interferometer has been arranged and tested. The company Meopta – optika contributes with development of new technology together with a design of a machine for processing and polishing of high-precision flat-surface optical components.

9525-167, Session PS

Narrow-linewidth tunable laser working at 633 nm suitable for industrial interferometry

Tuan Pham Minh, Václav Hucl, Martin Cížek, Bretislav Mikel, Jan Hrabina, Šimon Rerucha, Ondrej Cíp, Josef Lazar, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

Semiconductor lasers found a foothold in many fields of human activities, mainly thanks to its small size, low cost and high energy efficiency. Recent methods for accurate distance measurement in industrial practice use principles of laser interferometry, which are based on lasers operating in the visible spectrum. When the laser beam is visible the alignment of the industrial interferometer makes the measuring process easier. Traditional lasers for these purposes for many decades - HeNe gas laser - have superb coherence properties but small tunable range. On the other hand laser diodes are very useful lasers but only if the active layer of the semiconductor equips with a passive selective element that will increase the quality of their own resonator and also prevents the structure of its higher longitudinal modes.

The main aim of the work is a design of the laser source based on a new commercial available laser diode with Distributed Bragg Reflector structure, butterfly package and fibre coupled output. The ultra-low noise injection current source, stable temperature controller and supply electronic equipment were developed with us and experimentally tested with this laser for the best performances required of the industrial interferometry field. The work also performs a setup for frequency noise properties investigation with an unbalanced fibre based Mach-Zehnder interferometer and 10 m long fibre spool inserted in the reference arm. Except frequency noise measurements, an active suppression of the linewidth by this unbalanced interferometer in the feedback loop is demonstrated. The work presents the way to developing the narrow-linewidth operation the DBR laser with the wide tunable range up to more than 1 nm of the operation wavelength at the same time. Both capabilities predetermine this complex setup for the industrial interferometry application as they are the long distance surveying or absolute scale interferometry.

9525-168, Session PS

Multipath interference characterization of bend-insensitive fibers for short-reach optical communications

Massimo Olivero, Guido Perrone, Renato Orta, Alberto Vallan, Politecnico di Torino (Italy); L. Greborio, Telecom Italia (Italy); P. Regio, Telecom Italia Lab. (Italy); Paolo

Pellegrino, Telecom Italia (Italy)

Since the continuous demand for high speed data transmission at the end user, fiber-to-the-home (FTTH) technologies have become the milestones to fill the “last mile gap”. Passive optical networks (PONs) offer several advantages for the implementation of the FTTH concept, such as the reduced complexity of the physical layer. PONs architectures rely on multipoint transmission over standard G-652 (single mode) fibers, exploiting wavelengths around 1300, 1490 and 1550nm. However, because of the heterogeneous installation framework (i.e. multiple patchcords, tight bends, squeezed cable pipes), G-652 fibers are being replaced by bending-tolerant fibers, also named bend-insensitive fibers (BIFs). These fibers exploit technological approaches such as a depressed cladding design to obtain low bending loss while preserving good compatibility with standard G-652. On the other hand, they can support the propagation of two modes (LP01 and LP11) around 1300 nm, producing a spurious coherent interaction defined as multipath interference (MPI). MPI is defined as the fraction of power of the first high order mode LP11 that is coupled into the fundamental mode LP01. MPI is a detrimental phenomenon that can affect the performance of a short fiber optic link and standards have been devised to characterize BIFs in terms of MPI. MPI has been studied for short, single patchcords, but FTTH applications call for a detailed analysis of the cascade of several connectors and junctions separated by short jumpers.

This work addresses the comparison of two different setups for MPI characterization, based on a broadband source and a tunable laser respectively, highlighting their features and limitations. Both setups are devised to excite the high order mode LP11 in the fiber under test and measure its coherent interference with the fundamental mode LP01. A polarization scrambler is used to find the polarization state that maximizes the coupling between LP01 and LP11 modes. The effect of some critical components such as the polarization scrambler and the detector have been investigated and the uncertainty evaluated for the two setups. Further, it has been found that the use of an all-fiber polarization scrambler relying on piezo-electric fiber stretching can improve the MPI measurement range by 10 dB. For the first time to our best knowledge, an extensive characterization of BIFs from different manufacturers, performed with the tunable laser setup, has highlighted a negligible MPI effect for patchcords longer than 10m, whereas short jumpers (length ≤2m) equipped with field-installable connectors can produce MPI at undesired levels above -30dB. The effect of misaligned splices has been investigated, showing that the MPI becomes clearly detectable for offsets above 2?m. In order to reproduce an real-framework optical link with several field-installable connectors, the cascade of offset-splice short jumpers has been analyzed, showing that MPI can rise to a detrimental level for two cascaded jumpers and remains steady when more jumpers are subsequently connected.

9525-37, Session 8

Automatic complete high-precision optical 3D measurement of air cooling-holes of gas turbine vanes for repair

Christoph Munkelt, Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Lars Aschermann, Frank Seidel, MTU Maintenance Hannover GmbH (Germany)

High-resolution contactless optical 3D-measurements are well suited for determination of state and position of gas turbine vane cooling holes during maintenance rework. The air flow through the cooling holes forms an air film, which (together with thermal barrier coating - TBC) protects the turbine vanes from the high temperatures during engine operation. However, the TBC needs to be renewed during repair of the vanes. The renewal process can lead to partially or completely filled cooling holes. This paper describes a newly developed procedure to automatically detect and reopen such holes by laser drilling for an effective new repair process.

The turbine vane is scanned by a fringe projection based optical 3D-scanner. The resulting pointcloud of approximately 8 million 3D points, with an average lateral distance of 0.06 mm, delivers plenty of detail to automatically detect the more than 120 cooling holes with average diameter of 0.8 mm of a typical turbine vane. The entire scan is best-fit registered to the turbine-vane reference file using an iterative closest point (ICP) approach.

Starting from the reference file with default cooling-hole positions and orientations, each cooling-hole area is extracted from the 3D scan. Next, for each individual hole, we try to fit various geometric primitives to the scan data with ascending uncertainty: Cylinder fits using the default position and orientation of the reference have the lowest uncertainty. If they fail (due to partial or complete cooling hole filling with TBC), cone and sphere fits are tried respectively. Detected cooling holes with low uncertainty, which fulfill certain criteria, can be reopened using reduced laser power during the drilling process. Poorly detected or undetected cooling holes are interpolated from properly detected neighboring cooling holes and reference default cooling holes. Those are fully reopened using laser drilling.

For the resulting laser drilling process the precise orientation in the vane mount must be known (otherwise further time-consuming (tactile) referencing would be necessary). To this end, the position and orientation of the scanned vane in relation to the reference vane is determined using ICP. This master position and orientation has to be calibrated once in order to align the reference, 3D-scanner and laser-drilling coordinate-systems.

To validate the approach, numerous experiments regarding the cooling-hole extraction-performance were satisfactorily conducted. Real drilling experiments confirmed those findings and were used to validate the entire process.

To conclude, the position of the open and partial filled cooling holes can be reliably detected and automatically reopened with the developed process. Positions of completely filled holes are interpolated using the detected neighboring holes and default positions from the reference file and subsequently laser drilled.

9525-38, Session 8

Endoscopic fringe projection for in-situ inspection of a sheet-bulk metal forming process

Steffen Matthias, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

Sheet-bulk metal forming is a new production process capable of performing deep-drawing and massive forming steps in a single operation. However, due to the high forming forces of the forming process, continuous process control is required in order to detect wear on the forming tool before production quality is impacted. To be able to measure the geometry of the forming tool in the limited space of forming presses, a new inspection system is being developed within the SFB/TR 73 collaborative research center. In addition to the limited space, the process restricts the amount of time available for inspection. Existing areal optical measurement systems suffer from shadowing when measuring the tool’s inner elements, as they cannot be placed in the limited space next to the tool, while tactile measurement systems cannot meet the time restrictions for measuring the areal geometries. The new inspection system uses the fringe projection optical measurement principle to capture areal geometry data from relevant parts of the forming tool in short time. High-resolution image fibers are used to connect the system’s compact sensor head to a base unit containing both camera and projector of the fringe projection system, which can be positioned outside of the moving parts of the press. To enable short measurement times, a high intensity laser source is used in the projector in combination with a digital micro-mirror device. Gradient index lenses are featured in the sensor head to allow for a very compact design that can be used in the narrow space above the forming tool inside the press. The sensor head is attached to an extended arm, which also guides the image fibers to the base unit. A rotation stage offers the possibility to capture measurements of different functional elements on the circular forming tool by changing the orientation of the sensor head next to the forming tool. During operation of the press, the arm can be travelled out of the moving parts of the forming press. To further reduce the measurement times of the fringe projection system, the inverse fringe projection principle has been adapted to the system to detect geometry deviations in a single camera image. Challenges arise from vibrations of both the forming machine and the positioning stages, which are transferred via the extended arm to the sensor head. Vibrations

interfere with the analysis algorithms of both encoded and inverse fringe projection and thus impair measurement accuracy. To evaluate the impact of vibrations on the endoscopic system, results of measurements of simple geometries under the influence of vibrations are discussed. The effect of vibrations is imitated by displacing the measurement specimen during the measurement with a linear positioning stage. The concept of the new inspection system is presented within the scope of the TR 73 demonstrational sheet-bulk metal forming process. Finally, the capabilities of the endoscopic fringe projection system are shown by measurements of gearing structures on a forming tool compared to a CAD-reference.

9525-39, Session 8

Long wave infrared 3D scanner

Ernst Wiedenmann, Mohsen Afrough, Sven Albert, Robert Schott, Jan Tusch, Andreas Wolf, Aimess Services GmbH (Germany)

In industrial metrology, the system of fringe projection for the rapid determination 3D surface data is established. The combination of areal and structured projection with two-dimensional optical sensors and triangulation measurement principle allows dense point clouds with sufficient accuracy. State of the art systems have great difficulty with very dark surfaces. Transparent materials cannot be measured using the visible spectrum of light without surface preparation. We have therefore developed a new structured light projection system that solves these problems. For the first time in the geometric measurement technology, the physical principle of energy conversion is utilized.

Existing structured light projection systems are based on the reflection of electromagnetic radiation. Instead of reflection, our system relies on the absorption of the object. This enables the measurement of previously inaccessible surfaces, but calls for the transition to other radiation sources. We choose the infrared wavelength range, since most materials, which are transparent for visible light, show a strong absorption in this area. The absorbed energy is converted to heat, which can be detected by an infrared detector. The emitted radiation has two major advantages. On the one hand, heat radiation is an ideal Lambertian radiator. This means that the radiation density is constant in all directions in space, and thus the detection is independent of direction. On the other hand, both absorption and emission are usually confined to the surface.

For the calculation of 3D-Points and for calibration of the infrared system, new algorithms based on state of technology are developed. We use phase shifting technique for reconstruction of single measurement points. Therefore, we get for each camera pixel one 3D Point, which is essential in the infrared regime due to sensors with little number of pixels. Unique reconstruction of the 3D scene is done by the first implementation of a multi-period method in a commercial prototype.

Our development shows that this new technology offers a significant potential for industrial metrology. Using a projector model and calibration method developed by the Fraunhofer IFF in Magdeburg, we show 3D data on glass, PMMA, carbon fiber (CFRP) and painted sheet metal without treatment of the surface. We are going to present first measurement results about the accuracy and the measurement uncertainty of this new measurement principle.

9525-40, Session 8

Experimental comparison of laser speckle projection and array projection for high-speed 3D measurements

Stefan Heist, Peter Lutzke, Patrick Dietrich, Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Gunther Notni, Technische Univ. Ilmenau (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In many application fields, stereo vision-based active triangulation systems are used to reconstruct the three-dimensional (3D) surface shape of measurement objects. Typically, in order to solve the correspondence problem and increase the accuracy of the pixel assignment, a sequence of patterns is projected onto the object's surface and simultaneously recorded by two cameras. Most 3D measurement systems are limited to static objects. However, moving objects can be measured if the frame rate is high enough. This requires fast cameras as well as fast projection systems. While high-speed camera systems are available, pattern projection at high frame rates is a difficult task and only a few techniques exist at the moment. As the three-dimensional information of moving objects or deformation processes is of high interest in many scientific and industrial applications, new projection technologies have to be invented. In addition, the relationship between object velocity and frame rate with these new technologies has to be investigated.

We use an active triangulation system with high-speed cameras to measure reference objects with two different projection systems. The cameras can achieve frame rates of up to 13 kHz at a resolution of 1 megapixel. The first projection system is based on a laser speckle projection unit. Here, the different patterns are created by quickly changing the position of the focal spot of a 10-W laser on a diffusor. The second technique uses an LED-based multi-aperture projection system. Here, each pattern is generated by an incoherent superposition of miniaturized slide projectors, being illuminated by one LED or a cluster of LEDs. Changing the patterns is realized by quickly switching on and off the different LEDs.

Using both projection techniques, we take several measurements of two measurement objects: a plane and a sphere. During the measurement, we move the measurement objects at various speeds. We show the results obtained with each projection technique at several frame rates, and we compare the surface roughness and the completeness of the resulting 3D data to show the strengths and weaknesses of each projection method.

9525-41, Session 8

Development of a photogrammetry system for the measurement of rotationally symmetric forgings

Aneta Zatocilova, David Palou?ek, Jan Brandejs, Brno Univ. of Technology (Czech Republic)

Large forgings are semi-finished products which are used to manufacture components particularly for marine, nuclear and petrochemical industries. Most of available non-contact systems are not possible to use for this purpose, mainly due to high temperatures and large dimensions of forgings. This paper describes state of art in this area and presents development of measurement system which is based on passive photogrammetry and image analysis. Proposed system is based on assumption that the actual shape of the cylindrical forging axis can be determined (in the simplest case) from four boundary curves which lie in two mutually perpendicular planes. Four boundary curves can be obtained by detecting forging edges in two images. System uses simple best fit method, as a final step of orientation of extracted boundary curves. Main parts of the system, such as calibration, edge detection, spatial orientation and evaluation of information about shape and dimensions of measured parts, have been designed so that the entire measurement process takes only a few seconds.

The article focuses on individual parts of the software application. It discusses the suitability of usage of particular mathematical models and designed multi-step edge detection method, which is based on thresholding, directional median filter, validation and correction of detected edge points. First experimental measurements in laboratory conditions show accuracy in the order of tenths of mm, which is satisfactory with respect to the precision required in real conditions. The measurement results also show the presence of systematic error caused by approximation of scale in images. This error increases with the size of deflection ratio to the total length of the forging. Further development of the system considers elimination of this error by implementing the correction model. It is also intended to improve the method of edge detection in terms of reliability.

9525-42, Session 8

3D shearography with integrated structured light projection for strain inspection of curved objects

Andrei G. Anisimov, Roger M. Groves, Technische Univ. Delft (Netherlands)

Shearography (speckle pattern shearing interferometry) is a developing inspection technique frequently used for non-destructive testing (NDT) of modern materials and structures. Unlike other interferometry techniques (e.g. electronic speckle pattern interferometry (ESPI) that controls surface shape), shearography has a direct sensitivity to a surface displacement gradient providing surface strain quantitative measurement. Complete characterization of an object's surface strain, i.e. differentiating and measuring of six components of strain tensor (in- and out-of-plane, except bulk components) can be done with multicomponent shearography configurations. Those known configurations use multiple viewing or multiple illumination approach.

As most real-life objects especially in aerospace, transport or cultural heritage (e.g. sculptures) are not flat, their inspection with shearography and further proper strain mapping onto a highly curved or a free form surfaces is limited without inline shape measuring. Different developments were reported to overcome this drawback. That was done by direct generating of interferometric fringes to project them on the object to perform profilometry. A displacement of one of the sources with a posterior revealing of carrier fringes and their analysis was also used. Advanced researches were devoted to combination of shearography with ESPI to get shape information with subwavelength accuracy, but the depth range was significantly limited.

Our research is devoted to the practical questions of 3D shearography system development with integrated structured light projection for strain inspection of curved objects. For this a system prototype with three spatially-distributed shearing cameras, with Michelson interferometers acting as the shearing device, and one illumination laser source was developed.

Aforementioned results in shape shearography measuring aimed at the development of shearography optical part, but have limited measuring performance because of fringe distortion and significant difficulties in generating of multiple spatial frequencies of fringes. However development of modern digital light projectors provides the ability to use a relatively small structured light projector without significant system complication. So the developed prototype was equipped with a projector (LightCrafter™ by Texas Instruments) and well-known phase shifting technique. This formed a "shape shearography" system that was used for further experimental research.

In order to perform a shape measuring three system's cameras were geometrically calibrated with the projector as a multiple view computer vision system in a volume of 20?20?15 cm. The advantage of use of three spatially distributed cameras in the system made the shape estimation more accurate and reliable.

Preliminary results of integration of a structured light projector into the 3D shearography system are presented in the research. This includes estimation of actual shear distance, method for sensitivity vector correction within the field of view and because of the object curvature.

As reported before, a shear angle of a shearing device may be not uniform within a field of view because of aberrations and misalignments and has to be calibrated. That becomes more complicated with a "deformed" shear projection onto curved zones of an object. We propose a new way to identify it by projecting a predefined pattern on the object with further comparison of pattern images taken independently through shear and reference interferometer's arms.

The measured object's surfaces were presented as triangulated mech. Known surface flattening techniques (e.g. IsoMap) were employed for surface parameterization in order to perform coordinate transformation for estimation of surface strain components.

The 3D shape shearography system performance was compared with previously reported results obtained with shearography system dedicated for inspection of a cylinder-type sample with a predefined shape. The experiments were done with a cylinder specimen (length 400 mm, external diameter 190 mmm, loaded by internal pressure using oil). Results of the experiments are analysed with respect to the shape shearography system optimization with reducing of measuring errors.

Further directions of shape shearography technique development, strain mapping onto curved surfaces with ways of deep fusion of shearography technique with multiple view computer vision approaches are also investigated.

9525-43, Session 9

Temporal modulated deflectometry for painted surface inspection

Toru Kurihara, Kochi Univ. of Technology (Japan); Shigeru Ando, The Univ. of Tokyo (Japan); Michihiko Yoshimura, Ricoh Elemex Corp. (Japan)

1. Introduction

Deflectometry is widely used inspection configuration for specular objects, such as lens or mirror.

To improve system and measurement power, phase shifting method is used to yield continuous phase pattern.

But it requires multiple images, so that it cannot offer single image fast inspection.

In this paper, we propose single frame surface inspection system for detecting small defects on painted surface.

2. Principle

2.1 Correlation Image Sensor

The three-phase correlation image sensor(3PCIS) is a two dimensional imaging device, that outputs an ordinal intensity image and a correlation image.

The correlation image is the temporal correlation over one frame time in each pixel between the incident light intensity and three external electronic reference signals.

Let T be the frame time and $f(x,y,t)$, the instant intensity of the scene.

The intensity image, $g_0(x,y)$ which is common to conventional image sensor, is the integral during the frame time of f(x,y,t).

The correlation image sensor outputs another image, complex correlation image.

An orthogonal sinusoidal wave pair $(\cos\omega\, t, \sin\omega\, t)$ is usually chosen as reference signals.

Then (complex) correlation image, $g_\omega(x,y)$, is given as g_\omega(x,y)=\int_{t-T}^{t} f(x,y,t) e^{j\omega t}dt

2.2 Moving Strpie pattern

To make time varying intensity signal, we move stripe pattern.

The temporal modulation frequency of the stripe period L and moving velocity v is f = L/v;

BY using CIS, we can use binary pattern because higher order harmonics can be effectively eliminated by correlation.

3. Experiments and results

Various defects on the painted surface were inspected by our proposed system.

We classify those defects as amplitude defect, phase defect, intensity defect.

We show those defects can be captured and detected by our system.

The intensity defect shows uneven coloring on the surface.

The phase defect shows gradually gradient error over large area.

The amplitude defect shows local gradient error over small size area.

They were able to be captured and detected by the proposed system.

4. Conclusion

We have proposed single frame surface inspection system.

The method consists of a correlation image sensor and the modulated illumination pattern

9525-45, Session 9

Point-based deflectometry for measuring optical freeform topographies

Carsten Glasenapp, Carl Zeiss AG (Germany)

Here, a novel approach to measure the topography of optical surfaces via a deflectometric method is demonstrated. To find a solution that matches the demand of eyeglass manufacturers, a solution that can measure surfaces in a range of slopes from +45 ° to - 45 ° and a field of view of about 80 mm, or surfaces with a nominal optical power from -10 dpt to +10 dpt, is needed.

The solution is a hemispherical, dome type setup with approximately 2000 UV light sources. By measuring the spatial slope distribution of the sample, a “topography map” can be integrated or a “curvature map” can be derived.

Most deflectometric setups are fringe-based and limited by measuring only the curvature and not the topography of the surface. The approach using light spots instead of fringes is the key aspect to measuring topographies with an accuracy of one micron, as points are uniquely defined in all directions.

9525-100, Session 9

A Non-scanning Reflection Technique (NRT) for measurements of optical nonlinearities

Lin Zhang, Huan Ren, Yi Yang, Quan Yuan, Yong Liu, Zhendong Shi, Hua Ma, Bo Chen, China Academy of Engineering Physics (China); Tingkui Mu, Xi’an Jiaotong Univ. (China)

The Z-scan method enables the measurement of the magnitude and the sign of the optical nonlinearities. In this method, the investigated sample is moving along the direction of the focused incident beam and the phase or amplitude distortions of the beam are monitored in the far field. The optical nonlinearities are measured by analyzing the beam transmitted by the sample in the transmission Z-scan or the reflection Z-scan techniques. Reflection Z-scan technique allows the measurements of optical nonlinearities of highly absorbing media and surface of transparent media, when transmission Z-scan can not be used. However, Reflection Z-scan needs multiple measurements under strong laser pulse excitation in the scanning process. This can induce damage in the sample in some cases. In this paper, a non-scanning reflection technique for measurement of optical nonlinearities is presented to overcome this drawback. In this work, a phase plate which makes the phase of transmitted light changes without changing the amplitude is introduced into the measurement system. Both the nonlinear refraction index and nonlinear absorption coefficient can be determined by measuring the reflection in combination of variable attenuator and an aperture. In open aperture configuration, the refractive nonlinearities are measured by monitoring the total reflection coefficient in both linear and nonlinear conditions. Similarly, in the close aperture configuration, the absorptive nonlinearities, responsible for the phase changes in the reflected beam, are measured in linear and nonlinear conditions. Based on the Fresnel theory, a theoretical analysis of non-scanning reflection technique demonstrates the feasibility of this approach is given and a general expression for the normalized reflectance is derived. In order to illustrate our analytical results, we performed a numerical simulation of the normalized reflectance. It is shown that the normalized reflectance is highly dependent on the incident angle of the beam. For a sample with positive or negative nonlinear refractive index, the dependence of the normalized reflectance for the incident angle is analyzed. The results show that the maximum sensitivity is obtained when the incident angle is around the Brewster’s angle. The dependence of the normalized reflectance response on the incident angle is in agreement with the work of Martinelli et al. Besides, retardance and size of the induced phase plate also make contributions to the normalized reflectance. The retardance modulates the phase of the incident beam which leads to the result of the normalized reflection changing. In this work, the dependence of the normalized reflectance for the retardance of the phase plate is analyzed. It is shown that the sensitivity of the normalized reflectance is maximum when the retardance is . The size of the phase plate and the beam waist also have great effect on the normalized reflectance. When the ratio of the size of the phase plate and the radius of the beam waist increase, the sensitivity of the normalized reflectance decreases rapidly. If the ratio of the size of the phase plate and the radius of the beam waist is more than 0.4, the sensitivity of measurement will be so low that it is difficult to detect the changes of the reflected intensity induced by the optics nonlinearities. Moreover, this technique shows a higher sensitivity property compared with traditional reflection Z-scan method.

9525-161, Session 9

Three dimensional reconstruction of human torso using a portable multiview fringe projection device

Jaime Enrique Meneses Fonseca, Andrés L. González Gómez, Univ. Industrial de Santander (Colombia)

Fringe projection profilometry (FPP) has been extensively developed in order to meet the demands of various applications in medical and industrial sectors. In this technique, a fringe pattern is projected onto the surface of an object and then it is viewed from another direction using a CCD Camera. In the CCD camera image the projected fringes are distorted according to the object topography and this is mathematically coded in the phase distribution of sinusoidal fringe pattern. The phase distribution of the distorted fringe pattern is often recovered using phase shifting algorithms or methods based on Fourier transform. System calibration techniques have been developed to obtain the mapping relationship between phase distribution and 3-D object-surface coordinates. Currently two calibration approaches are used in the FPP: polynomial (also called direct) and model-based calibration (also called photogrammetric). In the polynomial calibration method, a plane is positioned in different positions successively respect to the camera. Good calibration results are obtained using a precise linear z stage. In the model-based calibration the projector and the camera are always modeled as pin-hole camera, and the intrinsic and extrinsic parameters can be calibrated by single device calibration. The process of obtaining calibration equations is significantly simplified and it is generalized as the systems are described by the transitions of the matrices, also the rotation and translation effects are considered.

In this work, a model-based calibration procedure for a FPP that does not need special method to calibrate the projector neither use precise linear Z stages, is proposed. An analytic expression is proposed to extract the 3D object surface coordinates based on intrinsic parameters of pin-hole model. The video-projector projects a pseudo-periodic pattern of equally spaced white dots on a reference plane. The hand-held reference plane is placed in the calibration volume with a colored checkerboard on its surface. The monochrome CCD camera captures several images of the reference plane in different positions into the calibration volume. The coefficients of analytic expression are calculated and they are employed in the reconstruction procedure. Experimental validations are realized with four fringe projection systems placed around the torso of a human body in order to extract 3D Information at 360° of global observation. Each fringe projection device extracts 3D information of human torso according to its field of view. The registration algorithm aligns the four sets of data into one coordinate system using linear transformations. The parameters are calculated using a 3D reference object. The final device composed by four fringe projection systems has two main features. The first one is the hand held calibration procedure of each fringe projection system without using high precision linear translation stages. Resolution of each system is on the order of 0.05 mm, experimentally evaluated. The second ones is its characteristic of portability. Each Fringe projection system is independent from each other.

9525-47, Session 10

Never-ending struggles with mid-spatial frequencies *(Invited Paper)*

Gregory W Forbes, QED Technologies (Australia) and University of North Carolina at Charlotte (United States)

No Abstract Available

9525-48, Session 10

Calibration and control of wavefront errors in measurements of cylindrical optics

Florian Wolfgramm, Jan-Peter P. Richters, Rainer Schuhmann, Berliner Glas KGaA Herbert Kubatz GmbH & Co. (Germany)

The fabrication of large high precision cylindrical optics creates challenges for the interferometric measurements of a complete map of the optical surfaces. This work discusses the analysis and the potential reduction of the influence of wave front errors of computer generated holograms as common correction elements.

9525-49, Session 10

Overview of characterization and metrology techniques for microlenses and microlens arrays

Myun-Sik Kim, Lisa Allegre, Jonathan Sunarjo, Wilfried Noell, Reinhard Völkel, SUSS MicroOptics SA (Switzerland)

Refractive microlenses and microlens array (MLA) are an interesting alternative solution for all applications, where miniaturization and reduction of alignment and packaging costs are necessary. Refractive microlens arrays offer perfect operation for the full wavelength range. For instance, microlenses made of fused silica cover the wavelength from 193 nm to 3 μm, and silicon MLAs are suitable for the infrared, wavelength from 1.2 μm to 5 μm. In industrial sectors, refractive microlens arrays are proven to be a perfect solution for high-power laser beam homogenizing and shaping. Refractive microlenses are manufactured using standard semiconductor technologies, which consist of photolithography, resist processing and reactive ion etching. These wafer-based manufacturing technologies allow a very accurate shaping of the lens profile and a precise positioning of the lenses within an array. Such fabrication techniques are very well developed and established in the industrial cleanroom fab. However, the characterization and metrology of microlenses are not a trivial task. To the best of our knowledge, there is no royal way to characterize microlenses. Typically, profilometers and interferometers are employed to characterize surface topography, where one can obtain the lens profile data like the radius of curvature (ROC) and conic constant. However, most of them do not allow complete characterization of microlenses. Therefore, one needs to combine various techniques to verify the results of other tools or to calibrate the raw data. Moreover, the actual performance of the fabricated microlenses is quite often not tested at the manufacturing fab.

In this paper, we review various metrology techniques for the characterization of microlenses. The aim is to highlight restrictions in each method, and then we will discuss how to overcome such restrictions and how to achieve better characterization routines at manufacturing fab. We will introduce the concept of complete characterization of microlenses, which consists of measurements of surface profile parameters, optical performance, and focal properties. First, we will look at the surface profile characteristics of microlenses, which are related to two primary parameters, a radius of curvature and a conic constant. A stylus-type surface profilometer will be compared with microscope-based optical profilometer like a confocal microscope. Second, the optical performance of the lens, which can be assessed by a Strehl ratio and Zernike coefficients, will be discussed. Usually, microscope-based interferometers are applied to characterize the optical performance. Advantages of such tools and difficulties at mass-production manufacturing fab will be discussed. Third, the measurement of 3D light distribution near the focus is aimed to characterize the focal properties, for instance, the spot size, the focal length, and the depth of focus. By applying numerical algorithm, which is called through-focus phase retrieval methods, one can retrieve the aberration from two shots of lateral intensity measurements near the focus. When the peak intensity at the focal plane is compared to that of the reference lens (i.e., the lens without any defects), it directly represents the Strehl ratio. It provides a glance of the optical performance by the peak intensity degradation. Measuring the focal spots of the MLA leads to a practical and fast characterization method for million microlenses at manufacturing fab. We will finally summarize which metrology techniques can be applied in the daily production of manufacturing fab.

9525-50, Session 10

Wavefront calibration in 3D space

Johannes Schindler, Goran Bastian Baer, Univ. Stuttgart (Germany); Christof Pruss, Wolfgang Osten, Institut für Technische Optik (Germany)

A method to calibrate the test volume of a non-null interferometer is presented. It is also applicable to common null setups. This works aims at a unified view of established calibration approaches and the recently introduced and more general method. The validity and limits of both methods are quantitatively assessed.

9525-51, Session 11

Traceability in interferometric form metrology *(Invited Paper)*

Michael Schulz, Physikalisch-Technische Bundesanstalt (Germany); Gernot Blobel, Physikalisch-Technische Bundesanstalt (Germany); Ines Fortmeier, Manuel Stavridis, Clemens Elster, Physikalisch-Technische Bundesanstalt (Germany)

No Abstract Available

9525-52, Session 11

New method for optical shape measurement of refractive surfaces

Mohamed Bichra, Florian Schurig, Stefan Sinzinger, Technische Univ. Ilmenau (Germany)

We present a new method for optical shape measurement of refractive surfaces. The concept is based on triangulation and proved to be suitable for measuring complex freeform surfaces with high inclinations.

High precision optical instruments require optical elements with a many degrees of freedom in order to achieve best possible performance. Aberrations are particularly reduced by using non-spherical (e.g. aspheric or freeform) optical elements. The technological progress in machines and tools enables the fabrication of high-quality freeform surfaces of reasonable.

A successful fabrication depends notably on the capability of quality control and metrology. This causes a high demand for precise and robust metrology techniques that are suitable for freeform optics.

Known methods such as interferometry and deflectometry are often limited in their measurement resolution. While interferometry is susceptible to vibration, deflectometry requires a significant calibration effort.

In this paper, we present a method that overcomes these drawbacks. The presented principle detects the surface gradient and surface depth by the use of a transparent three dimensional refractive screen. The screen

shape can be realized under various geometries such as plane, pyramidal and spherical. The screen contains one or more openings. Through this opening, a light pattern is directed onto the sample surface. It is then reflected and causes two scattering points: one on the inner surface of the screen and one on the outer surface. The direction of the beam is uniquely defined by the optical characteristic of the screen material and its geometry. Several Cameras are observing the screen from various angles. By evaluation of the scattering pattern and its position, the surface normal and the surface depth of the sample can be determined directly.

Our experiments the screen is made of PMMA. The spot detection is realized by standard cameras. The test sample is mounted on a precision positioning stage in order to realize an oversampling of the entire sample surface.

Numerical simulations and experimental tests demonstrated that this method which is supplementing existing principles shows high performance if areas with large slopes are measured. As the entire surface of the sample can be covered by the screen, the principle is not limited by the gradient angle of the test surface.

In addition, the measurement resolution was increased by using a sub pixel algorithm and the entire measurement has been automated. Moreover, calibration for the entire set up was developed.

9525-53, Session 11

Through-focus OTF-based alignment testing of whole slide imaging systems

S. Mojtaba Shakeri, Technische Univ. Delft (Netherlands); Bas Hulsken, Philips Digital Pathology (Netherlands); Lucas J. van Vliet, Sjoerd Stallinga, Technische Univ. Delft (Netherlands)

We present a tool for testing and monitoring the optical quality of whole slide imaging systems based on through–focus OTF measurements. The tool enables differentiation between the inherent aberrations of the optical design and the aberrations that arise from misalignment of the components and suggests a way to optimize decenter and tilt of the objective lens.

9525-54, Session 11

Unique characteristics of the fiber optic reference technique in absolute cylindrical testing

Ayshah Alatawi, Patrick J. Reardon, The Univ. of Alabama in Huntsville (United States)

Increasing demand for highly accurate cylindrical optics requires absolute testing techniques where all the errors of the system are separated from the error of the tested part. The fabrication of high quality cylindrical surfaces is limited by the lack of well-calibrated cylindrical reference wavefronts. The existing two methods for absolute cylindrical surface testing, tilt mirror and roof mirror, can not ensure the highly accurate measurements. For the tilting mirror method, the cylindrical wavefront that is affected with error meets with a plane mirror that placed at the focal line, and is then rotated about the focus line so that the wavefront is reflected at several different angles. Then by combining these measurements the interferometer error can be calculated. This method reveals only the error in one direction. For the roof mirror method, three measurements are taken. In the first measurement, the cylindrical mirror holds in the normal position and in the second measurement the cylindrical mirror is rotated 180 degree about the beam axis. In the third measurement, a 90 degree roof mirror replaces the cylindrical mirror. By combining these three measurements, the interferometer error can be calculated. The disadvantage of this method in addition to the alignment difficulties, the mirror quality is unknown.

The fiber optic reference technique has been merged with the random ball technique to achieve absolute cylindrical testing – the random fiber reference (RFR) technique. This technique can calibrate a cylindrical wavefront reference, with data provided in both the powered and planar directions. In this paper, some unique aspects of this RFR technique are discussed, with experimental results presented. The fiber optic reference test utilizes a specially processed optical fiber to provide a clean high quality reference wave from an incident line focus from the cylindrical wave under test. Fiber reference has a unique properties, it acts like a line spatial filter where it filter the error in the powered axis, passing the variation on the planar axis. The random ball test assumes a large number of interferograms randomly distributed over a good quality sphere with errors that are statistically distributed such that the average of the errors goes to zero. By taking measurements at different rotation and translations of the fiber, an analogous procedure can be employed to determine the quality of the converging cylindrical wavefront with high accuracy.

To describe the error in the fiber and facilitate the calibration method, we define four possible forms of geometric error on the fiber surface, fiber diameter variation, longitudinal error and random bumps. Averaging the measurements of randomly shifting the fiber different distances along its axis will eliminate the fiber diameter variation error. Randomly rotating the fiber around it axis will eliminate the longitudinal error. Also, by averaging the random shift and random rotation measurements, the random bump error will be eliminated. To assure the accuracy of (RFR) technique, misalignment error need to be analyzed. We experimentally study the effect of the fiber reference possible misalignment, defocus, decenter, tilt on the absolute testing technique. In this paper, the unique aspects of the RFR technique, such as how the 1-D filtering and specific fiber misalignment sensitivities affect the accuracy of absolute testing, are presented.

9525-55, Session 11

Measurement of aspheric and freeform optical surfaces with Diffractive Null Lenses with and without integrated Fizeau reference surface

Alexander Grigorievich Poleshchuk, Institute of Automation and Electrometry (Russian Federation); Jean-Michel Asfour, Dioptic GmbH (Germany); Victor P. Korolkov, Ruslan K. Nasyrov, Institute of Automation and Electrometry (Russian Federation); Frank Weidner, Dioptic GmbH (Germany)

We review our recent practical results on layout, fabrication and implementation of high precision binary diffractive null lens (DNL), diffractive Fizeau null lens (DFNL) and as well as high efficiency diffractive optical elements (DOEs) with continuous relief. Complementary advantages have been achieved by combining of the capabilities of the precision circular laser writing system (CLWS), direct laser thermochemical writing on chromium films and photosensitive materials with combination with optical lithography.

The main limitations and tolerances of writing methods are identified, and their influence on optical performance of DNL, DFNL and DOEs are investigated.

9525-56, Session 11

Point diffraction interferometry based on the use of two pinholes

Nikolay B. Voznesenskiy, VTT-NTM OÜ (Estonia); Dongmei Ma, Chunshui Jin, Haitao Zhang, Jie Yu, Changchun Institute of Optics, Fine Mechanics and Physics (China); Mariia Voznesenskaia, Tatiana Voznesenskaia, VTT-NTM OÜ (Estonia); Wenlong Zhang, Changchun Institute of Optics, Fine Mechanics and Physics (China)

Point diffraction interferometer (PDI) has become the high degree of accuracy device. In the optical wavefront testing the measurement accuracy is much higher than 1.0 nm RMS. The PDI plays an important role in the process of the development of high precision optical system.

The PDI would be used to test an interferometer reference lens and compare measurement results. The measuring method of point diffraction interferometry is studied based on the two pinholes. The prototype with phase-shifting is developed on the testing principle. Using the ideal diffraction wavefront as interferometric reference, the high accuracy measurement has been achieved. The device can test high NA and the interference fringe contrast is adjustable, etc. The measurement repeatability now has been sub-nm RMS (NA = 0.33). The experiment result provides guarantee for the measurement in the high degree of accuracy. In the paper there is presented a new version of PDI with two independently controlled beams – reference and test ones. This PDI differs from the known Sommargren arrangements and other similar versions by using a pinhole plate with two pinholes as a beam coupler instead of a single-mode fiber or single-pinhole plate. Each beam can be well focused to its own pinhole not disturbing adjustment of another beam. Phase shifting of the beams is made by a PZT unit which produces exact increments of the optical length of the reference beam.

Interferometric inspection of optical surfaces and wavefronts performed by this PDI has revealed great convenience of dealing without standard parts or transmission spheres for testing concave spheres, simplicity to arrange high accuracy measurements of convex spheres. However, regarding standards certification there is no problem of convex spheres measurement because all standards and transmission spheres for interferometers are only cavities.

In the paper there is theoretical analysis of the pinhole diffraction wavefront and double pinholes diffraction interference. In the double pinholes diffraction interferometer, generating two ideal spherical waves through two pinholes, one wave is as the reference wavefront for interference test, another ideal wavefront is reflected to the pinhole plate by spherical test mirror and the tested wavefront and reference wavefront bring interference. Advantages of such arrangement of the PDI are: high numerical aperture (NA = 0.55), clear fringe patterns of high contrast, high accuracy of surface figure testing and wave-front repeatability RMS error below 0.5 nm.

In the paper there is described experimental analysis of optical wavefront testing. A mass of the test images is acquired and analyzed on the test prototype. The good environment is provided (vibration isolation, constant temperature, clean, no stray light) in the laboratory. The wavefront testing results can be quickly obtained by image collecting and processing calculation. Due to the adoption of Zernike polynomial expansion, the optical wavefront aberrations has the characteristics of convenience, therefore, the test device using Zernike polynomial as the wavefront aberration function development base.

Performance of the PDI is illustrated by tables of repeatability and test surface profile plots.

9525-57, Session 12

Speckle interferometry in the long-wave infrared for combining holography and thermography in a single sensor: applications to nondestructive testing: The FANTOM Project *(Invited Paper)*

Marc P Georges, Univ. de Liège (Belgium)

No Abstract Available

9525-58, Session 12

Problems and solutions in measurements of engineering objects by means of digital image correlation

Marcin Malesa, Malgorzata Kujawinska, Warsaw Univ. of Technology (Poland)

Digital Image Correlation is a well-established method for displacements, strains and shape measurements of different kind of objects. The method is now being extensively used in research works in the fields of experimental mechanics, materials engineering and others [1,2]. Rapid development of the basic method and its modifications also enabled implementation in an industrial environment. Example applications in heat-and-power generating industries, petrochemical industry or building engineering are available in literature [3].

The scope of this paper includes displacement and shape measurements of structural elements used in aerospace industry with the use of Digital Image Correlation. Hybrid numerical-experimental methodology in the case of such elements includes exposing to extreme temperatures or big temperature variations. Appropriate temperature values during the experiments can be achieved by enclosing investigated objects in climate chambers. In order to enable DIC measurements of objects enclosed in climate chambers, the visibility of the object by the cameras has to be ensured.

Placing DIC cameras inside the chamber would be an option if the temperature changes were limited or if the cameras were enclosed in a casing, that protected from high temperatures. Otherwise high temperature would damage the cameras or would introduce significant changes to intrinsic and extrinsic parameters of the used DIC system. Because of this obstacle it is advisable to observe the object from outside the chamber. In this case however, other problems arise. If the cameras are placed outside the chamber, an object under investigation is viewed through the window of the chamber. In order to insulate from the temperature inside, the windows are composed of at least two glasses distanced from each other. The standard windows are not designed as to be used in optical measurements and in the case of DIC measurements they can significantly distort the results because of refraction index and possible reflexes (that may influence image formation from different views of the cameras). A quality or a type of the window in the climate chambers' doors may have an influence on:

• shape and out-of-plane displacement measurements - because of differences in image formation between the cameras in stereo setup,

• in-plane displacement measurements - because of differences in image formation between consecutive frames captured by a single camera.

In Figure 1 example results of 3D DIC measurements of object enclosed in a climate chamber is presented. A shape map obtained in the case when the object was observed through a window is presented in Figure 1a, while a shape map obtained in the case when the object was observed directly (with open doors) is presented in Figure 1b. In both cases appropriate 3D camera calibration has been carried out: in the first case calibration images have been acquired through the window, while in the second case calibration images have been acquired with open doors. The influence of through the window observation with 3D DIC is reflected as significant shape map modulations.

In the paper we present extensive research works on how through the window observation influences the DIC measurement results and what are possible solutions to diminish this effect (e.g. different post-processing algorithms). The presented research works are carried out as a part of the OTEST project, which aim is to develop a measurement system for experimental analysis of aerospace construction components.

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9525-59, Session 12

Objective speckle displacement resulting from the deformation of shaped objects

Thomas O. H. Charrett, Ralph P. Tatam, Cranfield Univ. (United Kingdom)

In many areas of non-contact optical measurement the properties of laser speckle are of great interest in particular in the measurement technique termed laser speckle pattern correlation [1] where the deformation of an illuminated object is related to the translation and de-correlation of its observed speckle pattern. The method was first described in the 1980's by Yamaguchi [1], who applied it to the measurement of object translation,

rotation and strain [2-4] and surface roughness [5]. More recently, there has been renewed interest in the technique with researchers investigating new applications in industry, including vibration [6], surface slope and topology measurements [7] and robotic vehicle odometry [8]. In many of these applications knowledge of how the illuminated surface shape affects the observed speckle translation is of fundamental importance. For example, in robotic vehicle velocimetry systems a shaped surface has been observed to cause significant errors in the measured velocities. Expressions for the speckle shift have been previously presented [1,9,10] however these theories have not addressed the cases of shaped or sloped objects, apart from cylindrical surfaces [3]. In this paper, an extended theory is presented that includes the influence of surface shape on the shift of the observed speckle pattern under deformation. The results of this extended theory are then compared to experimental measurements of the translational scaling factors (the ratios of speckle shift to object translations) are presented for a variety of detector/source configurations and surface gradients. These results indicate that the expressions in [1] and the new extended theory, using the same methodology and approximations, are only valid for on-axis detector positions. As a consequence improved expressions are derived, removing the need for some of the approximations used by Yamaguchi, which show good agreement with experimental results over a wider range of detector locations and also include the influence of surface shape/gradients.

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9525-60, Session 12

Optical system for the calibration and verification of correct axis positioning in medium-big sized milling boring machines

Marcomattia Mocellin, Massimo Fedel, Lorenzo Cocola, CNR-IFN UoS Padova (Italy); Renzo Casarin, FPT Industrie S. P. A. (Italy); Luca Poletto, CNR-IFN UoS Padova (Italy)

Very-large milling machine tools available for applications ranging from aerospace to automotive present a set of challenges when trying to match the traditional accuracies of the mechanical workshop. Effects of temperature, stresses on the carriages, low-term deformations, wear of the friction parts become important when machine calibration has to be guaranteed over time.

While conventional linear and rotary optical encoders are used to control axes positioning, and their resolution is already compliant with the needed accuracies, structural deformations of axis and sliding parts may introduce a systematic error that is not measurable by the encoders themselves.

An all-optical system for the automatic recalibration of the machine during the machining process has been developed. It uses collimated laser diodes, position-sensing photodetectors and passive optical components to measure both linear and angular displacements of the target center for each of the three machine axes, each one associated with its own beam. Therefore, the device performs simultaneous angle and displacement measurements on the 3-axes of the machine.

During the calibration phase, the controller receives data from the system's sensors; such data is then stored to be used in the measurement phase.

In this phase data acquired from the sensor is compared to the calibration data in order to obtain, through a physical model of the machine, the actual displacement values.

The system's output is then used by the machine's numerical control to improve its positioning accuracy as a recalibration technique.

The main aim of this work is to improve the operating principle and construction of the conventional laser spot tracker in order to make it suitable for the industrial milling machine recalibration described above. The device has been installed on a test column-type milling machine. The tests performed on the prototype demonstrate the unique capability of mapping the actual positioning offset with an error below tens of microns over the full working volume of the machine. The measuring blocks that form the final system geometry will be discussed in detail. The system is designed in a modular way in order to be suited to any 3D machine geometry.

9525-61, Session 12

Modified coherent gradient sensing method for slope measurement of reflective surfaces

Kang Ma, Huimin Xie, Tsinghua Univ. (China)

Residual stresses in thin films are very important and may significantly reduce the service lifetime of thin film/substrate systems. Generally, film stress can be calculated by the curvature of the system via Stoney equation. As for the curvature measurement, coherent gradient sensing (CGS) method is a full-field, real-time and non-contact optical technique, which is insensitive to vibration and able to provide the full-field curvatures of reflective specimens. The interference fringes of CGS method in reflection mode represent the gradient contours of the out-of-plane displacement of a surface, by which we can obtain the curvature of a reflective surface, then the residual stress can be calculated.

The phase analysis of fringes is very important to curvature and residual stress calculation. However, from the available literatures, there is still no effective method to obtain the phase field of interferogram efficiently and accurately in CGS. There are still many problems that haven't been solved in other interferometry to analyse the fringe pattern. Therefore, it is imperative to devise a method to obtain the phase field of interferogram efficiently and accurately.

In this report, a phase-shift based CGS method is proposed for the full-field measurement of the slopes, curvatures and shape of a reflection surface. In this method, a plane-parallel plate is placed between two gratings to introduce the phase difference of the original light beams. Different values of phase difference can be obtained by rotating the plane-parallel plate, which can be proved theoretically. The numerical result shows that the relation between phase difference and the rotating angle is linear in the right situation. The phase field then can be calculated by four successive fringe patterns and the four-step phase shifting method.

A standard specimen (spherical mirror of 5±0.005m curvature radius) is implemented to verify this method. The results show that the average value of curvature is 0.1998m-1, while the average relative error between the experiment result and the standard value of curvature is 0.10%, and the maximum deviation compared to the standard value is 0.68%, which shows the practicability and validity of this method. In addition, this method is implemented to an Au film/Si substrate specimen. A very small value of the stress in the Au film (-5.34 kPa) is calculated with this

method.

In conclusion, a novel phase-shift based CGS method is firstly proposed for curvature measurement. A four-step phase shifting method are deduced theoretically and thus the full-field phase value can be calculated accurately by four fringe patterns. The four-step phase shifting process can be carried out using a micro rotating device (MRD) to rotate precisely the plane-parallel plate between two gratings. This method is applicable to measure the slope, curvature and shape of thin film/substrate systems in a reflection mode.

9525-62, Session 13

Profilometry and interferometry in life science applications *(Invited Paper)*

Joris Dirckx, Univ. Antwerpen (Belgium)

The use of optical techniques for measurement of shape and deformation as used in industrial inspection also offers exciting opportunities in life sciences not only because of their high resolution but especially because of their non-contacting nature. Their application also involves additional challenges because biological objects often are optically non-cooperative and can be very unstable. In this paper we focus on a particular biomedical application, namely research on mechanics of hearing, and use it to demonstrate the opportunities optical profilometry, coherence tomography and interferometry can offer in this field of work.

The human middle ear contains an eardrum and three ossicles which transport sound energy from the air-filled ear canal to the fluid filled inner ear. The eardrum is the first component in this system, and its shape and structure play an important role in sound conduction. Constructing finite element models (FEM) helps us to understand the functioning of this complicated mechanical system, and models allow to optimize the design of implantable hearing aids and prostheses ossicles. As the eardrum is the first and very crucial component in the system, its morphologic and elastic characteristics are important input data for correct modelling.

We will discuss the use of a custom designed 3D porfilometer for measuring eardrum deformation, and the use of such data in back-engineering FEM calculations to determine elasticity parameters of this structure. Next we will demonstrate the use of optical coherence tomography as a tool to measure full-field thickness distributions of the eardrum, another factor which is indispensable to inspect eardrum integrity and to generate data for FEM calculations. Finally, we will discuss the development of a single-shot digital holography interferometry setup which allows to measure full-field deformation of a vibrating eardrum, and give a short view on a newly developed real-time profilometer integrated in the operation microscope.

9525-63, Session 13

Optical detection of mixture ratios and impurities in viscous materials based on fluorescence imaging

Patrik J. Murr, Anton J. Tremmel, Michael Schardt, Alexander W. Koch, Technische Univ. München (Germany)

Viscous materials are used in a large range of technical and everyday applications. Examples are the food, cosmetics, and machinery industries. The requirements for the viscous materials are specific, and the composition has to be adjusted to the respective application. It is necessary to manufacture aligned viscous material; therefor, a precise mixture of components in the viscous materials is essential. This leads to new challenges in the development of monitoring methods for viscous materials. The measurement systems should be able to detect slightest fluctuations in the mixture ratios. Another important field is the analysis of undesirable impurities in the viscous materials. For this purpose, viscous material is directly extracted from a technical process and is analyzed with respect to its composition and potential impurities. A detection of degree and type of contamination in the viscous material, for example, dust or material residues, enables a quality control of the investigated process. Currently, only three approaches for the analysis of viscous materials (infrared sensor, acoustic analysis, white-light microscopy) exist. All of them have several disadvantages. The infrared sensor and white-light microscopy have only a small spot size (micrometer range) for the evaluation. With the white-light microscopy, it is furthermore not possible to analyze the type, number, and size of the impurities automatically. The method described in this work enables for the first time an automated evaluation for both approaches in only one measurement system. The system consists of optical standard components. This leads to low acquisition costs and an easy adjustment to other materials. Further, to our knowledge it is the first method for quality control of viscous material based on fluorescence imaging. The basic idea of the method is that the system generates three similar images in different optical paths of the same fluorescing object. The three images are filtered in different wavelength ranges and are recorded with area scan cameras [1]. These data are the basic for the future evaluations. The size of one image is 6.65 x 5.32 mm, which corresponds to the size of the used camera-chips. The minimum resolution of the developed system is restricted to one pixel (5.2 x 5.2 µm) due to a one to one mapping. Through the use of an x, y-shifting table, the investigated measurement object area can include 3 x 3 cm, corresponding to 20 fluorescence images. The control of the mixture ratio is realized by a three dimensional evaluation. By merging the three images, a validation by reference to a defined acceptance solid is possible. Based on the variances, a feedback for the accuracy of the mixture ratio is achievable. Additionally, the presented method enables an automated analysis of viscous material concerning the number, size, and maximum x, y-dimensions of the contained impurities. The determination of these parameters is realized by different image processing algorithms in a LabVIEW-Software in real time. The main advantages of the developed method are the automated evaluations for viscous materials and the easy applicability to other fluorescing materials.

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9525-64, Session 13

Expanded beam spectro-ellipsometry for big area on-line monitoring

Miklos Fried, Csaba Major, Gyorgy Juhasz, Peter Petrik, Research Institute for Technical Physics and Materials Science (Hungary); Zoltan G. Horvath, MTA EK MFA (Hungary)

Non-destructive analysing tools are needed at all stages of thin film process-development, especially photovoltaic (PV) development, and on production lines. In the case of thin films, layer thicknesses, micro-structure, composition, layer optical properties, and their uniformity are important parameters. An important focus is to express the dielectric functions of each component material in terms of a handful of wavelength independent parameters whose variation can cover all process variants of that material. With the resulting database, spectroscopic ellipsometry coupled with multilayer analysis can be developed for on-line point-by-point mapping and on-line line-by-line imaging.

Off-line point-by-point mapping can be effective for characterization of non-uniformities in full scale PV panels or big area (even 450 mm diameter) Si-wafers in developing labs but it is slow in the on-line mode when only 15 points can be obtained (within 1 min) as a 120 cm long panel moves by the mapping station. Last years [1, 2], a new instrumentation was developed that provides a line image of spectroscopic ellipsometry (wl=350-1000 nm) data. Earlier a single 30 point line image could be collected in 10 s over a 15 cm width of PV material [3, 4]. These years we are building a 30 [5], a 45 and a 60 cm width expanded beam ellipsometer which speed will be increased by 10 X. Then 1800 points could be mapped in a 1 min traverse of a 60*120 cm PV panel or flexible roll-to-roll substrate. Another enhancement is the switch-over to rotating compensator measuring principle.

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9525-65, Session 13

Additive manufacturing: a new approach for individualized optical shape metrology

Andreas Heinrich, Philippe Maillard, Anne Suckow, Hochschule Aalen (Germany); Andrzej Grzesiak, Carl Zeiss Industrial Metrology (Germany); Peter Sorg, Uwe Berger, Hochschule Aalen (Germany)

In general in industrial manufacturing a larger lot size gives the potential to decrease the production costs. There is however also a big demand on individualization in order to cover all customer requests. These individual requests of a customer lead to production complexity and cannot always be covered with current manufacturing processes sufficient. In metrology we can see an equivalent situation. A metrology tool should be suitable for a large variety of parts. E.g. in shape metrology, the tool should be able to measure any kind of shapes (spheres, tips, steps, etc.). As a standard tool is not adjusted to an individual measurement task, the best performance is not reached equal wise for all shapes.

In this paper we want to present a new approach for shape metrology of parts, fabricated in small lots: the individualized metrology based on Additive Manufacturing. The main idea is, that the sampling signal of an optical metrology tool is individually adapted to the shape of the object to be inspected. This can be reached by an individual design of the optics, which is 3D printed afterwards.

In general an optical metrology tool is build up out of 3 components: Light generation, optical imaging and light detection. The individualization of the metrology tool should be restricted to the optical imaging path. Thus e.g. in in-line metrology it is easy to adapt to each task just by exchanging the imaging optics, exhibiting standard interfaces to light source and detector.

In this work we focus on shape metrology based on light section technique. The imaging optic distributes light into a line, which follows the individual shape of the part - e.g. a free form surface. As a manufacturing technique for the optics we decided to use Additive Manufacturing. This technique allows us to fabricate complex shaped optic parts, is suitable for a small lot size and we can directly use CAD data of our optics as input data for the 3D printer.

Based on this, we built up a prototype which should measure the shape of a complex free form. As a light source a laser diode is used, scattered light from the object surface is detected using a camera. The heart of the prototype is the additive manufactured optics, which generates a homogenous light line across the free form without any shadows. In this contribution we present the optic design of our sensor, which is based on light pipes. Thereby one has to take into account the special properties of the Additive Manufacturing process, e.g. minimal radii which can be printed. Additionally we discuss the challenges and advantages of using additive manufacturing for our optics and needed rework. The performance of the whole prototype will be shown as well as future potentials.

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3D shape measurements with a single interferometric sensor for in-situ lathe monitoring

Robert Kuschmierz, Yongle Huang, Jürgen W. Czarske, Technische Univ. Dresden (Germany); Stephan Metschke, Physikalisch- Technische Bundesanstalt (Germany); Frank Löffler, Physikalisch-Technische Bundesanstalt (Germany); Andreas Fischer, Technische Univ. Dresden (Germany)

Rising automation, decreasing tolerances and production of small batches require fast and precise process monitoring. An in-situ shape measurement of moving, objects with sub-micron uncertainty is an important task in next generation lathes. An interferometric sensor is presented, which allows for the simultaneous measurement of non-incremental distance and lateral velocity of rough surfaces. It enables a shape measurement of turning parts without exact knowledge of the rotational axis position. This is in contrast to conventional optical techniques such as chromatic confocal sensing, triangulation, multiple wavelength interferometry, low coherence interferometry or digital holographic interferometry, which only offer a distance measurement and are therefore prone to misalignment related to temperature drifts or vibration.

The presented laser Doppler distance sensor with phase evaluation (P-LDDS) is based on tilted interference fringe systems. While the lateral velocity is determined from the Doppler frequencies of the scattered light signals, the distance is coded in the phase offset between the signals. By superposing 3 interference fringe systems an unambiguous measurement volume length over 1mm is achieved [1]. The measurement uncertainty is reduced below to 200 nm by receiving optics matching [2] and optimizing the numerical aperture [3]. Utilizing diffractive optics a fiber coupled, compact sensor head has been realized.

Since the P-LDDS requires only keyhole access it can be fitted into a turning lathe at Physikalisch Technische Bundesanstalt (PTB). A tactile coordinate-measuring machine for reference measurements was provided by PTB. In-situ position, velocity, 3d-shape and vibration measurements were performed with measurement rates up to 2500 kHz. The measurement uncertainty in regards to the object roughness as well as the macro geometry is investigated. While systematic uncertainties are still to be considered, a shape resolution below 1 µm was achieved.

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9525-67, Session 13

Ultrafast 2K line-scan sensor for industrial inspection applications

Christian Nitta, Benjamin Bechen, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany); Ernst Bodenstorfer, Joerg Brodersen, Konrad J. Mayer, AIT Austrian Institute of Technology GmbH (Austria); Werner Brockherde, Olaf M. Schrey, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany)

Optical measurement systems require fast image acquisition at significantly enhanced resolution when utilized for advanced visual inspection tasks. Examples are quality assurance in security printing, high-

speed print inspection, real-time surveillance of railroad tracks, and in-line monitoring in flat panel fabrication lines. Ultra-high speed is an often demanded feature in modern industrial production facilities, especially, where it comes to high volume production.

A key technology in this context is the new high-speed sensor for line-scan camera applications with unmatched line rates up to 200 kHz (true RGB) and 600 kHz (b/w), presented in this paper. At this speed the line sensor provides full color images with, e.g., a spatial resolution of 50 μm at a transport speed of 10 m/s.

In contrast to conventional Bayer pattern or three-chip approaches, the sensor presented here utilizes the tri-linear principle, where the color filters are organized line-wise on the chip. With almost 100% fill-factor the tri-linear technology guaranties high image quality (almost no aliasing) at reduced costs.

The CMOS sensor is realized in a 0.35μm CMOS OPTO process and incorporates a total of 2048 pixel columns by 60 horizontal lines. The high-speed image sensor technique is based on a column wise architecture. The sensor employs 2048 10 bit ADCs and 3 x 2048 CDS amplifiers. This parallel signal processing drastically reduces the bandwidth requirements of the associated on-chip signal processing electronics, thus yielding best noise performance and true 10 bit resolution at a color line speed of 200 kHz. This line rate corresponds with a total sensor output data rate of 1.5 GB/sec. The color line-scan sensor has been characterized according to the EMVA1288 Standard and achieves 10 bit resolution with 32 electrons read noise and a total quantum efficiency (QE x FF) of 36% (@463 nm wavelength). The sensitivity of the sensor yields 0.052 DN/electron (10 bit), which allows for using standard illumination and optics. The total Dynamic Range is 52 dB and the Full Well capacity yields 37,000 electrons. These performance values are corresponding well with the targeted design goals and are subject of further optimization.

The sensor can be used as a pure monochrome chip, a Bi-linear version (using 2 lines of different color) or even as a multi- / hyperspectral sensor utilizing the maximum of 60 lines for wavelength separation. The only difference is in the color filter deposition in the back-end process. Thus, each camera can be developed based on the same sensor type. Another option is that if only one line (triple) is used, the multiple lines allow for electronic lateral adjustment during the mounting into the application.

Keywords: CMOS line-scan sensor, high-speed imaging, tri-linear, multi-spectral imaging, color filter, CMOS image sensor

9525-68, Session 13

Monitoring deformations of industrial objects using optical-electronic autoreflection system

Igor A. Konyakhin, Maksim A. Kleshchenok, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Currently, optical-electronic devices and systems play an increasingly important role in the measurement of angular and linear displacement, positioning and motion control of working bodies in the industrial control systems of technological processes. This is because the rapid development of new, more advanced element base allows all of us to improve the quality of the contactless control due to new concepts. The desired improvement of the quality (accuracy, range, reliability) can also be achieved through the application of new algorithms for digital information processing, which determines the relevance of the research and development of appropriate multi-functional, in the sense of versatility, transducers, instruments and systems.

Because such systems allow preventing (warn) technological disasters, the urgency of the problem increases in proportion to the technical progress of all mankind, to prevent the recurrence of tragedies have occurred, for example, the Bhopal disaster (1984), the Chernobyl disaster (1986), the Sayano-Shushenskaya power station accident (2009), pipeline spill in Israel (2014), which served as the impetus for the development of systems of this trend.

For the monitoring of linear deformations of the industrial constructions (turbines, dams, booms, bases plates, walls, pipelines) semi-active optical-electronic measuring instruments are used very effectively. Autocollimation and autoreflection schemes is two fundamental concepts of such systems. The autocollimation system has larger sensitivity than autoreflection ones. However, the autoreflection system is more effective for using of infrared emissions diodes as sources and at usage of matrix charge-coupled devices (CCD) as a receiver. In addition, the autoreflection system has larger working distance than autocollimation system. An experimental autoreflection system for control rotor turbines alignment was realized.

Parameters of a system are the following: infrared emission diode AL107B by power 10 mW as sources of radiation; the focal length of autocollimator objective is 250 mm, the CCD matrix as receiver with dimension of pixel (11.17 * 13.88) 10-3 mm. The experimental measuring error of this system is 0.007 mm on a working distance of 0.5 m and 0.06 mm on a distance of 8 m. After emission power and power supply stabilization for receiver, the measuring error is decrease at several ratio.

The obtained experimental data do not match with the theoretical model. Perhaps in the theoretical model there are no external factors such as vibration, the nonlinearity of the air tract, the instability of power supply and temperature parameters of the laboratory setup, which is planned to explore in the future.

9525-69, Session 14

High-speed digital in-line holography as multipoint vibrometry to analyze vibrations of structures

Julien Poittevin, IRT Jules Verne (France); Pascal Picart, François Gautier, Charles Pézerat, Univ. du Maine (France)

In the domains of vibrations of structures or flow-induced vibrations, Laser Doppler Vibrometer (LDV) is the most favorite instrument for velocity measurements [1]. To get simultaneously a collection of data points, multipoint vibrometers has been developed [2-5]. Such techniques are based on line scanning [2,3] (typ. 256 points along a line at up to 80kHz [2]), on holographic optical elements associated to a CMOS sensor (vibration at up to 100Hz measured [4]), on frequency multiplexing (20 points with 5?4 beams [5]), or also on three acousto-optic devices and a single high-speed photodetector (5?4 beams with a rate at 500Msamples/s [6]). Although these techniques are useful to give a set of measurements at several independent surface points, the number of simultaneous measurements at “one shot” is relatively low.

In this paper, we propose an alternative approach based on in-line high-speed digital holography to record transient phenomena, at their time-scale evolution. The approach does not require any Fourier filtering [7]. The optical phase is retrieved by numerically propagating the in-line hologram into the object plane. The set-up is arranged in an in-line configuration and a Photron Fastcam camera records the digital holograms. Experimental validation is performed by considering an aluminum beam submitted to a shock with temporal bandwidth in the range [20Hz-10kHz]. The experimental results show a very good agreement with those obtained from a point wise laser-vibrometer.

An application of the method to the study of an ABH (Acoustic Black Hole [8]) is proposed. The ABH is a passive method for reducing vibrations of panels; it consists in a local reduction of the panel thickness associated to a thin visco-elastic layer placed at the center. Such a pit acts as a trap for flexural waves. This type of structure induces a complex vibration field, exhibiting large variation in the spatial domain and large amplitude dynamic. The proposed multipoint vibrometer is well suited to investigate the properties of such complex behavior. Experimental results with ABH are discussed and highlight the great advantages of this new approach for multipoint vibrometry.

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9525-70, Session 14

Ultracompact vibrometry measurement with nanometric accuracy using optical feedback

Ajit Jha, Francisco J. Azcona Guerrero, Santiago Royo, Univ. Politècnica de Catalunya (Spain)

The use of nonlinear dynamic effects in a semiconductor laser with optical feedback combined with direct current modulation has enabled us to measure sub half wavelength λ/2 changes in the position of a vibrating object. So far, classical Optical Feedback Interferometry (OFI) has been used to measure displacement and vibration with amplitudes larger than λ/2. This limit is inherent to the technique as it is the minimum displacement required to produce a fringe in a given interferometric pattern. Some methods to increase the OFI resolution had been proposed by different authors, however, in all of the cases a minimum vibration of λ/2 was a requirement for the measurement. Due to the micro and nanotechnology industry advances, several applications now require the detection of vibration amplitudes smaller than λ/2. In this work, we present a variation of OFI taking advantage of continuous wave frequency modulation (CWFM) of the laser bias current, thus, inducing a frequency sweep of the laser emission. By inducing a linear modulation in the bias current of a few mA the frequency of emission changes linearly between the different mode hopping conditions. In order to produce the measurement, the laser operation point is fixed within one of the linear regions between mode hopping, and the modulation amplitude is chosen within the boundaries of the region, thus, preventing mode hopping. Therefore, a continuous, periodic wavelength shift is introduced following a triangular waveform with amplitude Am and frequency fm. Upon back reflection from a target placed at a distance D from the laser, and partial reinjection of the laser beam into the laser cavity, a beat is produced in the emitted laser power forming the well-known interference fringe pattern phenomena. Each fringe is produced as a function of the distance, the emitted wavelength and the laser frequency sweep. However, when any displacement is produced on the target, the appearance of each fringe can be also related to a λ/2 displacement. By mixing both concepts and making use of a differential arrangement between two interference patterns, one with a static target and another one with the target undergoing a displacement of amplitude At below λ /2 at a frequency ft, it is possible to extract the displacement information for very small amplitudes with an accuracy in the nanometric range. A detailed mathematical model, simulations, and experimental results will be presented to discuss the methodology of the technique and its potential to detect nanometric displacements even at high frequencies. Results will be presented confirming its use in amplitudes as small as λ/5 (137.5 nm) and an accuracy of λ/625 (1.09 nm), extending OFI to a condition never attained before. Some applications of the technique will be also presented.

9525-71, Session 14

Evaluation of the vibrational behaviour of a rotating disk by optical tip-clearance measurements

Iker García, Joseba Zubia Zaballa, Univ. del País Vasco (Spain); Josu Beloki, Aeronautical Technologies Ctr. (Spain); Jon Arrue, Univ. del País Vasco (Spain); Joel Villatoro, Univ. del País Vasco (Spain) and IKERBASQUE. Basque Foundation for Science (Spain)

Multiple rotating components of aircraft engines have been tested by the Aeronautical Technologies Centre (CTA), whose Zamudio facilities are equipped with a transonic wind tunnel for this purpose. During the assessment of a rotating disk by means of strain gauges, an optical sensor that was initially aimed at measuring blade tip clearance measurements of low pressure turbines also proved to be useful for the evaluation of the vibrational behaviour of a rotating disk [1,2]. The main component of the sensor is a trifurcated bundle of optical fibres. After several improvements in the configuration of the bundle and in the gain of the photodetectors, a precision of 28 μm was achieved for turbine rigs measurements [3].

Specifically, the tests were carried out on a rotating disk that separates two chambers with different pressures in a real aircraft engine. Due to the pressure difference of the two chambers, air flows through the existing gap between the edges of the disk and the frame of the chambers. When the pressure difference is high enough, the flow forces the disk to vibrate, and this happens even when the disk is not rotating. To avoid these vibrations, a complete characterization of the disk performance was necessary. Thus, two methods were employed to assess these vibrations. On the one hand, a traditional procedure was employed, in which several strain gauges were placed on the disk surface. On the other hand, an innovative non-contact technique was utilized, which is based on three equidistantly distributed optical sensors around the disk. The sensors were placed approximately 5 mm away from the disk edge (see Figure 1).

Due to the huge amount of data obtained in these tests, their processing is being carried out in an orderly fashion. For the moment, we have seen, for example, that the results corresponding to the non-rotating disk show a perfect agreement in the detection of the frequency of the vibrations with both kinds of sensors. Since the strain gauges and the optical sensors measure different points of the disk, the amplitude of the vibrations registered by each sensor are completely unrelated.

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9525-72, Session 14

Simultaneous laser vibrometry on multiple surfaces with a single beam system using range-resolved interferometry

Thomas Kissinger, Thomas O. H. Charrett, Stephen W. James, Cranfield Univ. (United Kingdom); Alvin Adams, Andrew Twin, Oxford Instruments plc (United Kingdom); Ralph P. Tatam, Cranfield Univ. (United Kingdom)

Using a novel range-resolved interferometric signal processing technique we present optical measurements vibration of on two surfaces using a single, collimated laser beam. Here, the first signal is provided by the Fresnel reflection of the window of a suspended vacuum chamber, while

the second signal is reflected off the target inside the chamber, where the target fixture is attached to a piston-driven coldhead. In this application it is important to characterize both the movements of the chamber itself and the additional vibrations of the target. The presented scheme allows these measurements to be performed simultaneously using a single beam and the technique is extendable to more than two signal sources.

The optical setup used consists of a laser diode, circulator and photo detector that are connected using regular single-mode fibre. The laser diode is a cost-effective laser operating at a wavelength of ?=1550 nm and all modulation and demodulation is carried out using field programmable gate array (FPGA)-based processing. In this technique, the interferometric reference is taken from the fibre tip reflection, providing an extremely simple, self-referencing configuration with complete down-lead insensitivity, and allowing a very compact measurement head consisting only of a standard fibre collimator to be used. The signal processing scheme is based on optical frequency modulation by sinusoidal injection current modulation of a continuous-wave diode laser. There are several techniques in prior art that are based on optical frequency modulation of a laser diode and that allow several interferometric signal sources to be spatially multiplexed in a self-referencing setup, including the well-known pseudoheterodyne techniques. However, all these techniques require the optical path differences of the multiple signal sources present in the setup to adhere to integer ratios, effectively resulting in a discrete grid of permissible source positions. In contrast, the presented technique allows continuously variable placement of the signal sources, without any apparent penalty in linear operation or crosstalk as long as a minimum spatial separation is observed, increasing greatly the practicality and flexibility of the approach.

With the particular laser diode used, displacement noise is dominated by laser phase noise but is still well below 0.1 nm?Hz^(-0.5) over a typical stand-off distance of 10 cm. The current system implementation allows an interferometric fringe rate of 90 kHz, equivalent 70 mm/s at ?=1550 nm, per range channel and the minimum spatial distance between sources is approximately 5 cm. Example measurements will be shown that highlight the usefulness of simultaneous determination of common-mode and differential movements between the two surfaces. It is thought that the ability to measure signals of multiple sources in a single-beam system could open up a whole variety of new applications for vibrometry or displacement measurements, particularly when signals from one or several windows or glass surfaces need to be evaluated along a common path.

9525-73, Session 14

Multi-point laser coherent detection system and its application on vibration measurement

Yu Fu, Nanyang Technological Univ. (Singapore); Chong Yang, China Academy of Engineering Physics (China); Yingjun Xu, Southeast Univ. (China); Huan Liu, Keyu Yan, Guo Min, Nanyang Technological Univ. (Singapore)

Laser Doppler vibrometry (LDV) is a well-known interferometric technique to measure the motions, vibrations and mode shapes of machine components and structures. The drawback of LDV is that it can only offer a point-wise measurement. In order to build up a vibrometric image, a scanning device is normally adopted to scan the laser point in two spatial axes. These scanning laser Doppler vibrometers (SLDV) assume that the measurement conditions remain invariant while multiple and identical, sequential measurements are performed. This assumption makes SLDVs impractical to do measurement on transient events. In this paper, we introduce a new multiple-point laser coherent detection system based on spatial-encoding technology and fiber configuration. A simultaneous vibration measurement on multiple points is realized using a single photodetector. A prototype16-point laser coherent detection system is built and it is applied to measure the vibration of various objects, such as body of a car or a motorcycle when engine is on and under shock tests. The results show the prospect of multi-point laser coherent detection system in the area of non-destructive test and precise dynamic measurement.

9525-35, Session 15

Smart optical distance sensor for automatic welding detection

Michael Kahl, Stefan Rinner, Andreas Ettemeyer, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland)

In this paper, we describe a simple and cost-effective method and measuring device for automatic detection of welding. The sensor is to be used in automatic darkening filters (ADF) of welding helmets protecting the operator from intensive hazardous UV radiation. For reasons discussed in detail below, conventional sensor principles used in ADF are being out-dated. Here, we critically revise some alternatives and propose an approach comprising an optical distance sensor. Its underlying principle is triangulation with two pin-hole cameras. The absence of optical components such as lenses results in very low cost. At first, feasability is tested with optical simulations. Additionaly, we present measurement results that prove the practicability of our proposal.

9525-74, Session 15

Realistic simulation of camera images of local surface defects in the context of multi-sensor inspection systems

Haiyue Yang, Univ. Stuttgart (Germany); Tobias Haist, Marc Gronle, Wolfgang Osten, Univ. of Stuttgart (Germany)

Industrial automation has developed rapidly in the past decades. Customized productions and short production time require flexible and high speed inspection systems. Based on these requirements, optical surface inspection systems (OSIS) as efficient and cheap systems for detecting surface defects become more and more important.

A general problem for the design of the hard- and software of an OSIS is the lack of sufficient knowledge concerning the expected defects and the variety of permitted object or surface variations. A lot of different parameters of an OSIS have to be defined and the optimum definition of these parameters is rarely possible without being able to obtain realistic measurement results/images. Even more, automatic optimization of the image processing in this context is only possible, if enough realistic training data is available. Of course, in a modern and flexible production environment often real measurement results or even samples of the parts are not available at all at the moment of the design of the inspection system. Even if one has access to some samples, typically, not enough representative samples (especially limiting samples) are available.

A virtual surface defect rendering method for multi-sensor surface inspection system is necessary to circumvent this problem. In this approach all defects would be simulated. The straight forward approach is to use ray tracing rendering methods. However, when the detection scale of the parts/defects to be inspected becomes smaller, the traditional geometrical ray tracing method has its limitation and the wavelike nature of light becomes more important. Hence it is important to find the limiting scale of ray tracing rendering method for OSIS.

In this contribution, we apply GPU based ray tracing for simulating traditional 2D image in a multi-sensor surface inspection system and compare with real measurements. In order to obtain the correct virtual representations of the defects and find the limitations of the ray tracing approach, three rendering models, Phong model, physically based model Cook-Torrance and BRDF model, are applied in different scales. In the experimental setup, the collimated white light is used as light source and the profiles of samples in the virtual inspection system are measured by confocal scanning optical microscopy and white light interferometry. In this work, we concentrate on scratches on rough aluminum and stainless steel materials.

9525-75, Session 15

Discrete modal decomposition for surface appearance modelling and rendering

Gilles Pitard, Univ. de Savoie (France); Gaëtan Le Goïc, Laboratoire Electronique, Informatique et Image LE2I UMR CNRS 6306 Univ. de Bourgogne (France); Hugues Favrelière, Laboratoire Systèmes et Matériaux pour la Mécatronique, SYMME EA 4144, Univ. de Savoie (France); Serge Samper, Laboratoire de Recherche en Mécanique Appliquée, LARMAUR - ERL CNRS 6274, Univ. de Rennes (France); Simon-Frédéric Désage, Maurice Pillet, Laboratoire Systèmes et Matériaux pour la Mécatronique, SYMME EA 4144, Univ. de Savoie (France)

Controlling surface appearance has become essential in the supplier/customer relationship. In this context, many industries have implemented new methods to improve the sensory inspection, particularly in terms of variability. A trend is to develop both hardware and methods for moving towards the automation of appearance inspection and analysis. If devices inspired from dimensional control solutions generally allows to identify defects far apart the expected quality of products, it do not allow fine appearance anomalies to be assessed, and decide on their acceptance.

To address this issue, new methods devoted to appearance modelling and rendering have been implemented, such as the Reflectance Transformation Imaging (RTI) technique. By varying the illumination positions, the RTI technique aims at enriching the classical information conveyed by images. Thus each pixel is described by a set of values rather than one value classically; each value corresponding to a specific illumination position. This set of values could be interpolated or approximated by a continuous model (function), associated to the reflectance of the pixel, generally based on a second order polynomial (namely, Polynomial Texture Mapping Technique). This paper presents a new approach to evaluate this information from RTI acquisitions. A modal projection based on dynamics (Discrete Modal Decomposition) is used to estimate reflectance surfaces on each measurement point. After presenting the acquisition device, an application on an industrial surface is proposed in order to validate the approach, and compare it to the more classical polynomial transformation. Results show that the proposed projection basis not only provides closer assessment of the reflectance surface (modelling) but also yields to a more realistic rendering.

9525-77, Session 15

Using speckle images correlation for real-time inspection of fatigue crack initiation and propagation

Alexander P. Vladimirov, Ivan Kamantsev, Institute of Engineering Science (Russian Federation); Valeriya E. E. Veselova, Institute of Engineering Science, (Russian Federation); Sergey Gladkovskiy, Institute of Engineering Science (Russian Federation)

Fatigue crack in metal constructions in many cases can be detected by conventional methods of nondestructive testing. However, the diagnostics of crack initiation during multicycle fatigue is rather difficult. Brief review of researchers concerning the usage of various physical methods of control including speckle methods aimed at the destruction precursors search is prepared.

The purpose of the report is to represent a new approach to fatigue phenomena analysis using time-average speckle. The peculiarity of this approach is the selection of the averaging time multiple of the cyclic loading. Single-lens system used in the speckle image forming is analyzed. Available information about displacements and changes in the vicinity of the speckle image plane of deformable surfaces are considered. The theory of in-time averaging speckle images adapted to the study of periodic deformations is given briefly. It is assumed that the scattering centers are simultaneously present in several types of motion: translational, periodic and random. Parameters characterizing random and deterministic changes in the reflecting surface shape and the parameters characterizing the dynamics of speckle are considered.

The object of the study was prismatic mild steel specimens with sharp V-type notch as a concentrator loaded by three-point bending scheme. Tests were carried out at room temperature using MIKROTRON (RUMUL) resonance machine at loading frequency of 100 Hz and stress ratio coefficient R=0.1. Surface changes were determined by scanning microscope and optical profilometer. Speckle dynamics was detected by digital camera.

The results of experiments in order to establish the relationship between surface changes of the polished and non-polished samples with changes in the speckle image are considered.

Based on these results the following conclusions are formulated:

- the proposed method allows one to register the change of relief height at 1nm and more;

- it make it possible to detect the fatigue crack initiation for 50000 cycles before the start of its propagation by distribution of the speckle images correlation coefficient;

- crack appears in the zone with diameter of tens micrometers and simultaneously with the formation of crack the plastic zone with diameter of hundreds micrometers is gradually formed;

- major changes in the speckle images are appear on most steep slopes of plastic zone;

- it is possible to determine fatigue crack velocity in real-time by registered changes of speckle-fields.

Promising method for creating optical devices used in conjunction with high frequency testing machine is elaborated.

9525-81, Session 15

In-line polariscopic checking of plastic molded-injected lenses: preliminary results

Josep Arasa, Univ. Politècnica de Catalunya (Spain); Daniel Mayershofer, Hochschule Aalen (Germany); Jordi Romero, Fondació ASCAMM (Spain)

Plastic molded-injected lenses have improved its performance and, nowadays are as usual as glass lenses in image forming devices. However the manufacturing process maintains the surface generation and the material transformation in the same stage, the process also includes an annealing stage to remove the internal stress with temperature cycles but the process not remove stresses upper than a certain value. During the manufacturing process of the plastic lenses a transformation process liquid-solid occurs, in this process not all the lens volume achieves the same density and, this change of density is translate in a local change of index and it can be expressed as a retardation phase plane using the Jones Matrix notation. Detect the value of the retardation of the phase plane is the clue to manufacture good quality plastic lenses.

We test on in-line polariscopic arrangement to obtain a 2D map of the distributed tension in the inner of the lens. This test is performed in the first 30 seconds after the molded-injected process for two main reasons: first the stress values is high because the lens do not have enough time to relax the internal tensions and obtain the final shape, and second we can remove the wrong lens in the first moment and introducing only the good one in the annealing stage.

The proposed instrument is based in a transmission polariscopic arrangement, a collimated light beam is used to illuminate the sample, once the light crosses the sample is collected with an afocal system and the image is recorded in a CMOS sensor. Select an afocal system to capture the image is a useful decision because the lateral magnification can be maintain when small changes in the sample position be introduced. However the lenses produced can vary its focal length from on series to another, to avoid problems with the change of the focal length, the lens is introduced in a matching index and the polariscopic measure is done. The proposed polariscopic arrangement uses two lineal polarizers, one acting as polarizer and the other acting as analyzer, this system instead of the use of one lineal polarizer and a lineal polarizer and an extra lambda/4 plate provide us an extra degree of freedom enabling

the possibility to put a certain degree of polarization in a well determined position of the lens, in our case the center of this lens

The aim of the project is select the minimum number of sets polarizer-analyzer and the right wavelengths to obtain a sure selection of the right lens, the preliminary results show that use two different wavelengths 470 & 627 nm is a good option to obtain robust image. The second free variables that must be adjusted to obtain good values is the minim number of set polarizer-analyzer necessary to obtain confident results, in our first tests seems that only recording at 0, 15, 30 and 45 degrees are enough good results.

We have checked the possibilities to use water instead of matching index because it's easy to use in a production chain, unfortunately water, or other non-matched liquids let too much residual optical power in the measurement cuvette when the lens under test is dipped, and the light that crosses is bended until a value greater that the acceptance angle of vision part of the set-up, so the bended rays are no longer capable to pass through the aperture stop of the imaging part of the polariscop.

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Part of Proceedings of SPIE Vol. 9526 Modeling Aspects in Optical Metrology V

9526-100, Session JS

Motion contrast 3D scanning *(Invited Paper)*

Oliver Cossairt, Northwestern Univ. (United States)

No Abstract Available

9526-101, Session JS

Analysis of bi-periodic composite materials made of stacks of tilted one-dimensional arrays of rods *(Invited Paper)*

Gérard Granet, Univ. Blaise Pascal (France)

No Abstract Available

9526-102, Session JS

Nonlocal light-matter interactions in noble-metal and graphene nanostructures *(Invited Paper)*

N. Asger Mortensen, DTU Fotonik (Denmark)

No Abstract Available

9526-1, Session 1

Enlarging applicability domain of the C method with piecewise linear parameterization: gratings of deep and smooth profiles *(Invited Paper)*

Xihong Xu, Lifeng Li, Tsinghua Univ. (China)

Scatterometry is an industrially viable tool to measure nondestructively shapes and critical dimensions of nanostructures, for which accurately and efficiently modeling diffraction behavior of periodic structures (gratings) of various shapes and dimensions is a prerequisite. The coordinate transformation method (the C method) is an efficient method to model gratings of smooth profiles; however, until recently the C method had two drawbacks. It could not converge (i.e., produce converged numerical results) for gratings of deep grooves (for sinusoidal gratings, depth-to-period ratio approximately greater than 2) and when it converges for gratings of shallow grooves its convergence range with respect to matrix truncation number is small, beyond which it diverges. While the root cause of this numerical behavior is not fully understood, its superficial cause is directly related to the fast-growing condition numbers of some matrices involved in the formalism as groove depth or truncation number increases. Recently, in the framework of the parameterized C method, by using a bilinear coordinate transformation we made the aforementioned convergence range of the C method practically unlimited and enabled the C method to converge for gratings of smooth profiles with groove depth-to-period ratios up to or greater than 10 [Opt. Lett. 39(23), 6644 (2014)].

In this work we generalize and elaborate the previous work. The bilinear transformation is replaced with the more general continuous and piecewise linear transformation. This gives us flexibility to handle more general grating profiles while retaining the simplicity of the linear transformation. We give some general, simple, and empirical rules on choosing the locations and slope change of the bending points of the piecewise linear transformation function. The end result is that both enlarged convergence range and increased groove depth-to-period ratio are achieved for a wider class of smooth grating profiles.

We also present our up-to-date understanding of why the proposed new C method works so well. To achieve the best convergence of the C method we must carefully balance the smoothness and sharpness of the grating profile function in various degrees of its derivatives in the transformed space. A grating profile with sharp edges, such as the triangular profile, suffers from slow convergence but its convergence range is virtually unlimited because the associated condition numbers remain small. A smooth grating profile (of shallow depth), such as the sinusoidal profile, gives rise quickly to initial convergence but soon after to eventual divergence due to divergence of the condition numbers. In the former case to improve convergence adaptive spatial resolution has been used to smooth out the sharpness. For the latter case in this work we go in the opposite direction. From the view point of solving ill-posed problems, our introduction of a discontinuous-derivative transformation function is to regularize the matrices that determine diffraction amplitudes. The goal is to change the grating profile function little in most places but introduce adequate derivative discontinuity at some critical locations so that the condition numbers of the relevant matrices are not too large.

9526-2, Session 1

Specialized scatterometry methods for two types of gratings with distinct groove profiles

Lin Yang, Tsinghua Univ. (China)

Scatterometry is a model-based indirect metrology technique for periodic microstructure. It reconstructs the groove profile by solving an inverse diffraction grating problem. On account of the ill-posedness of the inverse problem, there is no general scatterometry method efficient for all types of gratings; instead, a specialized one is usually preferred for each specific type of grating in practice.

In this paper we study specialized scatterometry methods for two types of featured grating structures: highly asymmetric triangular grating on a transparent substrate (type I), and standing-wave-patterned photoresist mask grating on a reflective substrate (type II). Compared with the conventional microstructures occurring in semiconductor metrology, both type I and type II have a distinct groove profile, which makes their specialized scatterometry methods also different from the conventional ones. Combining with two specific cases, we show the feasibility of specialized scatterometry methods with high profile reconstruction sensitivity.

For type I grating, it possesses a groove profile of high asymmetry, which leads to a highly asymmetric distribution of diffraction field. By utilizing this asymmetric field information, the profile asymmetry (difference of the two base angles in some ways) can be determined sensitively. Besides, the transparent substrate (fused silica in our case) occupies low refractive indices and low dispersion, which weakens the advantage of spectroscopic measurement over angular spectra measurement at a single wavelength. Therefore, with sensitivity analysis we choose the diffraction efficiency angular spectra of reflected ±1st orders (R1, including R+1 and R−1 specifically) in both TE and TM polarizations at 405nm wavelength as the measurands to reconstruct the groove profile of type I grating. Experimentally, measurements of 14 samples give average reconstruction uncertainties of 0.07° for blaze angle (~15°) and 0.76° for antiblaze angle (~70°). Comparison with AFM shows an average deviation of 1.4° for blaze angle.

For type II grating, its groove has wavy sidewalls, which are caused by the standing wave effect in holographic lithography. In view of this physical mechanism behind the profile, we propose a mechanism-based

profile model derived from the holographic exposure field distribution. With six physical parameters which have independent impacts on profile, the model is proven wide applicable and effective by experiments. In our case, a metal-based multilayer dielectric stack (MMDS) is used as the reflective substrate. With the proposed profile model above, we do sensitivity analysis and find the diffraction efficiency NIR spectroscopic spectra of reflected 0th order (R0) in TE polarization as good measurands for grating height and duty cycle, and NIR spectra of R−1 in TM as supplementary measurands to enhance the sensitivity of wavy-sidewall-related parameters (scattering is usually more sensitive to roughness in TM than TE). Experimentally, measurements of 12 samples give average reconstruction uncertainties of 4nm for grating height (~250nm) and 0.003 for duty cycle (~0.2). Comparison with SEM observations also shows good agreements for all samples.

9526-3, Session 1

Spatial mode projection for side-wall angle measurements

Luca Cisotto, Technische Univ. Delft (Netherlands); Yan Zhu, Delft University of Technology (Netherlands); Silvania F. Pereira, H. Paul Urbach, Technische Univ. Delft (Netherlands)

Scatterometry is a powerful technique to retrieve well-defined key parameters from a scatterer. For application in lithography in particular, this technique has extensively been used in the case of diffraction gratings. Such structures are usually modeled by defining four different shape parameters, which fully characterize the geometrical profile of a grating, namely MidCD (Middle Critical Dimension), SWA (side-wall angle), Height and Pitch.

It has been already proved experimentally[1] that it is possible to retrieve, with very high sensitivity, the values of the aforementioned parameters (such as the Height and the Period). Nevertheless, regarding the side-wall angle (SWA) measurements, the uncertainty is still quite large compared to the other parameters. We present here a new way that could potentially increase the precision of the detection for the SWA. The scatterer in our model is a step with a specific height and SWA. By means of a Spatial Light Modulator, we can expand the beam in several modes before its power is measured, and choose to detect the modes that are more sensitive to changes in the SWA.

Method

The main idea lies in the use of appropriate tailored modes (otherwise called spatial mode projection) in which we project the beam resulting from the interaction with a sample. The input beam consists of a collimated Gaussian beam, which interacts with an object designed to give a phase shift of ϖ in transmission. The beam propagates then to a phase-only Spatial Light Modulator (SLM) which, in the present case, can modulate the phase of the impinging beam up to 2ϖ. At this point, we need to project the beam into several modes which we will subsequently detect. We chose to use Laguerre-Gaussian modes as a basis to expand the output beam after the interaction with the sample, since they are a complete and orthogonal set of functions. It is well known from literature that it is possible to obtain these peculiar beams when a Gaussian beam is sent to a SLM which displays a fork grating hologram.

In this case, several diffraction orders will be created and each of them will contain a doughnut-shaped beam with a different azimuthal number (number of intertwined elices). Among all modes, it's important to select and measure the most sensitive ones to the side-wall angle change. To this aim, theoretical simulations based on scalar theory have been performed to find the mode which changes the most when a cliff-like object is used as a probe. Specifically, we calculated the energy content of each mode to find the most responsive one. The energy content (weight) has been defined according to the number Pn introduced in [3].

The detection part is made by coupling the designed modes into single mode fibers which are connected to a photodetector. A similar concept has been applied to the case of very precise height measurements for a cliff-like sample [2].

Results and Conclusions

Through a detailed theoretical analysis, we chose to study modes with azimuthal number between -3 and +3. Furthermore, we decided to focus our attention on a sample with SWA values bounded in the region [85?,90?] with intervals of 0.5?. In this configuration, we notice that most of the power is sent to the first order (+1 and -1) modes and almost nothing is left into the Gaussian channel. Moreover, the strength of these modes increases when the SWA increases (reaches values closer and closer to 90?). Interestingly, the mode decomposition suggests that we can design the detection system in two different ways. If we consider, for instance, a Gaussian beam as input beam, we could decide to detect the power transferred to the higher order modes, i.e. the Laguerre-Gaussian modes with azimuthal number +1 and -1, or, we could also detect the power loss of the zeroth order Gaussian mode. The results obtained by means of the modes decomposition technique seem very promising and could be useful to improve the state of the art for SWA (side-wall angle) measurements.

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9526-4, Session 2

Phase error analysis and compensation in fringe projection profilometry *(Invited Paper)*

Christian Bräuer-Burchardt, Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Gunther Notni, Technische Univ. Ilmenau (Germany)

Fringe projection profilometry became a standard technology for precise surface measurements in the last decades. However, the requirements concerning spatial resolution, measurement speed and accuracy are always increasing. But not only better hardware may improve the handling of the devices and the quality of the measurements. New algorithms and methodologies should help to improve the systems, too.

One of the error sources of insufficient measurement accuracy of optical 3D surface sensors based on fringe projection technique are phase errors. Whereas the influence of these errors to the 3D reconstruction result may be small in the case of the use of stereo cameras, it may be considerable in the case of systems having just one camera and one projector as optical components.

In this paper a new methodology for phase error compensation is presented which corrects any arbitrary phase error independently from its origin. This will be achieved using a generalized error model. The big advantage of the new technique is its applicability to any phase producing system. By using the generalized error model, the described method is more powerful than other techniques especially in the case of locally distinguishing phase error effects.

A general model for the description of phase errors is introduced. The origins of the phase errors such as quantization effects and shift errors are analyzed in dependence on certain parameters such as phase-shift angle, or the number of bits of the grey-value image. Phase errors as a result of inaccuracies at phase generation are considered as well as phase errors originated at observation. Systematic and random errors are distinguished in the model.

Although the treatment of random phase errors may be trivial, its compensation may be the basis of a successful detection and correction of systematic phase errors. Hence both kinds of phase errors are considered in the analysis process. An algorithm for the systematic phase error estimation is presented in the paper. It leads to a compensation function which is either a polynomial of trigonometric functions or a number of sample point correction values. This second kind of

compensation function is necessary because it is not always possible to find an analytical compensation function for the phase error correction.

In some examples several phase errors of real sensor systems are introduced with different error origins. It is shown, how the phase error compensation works at these examples. It can completely compensate so called ripple errors of 3D surface measurements as well as it significantly reduces noise and improves the measurement precision.

As a conclusion it may be recognized that careful error analysis always provides the possibility to subtract the error from the observation in order to achieve a sufficient signal correction. Future work should be addressed to the correction of phase errors of a variety of different sensors.

9526-6, Session 2

An application of compressed sensing for apple-core distortion in tomographic digital holographic microscope

Li-Chien Lin, Feng Chia Univ. (Taiwan)

In tomography Digital Holographic Microscopy, the coherence light source illuminates the rotating transparent micro-object and the transmitting wavefield is interfered with a reference plane wave. Then the interference pattern of these two wavefront is recorded by an electronic charge-cover device (CCD) camera; named as digital hologram. For each rotating angle of the sample object, a single view of the 3-D object is acquired. To integrate the holograms obtaining by the all rotating angles, one can reconstruct truly 3-D tomography information of the object. In this research, we simulate the tomography digital holographic microscopy by using the Fourier diffraction theory, whereas a single view of the micro-object for each rotating angle is sampling in the Fourier domain based on diffraction theory. With the TDHM scanning architecture, the data inside a specific region; shape like an apple core, of the Fourier domain is loss; named as Apple core distortion. In this thesis, the compressive sensing algorithm is used to accounts for the Apple-core distortion to achieve a better reconstruction.

Compressed sensing required only a small amount of data in the acquisition stage and employed the nonlinear inverse algorithm for the reconstruction based on the assumption of the data sparsity in a specific transform domain. In this paper, the digital reconstruction problem of the TDHM system with the apple-core distortion is modeling as a nonlinear inverse problem by including the additional sparsity assumption on the spatial derivative domain, which is formulated as the minimization of the total variation. In this way, we can formulate this problem as the compressive sensing inverse problem, and the nonlinear reconstruction algorithm; named as two-Step Iterative Shrinkage/Thresholding (TWIST), is developed for the reconstruction of the tomography data.

9526-7, Session 2

Metrological characterization of a large aperture Fizeau for x-ray mirrors measurement

Maurizio Vannoni, Idoia Freijo Martín, European XFEL GmbH (Germany)

The European XFEL is a large facility under construction in Hamburg, Germany. It will provide a transversally fully coherent X-ray radiation with outstanding characteristics: high repetition rate (up to 2700 pulses with a 0.6 milliseconds long pulse train at 10Hz), short wavelength (down to 0.05 nm), short pulse (in the femtoseconds scale) and high average brilliance (1.6·1025 photons / s / mm^2 / mrad^2/ 0.1% bandwidth). Due to the very short wavelength and very high pulse energy, mirrors have to present high quality surface, to be very long, and at the same time to implement an effective cooling system. Matching these tight specifications and assessing them with high precision optical measurements is very challenging.

In order to measure the mirrors and to characterise their interaction with the mechanical mounts, we equipped a Metrology Laboratory with a Large Aperture Fizeau. The system is a classical 100 mm diameter commercial Fizeau, with an additional expander of 300 mm diameter. Despite the commercial nature of the system, special care has been putted in the polishing of the references and in the expander quality. In this report, we show the preparation of the instrument, the calibration and the performance characterisation, and some preliminary results. We also describe the approach that we want to follow for the x-rays mirrors measurements. The final goal will be to be able to characterise very long mirrors, in the order of magnitude of 1 meter, with nanometer accuracy.

9526-8, Session 2

Signal simulation method for homodyne multiple target interferometers using short coherence length laser sources

Maik Fox, Thorsten Beuth, Karlsruher Institut für Technologie (Germany); Andreas Streck, ELOVIS GmbH (Germany); Wilhelm Stork, Karlsruher Institut für Technologie (Germany)

Homodyne laser interferometers for velocimetry are well-known optical systems used in many applications. While the detector power output signal of such a system using a long coherence length laser and a single target is easily modelled using the Doppler shift, scenarios with a short coherence length source, e.g. an unstabilized semiconductor laser, and multiple targets and scatterers demand a more elaborated approach for simulation.

The standard approach for looking at an interferometer output signal is in units of power. For velocity measurement, only time-dependent parts of the signal are of interest. An example is given by:

$$P\_I(t) = 2\sqrt{(P\_ref\ P\_target)} \cdot \gamma(z) \cdot \cos(2\varpi \cdot \Delta\omega \cdot t) \qquad \text{Eq. 1}$$

with a reference beam P_ref , a moving target P_target with Doppler shift $\Delta\omega$ and a coherence function $\gamma(z)$ given by the source and depending on the position z of the target. When looking at multiple target measurements, this approach is not much of a help, as in the power regime the superposition principle is not valid for coherent or semicoherent light, leading to convoluted formulas dealing with all occurring intermodulation terms. Furthermore, even as Eq. 1 can easily be transformed to the frequency domain, spectral effects of semicoherent interferometry might be ignored and just a single peak at the Doppler frequency with varying power according to the coherence function is available.

The here presented work uses a different approach by using properties of superimposed electro-magnetic waves to derive a time-invariant phasor term describing the targets, allowing a simple description of an arbitrary amount of scatterers (all different in velocity and intensity). Despite using wave properties, a result in the power regime is delivered. Time and frequency domain signals are computed. The formulas derived allow numeric calculations which are executable with high efficiency on standard computer hardware and are also easily parallelizable for multi-threaded computation. Moreover, the result of the approach for the monochromatic case can be converted mathematically to deliver the same formulas as the standard approach.

First of all, the approach is used for the case of monochromatic sources and multiple targets. The time independent scatterer property identified in interfering light waves is the phasor function ξ:

$$\xi(\mu,z) = \mu \cdot e^{i2zk} \qquad \text{Eq. 2}$$

The amplitude of a scatterer is given as factor μ relative to the reference wave amplitude, its position as z. Further analysis leads to the output power for one configuration of scatterers:

$$P\_I = P\_ref \cdot |1 + \sum\_x \xi(\mu\_x, z\_x)|^2 \qquad \text{Eq. 3}$$

For the simulation of movement, this process is executed repeatedly with changing target positions.

Statistical properties of light sources with Lorentzian spectra are evaluated and modelled using a random walk process, e.g. the Wiener process. The simple monochromatic model is extended for the quasimonochromatic case. This is achieved by calculating an exemplary phase function of the source, deriving an expression ζ for a time and distance dependent phase offset and using it as a factor for the individual scatterer's phasor function. Despite the time dependence now present, with several assumptions a similar expression for the power output can be found:

$$P_{(l,qm)}=P_{ref}\cdot|1+\sum_x \xi(\mu_x,z_x)\zeta(t,z_x)|^2 \quad \text{Eq. 4}$$

In the end, simulation results are compared with theoretical analyses for semicoherent spectra found in literature, yielding a good agreement.

Future work will include modelling effects of a real lab interferometer setup by developing a ray tracer for fiber components, providing means for a complete interferometer signal simulation.

9526-9, Session 2

A way for measuring the relationship between DM surface and wave-front aberrations in a beam rotate-90°laser system

Ping Yang, Institute of Optics and Electronics (China); Mingwu Ao, Univ. of Electronic Science and Technology of China (China); Shuai Wang, Lizhi Dong, Institute of Optics and Electronics (China); Yi Tan, Institute of Optics and Electronics, Chinese Academy of Sciences, (China) and Institute of Optics and Electronics, Chinese Academy of Sciences (China)

Adaptive optics (AO) schemes are often applied to the inertial confinement fusion (ICF) system, such as SG-? Prototype which has been set in china. This laser system mainly includes a pulsed seed laser source, a multi-pass laser amplifier with the configuration of beam rorate-90° and expansion. When AO system is employed in this system, the beam bounces twice on the deformable mirror (DM) which works as the cavity mirror (CM) of the multi-pass laser amplifier, moreover, after the first bounce on the DM, the beam rotate 90° and expansion with a ratio. Therefore, the relationship between the DM's correction stroke and the aberrations within the laser system must be known before applying an adaptive correction.

Conventionally, for a good correction of the aberrations in optical systems, the AO correction is based on the theory of beam linear propagation. However, there is a potential problem that the nonlinear effect could weaken the performance of aberration correction. Since the wave-front residual aberrations produced by a DM after correction joins in the beam propagation in the gain mediums of amplifier which may destroy the DM. Take this for consideration, DM operating as the cavity mirror (CM) of the master amplifier in SG-? Prototype is regarded as a better AO scheme which can decrease the nonlinear effect that gain mediums impress on the residual wave-front aberrations produced by the DM . In the new scheme, a hartmann-shack(H-S) wavefront sensor is employed to measure the aberrations from the output wavefront of the booster amplifier, the DM is put at the far end of the laser cavity where a beam bounces twice, moreover, at the second bounce the beam rotates 90°and expanded with a certain ratio. Although this scheme may be useful for compensating the nonlinear effects, however, it will also meet two problems: firstly whether any wave-front aberrations measured by H-S sensor can be corrected well by the DM, and then whether the correction capability of DM is limited or boosted when dealing with different aberrations. This paper demonstrates that any output wave-front aberrations within the DM's correction stroke range can be well corrected, as well as illuminates that the expansion ratio of beam and the types of output wave-front aberrations both affect the correction stroke range of DM. Furthermore, through building a theoretical calculating model and some simulation. The relationship between the DM's surface stroke needed and different aberrations within the laser system is ascertained clearly. Results show that this configuration is proper for compensating most low order aberrations besides some special ones. As a result, it will provides a useful guidance for those rotate-90°laser systems adopting adaptive optics technique.

9526-10, Session 3

Optical detectors based on thermoelastic effect in crystalline quartz *(Invited Paper)*

Vladimir P. Chelibanov, JSC OPTEC (Russian Federation); G. G. Ishanin, ITMO Univ. (Russian Federation)

Ishanin G.G., Chelibanov V.P.

In quartz crystalline (PTEK) attributed to the thermal detectors group. Such detectors occurred very effective for the registration of pulsed light energy or power of harmonically modulated laser radiation flux in a wide spectral (from UV to far IR) and dynamic ranges (from 10-6 to 300 W / cm2 with cooling) with a time constant up to10-6 seconds. When exposed to electromagnetic radiation occurs at the receiver thermal field which causes mechanical stress in the transient crystalline quartz, which in turn leads to a change in the polarization of crystalline quartz and, as a consequence, to an electric potential difference at the electrodes (the front surface with a conductive coating and damper). The presence of several successive elements of the radiation detector system, in which electromagnetic wave energy is converted into an electrical signal, insignificantly reduces the detector sensitivity. However, it should be noted that the transformation processes takes place in crystalline quartz - a material characterized by good stability of the physical properties over a wide dynamic range effects. This determines the stability and linearity of PTEC characteristics.. The relaxation time of electrons in the materials, used for the absorption of incident radiation flux, is from 10-11seconds, and hence does not deteriorate frequency characteristics of PTEC. The time constant of crystalline quartz as an electromechanical transducer is 10-13 ... 10-14 seconds. As the most inertial, apparently, can be considered a process of heat energy expansion through the electrode from the absorption cover to the quartz plate, followed by its sink into heat tap dumper. These process limit and determine the time constants of the detector ?up and ?down. As shown in [1], a potential difference arises at the detector basically because of the thermo elastic stresses, directed along the axis Y. Mechanical stresses along the optical axis Z of does not caused the potential difference due to the structural features of the crystal lattice of quartz. However, a signal appearing at the receiving element is affected by other phenomena which may become substantial under certain conditions, for example, a secondary thermo elastic effect of the complex structure also arises along the Y axis due to the difference of coefficients of linear expansion of the conductive coating and the quartz and because of difference in the linear expansion coefficients of quartz and the damper material. In real terms, this effect usually is the value of the second order, and can occur only at high frequencies, when the variable component of the no equilibrium temperature field focus into the thickness of the receiving electrode, and the main signal drops by several orders When working with short and the powerful pulses the dynamic longitudinal thermo elastic effect can appear along the X axis;: radiometric effect, electrostriction and the nonlinear polarization, as well as the electromagnetic radiation pressure. These effects are also significantly less than that of observed thermo elastic effect and the can be disregarded

The capacitive characteristic of the detector, based on a thermo elastic effect in crystalline quartz, eliminates the possibility of working with constant flow of radiation, which also affects at the frequency response of the detector, since the potential difference appearance in the piezoelectric plate depends on the direction of the forces relative to the axes X, Y, Z of the crystal. Therefore, a certain choice of orientation of the receiving element is necessary in accordance with the physical properties of crystalline quartz. In this paper, a calculation of the sensitivity and frequency characteristics of optical detectors based on the thermo elastic effect in crystalline quartz at the harmonic effects of electromagnetic radiation flux.are reported.

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9526-11, Session 3

Numerical modeling and uncertainty analysis of light emitting diodes for photometric measurements

Mohammed Zia Ullah Khan, Mohammed T. Abbas, Luai Mohammed Al-Hadhrami, King Fahd Univ. of Petroleum and Minerals (Saudi Arabia)

Light Emitting Diodes (LEDs) are increasingly being introduced into the lighting market, and solid state lighting (SSL) is now becoming a reality.

But, this new technology still faces many challenges. Lighting consumes a huge amount of energy, currently 22% of all electricity consumed in the U.S. is for lighting purposes. White LED sources are expected to be twice, or more, energy-efficient than fluorescent lamps. SSL is expected to have a big impact on a nation's energy savings. Research on all photometric aspects of solid-state lighting sources is currently underway with emphasis on color quality and measurement methods for high-power light emitting diodes (LEDs) and other SSL products. New SSL calibration standards and measurement methods are also being developed to improve the existing measurement methods. The development of new measurement methods has become essential to commercialize solid-state lighting products. The development of SSL measurement methods through experimental approaches may however become expensive and time consuming. On the other hand, measurement method development through numerical modeling and simulation is comparatively efficient. Numerical models facilitate the rigorous study of the LED performance metrics before fabrication. They also help to develop the link between the material properties and the performance of the LED device.

This work presents the formulation of an efficient numerical simulation model for LED measurements. The uncertainty analysis model is then developed using GUM law of propagation of uncertainty (ISO, 2009 a) for validation of the LED measurements.

The measurement of optical parameters and their uncertainties is performed for a blue Gallium Nitride (GaN) LED emitting at 460 nm wavelength. This task requires modeling the light propagation inside LED and formulation of a numerical model to perform uncertainty analysis. The optical phenomena in any electromagnetic device are described by the solution of Maxwell's equations. Therefore, the solution of these equations that represent EM field propagation inside LED is obtained by developing a 2D finite-difference-time-domain (FDTD) TM EM wave simulator with material independent perfectly matched layer (MIPML) absorbing boundary conditions. The EM wave simulator is validated by conducting two tests. First, it is tested for open homogeneous space, to find the resonance of a metallic cavity and compare it with the analytical value. A rectangular cavity filled with air and dimensions x= 2.193 cm and y=1.016 cm is simulated using TM FDTD simulator. The fundamental mode TM10 is obtained at a frequency of 6.893 GHz from simulation, whereas the analytical value computed is 6.84 GHz. Second, the MIPML absorbing boundary conditions are tested by measuring EM field with PML and comparing with EM field measured at same point without PML with boundaries increased form the source on all sides. The error between two fields is found to be less than 0.01%.

The LED structure studied for light propagation and uncertainty analysis is a practical GaN LED used in SSL systems. The optical properties of dispersive materials are modeled using multi-pole Lorentz-Drude model. Therefore, the time domain polarization is obtained by modeling the complex permittivity data of the materials using multi-pole Lorentzian function and then taking IFFT of frequency domain polarization. The optical properties of gold contacts are modeled using a six-pole Lorentz-Drude model, whereas for GaN, these are modeled using a five-pole Lorentzian model. The input dipole sources emitting light in the active layer are modeled using a Gaussian pulse line source at a central wavelength of 460 nm corresponding to blue light. The light propagation through different layers that causes reflection, dispersion and power loss at different interfaces is observed through simulation.

The computation model for uncertainties in LED measurement is then developed for the time domain EM simulator. The uncertainty analysis model is formulated using the GUM law of propagation of uncertainties. The expression for combined standard uncertainty in the light extraction efficiency due to uncertainties in inputs such as emission in the active layer and EM fields is developed using the GUM law. The uncertainty in GaN LED emission wavelength obtained from Full Width Half Maximum (FWHM) of the emission spectrum is computed to be 16.98 nm. Therefore, the uncertainty analysis model is then used to compute the corresponding uncertainties in the LED output measurements i.e. light extraction efficiency, LED output power and EM fields.

Therefore, the uncertainty analysis model formulated for lighting sources is expected to find applications in the solid-state lighting industry for development of efficient photometric measurement methods through numerical simulations. Such simulations require appropriate models that can facilitate the characterization of light propagation, material properties and measurement uncertainties. The LED model formulation presented in this research can be extended for characterizing advanced LED structures, lasers, photodiodes, solar cells etc., and facilitating all kinds of photometric measurements.

9526-13, Session 3

Radiometric uncertainty for spectrally broadband measurements of absolute mid-wave infrared radiance under variable ambient conditions

Thomas Svensson, Swedish Defence Research Agency (Sweden); Henrik Larsson, Linköping Univ. (Sweden); Johan Eriksson, Swedish Defence Research Agency (Sweden)

An infrared camera converts detected radiation from a target into digital data. The radiation hitting the camera's pixels will however not only depend on the object's radiation but also on the atmosphere and the radiation from optical components like lens and spectral filters. The influence of the atmosphere and optical components on the final result (radiance or temperature) have both a spectral and a temperature dependence, which must be characterized in order to make a correct analysis of the collected infrared data and to evaluate and compare infrared camera´s performances. For full traceability a number of additional camera parameters must be characterized. Examined parameters for the camera under test (InSb, 3-5 μm, 640x512, digital output 13 bit) in this paper are dynamic response, dynamic range and stabilization period. The dynamic response and dynamic range have been measured at various integration times for the camera and at various ambient temperatures. The stabilization period is the time it takes for a camera to stabilize after a change of the ambient temperature. The measurement uncertainty is analyzed according to GUM, Guide to the expression of Uncertainty in Measurements. The GUM analysis is performed both with and without including of the atmospheric influence. Comparisons are made between internal and external measurements of the camera's housing temperature regarding the measurement uncertainty. An estimate of the systematic error of the camera model is made, based on calibration protocols for the calibrated blackbody sources used.

The ambient temperature dependence has been evaluated in both a controlled way with the camera in a climate chamber and in the field, where the temperature is not as well defined. One conclusion that can be drawn is that a climate chamber is required for an accurate characterization of a camera´s ambient temperature dependence. It is then also possible to determine the temperature dependence of the camera´s overall system gain, which is typically very weak compared with the temperature dependence of the dark signal (the internal radiation). The saturation levels (and hence the real dynamic range) for the camera under test was found to be dependent both on the ambient temperature and the integration time, with a negative correlation for the saturation irradiation which becomes more significant at higher ambient temperatures. This is probably due to background noise filling up the detector elements at longer integration times, leading to less capacity for absorption of external generated photons.

A measurement result is difficult to assess without access to an estimate of the measurement uncertainty. In particular a measurement result is difficult to assess if a repeated measurement takes place under other conditions, which also makes the interpretation of the concept confidence interval difficult. In a radiometric calibration 1) the spectral distributions of the blackbody sources are known, 2) the sources are considered to be stable over time (allowing temporal averaging of data), and 3) the pixels responses are treated as spatially uniform (through pixel averaging). None of these three conditions apply during a field measurement of e.g. a point target. A discussion of the implications of these three differences for the measurement uncertainty is also given in the paper.

9526-14, Session 4

Horizontal geometrical reaction time model for two-beam nacelle LiDARs

Thorsten Beuth, Maik Fox, Wilhelm Stork, Karlsruher Institut für Technologie (Germany)

Wind energy is one of the leading sustainable energies. To attract further private and state investment in this technology, a broad scaled drop of

the cost of energy has to be enforced. There is a trend towards using Laser Doppler Velocity LiDAR systems for enhancing power output and minimizing downtimes, fatigue and extreme forces. Since most used LiDARs are horizontally setup on a nacelle and work with two beams, it is important to understand the geometrical configuration which is crucial to estimate reaction times for the actuators to compensate wind gusts. In the beginning of this article, the basic operating modes of wind turbines are explained and the literature on wind behavior is analyzed to derive specific wind speed and wind angle conditions in relation to the yaw angle of the hub. A Horizontal Axis Wind Turbine (HAWT) has a characteristic cut-in wind speed v_ci marking the start of the rotor blades rotation and a respective cut-out wind speed v_co. Overall there are three different states of operation: No rotation until the cut-in wind speed, rotation with maximized power output until a wind speed which is depending on the individual wind turbine and rotation with regulated power output until the cut-out wind speed. The wind energy is transformed into rotational energy by the rotor of the wind turbine. In general, the rotor speed can be either regulated by the pitch angle or the electrical load drain to deal with the torque minimization for gust impacts..

In the model, a two beam nacelle LiDAR placed at a distance l_rd behind the rotor disc measures the two wind speeds v_l and v_r at a line-of-sight distance l_m under a setup angle of α by Laser Doppler Velocimetry along two spatial separated probed volumes. The reconstruction of the wind vector length V and wind angle γ is known from literature by $\gamma=\arctan((f-1)/((f+1)\tan\alpha))$ and $V=\sqrt{(u^2+v^2)}$ with the relationship between the measured wind speeds f=v_l/v_(r) and the orthogonal components u=(v_l+v_r)/(2·cosα) and v=(v_l-v_r)/(2·sinα). The wind front has to travel a distance of l_lr=2·l_m·sinα sinγ to surpass both measuring points which leads to the problem of possible wind shear detection even for horizontal homogenous wind fronts varying in time, e.g. large scale gusts. A distance is defined in which the wind shear of such homogeneous wind fronts has passed the two measuring points which is used as a base to estimate further distance calculations. The reaction times of the controller t_cont and the actuators t_act have a negative effect on the effective overall reaction time for wind regulation as well, which is tried to be considered. To estimate reaction times, a worst case scenario based on the cut-out speed v_co is elaborated to be t_resp=l_r/v_co -(t_lidar+t_cont+t_act) with the distance l_r=l_l-l_lr orthogonal to the wind front at the moment of passing the second measuring point and the distance l_l=$\sqrt{((R-l_m \sin\alpha)^2+(l_m \cos\alpha-l_rd)^2)}$ sin(ϖ/2-β-α) orthogonal to the wind front at the moment of passing the first measuring point. The angle $\beta$is defined as β= arctan((R-l_m sinα)/(l_m cosα-l_rd)). In the end, exemplary calculations estimate benefits and disadvantages of system parameters for wind gust regulating LiDARs for a wind turbine of typical size. An outlook shows possible future improvements concerning the vertical wind behavior.

9526-15, Session 4

Investigation vignetting beams in optoelectronic autocollimation angle measurement system

Igor A. Konyakhin, Aiganym Sakhariyanova, Andrey A. Smekhov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Nowadays one of metrology problems is the measurement of angular values, in particular, angular deformations in the critical points of oversized objects. For the solution of this problem effectively use autocollimation systems. The autocollimator allows measuring a mirror turning angle as sensitive element in a point of angular deformation with a potential accuracy up to 0.005". Actually the error can exceed considerably the specified value because of existence of systematic error, one of which main components is the error owing to vignetting of a working beam. The reason of vignetting error is changing of irradiance distribution of the image on the autocollimator analyzer owing to cutting of a bundle of optical beams at a mirror deviation in case of angular deformation.

The component of systematic error due to vignetting of the beam can be eliminated in case of existence of the analytical description of changes in irradiance distribution of the analyzed image. Because of the complexity of the analytical description of the vignetting processes proposes the use of computer models. The simulation is based on approximation according to which each point of the finite image of a source of radiation essentially is the focused area of intersection of the entrance pupil and the elementary beam reflected by a mirror, and its energy is proportional to integral (the general energy) on this area.

The analyzer of an autocollimation system is executed as CCD matrix. One of its main characteristics is a noise level which consists of several components, such as a thermal noise, geometrical noise, a shot noise and others. During the computer experiment the simulation model of formation of a irradiance field in the vignetted image on the matrix analyzer considering the main noise components allowing to carry out researches image processing algorithms in an autocollimation system and to determine the dependence of an error due to vignetting of the image relocation was synthesized.

Based on this computer model of formation of the irradiance field in the image on the matrix analyzer we considered the influence of the main noise component in autocollimation systems. RMS value of the positioning error of the image defining the potential accuracy of the measurement was d≈10-3 pixels of a CCD.

For the analysis of vignetting we defined static characteristics of the analyzer for different coefficients of vignetting image. Based on the received dependence for compensation of systematic error of d=0.148 due to vignetting, it is practically possible to realize measuring accuracy close to the potential.

Using a computer analytical model to image processing on a matrix CCD were carried out the error estimate introduced by noises of the matrix analyzer and the imitative analysis of vignetting image for the correction the systematic error were made. In such way, changing the data processing algorithm can increase the working distance autocollimator in 1,7÷2 times.

9526-16, Session 4

Application of the ARMA model in distributed fiber vibration sensing system

Hongyan Wu, Haiyan Xu, HeKuo Peng, Fudan Univ. (China)

Distributed fiber vibration sensing system is widely used in the field of wide area security, communication cable of long distances and pipeline security. The principle of the system is that for a vibration signal applied at a particular position along the fiber, the response, in the frequency domain, presents a series of periodic maxima and minima (or nulls). These minima depend on the position of the vibration along a fiber. Power spectral estimation method is considered to denoise the power spectrum of the system and determine these minima precisely in the paper. The parametric modelling methods such as autoregressive-moving average (ARMA) model is used to improve the positional accuracy of the system. The experimental results show the high accuracy of the position using ARMA model.

A fast Fourier transform shows a series of odd-multiple nulls in the averaged power spectrum from which the position of the disturbance can be determined. Figure 1 shows the power spectrum of the output signal using FFT (fast Fourier transform).

The configuration of the power spectrum is so coarse that it is not enough to process the signal of the system just using FFT algorithm. So the parametric modelling method such as ARMA is proposed in the paper to improve power spectrum of the signal. Figure 2 shows Model-Based Spectrum Estimation using ARMA.

It can be concluded that the noise of the spectrum is much smaller using ARMA algorithm than FFT algorithm. The expected nulls in the frequency response can be clearly seen on the plot. The curve is so smooth after processing that the position of the disturbance can be precisely determined.

9526-17, Session 4

Fully-vectorial simulation and tolerancing of optical systems for wafer inspection by field tracing

Daniel Asoubar, Hagen Schweitzer, Christian Hellmann, Michael Kuhn, LightTrans Virtual Lab UG (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

The simulation, design and tolerancing of optical systems for wafer inspection is a challenging task due to the different feature sizes, which are involved in the setup. On the one hand light is propagated through macroscopic lens systems and on the other hand light is diffracted at microscopic structures with features in the range of the wavelength of light. Due to this variety of scale a plenty of different physical effects like refraction, diffraction, interference and polarization have to be taken into account for a realistic analysis of such inspection systems. We show that all of these effects can be included in a system simulation by field tracing, which combines physical and geometrical optics. Main idea is the decomposition of the complex optical setup in a sequence of subdomains. Per subdomain a different approximative or rigorous solution of Maxwell's equations is applied to propagate the light. In this work the different modelling techniques for the analysis of an exemplary wafer inspector system are discussed in detail. These techniques are mainly geometrical optics for the light propagation through macroscopic lenses, a rigorous Fourier Modal Method (FMM) for the modelling of light diffraction at the wafer microstructure and different free-space diffraction integrals. In combination with a numerical efficient algorithm for the coordinate transformation of electromagnetic fields, field tracing enables position and fabrication tolerancing. Exemplary different tilt tolerance effects on the polarization state and image contrast of a simple wafer inspection system are shown.

9526-18, Session 4

Wide-aperture laser beam measurement using transmission diffuser: errors modeling

Ivan Matsak, S.P. Korolev Rocket and Space Corp. Energia (Russian Federation)

Standardized and widely used methods and devices is appropriate for laser beams with width up to 1 cm. It is enough for most practical applications. But commercial devices are not applicable to measurements of laser beams with width from 5 cm.

To solve this problem there was built experimental setup for measurement of laser beam diameter up to 300 mm. The setup includes CCD camera, zoom lens, transmission Lambertian diffuser and PC. But transmission diffuser method has poor metrological justification required in field of wide aperture beam forming system verification. Considering the fact of non-availability of a standard of wide-aperture flat top beam modelling is preferred way to provide basic reference points for development measurement system. The method is appropriate for precision measurement of laser beam width from 10 mm up to 1000 mm what is impossible with other methods which based on slit, pinhole, knife edge or direct CCD camera measurement. The method is suitable for continuous and pulsed laser irradiation.

Instrumental errors of measurement wide-aperture laser beam diameter were modeled to build measurement setup and justify its metrological characteristics.

Modelling was conducted in MathCAD. Super-Lorentz distribution with an order 6-12 was used as a model of the beam. Using theoretical evaluations there was found that the key parameters influencing on error are: relative beam size, spatial non-uniformity of the diffuser, lens distortion, physical vignetting, beam tilt, CCD spatial resolution and, effective camera ADC resolution. Errors were modeled for two beam diameter criteria: 90% of power and second moment of distribution. 12-order Super-Lorentz distribution was primary model, because it precisely meets experimental distribution at the output of test beam forming system, although other orders were also used.

The analytic expressions were obtained as a result of approximation of modelling data for each influencing data. Attainability of 0.1% error based on choice of parameters of expression was shown. The choice was based on parameters of commercially available components of the setup. The results of modelling for 12-order Super-Lorentz distribution and 90% criteria are presented below.

Relative beam size should be less than 0.5, what is allows minimize the dimensions of the setup. Enough CCD spatial resolution is 512x512, so commercial available cameras could be used in measurement process. Effective number of bits is 8, what meets in the order of 10 bit ADC. Physical vignetting could be eliminated by using lens with field of view less than 12°. Lens distortion should be less than 0.5% (in tv-distortion units). It is required to provide beam tilt relatively diffuse screen plane less than 5°. The relative size of the inhomogeneities of the diffuser should be less then 5% at a level of 5% relative value of non-uniformity.

Parameters presented above is a not guarantee of 0.1% error, but it could be reference point for feasibility of precision measurement. Today the unsolved problem is a standard for calibration procedure. During the experimental works were used diffraction and image patterns, but they can't be equal to Super-Lorentz beams especially when used 90% criteria at the specified level of error.

9526-19, Session 4

Transferring the Rb+ hyperfine-structure stability to a Fabry-Perot resonator used as a frequency standard for astronomical spectrographs

Philipp Huke, Hanno Holzhüter, Ansgar Reiners, Univ. Göttingen (Germany)

We report on the experimental realization of locking a Fabry-Perot resonator onto a stabilized diode laser for the calibration of astronomical spectrographs. The diode laser is stabilized to the Rb+ hyperfine structure at 780nm with a pump-probe setup. The stability of the Rb+ hyperfine-structure is on the order of 10?13. The aim is to transfer this stability to a Fabry-Perot Resonator which can be used as an optical frequency standard. Therefore the resonator is locked to the stabilized diode laser using the Pound-Drever-Hall method. The theoretically reachable stability of a few mHz/Hz3 is limited by different noise factors.In order to identify these noise factors we a) follow the calculation of noise factors given by b) calculate the contribution of misalignment and insufficient mode matching by applying the generalized matrix-formalism and c) estimate the contribution of the initial laser linewidth and the present electronic noise sources.

9526-26, Session PS

Determination of refractive index by Moiré deflectometry

Mohammad Ahmadi, Khosro Madanipour, Soheila Javadianvarjovi, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Refractive index is one of the most important character of transparent material like glasses, liquids, polymers and ... that its Measurement is crucial in designing optical elements, material detection or other propose. Convenience and accuracy of Measurement are two important parameters of choosing a method. Moiré deflectometry is very simple and non-sensitive method. In this work we illuminated a piece of glass and measured its refractive index by analyzing Moiré fringes.Determination of ? as angle of ray accident to the glass surface, t as thickness of glass and l as deviation of beam from the reference, refractive index can be easily calculated .l is a small quantity and it must be determined by an instrument which measures the sub-Micron movements.when two grating place at the Talbot interval, the moiré fringes appear. Any small movement of gratings magnified at moiré fringes displacement so by use of this feature, the variation of l can be detected .The glass is placed between two gratings on the rotation state, where it covers half of plane waves that is traveling from one grating to another. other half will

experience air only as a reference beam.The accuracy for determination of refractive index for thickness (t) in order of 1milimeter is
2*?10?^(-3),and for t≈5mm is about 2.7*?10?^(-4) .

9526-48, Session PS

A novel autocollimating method for measuring the focal distances

Alexandr G. Ershov, S.I. Vavilov State Optical Institute (Russian Federation)

A novel autocollimating method for measuring the focal distances is presented. It may be used for measuring the focal distances of lenses and single optical elements in the visible, infrared and ultraviolet range. The relative uncertainty of this method is about 0,1%. The limited uncertainty is over 0,03%.

9526-49, Session PS

Modelling of microcracks image treated with fluorescent dye

Victor Glebov, Oleg U. Lashmanov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Generally, it is necessary to detect such small defects that can't be noticed during visual inspection and usage of optical devices is impossible because of insufficient contrast of defect on a metal background. The contrast ratio between image of defect and background can be changed in two ways. The first way is to polish the surface of controlled object with following its' acid etching. In this case the defect gets clogged with corrosion products, turns black and becomes observable on the light background of the polished material. This method has rather many restrictions particularly it's unprofitable to polish the surface of product and especially welds in the working environment. The way of etching is usually used for inspection of suspicious local areas of metal products.

The second way consists in changing light output of defects by filling them with special liquids called dye penetrants.

During the work the mathematical model of image of randomly located microcracks treated with fluorescent dye was created in MATLAB environment. Background noises and distortions introduced by the optical systems are considered in the model.

The factors that have influence on the image are listed below:

1. Background noise. Background noise is caused by the bright light from external sources and it reduces contrast on the edges of the field of view.

2. Noises on the image sensor. Digital noise manifests itself in the form of randomly located points that are differing in their brightness and color. It is necessary to use matrix with larger pixels and tight to each other lenses for noise reduction. Also it's possible to use color filters with high light transmission.

3. Distortions caused by abberations of optical system. After passing through the real optical system the homocentricity of the bundle of rays is violated or homocentricity remains but rays intersect at the point that doesn't coincide with the point of the ideal image.

The stronger the influence of the above-listed factors, the worse the image quality and therefore the analysis of the image for control of the item finds difficulty.

The mathematical model is created using the following algorithm: at the beginning the number of cracks that will be modeled is entered from keyboard. Then the point with random position is choosing on the matrix whose size is 1024x1024 pixels. This random pixel and two adjacent points are painted with random brightness, the points, located at the edges have lower brightness than the central pixel. The width of the paintbrush is 3 pixels. Further one of the eight possible directions is chosen and the painting continues in this direction. The number of 'steps' is also entered at the beginning of the program. These operations are repeated as many times as many cracks it's necessary to simulate. After that background noises and Gaussian blur are applied.

The method of dye penetrant inspection, its' advantages and disadvantages, the algorithm of this method and physical foundations are described. The mathematical model of the image of the cracks randomly located on the surface is designed considering noises on the photodetector, influence of an optical distortions and background light. This model will be used in the process of designing of the device for automatic microcracks recognition. Attention is given to the factors that gave influence on the quality of image.

9526-51, Session PS

High-angle light scattering to determine the optical fiber core

Grzegorz Swirniak, Wroclaw Univ. of Technology (Poland)

A constant evolution of measurement methods and their tools (i.e., measurement devices) is, undoubtedly, one of the most important factor affecting the boundaries of mathematical and empirical understanding and, in consequence, the scientific and technological progress. Among various tools for empirical cognition, the special role play those which allow for non-invasive measurement and testing with the use of beam of light.

The interaction of electromagnetic waves with matter may be considered as energy conversion. The form of this conversion depends on two phenomena – the scattering and absorption. This is the basis for all optical effects observable in nature and associated with light, such as rainbows, halos, glories, etc. From the observation of nature, physical laws and their mathematical interpretations are inferred. This in turn gives the foundations of the modern measurement methods such as interferometry, diffractometry, turbidimetry just to name a few, used for probing both single particles as well as multiphase samples.

This paper focuses on the problem of elastic scattering of a collimated beam of light of low temporal coherence. The beam interacts with an infinitely-long step-index optical fiber in such a way that a series of dark and bright fringes is formed in the far field. Much of this pattern is determined by two coupled, twin rainbows and depends on the fiber physical characteristics i.e., its dimensions, shape, and refractive index profile. In order to find a causal link between the scattering pattern and the fiber morphology, a spectral analysis (Fast Fourier Transform, FFT) is performed over the scattering intensity. From the spectral data, the core diameter of a step-index optical fiber is extracted inversely. The analysis aims to provide more qualitative conclusions rather than precise inverse relations.

The measurement method discussed in this paper fits the domain of non-invasive optical gauging of an optical fiber. So far, much effort in this field has been devoted to an inverse analysis of the scattering pattern for the case of incident coherent laser radiation. Due to significant complexity of both scattering pattern as well as its spectral representation, a qualitative understanding is still limited to outer features of scattering particles.

Potential applications of the analysis described here include non-invasive characterization of layered transparent particles, such as step-index optical fibers with outer diameter of tens to hundreds of micrometers. Key topics of the paper are: (i) spatial (angular) and spectral analysis of the light scattered at a high angle for the case of step-index optical fiber illuminated with a beam of light of different degree of temporal coherence, (ii) qualitative assessment of the scattering pattern spectrum in order to identify spectral components whose parameters depend on the inner diameter of the fiber under test.

9526-52, Session PS

Research of the use of autoreflection scheme to measure the error of the optical elements in space telescope's relative position

Kseniia Ezhova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Fedor V. Molev, OAO Avangard (Russian

Federation); Igor A. Konyakhin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Measurement of angular and linear movement is part of the task of determining the position of the metrology of optical elements of large optical systems for various applications. For this reason, a measurement system is complex and includes separate autocollimation channels for measuring linear displacement measurement channels and angles of rotation.

Analysis of the structure of the classic autocollimator working beam showed that autocollimation system has two operating stops - the aperture of the lens and the aperture of the reflector. Their images are formed in different planes, at some distance from each other along the optical axis.

Version of optical scheme is possible, in which first channel measurement analyzer is combined with the image plane of the aperture of the reflector, and the second - with the image plane of the lens aperture. Therefore, it is possible to build simple in structure of the measuring system with a single optical elements, combines the functions of the measurement of angular and linear displacements.

We consider two models of the autoreflection schemes that differ in the position and the size of the light source and the path of the rays in these scheme for a more visual presentation of the results is built.

In the first scheme, the finite size light source is located in the front focal plane of the lens and is used for forming a luminous mark, whose role is played by the lens frame, the second measuring mark is applied to the surface of the controlled plane mirror. In the second version of the point source is located at the top of the last surface of the lens and serves as a measuring luminous mark, the second measuring mark is applied to the surface of the controlled plane mirror.

Considered schemes were simulated in computer-aided design of optical systems Zemax.

Because the plane mirror is invariant to the transverse displacements, it was decided to offset the controlled plane mirror be fixed with rigidly attached on it a measuring.

Placing the receiver in a plane conjugate with the plane controlled mirror, we can register transverse displacement of the mirror by displacement registration marks placed on the mirror.

If the receiver is located in a plane conjugate to the lens frame (in Scheme 1) or with the plane of the source (in Scheme 2), it is possible to register a controlled plane mirror tilt by registering the image shift lens frame.

Models of these schemes were implemented for the experimental verification of the proposed models. Specially designed experimental autocollimator with internal refocusing, which allows you to move along the optical axis of the plane conjugation of the object and its image was used.

9526-53, Session PS

Modeling and analysis of the solar concentrator in photovoltaic systems

Janusz Mroczka, Kamil Plachta, Wroclaw Univ. of Technology (Poland)

This paper presents a mathematical model of the solar concentrator in the photovoltaic system. The concentrator system consists of mirrors arranged in ?-ridge, or V-trough shape. Solar radiation reflected from the concentrator is directed onto photovoltaic surface, thus increasing efficiency. Analysis of the mathematical model is performed in simulation software, designed for this purpose. The program allows to describe spatial distribution of solar radiation by application of an algorithm that uses the modified function BRDF (Bidirectional Reflectance Distribution Function). The algorithm works in two stages. The first embraces calculation of the global lighting, setting out the parameters of the incident radiation, which illuminates the point, and determines the amount of light reaching that point. The second, simulates local lighting and calculates transformation of the incident light to the light reflected from the surface at a given point. This solution distinctively imitates reflective properties of the anisotropic surface. The algorithm allows generation and analysis of the surface microstructure of the material used for the construction of concentrator.

The simulation for wavelength range ?=630-690nm shows the dependence of scattering angle ?s [degrees] from the value of BRDF function [1/sr], for silicon surface polished electrochemically and steel surface polished mechanically. The results showed that the component of directional radiation of the first surface is 97.4. Roughness described by spatial waves from all the measured spatial wavelength range do not affect the dispersion of diffusion. The results for the second surface confirm appearance of directional scattering near` the specular reflection and reduction in intensity of reflections. This demonstrates the greater roughness of surface of the steel polished mechanically by 9.6%.

Efficiency depends on parameters of the concentrator material. Analysis parameters: aluminum, copper, chromium, silver, steel and steel polished mechanically dependence of incidence angle (?) of the wavelength (?) in the range 350-750nm showed that a suitable material for construction of the concentrator system is aluminum. The value of the spectral reflectance (??) is 0.89 in entire measuring range. Similar value of the spectral reflectance reaches silver mirror for wavelength of 400-750nm. The remainder of its value decreases by 74%. The worst material is steel, the average value of the spectral reflectance is 0.54. but the average value of the spectral reflectance for steel polished mechanical is 0.8. Considering the weather resistance of the simulated materials, the best solution is the construction of the concentrator system made of mechanically polished steel.

The efficiency of a photovoltaic system depends on the opening angle (?) concentrator mirrors and resolution step (k) tracking system. Simulation presents the dependence of efficiency of the photovoltaic surface from opening angle (?) and the resolution step (k) tracking system for parameters temperate zone: day of year N=168; height of sun ?=+24°; transparency factor TF=3. Simulation results show that the system produces the most energy for the opening angle equal 57°. Change of the value of this parameter ±2° results in decrease of energy produced by 5÷8%. The opening angle exceeding 60° leads to a 40% reduction in energy produced comparing to opening angle equal to 57°.

The mathematical model of the concentrator system and its analysis by algorithm using a modified BRDF function allows calculation the following properties of surface: roughness, density of the material, factor of scattering, reflection, or absorption of the material from which it is made. The appropriate choice of this parameters allows for 6.3-8.7% increase the efficiency of photovoltaic surface, assuming that the efficiency monocrystalline photovoltaic panel is 14%.

9526-54, Session PS

In situ estimate of duty cycle of surface-relief holographic gratings during development by measuring TM/TE diffraction efficiency ratio

Biyao Shen, Tsinghua Univ. (China); Lijiang Zeng, Tsinghua Univ (China); Lifeng Li, Tsinghua Univ. (China)

Holographic exposure (i.e., exposure of a photoresist coated substrate in an interference field of two light beams), followed by development in alkaline solution and subsequent ion-beam etching, remains to be the most important technique for fabricating diffraction gratings, especially large area gratings, despite the advance of other techniques, such as direct laser writing and e-beam lithography. In this process as an intermediate product the photoresist grating serves as a mask for ion-beam etching. The shape and critical dimensions of the photoresist mask directly determine the shape and critical dimensions of the etched end product, which in turn determine the performance parameters of the grating, for example, diffraction efficiency. In a crude and yet often effective approximation the shape of the mask can be taken as rectangular and the critical dimension is duty cycle (ratio of ridge width to period). The groove depth is not critical, as long as it is large enough, and it can be controlled easily by adjusting the photoresist layer thickness during spin coating and by detecting the critical turning point of the diffraction efficiency curve of one of the grating's dispersive orders during development when the photoresist in the trough is completely removed. Once the maximum groove depth has been reached the following development process predominantly manifests as reduction of duty cycle. While the efficiency monitoring method is effective for detecting

the point of trough clearing, it is ineffective for measuring duty cycle. This is because the diffraction efficiency of a rectangular grating at a constant groove depth is insensitive to duty cycle change over the range approximately between 0.2 and 0.5 and more importantly because it is difficult to measure absolute efficiency.

A one-dimensionally periodic grating is an optically anisotropic structure when the groove period and light wavelength are comparable. Diffraction efficiencies of TE and TM polarizations (the electric and magnetic field vectors parallel to the grating lines, respectively) are different and their ratio is a monotonic function of duty cycle in the range of duty cycle of interest. We propose to use this property to estimate the duty-cycle of surface-relief holographic gratings during development. A linearly polarized He-Ne laser beam shines on the photoresist grating being developed at the ?1st-order Littrow mount, with its polarization direction forming a 45º angle with respect to the incident plane. The ?1st transmitted order passes through a Wollaston prism. From the sum of the measured TE and TM diffraction intensities we determine the beginning point of groove depth leveling, and then using their ratio and sum we estimate the duty cycle. The advantage of this method is that the ratio measurement is a relative measurement, so it is not influenced by incident laser intensity fluctuation and several other environment changes. The development is stopped when the desired duty cycle is reached. We will present our theoretical simulation results and experimental results.

9526-55, Session PS

Investigation of a mathematical model of the system of electro-optical sensors for monitoring nonlinear surfaces

Andrey V. Petrochenko, Igor A. Konyakhin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

With the advent of high-tech methods of construction of large-scale structures is impossible to disregard the problems associated with the safe operation of these facilities. In the problems of monitoring the state of the major construction projects survey is only possible with the use of different sensors, including optoelectronic. In turn, the data received from the tens and even hundreds of sensors to be processed in real time, to ensure an adequate level of safety in the operation of the facilities.

This article describes the design and implementation of software and hardware optoelectronic sensors system control of nonlinear deformations of surfaces such as roofs and facades of large-scale structures. Deformation of these objects is, as a rule, the nature of the deflection, the value of which must be checked regularly, especially during peak periods. The developed electro-optical sensor includes electro-optical converter and target point, consisting of three LEDs emit infrared.

Direction of the review and clearance of the measuring unit are opposite so that the reporting unit was the sighting target for opto-electronic converter subsequent block.

Determination of the spatial position of the measuring unit is divided into two main stages: determination of the spatial position of the point shooting (just the coordinates of the surface) and the angular position of the block in the space (the coordinates of the sighting purpose of the block).

During the investigation, mathematical model was developed opto-electronic system of sensors to monitor the deformation of nonlinear surfaces and confirmed the possibility of the technical implementation of this system, as well as program implementation of algorithms for identifying non-linear distortion surface, using the simplex method of calculating the spatial position of the intermediate points of the surface. The basis of this method uses an bundle adjustment algorithm for constructing a continuous surface. During the experiment the measurement error equal to 1 micron.

The data obtained in the course of the experiment showed that the developed algorithm can be applied to high-speed high-precision measurement of optical-electronic systems.

9526-56, Session PS

Using quaternions to control assembly and adjustment mirror-prism optical systems

Kseniia Ezhova, Victor Zverev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Mirror and mirror-prism systems are widely used in optical systems for optical and opto-electronic devices to solve various problems, for example, to reflect the image and reducing the size of the system. All transformations of the space produced by the mirror and the mirror-prism system, are a shifts and rotations. Generally, due to errors in the assembly of these systems, the angles between reflective surfaces in the plane of the principal section is changed, and the coplanarity of the normals to the surfaces of the mirror systems is disturbed. Therefore, in the assembly process measurement and control of relative location of mirror and mirror-prism system components is very important.

Different methods of calculation is used to determine design parameters of these systems, the path, the movement law, the conformity obtained transformations of the required conversion and conformity path direction of the radiation predetermined path.

The first method for such tasks was the method of spherical trigonometry. The application of spherical trigonometry to solve tasks related to the definition of angular movements, gives a visual representation of the solution process, and of the obtained results. However, if the system is composed of more than two reflecting surfaces, these advantages is lost.

Later, a vector calculation method mirror systems was developed based on the law of reflection in vector form. An important step in the development of vector method was the development of a vector-matrix method. This method has wide opportunities for the analysis of mirror systems and can be used to solve some tasks of their synthesis. But obtaining a general expression for describing the operation of the system, which consists of a plane reflective surfaces, by vector and matrix methods, is time-consuming and requires to solve the problem recount action operators mirror system from one coordinate system to another.

A simpler solution of such tasks is the use of mathematical apparatus of quaternions, which was proposed by Hamilton. Quaternion algebra allows to present the final rotate (conversion) in the space in a simple and convenient form. The quaternions method disadvantage is the impossibility to present of a rotation of space at the same time its shift in a simple form. In this case, set task is solved without space shift and inside the same system of coordinates.

The application of quaternions allows to present infinitesimal rotation and arbitrary transformations, which are finite rotations, in a single vector form for the successful solution the problem of determining the unit vector of the beam reflected from an arbitrary system of plane mirrors, and the position of the object's arbitrary point image formed by this system.

In general, theoretical and applied interest is not only the direction of the reflected beam from plane surfaces, but also the position of the image point formed by a plane mirrors system without defining the intermediate points of the image.

9526-57, Session PS

Absolute testing of flats in sub-stitching interferometer by rotation-shift method

Xin Jia, Fuchao Xu, Tingwen Xing, Institute of Optics and Electronics (China)

High-accuracy interferometeric surface metrology is constantly gaining importance, not only in the classical area of optical fabrication, but also for new application such as semiconductor and lithography lens. Requirements for the measurement resolution in the subnanometer range have become quite common. This includes not only the repeatability or reproducibility but also the absolute measurement accuracy, in which both the slowly varying shape error and the medium-to-high spatial frequency waviness of the surface under test, is important. Large-

aperture optical elements are widely employed in high-power laser system, astronomy, and outer-space technology. Sub-aperture stitching is an effective way to extend the lateral and vertical dynamic range of a conventional interferometer. Most of the commercial available sub-aperture stitching interferometers measure the surface with a standard lens that produces a reference wavefront, and the precision of the interferometer is generally limited by the standard lens. The test accuracy can be achieved by removing the error of reference surface by the absolute testing method. In our paper we use the different sub-apertures as the different flats to get the profile of the reference lens. Result of the testing contain the reference surface errors and test surface errors in the high-accuracy Phase shifting interferometeric which test the relative phase between the two surface. The test accuracy can be achieved by removing the error of reference surface. In this case, one of body of so-called rotation-shift absolute tests must be used which can test the systematic errors, including the reference surface, of the instrument to be used to improve the test accuracy. We review traditional absolute testing of flats methods and emphasize the method of rotation-shift functions. In the past paper, the Dove prism can be inserted in the cavity which will introduce more reproducibility error. The Dove prism is treated here as a device with perfect wavefront, whereas, in practice, inserting it in the measurement cavity is equivalent to adding an unknown surface to the problem that is not accounted for by the original three-flat analysis or that given here (there are indeed not enough measurements now to constrain the problem). We use the rotation-shift method to solve the problem. In our paper we use the different sub-apertures as the different flats to get the profile of the reference lens. According to the rotation-shear method we get the profile of the reference lens and the testing lens. Only two lens in the testing process which is fewer than the traditional 3-flat method. The arithmetic is present in this paper which uses the absolute testing method to improve the testing accuracy of the sub-aperture stitching interferometers by removing the errors caused by reference surface.

9526-58, Session PS

Scanning in the optical vortex microscope

Agnieszka Popiolek-Masajada, Lukasz Plócienniczak, Jan Masajada, Slawomir Drobczynski, Mateusz M. Szatkowski, Wroclaw Univ. of Technology (Poland)

We propose a microscopic system in which the Gaussian beam with embedded optical vortex is used. The special helical phase plate is illuminated by the Gaussian beam and then focused by the microscope objective into the sample plane. Such a beam carries the optical vortex – the zero intensity point around which the phase gradient becomes infinitely large. By moving the phase plate within the Gaussian beam, the singular point in the sample plane can be moved and such configuration can be used for scanning the sample. We found in our previous works that moving the phase plate along a straight line causes a movement of the optical vortex also along straight line. The angle of the vortex trajectory however depends on the observation plane position. There is a plane in which the trajectory is perpendicular to the phase plate shift. In this plane the core region of a vortex beam is extremely sensitive to any phase imperfections introduced into the beam. The analytical formula for the complex amplitude of the focused spot with off-axis vortex was calculated in order to calibrate the microscopic system. In this presentation the theoretical fundamentals of microscope are discussed. The conclusions are verified experimentally.

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9526-59, Session PS

Maximum power point search method for photovoltaic panels which uses a light sensor in the conditions of real shading and temperature

Janusz Mroczka, Mariusz Ostrowski, Wroclaw Univ. of Technology (Poland)

Disadvantages of photovoltaic panels are their low efficiency and non-linear current-voltage characteristic, and therefore it is necessary to apply the maximum power tracking systems whith are dependant on the sun exposure and temperature. Trackers, that are used in photovoltaic systems, differ from each other in the speed and accuracy of tracking. Typically, in order to determine the maximum power point, trackers use measure of current and voltage. The perturb and observe algorithm or the incremental conductance method are frequent in the literature. The drawback of these solutions is the need to search the entire current-voltage curve, resulting in a significant loss of power in the fast-changing lighting conditions. Modern solutions use an additional measurement of temperature, short-circuit current or open circuit voltage in order to determine the starting point of one of the above methods, what shorts the tracking time. For this paper, a sequence of simulations and tests in real shading and temperature conditions for the investigated method, which uses additional light sensor to increase the speed of the perturb and observe algorithm in fast-changing illumination conditions. Due to the non-linearity of the light sensor and the photovoltaic panel and the influence of temperature on the used sensor and panel characteristics, we cannot directly determine the relationship between them. For this reason, the tested method is divided into two steps. In the first step algorithm uses the correlation curve of the light sensor and current at the maximum power point and determines the current starting point with respect of which the perturb and observe algorithm is run. When the maximum power point is reached, in a second step, the difference between the starting point and the actual maximum power point is calculated and on this basis the coefficients of correlation curve are modified.

The simulations prove the high effectiveness of the method in real-shading and temperature conditions. Speed of the maximum power search does not depend on parameters that are provided by a manufacturer as in the case of a similar method which uses temperature measurement. By applying the step of the adaptive modification of the correlation curve, this method is not dependent on the used light sensor. In addition, it prevents the tracking errors connected with changes of temperature. Tracking performance is significantly increased by using a light sensor in the maximum power search algorithm. The study proves the correctness of the proposed method and its high efficiency in partial shading conditions. The speed of tracking has been increased by about 10% compared to the commercial solutions. The method is resistant to rapid changes of illumination and uneven lighting conditions thus it significantly increases the amount of energy from photovoltaic panels working in the places where partial shading may be found. The experiments also were examined the impact of the light sensor parameters on the search speed and accuracy of the method. The studies shows that the application of the modification algorithm of correlation coefficients function significantly reduces the impact of sensors parameters.

9526-60, Session PS

The study of the structural stability of the spiral laser beams propagation through inhomogeneous phase medium

Alexander A. Zinchik, Yana B Muzychenko, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

This paper discusses theoretical and experimental results of the investigation of light beams that retain their intensity structure during propagation and focusing. Spiral laser beams is a family of laser beams that preserve the structural stability up to scale and rotation with the propagation. Properties of spiral beams are of practical interest for laser

technology, medicine and biotechnology. Researchers use a spiral beams for movement and manipulation of microparticles. Functionality laser manipulators can be significantly enhanced by using spiral beams whose intensity remains invariable, up to scale and rotation, during propagation. It is well known, that these beams has non-zero orbital angular momentum. These beams can not only rotate microscopic particles about an axe of the beam, but also to move them along a predetermined path. Spiral beams have a complicated phase distribution in cross section.

In this paper we investigate the structural stability of the laser beams having a spiral phase structure by passing them through an inhomogeneous phase medium.

Laser beam is passed through a medium is characterized by a random distribution of phases in the range 0..2ϖ.

The modeling was performed using VirtualLab 5.0 (manufacturer LightTrans GmbH).

Compared the intensity distribution of the spiral and conventional laser beam after the passage of the inhomogeneous medium. It is shown that the spiral beams exhibit a significantly better structural stability during the passage phase heterogeneous environments than conventional laser beams.

The results obtained in the simulation tested experimentally. LCoS reflective spatial light modulator was used to simulate the environment with a random distribution of phase inhomogeneities in the specified range. Experimental results show good agreement with the theoretical results.

9526-62, Session PS

Simulation and analysis of lightweight space mirror design

Polina A. Abdula, Mikhail Y. Neutov, Nadezhda D. Tolstoba, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

This work devoted to a comparative study of different designs of lightweight mirrors, as well as a comparison of materials, of which these mirrors are made of.

At the present time, developers of space telescopes seek to increase the aperture defined, primarily, by diameter of primary mirror. An important issue in this case, determining not only the cost but also the possibility of creating of a telescope becomes mass reduction of the primary mirror, while maintaining a high quality form of its surface. One solution to this problem is to create rigid passive mirrors, which do not require control over the shape of its surface. It is, of course, lightweight mirrors. In addition to the direct problem of reducing the mass of the mirror to send it into orbit, lightening allows to create solid mirror of larger diameter, as well as reducing weight entails a reduction in the mirror deflection under its own weight.

In order to determine the optimal shaping contour of mirror for contoured back structures were investigated various curves. Modeling and comparative study of the basic structures to facilitate mirrors was made, taking into account the use of materials that meet the requirements for the creation of large mirrors.

In order to research large aperture space mirror, the lightweight of the mirror was designed, then the analytical model of the mirror system was created and calculated. In order to consider maximum amount of variants, several different positions and mounts of mirror were tested.

The effect of the mirror self-weight or other stresses may cause bad optical imaging quality.

The large-diameter mirror model was optimized based on material, lightweighting design and in the condition of gravity to satisfy the design requirements. Few variants of mirror has been designed, and were compared with each other and with the traditional lightweight design.

Analysis results show the most interesting material, design and mount. Also there are presented results of aberration research, so the paper shows ideas and examples of decisions in the lightweight design

9526-63, Session PS

Propagation invariant laser beams for optical metrology applications

Michael G. Soskind, Rutgers, The State Univ. of New Jersey (United States); Yakov G. Soskind, DHPC Technologies (United States)

Propagation invariant laser beams (PILBs) represent a class of coherent structured fields possessing several unique properties. One of the unique properties includes the beam shape invariance during free-space propagation [1, 2], when only the scale of the beam changes, while the beam pattern remains unchanged. Another remarkable property of PILBs is in the beam self-healing after encountering obstructions by objects during the beam propagation [2]. A limited number of PILB shapes can be produced as the output mode field distributions of stable laser resonators [3 – 5]. To extend the variety of PILB shapes, additional techniques have been developed that employ coherent interferometric beam combination [6, 7] and the beam transformations employing anamorphic optical systems [8]. The latter technique is insensitive to vibrations, and is easier to implement.

The unique properties of PILBs make them an attractive choice in several photonics applications, including superresolution microscopy [1, 9] and information encoding [2]. In this paper, we apply novel PILB shapes produced with anamorphic optical systems to optical metrology with structured illumination. We explore interactions between the PILBs and nanoscale phase objects of various sizes and phase delays, such as lithography mask patterns and grating structures. We model influence of the phase objects encountered by PILBs during propagation onto the resulting beam shape in the observation plane. Our results show that analysis of the localized structured beam nodes from the observed irradiance distributions can provide quantitative information for the location and shape of the nanoscale phase structures, and can be employed as a highly sensitive characterization technique. The described technique is based on a single propagating laser field, and is therefore simpler to implement than characterization techniques employing composite structured fields. Results of our study may be applied to high resolution detection of small phase objects, and can be employed in a variety of fields within optical metrology.

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9526-64, Session PS

A Bohmian analysis of Afshar’s experiment

Juan David Navia, John H. Reina, Univ. del Valle (Colombia); Detlef Dürr, Ludwig-Maximilians-Univ. München (Germany)

Bohmian mechanics provides an explanation of quantum phenomena in terms of point-like particles guided by wave functions, offering better interpretational tools in a realistic quantum theory in which the notion of measurement plays no fundamental role. It then provides a new and challenging scientific ontological description (or in simpler terms realistic quantum theory) that explains how to overcome the prevailing paradoxes and confusions arising from the orthodox interpretation of quantum mechanics where the duality in the time evolution of a quantum system is certainly a persistent controversial issue (the so-called measurement problem or collapse of the wave function). To explore the fundamental issues pertaining to this that still exist today. Here is presented the use of nonrelativistic Bohmian mechanics to address with the problem of measurement in optical systems. The ability of the Bohmian formalism to analyze this type of problems remains mainly unexplored by the scientific community. For such purpose was taken as case of study the analysis of the Afshar's experiment which is an optical interferometry experiment devised and carried out in 2005 (Afshar, 2005), and is a variation of the Young's experiment of quantum theory. Afshar claims that his experiment shows a violation of the Bohr's principle of complementarity which roughly states that the particle and wave aspects of quantum objects cannot be observed at the same time, and specifically the Englert-Greenberger duality relation (Englert, 1996). A number of scientists have published criticisms of Afshar's interpretation of his results. They are united in their rejection of the claims of a violation of complementarity, while differing in the way they explain how complementarity copes with the experiment. Then the problem remains open. In 2010, Flores and De Tata re-examined the Afshar's experiment (Flores and De Tata, 2010) and argued that Afshar's experiment turns out to be one where complementarity is not associated with the uncertainty principle (nor with quantum entanglement). Thus, orthodox quantum mechanics and Bohmian mechanics could well differ in their predictions for complementarity in Afshar's experiment.

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9526-20, Session 5

Simulating the coherent light propagation in a random scattering materials using the perturbation expansion *(Invited Paper)*

Maciej Kraszewski, Michal Trojanowski, Marcin R. Strakowski, Jerzy Plucinski, Gdansk Univ. of Technology (Poland)

Phenomena connected with the multiple scattering of a coherent light plays important role in the optical metrology. Probably the most important of these phenomena are the speckle patterns present in every optical imaging method based on coherent or partially coherent light illumination. In many cases the speckle patterns are considered as an undesired noise. However, they were found useful in various subsurface imaging methods such as laser speckle imaging (LSI) or optical coherence tomography (OCT). All features of the speckle patterns and their connection with microstructure of scattering materials was not fully exploited. Further research on this topic may lead to a simple and inexpensive optical diagnostic methods. Theoretical and numerical research could greatly facilitate development of such methods. However, this requires simulations of coherent light propagation through a random scattering media of a length larger than few hundreds of a light wavelength. During such propagation the light can be scattered by many tens of thousands of scattering particles.

The numerical methods, such as the radiative transfer theory and the Monte Carlo methods, allows to simulate propagation of the incoherent light in such a media but they do not consider the coherence properties of light. Moreover, they consider only average realization of the scattering medium and therefore does not allow to predict properties of any random fluctuations of the scattered light, such as a speckle patterns.

Direct solvers of Maxwell or Helmholtz equations, such as finite-difference or finite-element methods could solve this problem but their computational complexity limits their application to media no longer than about 10 to 20 wavelengths of the light. Here we show an alternative approach based on solving the integral form of the Helmholtz equation written as a so called perturbation expansion. We show the numerical algorithm for solving this equation.

The proposed algorithm uses the Green function formalism. This require computation of the scattered wave field only in the positions of scattering particles and small region of interest. This is an important advantage over the finite-difference (FD) method, since FD requires finding the wave field in the entire computation domain.

We have compared results of the proposed method with results of the same problems obtained with the FD method in case of small number of scattering particles. We have obtained an excellent agreement between the both methods.

Another advantage of the proposed method is possibility of a simple trade-off between the accuracy and the computation time. E.g. it is possible to reduce the computations to the so-called first or second Born approximations or to neglect interaction between light scattered multiple times by a distant particles. Application of the Monte Carlo approach for random selection of only some of all possible paths of scattered light is also presented and discussed.

The proposed method may become an useful tool in the research on coherent light propagating through the random media. Our future research will be focused on direct application of the developed method simulating the speckle patterns observed in optical coherence tomography (OCT) images. In particular, it will be used to study the connection between statistical parameters of the speckle patterns and the microstructure of the scattering medium.

9526-21, Session 5

The optical properties of tropospheric soot aggregates determined with the DDA (Discrete Dipole Approximation) method

Krzysztof Skorupski, Wroclaw Univ. of Technology (Poland)

BC (Black Carbon) particles soon after emission interact with both organic and inorganic matter. The main goal of this work was to approximate the accuracy of the DDA (Discrete Dipole Approximation) method in determining the optical properties of such composites. The incident wavelength varied from ?=300 to ?=900. The refractive index for BC was adapted from the work by Chang and Charalampopoulos. The refractive index for organic acid (organic matter) was adapted from the work by Myhre and Nielsen. Finally, the refractive index for sulfate (inorganic matter) was adapted from the OPAC database. For the light scattering simulations the ADDA algorithm was used. To approximate its accuracy the light scattering results were compared to the T-Matrix program by Mackowski. The first part of the study was to compare alternative models of a single primary particle with the diameter 30nm. The results proved that when the number of volume elements (dipoles) along its smallest axis is lower than 10 the resulting extinction error might be significant. Especially when a particle is covered with a thin (e.g. 5nm) layer. In this case the mesh of volume elements (dipoles) is not able to precisely describe the shape of structure. Therefore, in this work the number of volume element (dipoles) along the smallest axis of the core sphere (i.e. without coating) was 13 what resulted in ca. 1000 volume elements (dipoles). When only one material is considered the largest relative extinction error is associated with BC (ca. 2.8%) due to its large value of the imaginary part of the complex refractive index. For inorganic and organic matter it is not greater than 0.75% in any case. When BC particles are covered with an organic layer the amount of the light absorbed and scattered is significantly increased. There is no much difference between spheres and ellipsoids characterized by the same volume, and therefore, both models can be used interchangeably. The positions of volume elements (dipoles) of different materials should not be random – the coat must by properly described otherwise the results are erroneous, even if the volume is consistent. The next step

was to approximate the extinction error for large fractal-like aggregates composed of 50 primary particles. When aggregates are composed of uncoated primary particles (black carbon, organic and inorganic matter) the relative extinction error is ca. 2.6%. However, when an aggregate is composed of coated black carbon and sulfate particles the relative extinction error is lower than 0.5%. Finally, a more realistic aggregate model was created. It was composed of 50 ellipsoidal BC particles with the diameter ca. 30nm. They were connected together with small cylindrical necks. Next, 4 ellipsoidal sulfate particles with the diameter of ca. 60nm were added. The aggregate was covered with an organic layer characterized by a various thickness, i.e. 5nm, 10nm, 15nm and 20nm respectively. The light scattering results proved that both the extinction cross section and the scattering cross section increase along with the coat size. The same effect is observable for the single scattering albedo.

9526-22, Session 5

Nonspherical nanoparticles characterization by partially depolarized dynamic light scattering

Alexander Levin, Ekaterina Shmitkova, All-Russian Research Institute for Optical and Physical Measurement (Russian Federation)

Nonspherical nanoparticles (NP) are widely used in various fields of nanotechnology, including nanocomposite materials, nanoelectronics, biomedical technologies, solar panels. In many applications, non-spherical particles are used in a liquid (for example, in biomedical nanotechnologies), and in other cases in suspension, wherein the suspended particle is used during synthesis or at intermediate stages of the process (e.g., in the manufacture of nanocomposites). Information about size and shape of non-spherical NP are on importance for applications mentioned above, also for nanotoxicology research due to dependence of NP penetration capability from size and aspect ratio. High resolution microscopy (SEM, TEM and AFM) gives fairly complete information about NP size and shape, but have several essential limitations including inability of direct measurements in liquid, complicated and prolonged sample preparation, high price of equipment and large operating costs. Therefore in addition to direct imaging methods such as microscopy, indirect physical and chemical techniques are developed.

Dynamic light scattering (DLS) is one of the most effective indirect methods of nanoparticles sizing in situ, based on measurement of time-dependent fluctuations of laser light scattered from NP in colloid. Because these fluctuations are generated by Brownian motion of the scatterers, translational diffusion coefficients can be obtained from analysis of autocorrelation function (ACF) of time dependent scattering intensity. NP hydrodynamic diameter can be calculated from diffusion coefficient using Stokes-Einstein equation. In standard DLS scattered light with polarization such as that of the incident beam (co-polarized, or VV component) is measured. Only co-polarized component exists in the light scattered by spherical NP.

In the case of non-spherical particles component with the polarization orthogonal with that of the incident light (cross-polarized, or VH) also appears. In contrast to the spherical NP, non-spherical particles are involved both in translational and rotational diffusion. For non-spherical NP sizing depolarized dynamic light scattering (DDLS) technique can be applied. Both VV and VH components of the scattered light are measured in DDLS. The collection optics for the scattered light includes polarization analyzer (Glan-Tompson prism) which is adjusted to VV and VH positions. ACF of VV and VH components are related to the translational and rotational diffusion coefficients by the equations

Here and - first order (amplitude) ACF for VV and VH geometry, ? -delay time, Dtrans and Drot. - translational and rotational diffusion coefficients, correspondingly, q – wave number of scattering light ; (3) ,

where n is refractive index of the solvent, ? is the scattering angle between incident and scattered light, ? is wavelength of incident light.

Factors A and B describes relative contribution of two relaxation modes in gvv.; A + B =1.

Parameters Dtrans , Drot. , A and B can be determined by non-linear list square fitting of (1) and (2) to the experimental ACF.

Translational and rotational diffusion coefficients obtained form DDLS are related to hydrodynamic dimensions of non-spherical NP by a model, describing particle diffusion in liquid. In DDLS experiments, described in [1-3], such model suppose the cylindrical shape of the particle. Cylinder length L and diameter d have been calculated from experimental data, [1-2] for gold nanorods and for single-wall carbon nanotubes [3].

The main limitation of DDLS method is the need to measure very weak optical signals during registration of VH (cross-polarized) component of the scattered light. Thus it is necessary to use relatively high power lasers for scattering excitation and long measurement duration. To eliminate the need of very weak optical signals measurements (for polarization VH) authors propose an improved version of DDLS. This technique we call-partially depolarized dynamic light scattering – PD DLS.

Measurement of scattered light at several positions of the polarization analyzer, intermediate between the VH and VV are proposed. The model for ACF dependence from polarization analyzer position, corresponding to different proportions between polarized and depolarized components of the scattered light is developed. This dependence can be expressed by the equation similar to (1), but parameters A and B become the functions of the angle ? between polarization directions of incident and scattered light appears in the model. The following expressions are valid for A(?) and B(?).

(4)

Particular case ?=0 corresponds to VV geometry, and ?=900 - to VH.

Diffusion coefficients Dtrans and Drot. can be calculated by fitting of ACF determined by (1) and (4) to the experimental ACF with the help of non-linear least square (NNLS) algorithm. One of realization of NNLS is Levenberg-Marquardt algorithm, which is supported by lsqqurvefit function from Matlab Curve fitting toolbox.

The new technique was applied for characterization of water suspension of multi-wall carbon nanotubes (MWNT). We used custom-designed PD DLS setup with 12 mW He_Ne laser as light source. Experimental ACF were measured for ?=0 and two other values of ? (?=550 and ?=710) , Dtrans and Drot were calculated as described above. Model of cylindrical particles diffusion in liquid for estimation of nanotubes length and diameter was applied. PD DLS values of length are

weakly dependent on solvent viscosity and in agreement with SEM data (LPD DLS=284 ??, LSEM=320-350 ??). Values of cylindrical NP diameter estimated from diffusion coefficients strongly depends from solvent dynamic viscosity ?. PD DLS diameter value can be agreed with electron microscopy data in the case of using solvent effective viscosity 2-2,5 times higher than viscosity of water . In our case if ?=2,25?water dPD DLS=15 ??, dTEM=14,6 ??. Using of the increased solvent viscosity value for calculating of MWNT diffusion can be justified by the greater contact surface of MWCNT with water than by diffusion of the solid cylinder.

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9526-23, Session 5

Detection of fast flying nanoparticles by light scattering over a large volume

Federico Pettazzi, Stefan M. Bäumer, Jacques C. J. van der Donck, Alex Deutz, TNO (Netherlands)

Detection of nanoparticles is of paramount importance for contamination control in ultra-clean systems. Light scattering is a well-known method which is applied in many different scientific and technology domains including atmospheric physics, environmental control, and biology. It allows contactless and remote detection of sub-micron size particles.

However, methods for detecting a single fast moving particle smaller than 100 nm is lacking.

In the present work we report the preliminary design of an inline large area detector for nanoparticles larger than 50 nm which move with velocities up to 100 m/s. The detector is based on light scattering using commercially available components.

The presented design takes into account all challenges connected to the inline implementation of the scattering technique in the system: the need for the detector to have a large field of view to cover a volume with a footprint commensurate to an area of 100mm x 100mm, the necessity to sense nanoparticles transported in a fast gas flow, and the requirement of large capture rate with a false detection as low as one false positive per week.

The impact of all these stringent requirements on the expected sensitivity and performances of the device is analyzed by mean of a dedicated performance model. In particular, the combination of small particle size and large particle velocity implies that detectable scattering signals can be generated only when large power densities are used in the UV spectral range. The relative stringent requirements on the specific laser source to be used are fully discussed in relation to currently available systems, also taking into consideration the need of large field of view. Different options including high power pulsed laser with various repetition rates and CW lasers are presented and their performances are compared.

The developed detector performance model evaluates the expected capture rate of the system in relation to a given low allowable false positive rate. Specifically, it takes into account the main expected sources of noise in the measurement and provides an estimate of the capture rate as a function of particle size. The effect of degradation of detector components is also accounted for, which is of critical importance for inline systems operating with minimal maintenance over long period and when high power lasers in the UV spectral range are used. Finally, the possibility to increase further the sensitivity of the system is discussed in relation to the current technology available, and the main critical factors to be considered for an improved design are also outlined.

9526-24, Session 6

Nondestructive measurement of two-dimensional refractive index profiles by deflectometry *(Invited Paper)*

Di Lin, James R. Leger, Univ. of Minnesota, Twin Cities (United States)

We present a method for calculating a two-dimensional refractive index field from measured boundary values of ray position and angle. Angular deflection along the trajectories of interrogating rays yield nonlinear equations in terms of the index gradient, whose vector components (i.e. the partial derivatives of the index field) are treated as unknown field quantities of the inverse problem. By initially ignoring the dependence of ray trajectories on the index field, we show that the path integral describing beam deflection simplify to linear equations in the partial derivatives of the index field. A discretization of the partial derivatives allows us to construct a linear system from a large number of interrogating rays. Constraints enforcing equal mixed partial derivatives (index gradient must have zero curl) are incorporated into the linear system to reduce its degrees of freedom. The partial derivatives are then solved using LSQR, an iterative algorithm suitable for inverting sparse, ill-conditioned systems. Upon obtaining an approximate solution, numerical ray tracing is used to update the assumed ray trajectories and improve our approximations. We show that the approximate trajectories converge rapidly to the actual trajectories after a few iterations and the resulting index field obtained from this iterative approach yields a self-consistent solution, where assumed ray trajectories used to compute the solution are in agreement with those obtained from ray tracing through the solution. We demonstrate the efficacy of our proposed method through simulation, where numerical ray tracing is used to model angular deflection of interrogating beams propagating through a hypothetical rectangular test index profile. Internal boundary values of ray position and angle are generated from 800 interrogating rays and are used to reconstruct the index field on a 15?15 discrete grid. Using our approach, refractive index errors (RMS) of <0.5% of the total index range (n_max-n_min) are achieved when no measurement error is present. In addition, we identify three primary sources of error in reconstructing the index field using our approach. For modest noise levels, reconstruction error is shown to vary linearly with measurement error if there is uncertainty in measured data. Quantization error becomes dominant at extremely low noise levels. At extremely high noise levels, the dependence between reconstruction error and measurement error becomes superlinear due to the developing discrepancy in ray trajectories. Furthermore, we assess the importance of data redundancy and system conditioning in accurate reconstructions of the index field and show that there exists a threshold for both factors under which the reconstruction becomes inaccurate and produces large errors. The principles developed in this method are fully extendable to three-dimensional index fields as well as more complex geometries.

9526-25, Session 6

Problems in thin film thickness measurement resolved: improvements of the fast Fourier transform analysis and consideration of the numerical aperture of microscope headers and collimators

Michael Quinten, Faiza Houta, Thomas Fries, FRT, Fries Research & Technology GmbH (Germany)

Thin film thickness determination with a reflectometer suffers from two problems. One problem is the leakage in the Fast Fourier Transform caused by the fact that the two variables wavenumber 1/? and optical thickness n?d are not really independent, since the refractive index n of the film material itself depends upon the wavenumber. This causes uncertainties in the thickness determination in the order of up to 5% for highly refractive materials like semiconductors. We present a simple but effective improvement of this contribution of the leakage that reduces the uncertainty to less than 2% for highly refractive materials.

Another problem that mainly affects thin films below about 2 μm arises if one uses measuring heads collimators or even microscope headers to obtain high lateral resolutions in the thickness determination. The use of a header introduces angles of incidence different from the default angle ? = 0° in reflectometry. Then, the measured reflectance becomes polarization-dependent and the angle must be explicitely considered in the evaluation algorithm. For a microscope header however, all angles between 0° and the angle of aperture must be considered. We will present a solution that allows to reduce the work for each header on taking into account the polarization of the reflected light and a corresponding effective angle ?eff.

9526-27, Session 7

Methods for optical modeling and cross-checking in ellipsometry and scatterometry *(Invited Paper)*

Peter Petrik, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pannonia (Hungary) and Technische Univ. Delft (Netherlands); Balint Fodor, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pécs (Hungary); Emil Agocs, Research Institute for Technical Physics and Materials Science (Hungary) and Physikalisch-Technische Bundesanstalt (Germany); Peter Kozma, Judit Nador, Research Institute for Technical Physics and Materials Science (Hungary); Nitish Kumar, Technische Univ. Delft (Netherlands); Johannes Endres, Physikalisch-Technische Bundesanstalt (Germany); Gyorgy Juhasz, Csaba Major, Research Institute for Technical Physics and Materials Science (Hungary); Silvania F. Pereira, Technische Univ. Delft (Netherlands); T. Lohner, Research Institute for Technical Physics and Materials Science (Hungary); H. Paul Urbach, Technische Univ. Delft (Netherlands); Bernd Bodermann, Physikalisch-Technische Bundesanstalt (Germany);

Miklos Fried, Research Institute for Technical Physics and Materials Science (Hungary)

Indirect optical methods like ellipsometry or scatterometry require an optical model to calculate the response of the system, and to fit the parameters in order to minimize the difference between the calculated and measured values. The most common problem of optical modeling is that the measured structures and materials turn out to be more complex in reality than the simplified optical models used as first attempts to fit the measurement. The complexity of the optical models can be increased by introducing additional parameters, if they (1) are physically relevant, (2) improve the fit quality, (3) don't correlate with other parameters. The sensitivity of the parameters can be determined by mathematical analysis, but the accuracy has to be validated by reference methods. In this work some modeling and verification aspects of ellipsometry and optical scatterometry will be discussed and shown for a range of materials (semiconductors, dielectrics, composite materials), structures (damage and porosity profiles, gratings and other photonic structures, surface roughness) and cross-checking methods (atomic force microscopy, electron microscopy, x-ray diffraction, ion beam analysis). The high-sensitivity, high-throughput, in situ or in line capabilities of the optical methods will be demonstrated by different applications. [Acknowledgement: Support from the ENIAC E450EDL and EMRP IND17 projects is greatly acknowledged.]

9526-28, Session 7

Validation of advanced 3D modelling and data analysis for scatterometry

Sven Burger, Lin Zschiedrich, JCMwave GmbH (Germany); Frank Schmidt, Martin Weiser, Zuse Institute Berlin (Germany); Bernd Bodermann, Matthias Wurm, Victor Soltwisch, Physikalisch-Technische Bundesanstalt (Germany)

Optical scatterometry is an important method to measure the size and shape of periodic micro- or nanostructures on surfaces.

For this purpose the geometry parameters of the structures are obtained by reproducing experimental measurement results through numerical simulations.

The simulations are performed using parameterized models and nonlinear optimization algorithms for finding parameter settings which minimize differences between the measurements and the numerically obtained result.

We present numerical methods for performing parameter reconstructions using measurement data from three-dimensional, periodic nanostructures. For obtaining fast and accurate solutions to the forward-problem we use higher-order finite elements.

For solving the inverse problem we use Newton's method.

Measurements of a hexagonal two-dimensional Silicon grating with pillar shaped structures have been performed at PTB with a DUV-Scatterometer operating at a wavelength of 266 nm and with X-ray scatterometry in gracing incidence (GISAXS) at a photon energy of 6.5 keV.

Both type of measurements have been analysed and the reconstruction results are compared with SEM measurements.

9526-29, Session 7

The statistical inverse problem of scatterometry: Bayesian inference and the effect of different priors

Sebastian Heidenreich, Hermann A. Gross, Matthias Wurm, Bernd Bodermann, Markus Bär, Physikalisch-Technische Bundesanstalt (Germany)

Scatterometry provides a fast indirect optical method for the determination of grating profile parameters of photomasks. There are several inverse methods from simple least squares to the maximum likelihood method to obtain geometry parameters from intensities of scattered light. To further increase precision the consistent reconstruction of geometry parameters based on combined measurements is desirable. The Bayesian approach is able to solve the statistical inverse problem of combined measurements and provides an appropriate method to evaluate uncertainties according to the Guide for the evaluation of uncertainties in measurement. However, for computational expensive problems like scatterometry, the direct application of Bayesian inference is too time consuming. In our contribution we present the Bayesian approach to the statistical inverse problem of scatterometry by including different surrogate models. Specifically, we replace time consuming finite element calculations by three surrogate models to enable the Bayesian approach to scatterometry. The surrogate models considered are the nearest neighbor interpolation, the quadratic response surface methodology and the polynomial chaos expansion. We reconstructed geometry parameters of a photomask with each surrogate model based on simulated data. We analyzed approximation errors and convergence properties. Furthermore, we applied the algorithm to measurement data obtained by goniometric DUV scatterometry on structured Si gratings.

9526-30, Session 7

The effect of systematic errors on the hybridization of optical critical dimension measurements

Mark-Alexander Henn, Bryan M Barnes, Nien-Fan Zhang, Hui Zhou, Richard M Silver, National Institute of Standards and Technology (United States)

In hybrid metrology two or more measurements of the same measurand are combined to provide a more reliable result that ideally incorporates the individual strengths of each of the measurement methods. While these multiple measurements may come from dissimilar metrology methods such as optical critical dimension (OCD) measurements and scanning electron microscopy (SEM), we will investigate the hybridization of "similar" OCD methods. The presented results feature angle- and focus-resolved measurements performed at selected wavelengths and polarizations. Even though the methods are similar, different wavelengths and polarizations inevitably lead to different sensitivities to systematic errors. For example, errors due to line edge and line width roughness (LEWR) are known to contribute a systematic bias and its inherent correlated errors. In order to investigate the sensitivity of the measurement to LEWR we follow a modelling approach proposed by Kato et al. who studied the effect of LEWR on extreme ultraviolet (EUV) and deep ultraviolet (DUV) scatterometry.

Similar to their findings we have observed that LEWR leads to a systematic bias in the data. Since the critical dimensions (CDs) are determined by fitting the respective model data which is supposed to be a function of the critical dimensions f(x) to the measurement data y, i.e. minimizing the difference measure or chi square function (f(x)-y)^T V(f(x)-y), with V denoting a weight matrix, a proper description of the systematic bias is crucial to obtaining reliable results and even more to the successful hybridization of the methods. In scatterometry an analytical expression for the influence of LEWR on the measured orders could be derived. Accounting for this effect leads to a modification of the model function f ?(x,?_r) that not only depends on the critical dimensions x but also on the magnitude of the roughness ?_r. This modification led to a significant improvement of the solution.

However in the present case of OCD such an analytical expression cannot be derived, yet the presence of the systematic bias makes it necessary to account for it in some way. We demonstrate how this can be achieved and that, if certain conditions are met, a significant improvement of the reliability of hybrid metrology both for combining dissimilar and "similar" measurement tools can be achieved.

9526-33, Session 8

Simulation of light in-coupling through an aperture probe to investigate light propagation in a thin layer for opto-electronic application

Markus Ermes, Stephan Lehnen, Zhao Cao, Karsten Bittkau, Reinhard Carius, Forschungszentrum Jülich GmbH (Germany)

In thin optoelectronic devices, like organic light emitting diodes (OLED) or thin-film solar cells (TFSC), light propagation, which is initiated by a local point source, is of particular importance. In OLEDs, light is generated in the layer by the luminescence of single molecules, whereas in TFSCs, light is coupled into the devices by scattering at small surface features. In both applications, light propagation within the active layers has a significant impact on the optical device performance.

Scanning near-field optical microscopy (SNOM) using aperture probes is a powerful tool to investigate this propagation with a high spatial resolution. Dual-probe SNOM allows simulating the local light generation by an illumination probe as well as the detection of the light propagated through the layer. In our work, we focus on the light propagation in thin silicon films as used in thin-film silicon solar cells.

We investigate the light-incoupling from an illuminating probe via rigorous solution of Maxwell's equations using a Finite-Difference Time-Domain approach, especially to gain insight into the light distribution inside a thin layer, which is not accessible in the experiment. The structures investigated include flat and structured surfaces with varying illumination positions and wavelengths.

From the performed simulations, we define a "generation volume" which is characteristic for the local structure and illumination position. This quantity can help to identify structures which are beneficial as well as detrimental to absorption inside the investigated layer. Furthermore, we investigate inhomogeneity in local light propagation resulting from different surface structures and illumination positions.

For a full description of a dual-probe SNOM, both illumination and detection probe have to be taken into account. This requires a very high amount of computation time since for each position of the collection probe, a separate simulation has to be done. However, we demonstrated in earlier work [Proc. SPIE 8789, 87890I (2013), Proc. SPIE 9132, 91320G (2014)] that the detection probe can be taken into account by post-processing methods for the surface structures investigated here. Therefore, we only include the illumination probe in our simulations allowing for a more systematic investigation of the influence of the illumination probe with a feasible amount of computation time.

9526-34, Session 8

Effect of wavefront aberrations on a focused plenoptic imaging system: a wave optics simulation approach

Massimo Turola, City Univ. London (United Kingdom); Chris J. Meah, Richard J. Marshall, Iain B. Styles, The Univ. of Birmingham (United Kingdom); Stephen Gruppetta, City Univ. London (United Kingdom)

A plenoptic imaging system records the light field, which is a four dimensional function, also known as the plenoptic function, describing radiance along rays as a function of position and direction. The light field is recorded by adding a lenslet array in front of the sensor plane of the camera. A raw plenoptic image consists of an array of lenslet sub-images, corresponding to different point of views. The information encoded in a plenoptic image can be computationally post-processed for synthetic refocusing, 3D depth mapping, tomography, and potentially the evaluation of wavefront aberrations. According to geometric optics, ray directions are defined by the wave vectors k that describe a set of vectors perpendicular to the surfaces of constant phase of the wavefront. Aberrations are deviations from an ideal spherical reference wavefront and thus in an aberrated optical system the rays, in general, do not strike the focal plane at positions that correspond to the paraxial (ideal) image location. We consider the behaviour of a focused plenoptic camera in the presence of different wavefront aberrations. Deviations in ray directions that result from aberrations will produce a shift in each lenslet sub-image with respect to the ideal sub-image, and therefore the distribution and magnitude of the sub-image displacements gives an estimation of the aberrations in the system. We use a wave optics approach to simulate image formation in a plenoptic camera in the presence of aberrations.

Numerical simulations of light propagation in a focused plenoptic imaging system have been performed in MATLAB. The imaging system is modelled as a combination of two simple transformations: free space propagation and passage through a lens. Free space propagation is simulated using the angular spectrum of plane waves method. The optical field at the object plane U(x,y;0) is decomposed as a sum of plane waves with different spatial frequencies f_x and f_y, defined as the angular spectrum A(f_x,f_y;0), as shown in equation 1. The angular spectrum after the propagation is given by equation 3. The propagation can be treated as a linear filter whose transfer function H has a finite bandwidth that depends on the propagation distance z.

Optical elements such as a thin lens with focal length f and lenslet arrays are simulated as a circular pupil P(x,y), or an array of pupils, with a quadratic phase factor (equation 4).

Aliasing arising from the digital sampling of the transfer function is treated using the band-limited angular spectrum method. Similar considerations can be made to treat lens phase profile aliasing. Wavefront aberrations are modelled by adding a phase mask to the main lens (equation 5).

Switching to polar coordinates, the aberration function it can be expressed as a linear combination of polynomials orthogonal on the unit circle, the Zernike polynomials.

The simulated system (figure 1) consists of a main lens of focal length 120mm in a 2f configuration. The microlens array consists of 35 x 35 lenslets of focal length 8 mm and pitch of 143 microns, placed at distance a from the main lens image plane and b from the sensor plane respectively in order to satisfy the lens equation 1/f=1/a+1/b. a and b are respectively 32mm and 10.7 mm. Magnification was m=b/a=0.33.

After acquiring the non-aberrated raw image of a plane wave, low order aberrations were added on the main lens pupil. The shifts of each sub-image in the raw image have been estimated by cross correlating each sub-image with the sub-image in the same position in the ideal raw image. These values arranged in an array tell how much each sub-image is shifted because of aberrations.

Figure 3 shows maps of the vectors of displacement for a raw image of a plane wave, after the addition of a number of types of aberration. The aberrations added to the main lens are: vertical and horizontal tilt (n=1 m=-1 and n=1 m=1), astigmatism (n=2 m=-2 and n=2, m=2) and coma (n=3 m=-1 and n=3 m=1). For all these aberrations the magnitude 0.1 microns. For clarity reasons the shift vectors has been scaled by a factor of 2. Results of the simulations with high order aberrations have not been included in this abstract for brevity. In figure 4 are represented the aberrations functions used in these simulations.

This work has shown in simulation the effect that simple low order aberrations have on raw plenoptic images. Cross-correlating aberrated sub-images with the ideal case allows a displacement map can be generated. This information could be used in several ways, for example, through the creation of a library of displacement maps to be used during the calibration of plenoptic cameras in presence of aberrations. With a reverse ray tracing algorithm from the generated raw images, it should be possible to estimate the wavefront at any point during the propagation, converting a plenoptic camera into a wavefront sensor. The sensitivity of raw images to wavefront aberrations could be used to develop an imaging system capable of capturing intensity and phase information at the same time.

9526-35, Session 8

Total variation iterative constraint algorithm for limited-angle tomographic reconstruction of non-piecewise-constant structures

Wojciech Krauze, Piotr L. Makowski, Malgorzata

Kujawinska, Warsaw Univ. of Technology (Poland)

Optical limited-angle tomography is an important tool in imaging technical and biological samples. It is used when it is impossible to acquire projections of an object within full tomographic angular range (180° for projection tomography and 360° for diffraction tomography) or when the measurement speed is the key issue. In the former case, the structure of a measured object may limit the available angular range of projections, like in case of phase microtomography of bacterial colonies grown at the Petri dish. In the latter case, since smaller amount of data needs to be acquired, the measurement process takes less time and allows imaging of dynamic processes. In order to compensate the lack of data, special regularization techniques are commonly applied. State of the art algorithms utilize the compressed sensing approach, in which a sparse representation of the object is optimized. In those solutions the proper choice of the mapping domain has to be made, which depends on the characteristics of the object. One of the most successful techniques is the Total Variation (TV) minimization, which optimizes the first norm of the gradient of the reconstruction. This method gives very good results but is applicable only to piecewise constant structures. There is also a category of iterative algorithms optimized specifically for globally smooth samples. This, however, leaves a wide category of mixed-content objects uncovered. In this paper, we propose a novel algorithm for 3D limited-angle tomography – Total Variation Iterative Constraint method (TVIC), which expands the applicability of the TV regularization to objects bound by distinct edges, but not piecewise constant in the most part. This includes, for instance, biological cells. The proposed approach consists of two steps: in the first part, the TV minimization is used as a strong regularizer to create a prior, which then, in the second part, is iteratively applied in the tomographic reconstruction process as an external geometry mask. The obtained reconstructions look very promising – the effect of the limited angular range of projections is minimized and the resolution becomes more isotropic. According to our knowledge, this is the first attempt to utilize TV minimization to reconstruct non-piecewise constant samples. We also show that the efficiency of this new reconstruction algorithm is affected by illumination architecture type. In the paper a numerical analysis of different illumination architectures is presented. These architectures include: single and dual axis tomography, tomography with sources arranged in circles of different diameters, and others. Based on these results an optimal arrangement of sources for real tomography setups will be chosen.

9526-36, Session 8

A cascaded plasmonic superlens for near field imaging with magnification

Liwei Fu, Univ. Stuttgart (Germany); Philipp Schau, Karsten Frenner, Wolfgang Osten, Institut für Technische Optik (Germany)

With the growing development of nanoscience and technology, direct imaging techniques with subwavelength resolution become more and more desirable. Without the necessity of scanning or post-processing the imaging process will be greatly simplified and shortened. To realize such an imaging system, we focus on the field of plasmonic metamaterials, which is currently one of the most vibrant and diverse fields of science and technology [1-3]. Due to the coupling of evanescent fields and the confinement of light into subwavelength volumes, light can be manipulated and transferred efficiently with thin-layer metamaterials. It has been demonstrated that coupled metallic meander surfaces can be used for subwavelength imaging or focusing [4]. However, without magnification the near field imaging is still limited in the near field zone.

To overcome this limitation, different superlensing systems with magnification or far field superlens were developed. A novel cascaded superlens system with magnification was suggested recently [5], which is a promising solution to the current existing problem. In their approach, a metamaterial having an ideal elliptic or a hyperbolic dispersion (without referring to concrete nano-structures) was used to support the propagation of waves with large transverse wave vectors. Then a planar plasmonic lens (PPL) was used to couple the waves in the metamaterial into the free space through a phase compensation mechanism. Based on this principle, we developed a cascaded superlensing system composed of a double layer metallic meander structure (DLMS) and a PPL. The DLMS is used to couple and support the near field waves and the PPL is used to magnify the image and transfer the waves into the far field. In this report, we study numerically the whole coupled system in the near field regime to demonstrate the functionality as a superlens and its limitation. The near field interactions among them are discussed and preliminary results of experimentally fabricated structures using focus ion beam machine will be demonstrated. The authors acknowledge support from the Deutsche Forschungsgemeinschaft.

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9526-37, Session 9

Calibration of the amplification coefficient in interference microscopy by means of a wavelength standard *(Invited Paper)*

Peter J. de Groot, Jake L. Beverage, Zygo Corporation (United States)

A fundamental measurement parameter for areal surface topography is the amplitude coefficient, which provides a scaling factor between the output of a measuring instrument and the final height map. Traditionally, the amplitude calibration has involved a mechanical step-height standard artefact (SHS), often carrying a certification from a vendor or laboratory qualified to link the step height to a realization of the meter. The specified uncertainty of certification of a commercial SHS is typically on the order of 0.5%, to which we add the uncertainty associated with the measurement of the SHS.

The use of an SHS for calibration is common to all 3D microscope systems, including interference microscopes for areal surface topography measurement. This is ironic and somewhat disappointing, given that interferometers are often used as primary length standards themselves. For example, one would never think of calibrating a laser Fizeau interferometer using gage blocks or other mechanical artefacts, as this would only degrade the uncertainty. The reluctance to calibrate an interference microscope in a similar way, using known wavelengths, relates to the uncertainty in the light source spectrum and the optical geometry of the instrument, particularly at high numerical aperture. The only available alternative calibration for a 3D interference microscope today is an entirely separate displacement-measuring interferometer integrated into the system to monitor the motion of the mechanical scanner.

Here we propose an in situ method for establishing the amplitude coefficient for a coherence-scanning interferometry (CSI) microscope that dispenses with the traditional SHS while avoiding the complexity of added hardware. The method begins by linking the spectral properties of the microscope illuminator to an independent realization of the meter, using a well-known lamp emission as a reference standard, and a narrow bandwidth interference filter to define the optical spectrum. For the optical geometry, we combine a low-magnification objective with a pupil-plane aperture and a precise calculation of the obliquity factor. We then use the interferometer itself as a means to link the wavelength standard to the motion of the mechanical scanner of the CSI system. The procedure involves acquiring data over a sufficiently long scan to entirely encompass the coherence envelope of the interference signal, followed by a digital Fourier transform, to determine the peak frequency and in this way the scan speed. Once the scan motion has been calibrated, we can perform measurements with any light source spectrum or objective, using the scan speed is the fundamental metric for scaling the height data.

An uncertainty budget leads to a defensible k=2 expanded uncertainty of 0.1%, which is significantly better than the usual quoted accuracy of interference microscopes, while greatly simplifying the procedure for calibration. An added benefit is the ability to map in detail the linearity of the scan motion, so as to measure and verify scan linearity.

9526-38, Session 9

In-line digital holography with double knife edge

Claudio N. Ramírez, Univ. Autónoma de Barcelona (Spain); Claudio C. Iemmi, Univ. de Buenos Aires (Argentina); Juan Campos, Univ. Autònoma de Barcelona (Spain)

We study and test a new technique for in-line digital holography which avoids the formation of the conjugate images. In-line digital holography is based in a common path configuration, this makes it less sensitive to vibrations and more compact. In this case, the hologram is produced by the interference between the reference wave front and the diffracted wave front by an almost transparent object. The image of the resulting hologram is acquired with a CCD and it is sent to a computer for processing. From this image, the wave front can be reconstructed in any arbitrary position by using a diffraction integral equation. Usually, the in-line recording architecture leads to the fact that both, the real focused image and the conjugate defocused image are reconstructed simultaneously. As a consequence, twin images are obtained with obscured rings that difficult the determination of the best focusing plane. To avoid the conjugate image, the information of the magnitude and phase of the wave front are needed. Usually, to extract magnitude and phase information of a wave front it is necessary to applied a phase shifting method. But, this requires the recording of four sequential interferograms, where the positions of particles may change.

In a recent work a new in-line digital holography technique was proposed. In this method the object is illuminated with a plane wave front. A plane, close to the particles distribution is imaged onto a CCD by means of a convergent lens and at the same time, a knife edge is placed in the focal plane of the lens in order to block half of spatial frequency spectrum. In this way, by means of a numerical processing performed on the Fourier plane, it is possible to eliminate one of the components (real or conjugate) of the reconstructed images nevertheless it is observed a tiny deformation of the resulting hologram image.

To compensate this effect, we propose a new configuration in which we implement the knife edge technique on both parts of the spectrum at the same time. The object is illuminated with linearly polarized light at 45º with respect to the vertical of the laboratory. The knife edge is substituted with a spatial light modulator (SLM) of liquid crystal (LCoS) with its fast axis at 90º. We sent to the LCoS pixels two gray levels such that we obtain two areas with different phase retardance. The border between the two areas acts as a knife edge. One half of the frequency spectrum is reflected without changes, while the other half is passing through a half wave plate, and then, its polarization is orthogonal to the previous one. Next, we split the amplitude of the wave front in two. We place a linear polarizer at +45º in one of the fronts and one at -45º in the other one. In this form, we obtain the knife edge effect in one position and its complementary at same time. Immediately, we use two CCD to record the two complementary holograms. Finally in the computer, we process the holograms to build one complete without deformations. This hologram is used to recover the wave front at different planes without the influence of the conjugate image.

9526-39, Session 9

Fourier analysis of quadratic phase interferograms

Jesús Muñoz-Maciel, Miguel Mora-González, Francisco J. Casillas-Rodríguez, Francisco G. Peña-Lecona, Univ. de Guadalajara (Mexico)

Fringe analysis from a single interferogram is necessary when experimental conditions do not permit the implementation of phase shifting techniques. The phase recovery from a single interferogram that contains open fringes can be carried out with the procedure developed by Takeda performing a pass-band filtering in the Fourier domain. However, such procedure cannot be implemented with interferograms with circular or elliptical fringes. Here we perform a Fourier analysis of such interferograms. The phase of the interferograms may be composed by a second order polynomial of two variables (x,y). The Fourier transform of the interferogram is seen to be also a sinusoidal function of a second order polynomial in both the real and imaginary parts. In this work we take a discrete Fourier transform of the interferogram and then we take separate inverse discrete transforms of the real and imaginary parts of the interferogram spectrum. This results in two new interferograms corresponding to the sine and cosine of the quadratic term of the phase modulated by the sine and cosine of the linear term. The linear term of these interferograms may be recovered with similar procedures of fringe analysis from open fringe interferograms. Once the linear term is retrieved the quadratic phase of the interferogram being analysed can also be calculated. The present approach may also be implemented for interferograms with nearly circularly symmetry given that the phase contains a small tilt. This occurs because the Fourier transform of an interferogram with a circularly symmetric phase will have also circular symmetry. Then the introduction of a small tilt will shift the lobules respect to the centre of the interferogram spectrum. Taking separate inverse transform of the real and imaginary components will results in the cosine and sine components modulated by the cosine and sine of the tilt term. The described procedure of Fourier analysis from quadratic phase interferograms of nearly symmetric interferograms may be implemented instead of complex and time consuming algorithms for phase recovery from fringe patterns with closed fringes. Finally, the method is tested in simulated and experimental data.

9526-40, Session 9

Phase retrieval based on diffraction element array with single far field

Shuai Wang, Ping Yang, Lizhi Dong, Bing Xu, Institute of Optics and Electronics (China); Mingwu Ao, Univ. of Electronic Science and Technology of China (China)

Phase retrieval based on single far field has a brief implementation compared with those methods who need two or several far-field images. But the multi-solution problem always prevents this method from moving forward. With just single far-field diffraction image, the phase distribution that conventional algorithms solve is usually quite different from the incident one. Therefore, this strategy is used for designing diffraction optical elements rather than recovering wavefront. On the other hand, we noticed that the widely used Shack-Hartmann (SH) wavefront sensor can reconstruct phase aberration very well with single far-field image. With the help of a diffraction element array, such as a lenslet array, the incident phase distribution is able to be acquired correctly by analyzing far-field intensity patterns of spot array. However, there is still one main existing problem that the spatial resolution of a Shack-Hartmann (SH) wavefront sensor is limited by the lenslet array strictly. Except the local tilt, wavefront details over the subapertures cannot be sensed or recovered. This limitation makes it difficult to improve SH wavefront sensor's measurement accuracy, except adopting more subapertures. Moreover, with very sparsely subapertures, SH wavefront sensing reconstruction algorithms, whether the model method or the zonal method, only perceive low frequency phase distortions. It is almost impossible to recover wavefront details in this conditions.

We proposed a kind of phase retrieval algorithm based on diffraction element array with just single far-field image. The simple and classical phase retrieval algorithm has been modified according to the complex amplitude transmittance function of the diffraction element array. Then the incident wavefront can be retrieved precisely with single far field through iterative calculating the diffraction between the incident near filed and the far filed behind the diffraction element array. In order to verify our method, we did the simulation experiments with randomly generated wavefront that contains 65 Zernike polynomials. For different input phase patterns, the method properly retrieved every distribution using just single sport-array images. The problem of multi solutions went away. With a dense or sufficient diffraction element array, or subaperture division, the SH wavefront reconstruction algorithms work very well. And our method could add much more wavefront details to their results and help SH wavefront sensor enhance the measurement accuracy dramatically which could exceed the spatial resolution of diffraction element array. Even with just a dozen subapertures, this algorithm also acquired 65 Zernike polynomials exactly while common SH wavefront reconstruction algorithms had already reached their limitation. There results shows that the proposed method is an effective way of retrieving phase with single far field. Meanwhile it fully utilizes the information

of spot-array intensity distribution, not just the centroid offsets, and retrieves wavefront much more accurately on the foundation of conventional algorithm with the same single far-filed image. So it is also a feasible method to improve SH wavefront sensor's spatial resolution and wavefront measurement precision upon present-existing reconstruction algorithm.

9526-41, Session 9

Dynamic stitching interferometric testing for large optical plane

Xin Wu, Shanghai Univ (China) and Univ. of Huddersfield (United Kingdom); Te Qi, Shanghai Univ (China); Linna Zhang, Zhengzhou University (China); Yingjie Yu, Shanghai Univ (China)

it is necessary to improve an accurate and efficient measurement method for efficiency of large optical plane machining. In this paper, a system is proposed to testing large optical plane in the workshop environment, which combined dynamic interferometry and stitching method. Dynamic interferometric stitching measurement experiment system is established, and with a lot of experiments, some problems were analyzed, including the relationships between the measurement accuracy and vibration, temperature and precision of mechanical structure. Computer simulation and experiment proves the validity of the proposed method.

9526-42, Session 10

Mueller matrix scatterometry: revisited from the viewpoint of computational metrology *(Invited Paper)*

Shiyuan Liu, Xiuguo Chen, Chuanwei Zhang, Hao Jiang, Huazhong Univ. of Science and Technology (China)

Ellipsometric scatterometry has gained wide industrial applications in semiconductor manufacturing after ten years of development. Among the various types of ellipsometers, Mueller matrix ellipsometer (MME) can provide all 16 elements of the 4 by 4 Mueller matrix, and consequently, MME-based scatterometry, or named Mueller matrix scatterometry, can acquire much more useful information about the sample and thereby can achieve better measurement sensitivity and accuracy. In this talk, we will review the principles and potential of MME in nanostructure metrology to provide a complete picture of this technique. We will first present the basic principles and instrumentation of MME, with a demonstration of the development of a broadband dual rotating-compensator Mueller matrix ellipsometer in our lab. Then we will introduce the concept of computational metrology and will revisit the data analysis in Mueller matrix scatterometry from the viewpoint of computational metrology. It is pointed out that Mueller matrix scatterometry is essentially a computational metrology technique by modeling a complicated forward process followed by solving a nonlinear inverse problem. Several case studies are finally provided to demonstrate the potential of MME in nanostructure metrology.

9526-43, Session 10

Measurement errors induced by axis tilt of biplates in dual-rotating compensator Mueller matrix ellipsometers

Honggang Gu, Chuanwei Zhang, Hao Jiang, Xiuguo Chen, Weiqi Li, Shiyuan Liu, Huazhong Univ. of Science and Technology (China)

The dual-rotating compensator Mueller matrix ellipsometer (DRC-MME) has been designed and applied as a powerful tool for the characterization of thin films and nanostructures. The compensators are indispensable optical components and their performances affect the precision and accuracy of DRC-MME significantly. Biplates made from birefringent crystals are common used compensators in the DRC-MME, and their optical axes invariably have tilt errors due to imperfect fabrication and installation in practice. The axis tilt errors cause a continuous deviation in the retardance of the biplate from its nominal value when the biplate rotates with the motor, which is difficult to be calibrated in the DRC-MME. In this paper, we propose a simple and valid formula to calculate the retardance of the biplate under arbitrary tilt angle and azimuth angle based on the ray tracing theory. Using this formula, we study different kinds of axis tilt errors in the rotating biplate compensator and analyse their effects on the measurement of the DRC-MME. We further study the relations between the measurement errors of the DRC-MME and the biplate axis tilt. Experiments on the measurement of the air Mueller matrix under different axis tilt errors are completed with a home-made DRC-MME, and the experimental results are presented and discussed. This work can be used to guide the selection, installation and commissioning of the biplate compensator in the DRC-MME to minimize or avoid the measurement errors due to the biplate axis tilt.

9526-44, Session 10

Development of Mueller matrix imaging scatterometry for nanostructure metrology

Xiuguo Chen, Weichao Du, Chuanwei Zhang, Hao Jiang, Shiyuan Liu, Huazhong Univ. of Science and Technology (China)

In order to achieve effective process control, fast, inexpensive, nondestructive and reliable nanometer scale feature measurements are extremely useful in large-scale nanomanufacturing. Among the possible techniques, optical scatterometry is relatively ideal due to its high throughput, low cost, and minimal sample damage. However, this technique is inherently limited by the size of the illumination spot providing the lateral resolution of the instrument as well as the low efficiency in construction of a map of the sample over a large area. Aiming at these issues, we introduce conventional imaging techniques to optical scatterometry and combine them with Mueller matrix scatterometry, which is expected to be a powerful tool for nanostructure metrology in the future large-scale nanomanufacturing, and propose to apply Mueller matrix imaging scatterometry (MMIS) for the measurement of nanostructures. The experimental results demonstrate that we can achieve Mueller matrix measurement and analysis for grating structures with pixel-sized illumination spot by using MMIS. We can also directly construct parameter maps of the grating structures over a large area with pixel-sized lateral resolution by performing parallel ellipsometric analysis for all the pixels of interest

9526-45, Session 10

Correction of depolarization effect in Mueller matrix ellipsometry with polar decomposition method

Weiqi Li, Chuanwei Zhang, Hao Jiang, Xiuguo Chen, Honggang Gu, Shiyuan Liu, Huazhong Univ. of Science and Technology (China)

Recently, Mueller matrix ellipsometry (MME) has been demonstrated as a powerful tool for nanostructure metrology in high-volume manufacturing. One of the critical procedures in MME is to acquire the accurate Mueller matrix spectrum of the sample. Many factors may induce depolarization effect in the Mueller matrix measurement, and consequently, may lead to accuracy loss in the nanostructure metrology, such as the finite spectral bandwidth of the monochromator, the finite numerical aperture (NA) of the focusing lens in the measurement system, the thickness nonuniformity in a thin film formed on a substrate, and the large surface or edge roughness of a sample. Among these factors, the finite bandwidth and finite numerical aperture are caused by the MME instrument, and cannot be avoided. In this paper, we propose to apply a Mueller matrix decomposition method for the Mueller matrix measurement to separate the depolarization effect caused by the MME system. The method is based on the polar decomposition by decomposing the

measured depolarizing Mueller matrix into a sequence of three matrices corresponding to a diattenuator followed by a retarder and a depolarizer. When the depolarization effect is mainly induced by the MME system, this effect will be only reflected in the depolarizer matrix. Therefore, we may simply use the other two matrices to extract the structure parameters of the measured sample. An experiment is performed on a one-dimensional silicon grating structure with a home-made MME layout, and it is expected that the proposed method could achieve a higher accuracy in the nanostructure metrology with the depolarization effect caused by the MME device.

9526-46, Session 10

Snapshot polarimeter based on the conical refraction phenomenon

Alba Peinado, Angel Lizana, Alejandro Turpín, Irene Estévez, Univ. Autònoma de Barcelona (Spain); Claudio C. Iemmi, Univ. de Buenos Aires (Argentina); Todor K. Kalkandjiev, Jordi Mompart, Juan Campos, Univ. Autònoma de Barcelona (Spain)

There are numerous fields where an accurate knowledge of the polarization state is relevant. For instance, in astronomy for detecting exoplanets, in remote sensing for characterizing the polarization signature of different scenes, in biomedicine for diagnosing and staging of some cancers and in material characterization for determining optical parameters of thin films, among others. Polarimeters are the basic devices to obtain polarization data by means of intensity measurements. Different architectures have been proposed, leading to different performances with strengths and weaknesses in terms of their metrological capabilities.

The conical refraction (CR) phenomenon occurs when light travels along one of the optical axes of a biaxial crystal, leading to a bright ring of light at the focal plane of the system. Besides other interesting features related to CR, intensity distribution along the focal plane ring depends on the state of polarization (SOP) of the incident beam. In particular, when illuminating with unpolarized light or circularly polarized light, there is a uniform intensity pattern along the ring. Whereas when illuminating with linearly polarized light, the ring is broken, having a maximum and a null of intensity in opposite diametrically points of the ring, and the orientation of that broken ring depends on the azimuth of the linear SOP.

In this work, we present a complete and punctual Stokes polarimeter based on the conical refraction (CR) phenomenon. We propose using the connection between the intensity pattern of the CR ring and the SOP of the incident beam as a new tool for polarization metrology. In order to implement a complete polarimeter, the instrument is designed with a beam splitter and two biaxial crystals (BCs), one BC for each sub-beam. In the second sub-beam, a retarder is introduced before the BC, allowing us to measure the ellipticity content of the input SOP. The two CR rings of light are simultaneously recorded with two CCD cameras. Finally, by conducting a data reduction calculation from these two raw images, the input SOP is fully characterized.

The CR-based polarimeter presents several appealing features compared to standard polarimeters. To name some of them, CR polarimeters retrieve the polarization state of an input light beam with a single snapshot measurement, allow for substantially enhancing the data redundancy without increasing the measuring time, and avoid instrumental errors related to rotating elements, such as beam wander, or to dynamic devices, such as a deviation of the calibrated phase-to-voltage function.

This work shows the design of the instrument, in particular the parameters of the set-up have been optimized in order to reduce the amplification of noise. Moreover, the effect of experimental error on the accuracy of the polarization measurements is analyzed. Then, the experimental implementation of the instrument is detailed, including some concerns and recommendations during the alignment of the experimental set-up. Finally, the implemented polarimeter is experimentally tested by measuring different states of polarization, including fully and partially polarized light.

9526-47, Session 10

Parallel aligned liquid crystal on silicon display based optical set-up for the generation of polarization spatial distributions

Irene Estévez, Angel Lizana, Xuejie Zheng, Alba Peinado, Claudio N. Ramírez, Univ. Autònoma de Barcelona (Spain); José Luis Martínez, Univ. Miguel Hernández de Elche (Spain); Andrés Márquez, Univ. de Alicante (Spain); Ignacio Moreno, Univ. Miguel Hernández de Elche (Spain); Juan Campos, Univ. Autònoma de Barcelona (Spain)

Due to the significant capability of Liquid Crystal Displays (LCDs) to spatially manipulate the phase information of an incident light beam, this technology is been widely applied in a large number of optical applications. Nowadays, they are employed as Spatial Light Modulators in many areas, for example, in Optical Image Processing, in Holography Data Storage, in Programmable Adaptive Optics, in Medical Optics, or in Diffractive Optics, among many others.

The Liquid Crystals on Silicon (LCoS) displays are a type of LCDs that work in reflection. Such devices, due to the double pass that the light beam performs through the LC cells, lead to larger phase modulation than transmissive LCDs with the same thickness. This appealing phase modulation capability, together with other technical characteristics, has caused that LCoS displays are nowadays a key optical element in a large number of applications which require producing, to a given incoming light wavefront, certain spatial phase modulation.

By taking advantage of this modulation capability exhibited by LCoS displays, in this work we propose a new experimental set-up which is able to provide customized state of polarization spatial distributions. Note that some specific polarization patterns are very interesting in some applications. For instance, cylindrical vector beams, of which radially and azimuthally polarized beams are a subclass, are especially interesting due to their very appealing properties upon focalization with high aperture lenses, or because their relation with the orbital angular momentum of light. Additionally, they are eigen-solutions of cylindrical resonators and optical fibers.

As provided in the literature, by using two Parallel Aligned (PA) LC panels, with 45 degrees between their LC directors, any state of polarization can be generated. Thus, with a proper pixel to pixel alignment between two PA LCoS displays, any desired spatial distribution of polarization may be generated, being the polarization pattern resolution limited by the pixel size. However, the requirement of using two LC modules noticeably increment the cost of the optical set-up, and in addition, a pixel-to-pixel alignment between the two different modules must be conducted, which increases the difficulty of the set-up implementation.

In this work, we provide a novel experimental design able to generate arbitrary spatial distributions of polarization by using a unique Parallel Aligned (PA) LCoS display. To this aim, a double reflection on different halves of the display is properly performed. This fact is achieved by including a compact optical system that steers the light and performs a proper polarization plane rotation. In addition, we do not only propose and analyze this new optical architecture, but the corresponding experimental implementation and set-up calibration are also provided and discussed. Finally, the suitability of the system is provided by generating different experimental spatial distributions of polarization, both uniform and non-uniform ones. In this last group, well-known polarization distributions, as axial, azimuthal or spiral linear polarization patterns are here implemented. Based on the excellent results obtained, the suitability of the system to generate different spatially variant distributions of polarization has been validated.

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9527-1, Session 1

Ultraviolet and infrared laser removal of crustose lichens from heritage dolostone *(Invited Paper)*

Marta Castillejo, Mikel Sanz, Mohamed Oujja, Carmen Ascaso, Asunción de los Ríos, Sergio Pérez-Ortega, Virginia Souza-Egipsy, Jacek Wierzchos, Mariela Speranza, Consejo Superior de Investigaciones Científicas (Spain)

Laser removal of biodeterioration films from stone has been investigated in foregoing studies. The action of Er:YAG laser, operating at 2940 nm, has been tested for the removal of lichens on limestone [1]. Elimination of biological crust from granite was studied in [2], using nanosecond laser pulses of 355 nm. In a previous work [3], we reported on the control of biodeterioration processes induced on dolostones by the lichen species Verrucaria nigrescens using a Q-switched ns Nd:YAG laser at 1064 nm. These previous investigations have shown that the laser effects on biological encrustations vary with the type of treated lithobiontic communities and with the petrographic and mineralogical characteristics of the substrate. Therefore, research aiming at examining and characterizing laser parameters for treatment of biological encrustations, while ensuring safe preservation of heritage stone substrates, is crucial for taking advantage of laser methods in the conservation of monuments and historical buildings.

Here we report on the laser removal of biological crusts on dolomite stone samples from heritage sites in central Spain. Monumental stones from Segovia and from an historical quarry in Redueña, Madrid, selected for laser treatment, presented superficial areas colonized by epilithic crustose lichens of the species Caloplaca sp. and Verrucaria nigrescens. A comparative study was carried out by applying infrared (1064 nm) and ultraviolet (355 nm) nanosecond pulses and sequences pulses of the two colours using a Q-switched ns Nd:YAG laser system, to identify irradiation conditions for damage and removal of epilithic colonizers and endolithic microbiota. To evaluate the structural and physiological damage inflicted on the biological material by laser irradiation, and also to assess possible morphological and chemical changes on the treated stone, we used several analytical techniques. Stereomicroscopy served to detect morphological changes, while cross sections of the treated stone samples were observed by scanning electron microscopy with backscattered electron imaging (SEM-BSE). This technique permits the assessment of the structural modifications of biological crusts and the fine monitoring of the action of the laser at cytological level. Fourier transform Raman spectroscopy was employed to identify possible structural and chemical changes on the irradiated stones. Dolomite is a lithotype widely used in construction all over the central region of Spain. Therefore the results derived from this study are of great significance in future planned conservation campaigns aiming at control of biodeterioration layers on heritage buildings and stone monuments.

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9527-2, Session 1

High-selectivity cleaning of historical paper samples with sizing through femtosecond laser ablation

Tansu Ersoy, Cetin Yaman, Istanbul Technical Univ. (Turkey); Mehmet Uguryol, Yildiz Technical Univ. (Turkey); Gurcan Mavili, Mimar Sinan Güzel Sanatlar Üniv. (Turkey); Selcuk Akturk, Istanbul Technical Univ. (Turkey)

Using lasers for cleaning of historical artifacts began in 1970's. In the first studies, stones have successfully been cleaned by laser irradiation. Laser cleaning of stone samples can be performed relatively easily and in a self-limiting manner due to strong color contrasts. During the last decades, developments in laser technology improved usage of this technique in art conservation, on various material types. On the other hand, laser cleaning of fragile and fibrous materials such as parchment and paper still remains challenging. High thermal loads and stress occurring during laser ablation can potentially damage the fibers. For this reason, lasers with femtosecond (fs) pulse durations can be more suitable for paper cleaning than lasers with longer pulse durations. When fs pulsed laser is used, non-thermal ablation occurs and there is no heat deposition in cleaned material. Consequently, fs laser cleaning minimizes damage to paper.

In this work, we concentrate on using non-thermal ablation by fs laser pulses for cleaning of paper samples; particularly those prepared according to common practices observed in Turkish-Islamic handwritten documents (such as application of sizing). In our experiments, historical and artificially aged papers in different states, colors and features are cleaned by Yb:Glass fs-laser which has 1030 nm center wavelength. In the first step of the study, we cleaned empty parts of the papers. The samples are placed on motorized stage moving in three dimensions. Laser beam is focused to a line on surface of the sample by means of cylindrical lens. Paper cleaning was carried out with different laser pulse energies. Over-bleaching was observed for excess energies, whereas minimal discoloration (with respect to clean regions) can be obtained at lower energies.

Next, in order to enhance practicality of the method, we work on automation of the laser cleaning procedure. The main challenge is to avoid original writings receiving laser irradiation. In our work, we adopted an approach commonly used in laser marking applications. We used galvo-scanners and f-theta lens to have a wide field of view on the sample. We than digitize the sample in black-and-white and subsequently converted colors. A computerized system then raster scans the beam over the sample surface, shutting the laser whenever white regions appear on the inverted-digitized control image. We demonstrate that the method is very efficient, safe and fast.

In conclusion, we have shown that fs-laser cleaning can be very efficient and art-friendly tool for cleaning of fragile paper samples. We also demonstrate automation procedure for application of the method in practical cases.

9527-3, Session 1

Evaluation of surface laser cleaning for restoration of tarnished silver artefacts

Teresa Palomar, Ctr. Nacional de Investigaciones Metalúrgicas (Spain); Mohamed Oujja, Consejo Superior de Investigaciones Científicas (Spain); Blanca Ramirez-Barat, Emilio Cano, Ctr. Nacional de Investigaciones Metalúrgicas (Spain); Marta Castillejo, Consejo Superior de Investigaciones Científicas (Spain)

Tarnishing is the most common alteration on silver artefacts produced by gaseous sulphur compounds from atmospheric pollution. It induces the formation of Ag2S deposits which produce the loss of shine and change of the surface colour (dark appearance). To remove sulphur tarnishing from silver artefacts, mechanical, chemical and electrochemical procedures were usually applied. However, these methodologies can generate surface alterations and a significant mass loss of the underlying silver. In recent years, lasers have been successfully used for cleaning of archaeological and historical metal objects; however studies to assess the effects of laser treatments on tarnished silver objects are scarce.

In this study we present the assessment of laser cleaning of tarnished silver. Different coupons of silver and sterling silver (92% Ag/ 8% Cu) with sulphur based deposits (Ag2S, Cu2S) were considered. Laser irradiation was carried out using a nanosecond Q-switched Nd:YAG laser emitting at the fundamental wavelength 1064 nm and its harmonics 532 and 266 nm. Six cycles of induced tarnishing and laser cleaning were considered on pure and sterling silver coupons to evaluate the effect in the long term. A set of analytical techniques to assess the physicochemical effects (surface morphology, composition, weight, colour and luminosity) accompanying laser irradiation were used, including optical microscopy, scanning electron microscopy/energy dispersive X-ray spectroscopy, micro-Raman spectroscopy and X-ray photoelectron spectroscopy.

In comparison to mechanical and chemical cleaning treatments carried out previously, laser removes the sulphur based compounds (Ag2S, Cu2S) without leaving cleaning residues. The optimal laser conditions for removal of the sulphur based deposits, while ensuring preservation of the underneath silver and silver/cooper metal substrates, were obtained for the laser irradiation at 532 nm.

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9527-29, Session PS

Microtopographic characterization of pre-colonial Brazilian archaeological ceramics

Manuel Filipe P. C. M. Martins Costa, Univ. do Minho (Portugal); Wagner V. Magalhães, Márcia A. Alves, Univ. de São Paulo (Brazil)

Optics and optics and photonics based inspection tools and methods had expensively proven their invaluable importance in the preservation of cultural heritage and artwork. The non-invasive inspection of the 3D shape of objects and of the micro-relief structure of its surfaces can be of high importance in the characterization process required in most works of restoration or preservation of archeological artwork. In this communication we will report on the non-invasive optical microtopographic characterization of the surface of pre-colonial ceramics and pottery of hunter-recollector-farmer' tribes of the Paranaiba valley in Minas Gerais, Brazil. The pottery found is decorated with incisions with different geometric distributions and levels of complexity corresponding to two periods of indigenous Indian occupations: one from a period dated at 1,095 ± 186 years ago and another of the early nineteenth century dated between 212 ± 19 years and 190 ± 30 years ago seemingly corresponding to the occupation of the territory by southern Kayapós tribes.

9527-30, Session PS

Thermal imaging method to visualize a hidden painting thermally excited by far-infrared radiations

Tanguy Davin, Xingkai Wang, Abderrahim Chabane, Romain Pawelko, Géraldine Guida, Bruno Serio, Philippe Hervé, Univ. Paris Ouest Nanterre La Défense (France)

Optical techniques are powerful and versatile tools for the diagnosis of works of art. Infrared methods are often used in non-destructive testing of materials for inspecting or identifying defects using an either passive or active approach. Passive Infrared thermography is an easy technique to implement since measurements can be performed quickly and surfaces to analyze can be very large. This technique is then well suited to visualize surface alterations. For instance, the aging of a work of art can be studied. However, the technique is not really suitable to visualize elements such as paintings hidden under an opacifiant layer covering a fresco. Most of the time, this kind of layers are made of lime or plaster and have been deposited on a work of art often for a historical reason. Since these materials are semi-transparent in the far infrared domain, which is not the case of the painting, masked painting recovery becomes possible. Indeed, thermal radiation of the painting depends on the emission of its pigment. Terahertz cameras are still not sensitive enough to detect radiation through a covering material without excitation. Active approaches are then generally used. Classical optical method used to probe this kind of layers consists in exciting the surface in the mid-infrared domain. The first drawback of this approach is the relatively high absorbance of the covering material, highly reducing the contrast of the thermal imaging signal. The second one is due to the reflection of the infrared light occurring on the covering surface, which produces camera glare effect.

In this study, another approach for which far infrared radiation is considered as the excitation source is proposed. Since the absorbance of the covering material is highly reduced in this wavelength domain, the two unwanted effects encountered with the classical method are canceled. Indeed, far infrared radiations, which are poorly absorbed by the covering material, are applied to the surface of the painting. The painting heats up and by thermal conduction, temperature rises in the covering layer. Analysis is then based on the visualization of the covering surface temperature by an usual infrared camera.

The paper will present this new method based on a temperature rise localized at the interface between a lime layer and a painting layer. In order to achieve this, far infrared radiations, namely in the 20 μm – 200 μm wavelength range, have been used as thermal excitation source. A high resolution, mid-infrared camera, at around 5 μm working wavelength has been employed for the lime surface heat conduction thermal effect visualization. With this camera, a detection limit before signal processing of about 20 mK has been obtained. Both the technique principle and materials spectral transmittance measurements in far infrared will be presented. Finally, reconstituted images of mural samples covered by a lime layer will be shown. Since the lime is often used to hide some murals, this method represents a major interest for both curators of historical monuments and other actors of the heritage.

9527-31, Session PS

'Cranach inc.' A case study determining the nature and extent of Lucas Cranach the Elder's involvement in his industrious workshop using image processing

Ruth Lubashevsky, Ben Gurion Univ. of the Negev (Israel)

The world of art history research is undergoing revolutionary changes in recent decades. It was only a matter of time until technological advancements will be harnessed as scientific tools which have introduced a whole host of new and exciting possibilities in art research, and allowed access to information that wasn't even dreamed possible just a few decades ago. Scientific tools such as infra-red and X-ray imagery, chemical analyses (such as pigment analysis and carbon dating), etc., enable researchers to quantify what was considered for centuries unquantifiable, better understand the creation process of artworks and

artists, and determine more accurately the time and location in which artworks were brought into existence. The significant contribution of these tools to the efforts of art authentication and attribution is undeniable.

However, the use of novel methods in art research often seeks to dethrone long-existing schools of research, rather than complement them in order to paint a more comprehensive picture. This is precisely what my proposed research sets out to accomplish. I will argue that in addition to breaking down artwork to its physical properties, there are other established approaches, namely connoisseurship and art historical research, which remain relevant and still have much to offer in art attribution. I will therefore endeavor to develop a three-pronged approach using connoisseurial, historical, and technical viewpoints to formalize an all-inclusive process to correctly and accurately attribute artwork.

I will demonstrate this approach using the German Renaissance artist, Lucas Cranach the Elder's (LCE) astonishing oeuvre amounting at 1,000 artworks, of which 857 known panel paintings survived. By means of these three viewpoints, the conclusion of this paper, based inter-alia on comparisons between Infra-red images and the visible-light paintings, I will argue that as of 1518, the year Cranach opened his huge workshop, he becomes virtually non-existent in the hundreds of paintings still widely attributed to him.

The conclusion of this paper, based inter-alia on comparisons between Infra-red images and the visible paintings, shows that the 8 surviving panel paintings from 1500-1505, are rightfully attributed to LCE, as opposed to his years in the castle workshop, where out of the 44 panel paintings, it appears that 20 belong to LCE, 12 to his apprentices and 11 are collaborations. Those attributed in this paper to LCE display the style from his early years in the Infra-red images as opposed to the finished painting. Of the 132 panel paintings from his first workshop in the town of Wittenberg, only 7 can be attributed to LCE according to Infra-red images, 8 are collaborations and 117 are his apprentices'. As of 1518, the year he opened his huge workshop, LCE becomes virtually non-existent, producing a meager three panel paintings, while 669 panels may be attributed to his apprentices.

9527-33, Session PS

Quality assessment of the TLS data in conservation of monuments

Jakub S. Markiewicz, Dorota Zawieska, Warsaw Univ. of Technology (Poland)

Laser scanning has been recently confirming its high potential in the field of acquiring 3D data for architectural and engineering objects. Terrestrial laser scanners are used for fast, remote acquisition of spatial data. These lasers differ with respect to their measuring range, field-of-view, the accuracy of measurements, the speed of data acquisition, robustness and size. The basic input data is supplied by the scanner in the form of point clouds – the cloud of point, i.e. the set of consisting of hundreds thousands reference points of known x, y, z spatial co-ordinates. Then data registered in this way may be used for creation of 3D models of objects or their 2D projections.

Usually architects or monuments conservators are not only interested in geometric relations, but also in information about the surface. Therefore the point cloud acquired from laser scanning is often amended with vertex descriptors, containing information about the colour and the reflectance intensity from measured surfaces. The majority of monumental buildings are highly complicated constructions. Depending on the period of origin, they may differ in geometric typology, the system of construction, the size of elements and the type of applied building materials. The geometric analysis of monumental constructions is important for the understanding of their current status, including damages and destruction of materials, as well as for the spatial modelling or creation of other, metric products (such as orthoimages), for the needs of further conservation or inventory of a given monument. 3D modelling of monumental objects with the use of the TLS data in not an easy task. Before the measurements it is necessary to learn not only the geometry of the object construction and its particular elements, but also to gather the knowledge concerning the accessibility for measuring stations and the reflectivity and the structure of analysed surfaces. The terrestrial scanner technique is usually applied for 3D modelling of monumental objects. The high accuracy of reconstruction of geometric shapes of a given historical object is not always required. The TLS has been more often applied for sophisticated investigations in the field of the cultural heritage.

The objective of this paper is to analyse the quality of the TLS data acquired for different surfaces of monumental objects, with consideration of distances, scanning angles and the number of stations. Tests concerning the quality of the survey data and shapes of architectural objects, characterised by diversified curvature, structure and the uniformity of the surface, were also performed. Performed tests proved that the utilisation of the terrestrial laser scanning technique does not allow for achieving the expected results for some surfaces of monumental objects. In such cases it should be substituted by other, alternative, photogrammetric techniques. Therefore the typology of constructions of monumental objects is important for the selection of the optimum technique of surveys, but also for its appropriate utilisation.

The test sites were the historical buildings and details of the Palace Museum of King Jan III's Palace at Wilanów. Scans were acquired using the Z+F 5006i scanner, with consideration of variations in the distances, the scanning angles, and the intensity of the laser beam. Different geometry of scans was tested, together with the analysis of relations between the specified number of scans and the achieved real accuracy. In the case of operations performed by conservators it is often important to precisely reconstruct the surface, in order to specify its damages. Therefore the repeatability of acquired data for different historical surfaces was also analysed. External, as well as inner surfaces were analysed, which are covered not only by gilded elements, but also which have the heterogeneous structure, and surfaces containing different fabrics or other materials of this type.

Obtained results and presented conclusions may be useful for various groups of historians of arts or architects. They may be applied in investigations performed by conservators, where the speed of surveys, as well as the precision and repeatability of results are required.

9527-34, Session PS

The influence of environment on corrosion of cast iron and carbon steel representing samples of outdoor metal technical heritage

Marek Strzelec, Jan A. Marczak, Wojciech Skrzeczanowski, Antoni Sarzy?ski, Military Univ. of Technology (Poland); Anna Zatorska, Academy of Fine Arts, Warsaw (Poland); Krzysztof Czy?, Military Univ. of Technology (Poland); Dariusz Zasada, Military Univ of Technology (Poland)

The paper presents the results of annual measurements of the corrosion progress at test samples of cast iron and carbon steel placed in the different natural environment. The main aim of the analyses was the diagnosis of maintenance needs and the development of the most adequate protection process. Comparative tests were performed in two outdoor stations, one at the Railway Museum in central Warsaw and one at the Railway Museum location in the small town of Sochaczew, 50 km west of Warsaw. Test metal samples in both locations included four plates made of carbon steel and four plates of cast iron. Additionally, the influence of surface roughness on corrosion development was determined by two kinds of treatments of all sample surfaces, using (1) metal brush and (2) grinding. One set of both materials was removed and tested quarterly, and replaced by a set of fresh plates to study the influence of seasons. Environmental measurements at the Warsaw Railway Museum indicated a medium corrosivity for the atmospheres, which is typical of northern European inland environments with low chloride concentrations and a relatively low SO2 concentration. Measurements in Sochaczew showed a significant contribution to corrosion from anthropogenic sources, with SO2 as the main pollutant.

Stratigraphy and composition of corrosion products in quarterly periods were analysed with laser-induced breakdown spectroscopy (LIBS) and Raman laser spectroscopy as well as a scanning electron microscopy (SEM) system equipped with an energy dispersive spectrometer (EDS), and micro-chemical analytical methods using sections of samples. Comparing the materials and surface roughness of samples, the

corrosion layers on carbon steel were on average thicker than on cast iron, and thicker on the brushed parts of both materials. If we compare the location of samples, a thicker corrosion layer was found on the cast iron test samples exposed in Sochaczew than in Warsaw. The last result was confirmed by LIBS stratigraphy of Al content. Aluminium is a trace element in steel and cast-iron composition, but typical of atmospheric deposits, which easily penetrates into iron corrosive layers. Different iron oxides, namely lepidocrocite, goethite, hematite and magnetite were identified in the surface Raman spectra of corrosion layers, the last compound only in the sample from Sochaczew. SEM EDS measurements of surface elemental concentrations showed a higher concentration of sulphur in all samples from Sochaczew.

Registered LIBS spectra have been additionally analysed with statistical approach. Namely, the Principal Components Analysis (PCA) and Factorial Analysis FA) have been applied. Both methods come down to an orthogonal conversion of an input object set of any nature (input matrix) by a linear combination of new, non-correlated, sometimes non-observable characteristics called principal components or factors and allow comparing objects or sets consisting of many variables and quick finding the most important similarities and differences. The PCA/FA methods applied to various samples in the successive measurement periods clearly indicate that corrosion and deposition processes taking place on samples surface occur in a different way in both tested locations and even on brushed and grinded surfaces on the same sample even though they are situated close to each other. The PCA/FA analyses showed that additional historical samples, taken from steam locomotives had been made of various steel materials (at least from various casts). Results generally confirmed conclusions drawn from SEM/Raman/LIBS results.

9527-35, Session PS

Painting recognition with smartphones equipped with inertial measurement unit

Andrea Masiero, Alberto Guarnieri, Francesco Pirotti, Antonio Vettore, Univ. degli Studi di Padova (Italy)

In the last decade several works have been proposed in the literature to take advantage of the diffusion of smartphones to improve people experience during museum visits. The rationale is that of substituting the traditional museum written and/or audio guides with interactive electronic guides directly usable on a mobile phone. Furthermore, augmented reality systems are usually considered in order to make the use of such electronic guides more simple to use for the end user.

Indeed, augmented reality systems allow to integrate the information already visible to the human eye with a (potentially large) amount of additional information on the subject of interest to the user. The key point for the success of such system is clearly its usability, e.g. in terms of ease of use (easy human interaction with the system), ability in retrieving information of major interest with low effort by the user, speed (small waiting time), and clearness in presenting the information.

In such a system, the achievement of the main goal (providing the user with the information of his/her interest) can be obtained by properly executing the following three tasks: recognizing the object of interest to the user, retrieving the most relevant information about it, properly presenting the retrieved information to the user (and allow him/her to simply interact with the system in order to improve the obtained results).

This paper focuses on the first of the tasks listed above. To be more specific, here we consider the problem of painting recognition by means of measurements provided by a smartphone, i.e. we assume that the user acquires one image of the painting of interest with the standard camera of the device. Then, such acquired image is compared with a set of preloaded reference images of the museum objects in order to recognize the object of interest to the user. Since comparing images taken in different conditions (i.e. acquired by different points of view) can lead to unsatisfactory recognition results, the acquired image is typically properly transformed in order to improve the results of the recognition system: first, the system estimates the homography between features matched in the two images (the user and the reference image). Then, the user image is properly transformed accordingly to the estimated homography. Finally, the obtained image is compared with the reference one.

This work proposes a novel method to exploit IMU measurements to improve the system performance, in particular in terms of computational load reduction. For instance, IMU measurements are exploited to dramatically reduce the computational burden required to estimate the transformation to be applied to the user image before being compared with the reference image. Furthermore, IMU measurements are used to reduce the number of reference images to be compared with the user image, as well.

Performances of the proposed method are investigated on a data set of images acquired in a museum in Padua, Italy.

9527-36, Session PS

Characterization of multispectral imaging systems on frescoes: CMOS versus scanning devices

Raffaella E. M. Fontana, Istituto Nazionale di Ottica (Italy); Jana Striova, European Lab. for Non-linear Spectroscopy (Italy); Marco Barucci, Enrico M. Pampaloni, Istituto Nazionale di Ottica (Italy); M. Raffaelli, Istituto Nazionale di Ottica, INO-CNR (Italy); Claudia Daffara, Carlo Reghelin, Univ. degli Studi di Verona (Italy); Paola Illaria Mariotti, Opificio delle Pietre Dure (Italy)

Near-Infrared (NIR) reflectography is a well-established techniques for painting diagnostics, offering a fundamental contribution to the conservation of paintings. Since the '80s it has been routinely applied to study the execution technique of the author, as well as the presence of pentimenti (an alteration in a painting, evidenced by traces of previous work, showing that the artist has changed his mind during the process of painting), retouches, integrations or underdrawing (the drawing done on a painting ground before paint is applied). In the last decades IR reflectography has been extended to the visible (Vis) spectral range, providing information about the pigment composition. Up to now the multispectral analysis is still applied at an experimental level, as the processing of the image set is not straightforward.

Rarely multispectral Vis-NIR application has been applied to frescos, probably due to the lack, in most cases, of a scattering background.

In this work we present a characterization of the performance of two devices for multispectral imaging: a CMOS array camera, working in the 300-1050 nm spectral range, and a scanning device (single sensors), working in the 380-2500 nm. The camera is custom designed for multispectral full-range acquisition starting from low-cost commercial-grade components, while the multispectral scanner is a laboratory prototype specifically built for research-grade imaging. The aim is to validate the camera, through the comparison with the scanner, and to enable the complementary use of the two instruments in situ.

The two technique have been applied on a sample where an underdrawing, made of either carbon or iron-gall ink, were covered by different surface layers of limewash (the so-called scialbo).

9527-5, Session 2

High resolution Fourier domain optical coherence tomography at 2 microns for high depth of penentration *(Invited Paper)*

Haida Liang, Chi Shing Cheung, Nottingham Trent Univ. (United Kingdom); Jae M. O. Daniel, Univ. of Southampton (United Kingdom) and Aether Photonics (Australia); Masaki Tokurakawa, Univ. of Southampton (United Kingdom) and The Univ. of Electro-Communications (Japan); W. Andrew Clarkson, Univ. of Southampton (United Kingdom); Marika Spring, The National Gallery (United Kingdom)

Optical Coherence Tomography (OCT) is by now a well-established technique in biomedical imaging. In recent years, its applications in art

conservation, history and archaeology along with other non-biomedical fields that require non-invasive imaging have been expanding. However, one of the limitations of OCT is the probing depth for materials that are either highly absorbing or highly scattering. It is known that for most materials, the optical scattering coefficient decreases with increasing wavelength. A recent systematic survey of paint transparency found that the optimum spectral window for OCT imaging of paint is around 2.2 microns. However, since most biomedical materials contain water which absorbs strongly around 2 microns, most OCTs were not built at this wavelength. The situation is different in non-biomedical applications such as the non-invasive imaging of paintings where there are many materials with low water content. As proof of concept we first developed a time domain OCT with an ASE source developed in-house. While it demonstrated the improved depth of penetration, the bandwidth of the ASE source was still too narrow to give the high resolution required to resolve most paint layers and the time domain OCT was slow and therefore time consuming to image an area large enough for the study of underdrawings. In this paper, we demonstrate a Fourier domain OCT using a newly developed supercontinuum source with 220nm bandwidth at 1960nm. We present the first Fourier domain OCT developed in the 2 micron wavelength regime that allows fast, efficient capturing of 3D image cubes at a high axial resolution of 9 micron in paint.

9527-6, Session 2

Surface reconstruction from photometric normals with reference height measurements

Lindsay W. MacDonald, Univ. College London (United Kingdom)

The photometric stereo technique enables the normal at each point of an object surface to be determined for a single viewpoint, using the principle that the intensity of the reflected light depends on the angle of incidence of the light onto the surface. With a perfectly Lambertian surface and in the absence of noise, only three intensity values from non-coplanar light sources would be sufficient to solve for both normal direction vector N and surface albedo ?, but this does not give the correct result for a non-Lambertian surface. The solution of the photometric stereo equations causes the surface normal to be orientated closer to the specular direction vector S than it actually is, producing a distorted normal N'. A new method has been developed to estimate surface normals more accurately by solving the photometric normal equations as a regression over a set of illumination angles and intensities selected from the subset corresponding to the diffuse component of reflection from the object surface (the 'body colour').

The normals calculated by the bounded regression method and the resulting gradients for a test object (a terracotta relief of Chopin) are shown in Fig. 1. The P gradient ($\partial I/\partial x$) and Q gradient ($\partial I/\partial y$) are encoded so that zero is mid-grey, white is maximum positive and black is maximum negative.

We seek an effective method of integrating the gradients to reconstruct a digital terrain map, with a value for height at each point on the pixel array. A suitable technique was introduced by Frankot & Chellappa, using the Fourier transform to regularise (i.e. enforce integrability of) the gradients in the frequency domain.

Applying this technique to the Chopin gradients yields a 3D surface that is continuous and is recognisably Chopin (Fig. 2 left), but is distorted over the whole area with the height greatly amplified (Fig. 2 right). The problem is that although the gradients give a good representation of the spatial frequencies in the surface, right up to the Nyquist frequency, they are not accurate for very low frequencies of a few cycles over the full object diameter. Such frequencies are represented in the Fourier plane by only a few sample points close to the (shifted) origin. Errors in these frequencies can result in 'curl' or 'heave' in the baseplane, even though the superimposed higher spatial frequencies may be accurate. The solution is to replace the inaccurate low frequencies of the photometric normals by the more accurate low frequencies of a surface constructed from a few known heights. This can be conveniently achieved from the values measured by the digital height gauge (Fig. 3) by interpolating to produce a smooth 'hump' and then transforming into the frequency domain by an FFT.

9527-7, Session 2

Combined use of OCT and macro-XRF for examination of easel paintings

Magdalena A. Iwanicka, Bogumila J. Rouba, Justyna Olszewska-Swietlik, Marcin Sylwestrzak, Piotr Targowski, Nicolaus Copernicus Univ. (Poland)

Optical Coherence Tomography (OCT) is well established albeit not very popular technique for examination of subsurface, semi-transparent layers of easel paintings. By non-invasive visualisation of cross-sections of structures it permits localisation and thickness determination of varnish and glaze layers within the structure. The instrument, used in this study was built in our laboratory especially for examination of object of art and offers 3 μm axial and 12 μm lateral resolutions within the imaging cube 1.4 x 17 x 17 mm3. It is, however, not capable of revealing a chemical composition of structures visualised.

Macro-XRF is a novel variation of the popular energy dispersive X-ray Fluorescence examination capable of detecting elemental composition of the object examined. In this case the extensive surface scanning is performed and the maps of distribution of chemical elements are generated from large areas. The results to be reported in this study have been obtained with M6 JetStream scanner from Bruker-nano GmbH, Germany capable of recording maps of dimensions up to 800 x 600 mm2 with adjustable lateral resolution from 650 ?m down to 50 μm due to the policapilary optics.

In this contribution, using various examples of easel paintings examined in our laboratory, we will show how both techniques used together at the same location provide complementary information on the structure of the painting. The obtained data can be used for examination of the painter's technique as well as to identify the character and range of former restoration interventions.

9527-8, Session 2

Signal processing and optimization of optical coherence tomography measurements of wood coatings

Liesbeth M. Dingemans, Vassilis M. Papadakis, Ping Liu, Aurèle J. L. Adam, Roger M. Groves, Technische Univ. Delft (Netherlands)

Optical Coherence Tomography (OCT) is a contactless and non-destructive technique based on low-coherence interferometry. Transparent and semi-transparent samples can be measured using the light reflections from the interfaces and their stratigraphy can be mapped by reconstructing cross-sectional and volumetric images. Recently, OCT has been growing as a popular technology in the field of non-destructive testing, with applications ranging from detecting damages in aerospace materials to examining museum objects. As a non-destructive technique, OCT provides better resolution than ultrasound and better image contrast of deeper structures than confocal microscopy. This is one of the reasons why the use of OCT has recently become popular in the field of cultural heritage with applications ranging from investigating paintings to examining an 18th century violin. However, research using OCT to study coatings functioning as protective layers for wood has not yet been performed extensively.

In this study, coatings on wood surfaces and their penetration into wood structures were measured with a customized fiber optic OCT system. This prototype system was able to perform both time-domain and Fourier-domain OCT (TD-OCT and FD-OCT) measurements, by using an optical delay line (ODL) or a NIR spectrometer respectively. The operational wavelength of the superluminescent diode source is 1550 nm, with a full width at half maximum (FWHM) of 60 nm and a coherence length of 34 μm in air. The resulting spot size is 20 μm and the axial resolution is 11 μm inside the coating layer (n=1.55).

In order to enhance the understanding of the OCT measurements of coatings on real wooden samples, optimization of the measuring and analyzing methodology was performed. This was achieved by performing a number of reference measurements both in TD-OCT and FD-OCT, by

assessing different averaging approaches and by post-processing the data.

To fully understand the analytic capabilities of the technique, wood coatings with an average thickness of roughly 150 μm deposited on a silicon wafer have been developed and analyzed. Due to the high reflectivity of the polished silicon wafer at the used wavelength in combination with the low surface roughness, the reference samples could be used to test the techniques for imaging the coating, to determine certain coating parameters such as the refractive index and to assess the noise present in the setup. Preliminary measurements from the reference samples have shown that both TD-OCT and FD-OCT are successful in imaging thin coating layers with an average depth resolution of 15 μm, however noise and artifacts distort the images. The main noise in the TD-OCT system is due to nonlinear acceleration of the ODL. This has made it difficult to extract the real positions of reflection peaks. In addition to that, it appeared that even small surface height and profile variations resulted in a diminished intensity at the detector.

In TD-OCT, averaging a number of A-scans at a single point helped to overcome problems such as accurately determining the real positions of the primary peaks resulting from the air-coating interface. In the case of FD-OCT, averaging measurements taken at different axial shifts played a role in reducing noisy artifacts. Post-processing took into account uncertainties or noise arising from the setup and successfully corrected for it by alignment of the primary peaks. In addition to that, by for example aligning the secondary peaks in a line scan occurring from the coating-substrate interface, the coating thickness over a certain line segment can be estimated. However, for deteriorated wooden samples with a high surface roughness, mathematical alignment of peaks resulted into a loss of information regarding the actual surface profile.

Signal optimization has also been used on real case samples consisting of naturally aged and deteriorated coated wood and the results of this signal optimization have shown that the sensitivity of the measurements increased. In addition, when combing the signal optimization with post-processing, it may be possible to adapt the obtained data, taking into account certain disrupting sample parameters such as surface roughness. A comparison between the raw, signal optimized and post processed data will be shown and further discussed.

Finally, in order to better understand the surface and in-structure features in the obtained data from real deteriorated and aged coatings on wooden samples, OCT measurements will be complemented by other techniques as hyperspectral imaging and terahertz imaging. The unique character of OCT and its advantages will be discussed for all different applications (studying damages, monitoring absorption, measuring thickness) and for different possible end users (paint producers, cultural heritage researchers).

9527-11, Session 3

Resolution limits in holographic display with LED illumination

Maksymilian Chlipala, Tomasz Kozacki, Warsaw Univ. of Technology (Poland)

Holography is the only known technique which allows to reconstruct 3D objects as they appear in real life. Therefore building holographic display would certainly revolutionize display industry. In consequence numerous application of such device would be found in entertainment as well as in science. One of them is 3D imaging of cultural heritage objects.

The most optimal way to realize holographic display is the application of spatial light modulators (SLM). There are two types of SLMs: amplitude-only and phase-only. They can be treated as diffractive optical elements which modulates incident light and controls amplitude or phase of reconstructed field. Phase-only are usually chosen in holographic display since they provide higher diffraction efficiency and improved quality of reconstructed image. Direct design of holographic display with phase-only SLM require some propagation distance. However by limiting bandwidth of the SLM and applying appropriate coding and decoding techniques it is possible to produce proper complex wave modulation by either amplitude-only and phase-only SLM. This allows to obtain correct hologram reconstruction near or even in plane of the modulator.

Holographic display systems designs are mostly based on coherent sources. Such illumination has significant drawbacks. It is dangerous for eyes and it produce high speckle noise in reconstructed image. Incoherent illumination provides solutions to this problems. The most efficient way to build holographic display is to apply LED illumination in its design. They are safe and have large power. Moreover LED are economically beneficial. They are cheap and widely available. On the other hand coherent laser source can produce hologram of infinite depth while incoherent sources introduce limits in holographic reconstruction in both: depth and resolution. It is therefore very important to investigate and optimize influence of this effects.

In this work theoretical investigation of spatial and temporal coherence effects on the resolution and the depth of hologram reconstruction obtained in single phase-only SLM holographic display with LED illumination is performed. The paper theoretical analysis are proven with presented computer simulations. Presented theory and simulations are based on the analysis of the partially coherent diffraction patterns. To experimentally validate theoretical results series of hologram reconstructions with varying distances from SLM plane are provided. This allows to evaluate volume of 3D reconstructions and to optimize light source which can be used in holographic display design.

Additionally in the paper high quality hologram reconstructions obtained with incoherent LED illumination are shown. The build of holographic display setup employs complex modulation achieved by Fourier filtering in 4F imaging system. In presented system several LEDs are applied as light sources. High quality holograms here reconstructed not only with single color LED but also with white light LED as well. During experimental tests hologram of different content are presented: 3D cloud of point hologram achieved for art objects, real hologram obtained from holographic registration and flat object holograms.

9527-12, Session 3

Light calibration and quality assessment methods for reflection transformation imaging applied to artworks analysis

Claudia Daffara, Andrea Giachetti, Carlo Reghelin, Univ. degli Studi di Verona (Italy)

Reflection Transformation Imaging is becoming a popular tool for the acquisition of paintings and other kinds of artworks, due to the possibility of performing the acquisition with a simple setup based on a camera, a single light source and a reflective sphere for the estimation of the illumination direction (Dellepiane et al. 2006, Earl et al 2011). This kind of setup is quite low cost, flexible, and portable, being therefore particularly suitable for the acquisition of large surfaces of artworks e.g. mural paintings and bas-reliefs on site.

However, the results obtained with this simple setup may be not suitable for the quantitative analyses derived from the RTI reconstruction and proposed in the literature - as normal estimation, 3D reconstruction, material classification (Wang et al. 2009) - due to lack of uniformity in the illumination intensity and direction.

This fact is a relevant limit for the possible exploitation of the acquired data because the accuracy in the recovery of details and the possibility of having a good characterization of the reflective properties of materials are extremely important in Cultural Heritage applications, as they could give relevant hints for the historical analysis of the artworks and to understand and recognise different painting techniques. Errors in the assumptions regarding the illumination pattern may also create artifacts in the shape detail reconstruction and may affect the correct interpretation of the data.

In this paper we analyse these problems and propose a novel method for the characterization of the light source used and the automatic correction of the pixel intensity of the input images, testing it both on static LED sources and flash lights. Furthermore, by means of a specifically designed 3D printed pattern, we analyzed the accuracy of the acquisition obtained both for spatial discrimination of small structures and normal estimation, thus evaluating the effects of the image acquisition and preprocessing choices on the resulting quality of the reconstruction. In this way it is possible to derive standard procedures and guidelines that can be considered as a starting point to turn the cheap and common RTI acquisition setup from a simple way to enrich object visualization into a powerful method for extracting quantitative characterization of surface geometry or of reflective properties of different materials.

Preliminary tests aimed at characterizing and discriminating different

materials used in mural paintings demonstrate the usefulness of the proposed approach.

9527-13, Session 3

Test monitoring of the Centennial Hall's dome, Wroclaw (Poland)

Lukasz Jan Bednarz, Jerzy Jasienko, Tomasz Nowak, Wroclaw Univ. of Technology (Poland)

Centennial Hall is a unique venue on the map of Poland, where history harmoniously interacts with modernity. Centennial Hall was designed by Max Berg, an architect and constructor, an outstanding city architect, and recognized as one of the top masterpieces of the 20th century architecture, the most famous work of Wroclaw Modernism. Its structure was erected between 1911 and 1913, and its interiors held Centennial Exhibition to commemorate 100th anniversary of Napoleon's defeat at Leipzig. Wroclaw's debate on establishing permanent recreational and exhibition grounds was started already in the 19th century. Developing city needed a major characteristic structure with capacity to hold a large number of exhibitors and visitors. Facility was to be erected in the grounds of Szczytnicki Park, in the place of a former horse racecourse. Max Berg, a municipal construction adviser at the time, was awarded the contract to develop Wroclaw Exhibition Grounds. In the early 1911, Berg presented his first sketches of the structure. Despite numerous objections, the City Council approved implementation of the Architect's visionary design.

The designer assumed that the Hall was to serve citizens of Wroclaw and visitors to Lower Silesia's capital city, and it continues to perform this function successfully. Multi-purpose space, unusual structure, unique and spacious location represent just a few of its strengths. Centennial Hall complex currently is one of the most desired venues among domestic and foreign organizers of major exhibitions, conferences, cultural, sport and congress events. The Hall's inscription on UNESCO World Heritage List in 2006 emphasized the rank of this facility. Undoubtedly it is one of the most characteristic flagships of Wroclaw in the international scale, and exceptionally magic site in the city where the charts of history record its multi-generational experience.

The most important element in the Centennial Hall structure is tension ring of the dome. Authors of the paper present the results of measurements made in tension ring of the dome. Measurements were made using the total station theodolite (TST) and 3D laser scanner. The analysis results are based on software Reconstructor Gexcel. The FARO Focus3D X 330 laser scanner is specially designed for outdoor applications due its small size, light weight, extra-long range, extended scanning possibilities even in direct sunlight and easy positioning with to the integrated GPS receiver. Reconstructor software was designed to easily create 3D colored models using High Resolution RGB images acquired both from the cameras mounted on the laser and from independent external cameras. Software create mesh models from point clouds or import mesh from third parties software, calibrate and map full resolution RGB images on mesh models and extract High Resolution orthophotos for a perfect colored representation.

9527-14, Session 3

3D Wayang Kulit: traditional shadow puppetry meets modern display technology

Gea O. Parikesit, Univ. Gadjah Mada (Indonesia)

Displaying shadows stereoscopically in three dimensions may help to preserve the art of Wayang Kulit, i.e. the UNESCO-listed traditional shadow puppetry originated in Indonesia. This paper presents the optical engineering of stereoscopic shadows as applicable for a Wayang Kulit performance. Using a set of governing equations that is developed using the geometrical optics of shadows, we perform numerical analysis on how various parameters can influence the stereoscopic shadows. Experimental demonstration of the method is described using a model setup of Wayang Kulit. Our results may provide useful technical guidelines not only for Wayang Kulit puppeteers but also for all shadow puppeteers in general who desire to use stereoscopic three-dimensional display in their performances.

9527-25, Session 3

Cultural heritage applications of ultrafast pump-probe microscopy *(Invited Paper)*

Tana E. Villafaña, Martin C. Fischer, Duke Univ. (United States); William P. Brown, North Carolina Museum of Art (United States); John K. Delaney, Michael Palmer, National Gallery of Art (United States); Warren S. Warren, Duke Univ. (United States)

The three dimensional (3d) structure of a cultural heritage object holds the key to understanding the history of the object and the methodology of its making, as well as the necessary information for proper treatment. For a painting, the 3d structure is often studied by the removal of a cross-section sample that is subjected to a multitude of analytical techniques (1). While there are a number of important noninvasive techniques that allow for the material investigation of historic artworks, such as Raman (2,3), reflectance imaging spectroscopy (4) and x-ray fluorescence (XRF) intensity mapping (5), none of these techniques can provide quantitative depth information. Pigments are highly scattering and absorptive, which makes traditional light microscopy a poor choice for providing optical sectioning. There are a growing number of noninvasive 3d imaging techniques that are under active research; confocal XRF, absorption near edge structure imaging (XANES) (6), optical coherence tomography (OCT) (7) and terahertz imaging (8). While promising, OCT and terahertz imaging cannot provide pigment specific contrast, while x-ray techniques are more suited for pigments with heavier elements (9,10).

Nonlinear microscopies, a mainstay in biomedical and biological imaging applications (11), can provide optical sectioning in highly scattering media and here; we apply a novel nonlinear imaging technique (femtosecond pump-probe optical microscopy) to a cultural heritage research (12). Femtosecond pump-probe optical microscopy detects molecular signatures from a wide range of multi-photon processes (13), which can be utilized to create high-resolution 3d images with chemical contrast. This technique was recently demonstrated in a 14th century painting, The Crucifixion by Italian artist Puccio Capanna (14), creating virtual cross-sections of thick and complex pigment layers.

Here we demonstrate the broad utility of pump-probe microscopy to cultural heritage research. First we correlate pump-probe dynamics with Raman spectroscopy in order to understand the molecular origin of our nonlinear signal in natural and synthetic ultramarine pigments, with sub-crystal resolution. We also investigate the dependence of our pump-probe signature on pottery firing conditions and on the ratio of the indigo dye to its binding medium. Second we image indigo and ultramarine pigments (using their unique pump-probe contrast) while simultaneously collecting nonlinear fluorescence from their paper supports, localizing the pigments within cotton, wood pulp, Whatman, and linen papers. Finally we attempt a completely noninvasive investigation of two 15th century Italian roundels, in an effort to discern if both works are from the workshop of Lorenzo Lotto, by applying pump-probe microscopy in-lieu of the physical removal of a cross-section sample. Sampling areas were chosen based on the collective noninvasive analysis from FORS, XRF, and macroscopic photography techniques. The pump-probe virtual cross-sections indicate that the two roundels were painted with a highly different methodology. These results highlight the sizable impact pump-probe microscopy can have in cultural heritage research and also the ability of the technique to provide complementary information alongside traditional methods of study.

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9527-15, Session 4

Design, construction and performance of a high-resolution near-infrared (1000-2500 nm) hyperspectral camera for paintings and works on paper *(Invited Paper)*

John K. Delaney, National Gallery of Art (United States); Damon M. Conover, The George Washington Univ. (United States); Kathryn Dooley, National Gallery of Art (United States) and The George Washington Univ. (United States); Suzanne Lomax, National Gallery of Art (United States); Murray H. Loew, The George Washington Univ. (United States)

Imaging spectroscopy, the collection of hundreds of contiguous narrow-band images, offers an improvement over site-specific fiber optic reflectance measurements by combining both spatial and spectral information. In prior studies we have utilized optimized portable Si CCD and InGaAs transmission grating hyperspectral cameras to map and identify artist pigments in Old Master paintings, such as the panel of Mary in the Early Italian Renaissance painting 'The Annunciation with Saint Francis and Saint Louis of Toulouse' (c. 1475) by Cosimo Tura [1]. These cameras have been modified to include high sensitivity focal plane arrays (e.g. cooled backside illuminated Si CCD array and low noise, high gain InGaAs array) to achieve the required signal to noise at flux levels of 1000 lux. These cameras have allowed us to collect reflectance and luminescence spectral image cubes from 400 to 1680 nm with a few nm sampling. To map and identify paint binders, we have utilized a novel hyperspectral camera utilizing an InSb detector array operating from 1000 to 2400 nm with 4.4 nm spectral sampling and 90 pixels per inch spatial sampling. By limiting the illumination from 1650 to 2400 nm, adequate signal to noise was obtained in order to map the weak spectral binder features found in the 1700 to 2400 nm region. Using this camera we mapped the selective use of animal skin glue and egg yolk in 'The Annunciation with Saint Francis and Saint Louis of Toulouse' [2].

Here we also report on the design, fabrication and testing of a new hyperspectral camera with higher spatial/spectral sampling and light sensitivity for the near infrared (1000 to 2500 nm). The camera consists of a telecentric lens fore optic, transmission grating spectrometer, a telecentric relay lens with external exit pupil and a low noise InSb array having a digital ROIC with 12 micrometer square pixels. The 1280 by 1024 pixel array operates at 70K and is cooled by a Stirling cooler. The use of a relay lens having an external exit pupil and detector array with a cold stop and optimized cold filter has reduced the effective dark current to allow long exposures (10 to 100's of msec). The camera has a spectral sampling of 2.8 nm per pixel with a spectral response function of 7 to 9 nm (FWHM). The spatial sampling is 250 pixels per inch. The measured peak signal to noise is 700:1 at 1600 nm from a white standard illuminated by four 125-watt lamps on a rheostat (1000 lux in visible) and integration time of 150 msec per image line. Artwork can be scanned using a whiskbroom mirror or using the Gallery's computer-controlled easel. Over 10 paintings have been imaged to map pigments and binders, as well as to reveal compositional paint changes. Works studied to date have included paintings by Van Gogh, Fragonard, Pollock, and Rembrandt.

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9527-16, Session 4

Automated analysis of large scale remote spectral imaging of paintings

Sotiria Kogou, Golnaz Shahtahmassebi, Andrei Lucian, Chi Shing Cheung, Nottingham Trent Univ. (United Kingdom); Bomin Su, Dunhuang Academy (China); Haida Liang, Nottingham Trent Univ. (United Kingdom)

Spectral imaging is increasingly being adopted as a non-invasive tool for the analysis of historical paintings and objects. However, large scale imaging is still limited due to the time constraints on data capture and analysis. It is therefore important to design systems and methods for efficient and automated data capture and analysis. PRISMS, the remote spectral imaging system developed in our group for high resolution remote multispectral imaging at standoff distances of tens of metres was designed for efficient large scale imaging of paintings of any size including ceiling paintings at heights of tens of metres. The basic form of PRISMS is low cost and operates in the 400-900nm range using 10 broadband filters for efficient data capture with a trade-off in spectral resolution. Given that most painting material have only broad spectral features in this wavelength range, higher spectral resolution will only improve specificity in the identification of a handful of pigments. Nevertheless, we complement the large scale multispectral imaging with high spectral resolution Fibre Optic Reflectance Spectroscopy (FORS) at selected points. In addition, we complement the optical reflectance spectra (PRISMS and FORS) with elemental information from XRF. Spectral imaging has been shown to have the capability of revealing faded or 'hidden' writings in the UV (reflectance or fluorescence) or NIR spectral bands or through taking difference images depending on the different compositional makeup of the writings/drawings, paint and substrate. In this paper, we explore imaging and spectral processing methods to automatically reveal faded writings and drawings without a priori knowledge; and demonstrate pigment identification including degraded pigments using a multimodal technique. Examples based on data from the UNESCO site of Mogao caves in the Gobi desert will be illustrated.

9527-17, Session 4

The role of the masonry in paintings during a seismic event analyzed by infrared vision

Fernando López, Univ. Federal de Santa Catarina (Brazil); Stefano Sfarra, Univ. degli Studi dell'Aquila (Italy); Clemente Ibarra-Castanedo, Univ. Laval (Canada); Dario Ambrosini, Univ. degli Studi dell'Aquila (Italy); Xavier P. V. Maldague, Univ. Laval (Canada)

Masonry construction has been used for at least 10,000 years in a variety of structures, such as historical monuments. The masonry of ancient times involved mainly two materials: bricks, manufactured from sun-dried mud or burned clay and shale; and natural stones.

The detection of the masonry's morphology is a concern for the restorers when it is used as support in paintings, and it is not possible or desirable to proceed with the separation or tear methods that might damage the structure. The earliest examples of mural paintings are just hand prints made with liquid coloring matter around 30,000 BC. Later mural paintings were conceived as part of an essentially open physical system, a consequence of contact with contiguous structures (arriccio, sinopia, plaster, intonachino, paint layer). It is well known that both, the plaster and the paint layers are structures in which the pores can intercommunicate easily. The same concept can be extended to the connection among stones and the arriccio (the first coat of plaster) layer.

The structural performance of masonry can be understood by retrieving: a) its geometry, b) the characteristics of its texture, and c) the characteristics of masonry as composite material. Strictly speaking, single or multiple leaf walls are used as support in the realization of mural paintings. In these types of artworks the a) and c) points are well-known.

As L. Binda and A. Saisi correctly affirmed, the worst defect of multiple leaf masonry walls is that they are not monolithic in the lateral direction. This is not the case of the present research work. Firstly, because the supports explored by infrared thermography (IRT) are constituted by a single leaf. And secondly, because the sides of the inspected paintings are confined inside marble frames or buried horizontal and vertical structures. Hence, the analyzed paintings can be considered as monolithic structures. IRT can help to understand the masonry morphology if exist structural continuity between the arriccio layer and the support, i.e., if the mural painting is free of insulating layers of air. In this case, if the heating provided by lamps or propane gas is enough to reach the support, the masonry texture can be visualized. The application of image processing techniques greatly enhances visualization of internal features. Pulsed phase thermography (PPT), principal component thermography (PCT), and partial least squares thermography (PLST) techniques were used in order to enhance the contrast among subsurface characteristics of the paintings investigated. Two paintings are preserved inside the Santa Maria della Croce di Roio Church in Poggio di Roio (L'Aquila, Italy) and executed on two masonries built in different times, while the last one was realized in Montorio al Vomano (Teramo, Italy) on the internal walls of the Zoccolanti's Church (1580). These two villages are separated by 50 km, and were partially destroyed by 2009 earthquake. During the seismic event, the role played by the masonry is linked to the formation of surface defects.

Finally, near-infrared reflectography (NIRR) technique is used to investigate the healthy state of the painting layer.

9527-18, Session 4

Semi-automatic system for UV images analysis of historical musical instruments

Piercarlo Dondi, Claudia Invernizzi, Maurizio Licchelli, Luca Lombardi, Marco Malagodi, Tommaso Rovetta, Univ. degli Studi di Pavia (Italy)

The selection of representative areas to be analyzed is a common problem in the study of Cultural Heritage items. UV fluorescence photography is an extensively used technique to highlight specific surface features (e.g. restored parts or treated with different materials), which cannot be observed in visible light. UV radiation penetrates only superficial levels, so it is not possible to see the fluorescence of underlying paint coats; however the resulting image can be used as a guide to apply further not destructive techniques such as X-ray fluorescence spectroscopy (XRF) and Fourier transform infrared spectroscopy (FTIR).

This imaging technique seems to be particularly useful in the study of historical musical instruments. Our research concerns the study of Stradivari violins stored by "Museo del Violino" in Cremona. Due to the limited availability of the instruments, it is very important to speed up the scientific analyses. Here we propose a new semi-automatic solution for selecting areas with the same perceived color (a simple clue of similar materials) on UV photos, using a specifically designed interactive tool.

The proposed method works in two steps: (i) users select a small rectangular area of the image; (ii) program automatically highlights all the areas that have the same color of the selected input. The result is more accurate than a manual selection, because it can detect also points that users do not recognize as similar due to perception illusion.

Although the region selected by the user could be sensed as an almost uniform color area, it is actually composed by a range of colors with small variations in hue and some outliers caused, for example, by small cracks in the wood, variations in painting or noise generated by the high exposure time needed in UV photography. To overcome these issues and find the correct range of hues, the program applies different refinements. Firstly a median smooth is applied to remove the artificial noise and make the surface more uniform. Then the color model of the image is converted from RGB to HSV (Hue, Saturation and Value), a model more similar to the human perception. The most diffused color inside the input area coincides with the peak in the Hue histogram. A low pass filter is applied to it before the peak selection, in order to compensate the outliers. The median of the Value channel of the chosen area provides a further refinement. The search is made with a certain tolerance in a neighborhood of the found peak to detect all the zones with a pattern similar to the selected one. So it is possible finding a specific color in a specific range of lightness. Saturation channel can be used in alternative or in combination with the Value one, but it is generally less influent in this context, so its application is limited only to particular cases. Default experimental tolerance thresholds are adopted, but expert users can modify them on-the-fly.

We are now collecting a database of more commonly colors/materials present on UV photos of violins to allow the users to choose directly a color from a predefined list avoiding the manual selection. The application has been developed following the rules of usability, and Human Computer Interface has been improved after a series of tests performed by expert and non-expert users.

9527-19, Session 5

Mid-infrared thermal imaging for an effective mapping of surface materials and sub-surface detachments in mural paintings: integration of thermography and thermal quasi-reflectography *(Invited Paper)*

Claudia Daffara, Univ. degli Studi di Verona (Italy); Simone Parisotto, Univ. of Cambridge (United Kingdom); Paola Ilaria Mariotti, Opificio delle Pietre Dure (Italy)

Cultural Heritage conservation is discovering how precious is thermal analysis as a tool to improve the restoration workflow, thanks to its ability to inspect hidden details. Most used techniques for investigation of in-depth defects are based on the acquisition of the LWIR band, emitted by the object, in passive or active (after heat stimulus) modes. A limit of the long infrared imaging is a typical low resolution and the fact that around room temperature (safe for artworks) the emission is largely affected by reflections, leading to spurious information. For this reasons, a precise mapping of fine delaminations is impracticable. Differently, the mid-IR band exhibits lower optical diffraction and background radiation, which give a sharper imaging with a better contrast. Moreover, mid-IR can be used also as a reflective band, suitable to gain information about the materials on the surface layer. This was well demonstrated with the introduction of the recent Thermal Quasi-Reflectography (TQR), with great results for art-diagnostics.

In this work we demonstrate an effective procedure in the mid-IR based on the integration of thermography and thermal quasi-reflectography to investigate the detachments in mural paintings and produce a reliable map of the defects over a large surface. This is of great importance in restoration processes as the tracking of detached areas is still done by "knocking" on the wall.

The method is shown on the notable Monocromo by Leonardo da Vinci in Italy.

We performed a dual-mode acquisition based on fixed geometry and multiple excitation sources set-up in order to capture two spatially registered dataset: the thermal images in quasi-reflectography modality and the high-frame thermal sequences in emission modality after long-pulse heat stimulus. We employed a scientific-grade FLIR X6540sc

camera, InSb 640x512 sensor with mid-IR sensitivity, available thanks to the FLIR company). The acquisition setup was adapted to obtain a spatial resolution of less than 0.5 mm.

For each section, the thermographic sequence was used for the inspection of sub-surface defects; the TQR image was used for inspection of the surface materials and it was used for referencing the thermogram with the visible. The TQR response, after calibration with a reference target in-scene, allows under some restrictions an estimation of the emissivity from the reflectances. Differences in pixel emissivity are, anyway, a difficult issue in the thermography of artwork. Thermal decay response is affected by the presence of different kind of materials, original or from past restoration, both in the sub-surface and in the surface layers. Due to the complexity of material stratigraphy the segmentation problem was solved using statistical descriptors.

For the restorer it is mandatory to obtain a high resolution map of the defects perfectly referenced to the visible image. In order to do this, we captured different areas and solved the referencing and mosaicking problem first for the TQR dataset (affine transformation, optical and radiometric corrections) and then we applied the mask to the thermal sequence. We finally obtained the visible, TQR, and thermal maps perfectly spatially registered, that represented a valuable tool for the restoration of the detaches.

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9527-20, Session 5

Optical characteristics and visual appearance for artwork materials

Michela Radis, Paola Iacomussi, Istituto Nazionale di Ricerca Metrologica (Italy); Chiara Aghemo, Politecnico di Torino (Italy)

The purpose of any museums or art exhibitions is to guarantee the correct conservation of exhibited artwork, and to assure the best visual and conceptual appearance of artefacts in order to improve the observer experience. To hit this mark, is necessary to know how the interaction of incident light radiation, material optical properties and observer affect the perception of visual attributes (colour, gloss, etc.) of the art works.

The available measurement methodologies for characterize the optical physical properties of materials useful to study the visual perception are based on methods and quantities not perfectly homogenous with the human perception or not enough accurate when new lighting systems are involved (i.e. Solid State Lighting -SSL). Indeed the available methodologies were developed for materials different from cultural heritage materials. Therefore, new measurement methods or corrections factors are necessary for a better application of the available results especially when color perception and visual enjoyment experience are fundamental as in the case of works of arts expositions.

The main goal of this study is to evaluate experimentally, through objective and subjective investigations how the interaction between SSL sources and material optical properties (i.e. spectral reflection factor) affect the human perception of visual attributes of artworks exhibited, providing useful indications for works of art exhibition designers.

Two pair of identical polychromatic images (one couple with warm colours and one with cold colours) were spectrophotometrically characterized and exposed under two different lighting conditions to observers judgments.

The observer had to compare and judge at the same time, the two identical images under two different lighting: one with SSL and one with non-SSL lighting sources (i.e. fluorescent and incandescent sources), the two sources had the same CCT (Correlate Colour Temperature) but different colour rendering index. Then with a questionnaire the perceived visual attributes (hue, saturation, brightness) of samples in function of the lighting condition were evaluated.

The subjective data were statistically analysed and compared with objective results calculated from the spectral reflectance factor using the available methodologies for hue, saturation, brightness evaluation, with the aim was of investigate if the objective results and the available methods of evaluation are in harmony with subjective responses.

The results show that the perception of visual attributes (hue, brightness, saturation) differs from objective data when SSL sources are involved and when colours are perceived in complex samples (the samples were polychromatics). For example the results show that in some cases the visual perception is less sensible to colour differences than the available methods for predicting colour differences (the so called ?E): in fact the visual system is more permissive as the colour constancy principle shows.

In the paper the whole research, subjective analysis and materials characterisation correlations are showed and the correlation with model prediction are analysed.

9527-21, Session 5

Terahertz and hyperspectral imaging of a Tanda painting

J. Bianca Jackson, The Univ. of Reading (United Kingdom); Marcello Melis, Profilocolore Srl (Italy); Gillian C. Walker, The Univ. of Reading (United Kingdom); David Giovannacci, Dominique Martos-Levif, Lab. de Recherche des Monuments Historiques (France); John W. Bowen, Lab. de Recherche des Monuments Historiques (France) and The Univ. of Reading (United Kingdom); Matteo Miccoli, Profilocolore Srl (Italy); Vincent Detalle, Lab. de Recherche des Monuments Historiques (France)

We systematically examined the mid-20th century Italian painting "After Fishing" (Figure 1) by Ausonio Tanda using multi-spectral (UV, RGB visible, tri-band IR), x-ray, and terahertz time-domain spectroscopic imaging for comparison. For the multispectral measurements, we used a Nikon D800FR (Full Range) camera. This is a 36megapixel reflex camera modified under a Nikon/Profilocolore common project, to achieve a 300-1000nm range sensitivity. THz-TDSI was performed in both transmission and reflection geometries using a fiber-coupled Picometrix T-Ray 4000 time-domain spectrometer with a raster scanner. The painting's specific pigments and binder are unknown, but assumed to be modern. The support is a cardboard composite.

In transmission, qualitative comparisons were made between the x-ray density image (Figure 2a) and THz images calculated using the time-domain peak analysis—including maximum, minimum and peak-to-peak amplitude (Figure 2b), and pulse power integration—and frequency domain analysis (Figure 2) between 0.1 and 0.7 THz. Figure 3 shows the principle component analysis of a region of interest between the x-ray density image and the time-of-flight of the transmitted terahertz pulse. It indicates that that many features appear in both the x-ray and THz images, despite the difference in spatial resolution quality. However, the terahertz images reveal absorbing spot-like features in the painting which do not correspond to features visible on the painting surface or in the x-ray. These features are likely to be defects in the support.

In reflection, qualitative comparisons were made between the reflectance images at the seven separate optical bands and the terahertz images calculated from the first pulse reflection in the time domain and the frequency domain between 0.1 and 0.7 THz (Figure 4). The time-domain terahertz image shows many similarities to the UV reflectance, with the exception of the higher reflectance of the pigments used for the box and blanket. A few of the defective spots, though not all, were also visible only in the terahertz images. It was found that the image quality was significantly reduced above 0.3 THz due to the curvature of the support. Additional analysis was done on subsurface reflections to confirm defects observed in the THz transmission images.

The availability of the spectral reflectance of the whole examined artwork, pixel by pixel, allows us to make comparisons between all the pixels of the image to determine the multi-variant spectral similarity with respect to a fixed pixel. Figure 5a shows the spectral reflectance, using all seven components, of regions with least spectral similarity as blue and greatest similarity as red; while Figure 5b includes the x-ray density component.

Acknowledgements

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9527-22, Session 5

Case study of Sainte-Marie Chapel, Fontaine Chaalis (France): complementarity of different optical techniques

David Giovannacci, Vincent Detalle, Dominique Martos-Levif, Lab. de Recherche des Monuments Historiques (France); Jonh W. Bowen, Gillian C. Walker, The Univ. of Reading (United Kingdom); Kamel Mouhoubi, Jean-Luc Bodnar, Univ. de Reims Champagne-Ardenne (France); Vivi Tornari, Eirini Bernikola, Kostas Hatzigiannakis, Foundation for Research and Technology-Hellas (Greece)

The abbey's church of Chaalis, in the North of Paris, was founded by Louis VI as a Cistercian monastery on 10th January 1137. The chapel was built in the 13th century, and has 16th century mural paintings by F. Primaticcio. Since the 16th century, several interventions (including reconstruction and restoration of the paintings) have been carried out in the chapel and on the mural paintings. A large and well documented campaign of works had been implemented by the end of 2005.

In 2013, in the frame the European Commission's 7th Framework Program project CHARISMA [grant agreement no. 228330] the chapel was used as a practical case-study for application of the work done on WP Best practices and protocols toward common standards , task devoted to historical buildings and monuments: multidisciplinary analysis and monitoring.

Three areas were identified as relevant for our case study. The general map of the chapel is presented in figure 1, where the 3 zones are located.

The first zone was used to make an exercise on diagnosis of the different deterioration patterns: what, where, how many, why? The second zone was used to analyze a restored area: where has it been done, are the problems still pending, what are the products and where were they used? Can we produce map of deterioration? Can we produce any assessment of the reversibility of the treatments used? The third zone was selected to test some hypotheses on the possibility of using the portable instruments to answer some questions related to the deterioration problems.

For all the 3 zones, the same approach was followed:

1. a condition report on the zone, made by a conservator-restorer, with mapping of the different painting techniques and the deterioration patterns

2. An image made by picture on picture superimposition, of one technique on another one, to enhance the complementary of the different methods.

To inspect this area, different tools were used:

- Visible fluorescence under UV. A methodology developed by LRMH allows the study of the visible fluorescence to be carried out, due to UV excitation and the recognition of the color coordinates of different products. The setup is composed of a LED UV light, in a restricted range of UV and a simple camera. The color coordinates obtained are compared with a home made database

- THz system. All experiments in this paper were carried out using a Picometrix T-Ray 4000® (TR4K) THz-TDS system, which generates pulses of picosecond duration. It is these ultrashort pulses which are reflected from any variation in the refractive index of the wall plaster (caused by paint layers, air gaps, cracking etc.), back to the detector, giving an indication of the sub-surface construction of the wall up to 1 cm in depth

- Stimulated Infra-Red Thermography (SIRT). The experiments were done with a FLIR B20 HS LW ® I.R. camera. The stimulation was done under IR Lamp (6 mm), with an heating time of 3 min. This system is able to detect defects under the surface up to a depth more than 2 cm. These defects are usually voids or delaminations. This technique can also detect the presence of metallic leaf due to the high reflectivity of this material.

- Digital Holographic Speckle Pattern Interferometry (DHSPI). The surface under examination is illuminated by the laser light and the scattered light interferes with a reference wave from the same laser and that image is recorded on a CCD video camera, digitized, and stored on a computer. By comparing subsequent images, deformations become visible as "dark and bright correlation fringes" showing isolines of equal displacements. DHSPI based on Holography principles allows reaching of high spatial frequencies that carry the information from the object. he object's surface is naturally or artificially excited, in-homogeneities in the surface and in the bulk of the object are expressed in differences in optical displacement.

- Condition report by conservator-restorer.

The complementarity and synergy offered by the profitable use of the different integrated tools is clearly shown in this practical exercise. For example, the conservation report and SIRT pictures give the same information but with different accuracy.

By this work on the field we can see that a gradual answer can be reached based on detailed observation of the artwork and the damages. Then, the dialogue with the stakeholders can start immediately during the diagnosis operation.

9527-23, Session 5

Photogrammetry in maritime and underwater archaeology: two marble wrecks from Sicily

Caterina Balletti, Francesco Guerra, Paolo Vernier, Univ. Iuav di Venezia (Italy); Carlo Beltrame, Univ. Ca' Foscari di Venezia (Italy); Elisa Costa, Univ. Iuav di Venezia (Italy)

Underwater survey, compared to land archaeology, needs specific techniques, because the application of some active 3D sensor, such as laser scanner, is obviously impossible. The necessity to produce three-dimensional survey, offering the same accuracy of classical terrestrial laser-scanning or photogrammetric methods, combined with the request of low costs and rapid solutions, led the researchers to test and apply oftentimes image-based techniques.

In the last two years the Ca' Foscari University and University IUAV of Venice are conducting a research on the application of integrated techniques to support underwater metric documentation, comparing them to the manual traditional one. The gained experience (and confirmed by other recently published papers) shows that the actual multi-image digital photogrammetry is a good solution for the underwater archaeology. This approach is useful both from a metric and a recording point of view, because it achieves high quality results, such as accurate 3d models or 2d representations, offering a complete documentation of underwater sites.

But photogrammetry has to be supported by a topographical survey (to acquire ground control points - GCP) to georeference all the finds in the same reference system.

This paper presents the integrated survey of two roman shipwrecks, approaching differently in the GCP's acquisition just for the different morphological characteristic of the sites.

The wrecks' cargos are huge marble blocks, presenting differences in quantities, layout and depths. Those characteristics determine the choice of the topographic survey.

The first shipwreck, near Marzamemi in south-east Sicily, has 14 marble blocks, columns, pseudo-columns and squared items, positioned scattered on the seabed, some of them far from the principal cluster. This involves a subdivision of the photogrammetry in four different clusters, which are then positioned in the same reference system with a trilateration method.

The realized trilateration on numbered markers, placed on the upper side of some blocks, has been computed as a 3d topographic network using rigorous Least Squares techniques. In this case study, the topographic net adjusted only 3d distances observations. The main problem was the Datum's definition, which is the alignment of the Z axe on the vertical direction.

The coordinates are in a relative local system, which can be then georeferenced by GPS' survey in the world system.

The second shipwreck, near Granitola in south-west Sicily, is an homogeneous cargo of 65 squared marble blocks, found in stowage position; the depth of the wreck is about 3 meters under the sea level.

In this case study markers on the block were surveyed by GPS RTK's measurement mounting the antenna on a 4 meters pole. The master

station was positioned on a IGM trigonometric point.

The dense point cloud coming from the photogrammetric block was referred to GPS GCP.

A photogrammetric strip was realized for each wreck, as in aerial photogrammetry. As a matter of fact the photographer "flies" swimming over the shipwreck. Moreover, other oblique (45°) strips were acquired for a better coverage. All the images (about 300 for each site) were aligned in the same time with Photoscan software, realizing a single wide photogrammetric block. Some CGP were not used in the absolute orientation phase but later as check points in order to evaluate the final accuracy.

The results of the survey are two 3d polygonal textured models of the sites which can be easily used for different analyses and reconstructive hypothesis, opening new possibilities of documentation with both specialists and the wider public. 3d models are the geometric base for 2D orthophotos e cross section extraction.

The paper will illustrate all the phases regarding the survey's design, acquisition and realization and the data processing to obtain 2d and 3d final representation.

9527-24, Session 5

Spectral characterization as a tool for parchment analysis

Michela Radis, Paola Iacomussi, Giuseppe Rossi, Istituto Nazionale di Ricerca Metrologica (Italy)

Spectral Reflection Factor (SRF) and Spectral Transmission Factor (STF) are physical characteristics own of a material, able to describe how a material modifies the incident light radiation. SRF (STF) is measurable with specific devices, called spectrophotometers, able to analyze spectrally the incident luminous flux and the reflected (or transmitted) flux emitted by material in different geometrical conditions of measure.

Usually, alterations of conservations conditions of historical parchments are identified by physical-chemical analysis. However, these techniques are micro-destructive and not always suitable to characterize historical parchments because it is always necessary to take small samples.

The paper presents an investigation on the correlations spectral characteristics, SRF and STF, of parchment and its conservation conditions with the scope of define a NON invasive methodology for spectral investigations able to detect and monitor deterioration process in progress in historical parchment without the need of taking small samples.

In order to verify the feasibility and define the most appropriate measurement method, several samples of contemporary parchments produced using historical techniques from different animal species (lamb, goat and calf) and with different degrees of artificially induced damage, were analyzed.

The SRF and STF of each sample were measured in the same point, before and after each step of the artificial deterioration process. Having at disposal a parchment coming from a whole lamb leather, it was possible to study the correlations between the variations of SRF/STF and intrinsic factors of sample, such as anatomic variability of animal skin and/or manufacturing, assessing the sensitivity of measuring method and reference spectrum with accuracy limits.

The definition of a reference spectrum with accuracy limits is a fundamental step for understanding measurement results of historical parchments: the research demonstrated that every animal species has its own spectral signature and that the method has high sensitivity in recognizing variations, but the reference spectrum with accurancy limits allows to confirm that measured alterations are due to damage process in progress and not to the variability of the parchment.

The method has been applied to characterize the conservation conditions of two historical parchment rolls stored at the Archivio di Stato di Torino and the results will be show in the paper. The first roll, called "Peveragno", dates 1430 while the second roll, called "Contége", dates 1457. The SRF (STF) of both rolls was acquired in several point of the roll, the average spectrum of each roll was compared with the reference spectra with the relative tolerance limit. Thus, it was possible to appreciate the damage degree and to exclude that alterations of SRF are due to the heterogeneity of historical sample. Moreover, it was possible to identify the origin animal species of the parchments.

In conclusion, the developed metrics allows to obtain a quantitative and overall assessment of damage conditions of historical parchments and it is non-destructive investigation. Furthermore, to know the spectral characteristics of historical parchments is useful also for evaluate what are the optimal lighting conditions for exhibition and to improve the legibility of document. The comparison between SRF of historical parchment and the reference spectra showed that the damage suffered from the samples of contemporary parchments, exposed to artificial deterioration processes, is greater than the damage suffered from the historical parchments in the course of six centuries.

Indeed, the artificial aging processes, generally used, don't follow the recommendations for cultural heritage conservation. Aim of these processes is to destroy the collagen, the main element of parchment.

9527-9, Session 6

Multiscale study of parchments and their degradation using nonlinear microscopy and AFM-IR *(Invited Paper)*

Gaël Latour, Univ. Paris-Sud 11 (France); Laurianne Robinet, Muséum national d'Histoire naturelle (France); Ariane Deniset-Besseau, Alexandre Dazzi, Univ. Paris-Sud 11 (France); Marie-Claire Schanne-Klein, Lab. d'Optique et Biosciences (France)

Parchment was the main writing material in the Middle Ages in Western Europe up to the growth of paper production in the 14-15th centuries. Made from an untanned animal skin it was preserved by liming, scraping and drying the skin under tension. Parchment is very sensitive to water, causing in extreme case the denaturation of collagen, its main constituent, to gelatin. The aim of this work is to demonstrate the interest of using complementary multiscale techniques to better understand the mechanisms involved during degradation.

Nonlinear microscopy is an emerging and promising optical technique for the investigation of artworks. The potential of pump-probe microscopy has been proven for the discrimination of pigments in painting [1] and multiphoton microscopy (MPM) based on simultaneous detection of two photon excited fluorescence (2PEF) and second harmonic generation (SHG) has been shown to give insight into the structure and the nature of the components of varnishes (binders, fillers, pigments) [2]. This latter technique performs non-invasive three-dimensional (3D) imaging with micrometer-scale resolution based on an intrinsic optical sectioning. A key advantage is probably its multimodal capability with different modes of contrasts that are directly linked to the structural and chemical nature of the materials. 2PEF signals are emitted by a wide range of materials (fluorophores) in historical artifacts with specific absorption and emission fluorescence spectra [2]. SHG signals are specific for non-centrosymmetric structures, with no counterpart in usual (linear) optical techniques. Fibrillar collagen emits strong SHG signals as widely used in biomedical imaging (cornea, skin...).

In this study, we show that SHG microscopy provides structural information of the 3D organization of the fibrillar collagen within parchments. First, collagen and gelatin references are studied to determine the typical signals obtained by pure collagen in both forms. Then, historical parchments at different states of degradation are investigated going from a well-preserved to a gelatinized parchment. We demonstrate that during degradation SHG signals vanish due to molecular and/or macromolecular modifications.

The gelatinization process induces in the collagen molecule a change from a triple helical to a random structure which can be characterized by infrared spectroscopy. Infrared spectroscopy is used routinely in cultural heritage to examine parchment modifications at the molecular level; however the structural heterogeneity within a collagen fiber, the spectral distortion caused by a fiber diameter (~1-5 μm) below the beam size and the interference of the carbonate signal (originating from the liming process) in the spectra often renders data interpretation difficult when working at the micrometer scale. To overcome this limitation, infrared analysis at the nanometer scale is crucial. We report the first parchment fibers analysis at the nanometer scale using AFM-IR (AFM imaging coupled with IR illumination to record IR spectra with nanometer scale resolution). We then discuss the potential of coupling AFM-IR with other

microscopy imaging techniques (conventional optical microscopy and especially multiphoton microscopy) to obtain clues about the degradation of the collagen structure and to characterize different degradation steps.

9527-26, Session 6

Hyperspectral remote sensing techniques applied to the noninvasive investigation of mural paintings: a feasibility study carried out on a wall painting by Beato Angelico in Florence

Costanza Cucci, Marcello Picollo, Istituto di Fisica Applicata Nello Carrara (Italy); Leandro Chiarantini, Barbara Sereni, SELEX ES S.p.A. (Italy)

Multi and hyperspectral imaging applied to the investigation of paintings and polychrome surfaces has flourished in the last decade, with relevant technological developments and new applications to different artifacts. Hyperspectral imaging techniques are based on the non-invasive acquisition of a sequence of quasi-monochromatic reflectographic images of the polychrome surface under investigation. The data set is acquired over an extended spectroscopic range, typically the Visible (VIS) and/or Infrared (IR) regions. The availability of hundreds of spectrally contiguous images of the same scene allows extraction of high-resolution spectra per each pixel of the imaged area. This provides useful information on the constituting artistic materials and on their distributions on the painted surface. In some cases, the spectral fingerprints of specific degradation products may effectively be used to assess the extent of degradation phenomena on the surface. In addition, by means of suitable algorithms, hyperspectral data may be processed to extract multiple elaborated images, or maps, where several hidden structures and details, such as retouches, pentimenti, underdrawings, etc., may be visualized, or enhanced.

Thanks to these advantages, nowadays hyperspectral imaging is well-established as an effective methodology for the non-invasive diagnostics on polychrome surfaces and is increasingly used in conservation field. However, so far this technique has been mainly applied to the study of easel paintings or paper based artifacts. Moreover it has been implemented by means of several types dedicated devices, all specifically designed and tailored for the museum context. Typically these devices work at close- or short-distance from the targets and are designed to cover limited size surfaces.

Instead, almost still unexplored remain the applications of hyperspectral imaging to the investigations of frescoes or other kind of large size mural paintings. For this type of artworks a remote sensing approach, based on sensors suitable to acquire high quality hyperspectral data from distances of the order of tens of meters, is often needed. To address this issue hyperspectral systems originally projected for different applicative sectors, such as earth surface observations from platforms like satellite or airborne, may offer interesting perspectives.

This paper illustrates an application of hyperspectral remote sensing to a valuable wall painting by Beato Angelico, located in the cloister of San Marco Museum in Florence. Measurements were carried out using a readapted version of the Galileo Avionica Multisensor Hyperspectral System (SIM-GA), a modular pushbroom avionic hyperspectral imager designed for applications from mobile platforms. This hyperspectral imager includes two electro-optical heads operating in the VNIR and SWIR spectral ranges respectively, so as to cover the extended region from 0.4 μm up to 2.5 μm. The digital acquisition system operates with over 700 channels, thus guaranteeing acquisition of high resolution hyperspectral data, exploitable for materials identification and/or discrimination. The preliminary results obtained on the Angelico's wall painting are discussed, with highlights on the main technical issues addressed to optimize the SIM-GA system for new applications on cultural assets.

9527-27, Session 6

Combination of topology and structural information for damages and deterioration analysis of artworks

Dominic Buchta, Univ. Stuttgart (Germany); Niclas Hein, Carolin Heinemann, Staatliche Akademie der Bildenden Künste Stuttgart (Germany); Giancarlo Pedrini, Univ. of Stuttgart (Germany); Christoph Krekel, Staatliche Akademie der Bildenden Künste Stuttgart (Germany); Wolfgang Osten, Univ. Stuttgart (Germany)

Because artworks are a major part of our culture their preservation is of great importance and therefore they need to be protected from any damage. But even with the greatest effort it is impossible to avoid all types of damage. There are two processes, which are mostly responsible for the occurrence of damages; ageing and transport. Although the transport induced defects arise much faster than the ageing induced ones, the reason for the damages are often the same. In both cases the change of environmental conditions like temperature or humidity leads to internal stress, which can result in different defects like delaminations or cracks. To prevent the arising of such defects it is necessary to understand the behavior of artwork under climatic change and to have a tool allowing early defects detection. This tool should be non-destructive, fast, easy in use and robust against vibrations. We are developing such a tool by using a combination of fringe projection and shearography. With the fringe projection a 3D-pointcloud containing the information about the topography including defects on the surface, is generated. Shearography is used to obtain more information about the structure of the artwork. This interferometric technique measures the deformation after a loading and allows the detection of damages which occur under the surface. For a meaningful evaluation of the changes during ageing or transport it is important to ensure a complete detection of all defects. Therefore we manufactured different test samples with typical damages. Measurements with shearography showed that different types of defect can be detected by using different loading types. While shearography is not able to detect global deformation, a comparison of two states (e.g. before and after transportation) using the fringe projection provides a lot of information concerning distortion and detachment of the upper layer of paint. Through specific ageing in a climate chamber it was shown that even a small change in temperature or humidity leads to a non-negligible distortion of the edges. So a combination of fringe projection and shearography allows to detect both global and local deformation produced by structural weakness. For the combination the irregularities in the shearogram are marked and mapped on the color image of the artwork. Afterwards the 2D image is matched on the 3D point cloud using the edges as reference points. The resulting data gives a 3D model of the painting including color and structural information. On one hand, the conservator can use this tool to identify a big number of defects, on the other hand it can be used for further investigations on the behavior of the samples during a climatic change and expect new insights in the damage analysis of wooden panel and canvas paintings.

9527-28, Session 6

Measuring environmental impact by real time laser differential displacement technique in simulated climate conditions

Eirini Bernikola, Vivi Tornari, Foundation for Research and Technology-Hellas (Greece); Nota Tsigarida, Ctr. for Research and Technology Hellas (Greece); Kostas Hatzigiannakis, Foundation for Research and Technology-Hellas (Greece); Michalis Andrianakis, Ctr. for Research and Technology Hellas (Greece); Johanna Leissner, Fraunhofer ISC (Germany)

Over last decades environment change witness a steady temperature increase. The recorded increase occurs slowly but steadily that is interrupted by extreme climate effects. Is this scenario an endangered one for Cultural Heritage perspective maintenance or it is slow enough to be considered among the safe value limits as these are defined by conservation community forms the question to be explored in the presented experiment.

The experimental methodology explored a new approach in conservation science based on direct measurement of surface displacement under simulated climate conditions measured in real time enabling even minute surface displacement data to serve for differential comparison over selected intervals. Geographical zones provide the temperature and crucially the moisture fluctuations in different range of humidity values and the time intervals are depended on the time period required to achieve the meteorology data of specific geographical zones.

In this paper it is described the experimental concept, method and procedure to achieve significant measurements of surface displacement values and the interpretation of data in regards to the reactions recorded from the employed hygroscopic material surfaces or as termed here the risk index. The results are systematic and repeatable and confirm the hypothesis that continuous fluctuations accelerate the impact on structural condition and suggesting that the safe value limits may should be reconsidered in the era of climate change.

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9528-1, Session 1

Light field-based videometry *(Invited Paper)*

Bernd Jähne, Ruprecht-Karls-Univ. Heidelberg (Germany)

No Abstract Available

9528-2, Session 1

Light-field camera design for high-accuracy depth estimation

Maximilian Diebold, Oliver Blum, Marcel Gutsche, Heidelberg Collaboratory for Image Processing (Germany); Sven Wanner, HCI (Germany); Christoph S. Garbe, Harlyn Baker, Bernd Jähne, Heidelberg Collaboratory for Image Processing (Germany)

Light-field imaging is a promising research field and suitable for a wide variety of applications. In contrast to stereo or multi-view stereo approaches, capturing light-fields means to observe every point by densely sampling a target scene from several different directions. The underlying disparity / depth is then visible as orientations in the epipolar plane image (EPI). Thus it becomes more robust in the depth measurement and makes it also possible to estimate optical surface properties like BRDF. The main benefits are that one can get rid of error prone and computational intensive correspondence searches. The nearly continuous orientation space also allows to compute highly accurate and dense depth maps. That makes light-field imaging not only interesting for industrial surface inspection but also yield high potentials for robot vision.

In light-field imaging the observable depth range of a given light-field setup is limited by the measurable orientation range. In case of the structure tensor as orientation estimation algorithm this range is a two pixel environment around a fix disparity value of a given horopter. Without a depth range adjustment with respect to the target scene depth, either a low depth resolution or an unnecessary increase of computation time is the consequence.

In this paper we present how to exploit the given orientation range to get the best possible depth resolution of a defined depth range. Thus we detail the process of selecting an appropriate light-field setup through specifying important relationships and constraints.

Firstly, we introduce the connection between the baseline, the focal length and pixel pitch of our light-field setup with the horopter, the depth range of the bounded frustum and the disparity range. Additionally, also the constraint for sharp images enforced by the depth of field and diffraction as well as practical limits such as camera size in case of array setups and objective values are taken into account. To conclude the first part we illustrate different light-field setups, having optimal and badly selected parameters with respect to a predefined bounded frustum.

Secondly, we analyze the resulting depth accuracy and precision, achievable inside the bounded frustum for different possible setups. Additionally we show how camera position inaccuracy and focal length inaccuracies influencing the depth precision. Thus, we transfer the accuracy evaluation from the depth space to the disparity space. This means, that the accuracy in evaluating the orientation is now related to a given disparity accuracy which makes the evaluation independent of the light-field setup. Aside the achieved accuracy also information about the rotation symmetry of different compared derivative filters can be obtained. The resulting accuracy can then be referred to a given baseline or focal length accuracy of predefined setups. This link makes it possible to define the depth accuracy only dependent to camera position accuracy and focal length accuracy. Finally we demonstrate which occurring inaccuracies are correctable using an appropriate light-field camera calibration and which inaccuracies need to be avoided already during mounting the setup.

9528-4, Session 1

Knowledge guided object detection and identification in 3D point clouds

Ashish Karmacharya, Frank Boochs, Burkhard Tietz, i3mainz (Germany) and Hochschule Mainz (Germany)

Most existing 3D processing algorithms for object detections and reconstructions are either based on data or model driven approaches. These approaches are highly dependent on the nature of data and are not able to handle deviations. They are mostly restricted to single data type restricting them to integrate other suitable algorithms in between. Additionally, the models are based on hypothesis constitutes the geometric and optical behaviors of the objects and excludes other important knowledge to support the hypothesis. Moreover, such models are optimized for any given particular strategy. This rigidness in the flexibilities has huge disadvantage in handling new born situations. The processing strategies themselves lack intelligence that could guide them through the unexpected situation they may entangle in between. There have been efforts to provide intelligence to the processing approach by injecting machine learning concepts to enforce the robustness in such mechanism but these methods again generally require huge training datasets in order to get good results.

The paper proposes the use of semantics that first semantically binds the objects and other related knowledge domains to the numerical algorithms to detect geometries and then use experts' rule to annotate them to the respective objects. The use of semantics facilitates machine to formalize knowledge from all related expert domains to assist numerical processing and classification process. It has key advantages over the conventional data driven approach. First and far most, the approach provides much needed intelligence that makes it flexible enough to align itself in different situations that may arise during the entire process of object detection, identification and reconstruction. Secondly, the approach does not demand training datasets and can function with the underlying semantic models based on experts' interpretations.

The approach presented in this paper has been tested in a prototypical application within the project "Wissensbasierte Detektion von Objekten in Punktwolken für Anwendungen im Ingenieurbereich" or simply WiDOP. The application rests on the fundamental knowledge domains that were consider important: a) scene knowledge – that describes the scene, the expected objects inside, the geometric and topologic relationships between objects and their surroundings, b) data knowledge – that describes the behavior and nature of data and c) algorithmic knowledge – that describes which algorithms are suited to detect what kind of features, how the algorithms are interrelated, what parameters fit best on what kind of situations and so on. The knowledge domains can be extended further depending on their requirements and impacts that they can provide to the end results. This prototypical application was tested with two entirely different cases of Deutsche Bahn (German Railway System) and Fraport (company that handles Frankfurt International Airport).

Figure 1 illustrates the architecture of WiDOP prototypical application. Knowledge from different expert domains is expressed through the Web Ontology Language (OWL) which is W3C standard to express knowledge in ontology. This includes the results from in-depth analytical investigation of algorithmic behavior against other knowledge domains in different situations. This structuring of algorithmic knowledge forms a base for Algorithmic Selection Module (ASM). ASM is also extended with modular algorithms. The relations of algorithms to different knowledge domain inside the knowledge model trigger right algorithm/algorithm sequence with most suitable parameters for the situation. This helps to detect geometries more efficiently. The geometries are then populated

and combined together inside the knowledge base to detect objects' geometries. Consequently, classifiers annotate them into rightful objects. Classifiers consist of expert observations on objects geometric, topographic and semantic characteristics and are expressed through expert rules. These rules are expressed in Semantic Web Rule Language (SWRL).

WiDOP detects and classifies objects in iterations. It adopts coarse-to-fine approach. Expected objects' features inside the knowledge base provide first hints on which algorithms ASM must select to detect first sets of primitive geometries. These geometries outline the coarse detection of objects in the first iteration. Similarly, they provide more semantic cues that can be exploited in second and other consecutive iterations. The iteration concludes in two conditions: 1) every object is detected and identified 2) The system could not identify detected geometries and knowledge model should extend the semantics to identify them.

We present noise-cancelling-wall that can normally be found running parallel to the last railway tracks as an example to demonstrate the detection and identification process. Noise-cancelling-wall is a vertical plane extending to a certain length.

Experts' knowledge on the noise-cancelling-wall is already expressed in the ontology knowledge model. ASM initiates the execution of algorithms/algorithm sequence based on this knowledge. A sub-set of algorithms prescribed by ASM to extract features of the wall is given below:

--> NormalEstimateOMP --> SACSegmentationFromNormals-->

The above sub-set of algorithm sequence was selected as the wall describe in the knowledge base is horizontally straight plane (see fig 2 a). However, the shape of the wall can change depending on the scene (see 2 b). In such cases, different sequence of algorithms should be selected. The ASM takes this change into account and select entirely different sequence of algorithms. The sub-set of algorithm sequence that was considered was:

--> NormalEstimateOMP --> ConditionalEuclideanClustering --> setConditionFunction --> pRegionGrowingFunction

The detected vertical geometries are populated into the knowledge base. Experts' rules are then applied to qualify these vertical standing geometries as noise-cancelling-wall. The example equation below illustrates such expert rule:

Geometries(-->g) ^ hasHeight(-->g, -->h) swrlb:greaterThan(-->h, 2.5) ^ hasLength(-->g, -->l) ^ swrlb:greaterThan(-->l, 10) ^ hasVerticalAngle (-->g, 90) ^ Railtrack(-->r) ^ isParallel(-->g, -->r) --> noise-cancelling-wall(-->g)

In simpler expression: geometries running parallel to the railway track and having height between 2.5 meters and 3.5 meters and the length longer than 10 meters with vertical angle of 90o (i.e.; vertically standing) is a noise-cancelling-wall. This annotates every vertical standing feature with the provided characters as noise-cancelling-wall which might be false. Henceforth, more unique features of objects are defined in the expert rules more correct identification of the objects are carried out.

9528-5, Session 1

The analysis of selected orientation methods of architectural objects' scans

Jakub S. Markiewicz, Irmina Kajdewicz, Dorota Zawieska, Warsaw Univ. of Technology (Poland)

The point cloud, which is acquired from the terrestrial laser scanning, is measured in the internal reference system of the instrument. In the case of more data sets (for big and complicated objects), it is necessary to unify the reference system. This is performed by means of transformation of the point clouds into the external system, which may be the state co-ordinate system, the local co-ordinate system or the internal system of one of the scans, i.e. the reference (or the master) scan.

The process of orientation comprises the estimation of orientation parameters and utilisation of those parameters for transformation of the point cloud. Usually, the 3D affine transformation is applied. It is also applicable to apply the similarity transformation, when the scales of the external reference system and the scanner system are different. The transformation is performed basing on matching points, which should be evenly distributed within the entire area of the common coverage of the clouds. Their minimum number equals to 3; when it is increased, redundant observations are created and this allows for eliminations gross errors and increases the orientation accuracy.

The, so-called, point-based registration method of orientation is mostly. Two categories of this methods are distinguished: the target-based approach, which is based on the knowledge of point co-ordinates in the scanner and global systems, and the ICP method, which assumes that those co-ordinates are not known.

The recent research works have been focused on the orientation performed by means of recognition of geometric shapes on the scans, which serves for estimation of the transformation parameters.

Many factors influence the accuracy of the terrestrial laser scanning. Some of the external factors, which may directly influence the scan orientation will be discussed in the paper. They include the laser beam incidence angle, the reflectivity of the object surface and the assumed method of TLS data. Scans of historical facilities of the Museum of King Jan III's Palace at Wilanów in Warszawa, acquired by the Z+F 5006i scanner, were used for the discussed research works.

The proposed paper will discussed the results of the utilisation of the target-based method using the Z+F Control tool. Marks distributed on walls of the historical chambers were used for the needs of the scan orientation. Different approaches to the orientation were applied, with the consideration of the distribution and the number of those marks.

The target-based method is the conventional approach to the point-based orientation. The orientation is usually performed with the use of special survey marks, which have been distributed within the object. At present research works are performed which aim at the elimination of survey marks from the discussed process. After generation of raster images from the scans, image processing algorithms may be applied in order to automatically search for corresponding natural points. Computer vision is the area which deals with the computer acquisition of information from images and with its further processing and analysis. The objective is to achieve the electronic perception and understanding of images by the computer similarly to the human perception. Computer vision is, first of all, connected with the image matching – it is the key factor for such tasks, as recognition of places or objects, tracing moving objects or reconstruction of 3D structures using many images. The best known is the SIFT algorithm; its modification, called SURF, is also known. The modified version is characterised by the reduced time of computations.

Successive parts of the paper will discuss experiments concerning the use of SIFT and SURF algorithms in order to identify homological points in images generated from the TLS data. Scans of the same historical chambers in Museum were analysed. Co-ordinates of the detected points were used in the LupoScan tool for the scan orientation. The case of utilisation of automatically identified, natural points for the TLS data orientation, was analysed. The results of utilisation of both methods for the TLS data orientation were summarised and presented in the numerical and graphical forms.

9528-42, Session 1

Improving depth estimation from a plenoptic camera by patterned illumination

Richard J. Marshall, Chris J. Meah, The Univ. of Birmingham (United Kingdom); Massimo Turola, City Univ. London (United Kingdom); Ela Claridge, Alex P. G. Robinson, Kai Bongs, The Univ. of Birmingham (United Kingdom); Stephen Gruppetta, City Univ. London (United Kingdom); Iain B. Styles, The Univ. of Birmingham (United Kingdom)

Plenoptic imaging is a technique in which a microlens array is placed between the main lens system of the camera and the sensor. In doing this, both spatial and directional information is stored in the raw data in the form of many microimages created by the individual microlenses. The data can then be computationally processed to shift perspective, digital refocus, extend the depth of field, manipulate the aperture synthetically and generate a depth map from a single image. Some of these capabilities are rigid functions that do not depend upon the scene

and work by manipulating a well-defined set of pixels in the raw image. However, depth mapping requires specific features in the scene to be identified and registered between consecutive microimages. This process requires that the image has sufficient features for the registration, and in the absence of such features the algorithms become less reliable and incorrect depths are generated. The aim of this investigation is to see how projecting patterns onto scenes with limited texture or features affects the accuracy of the depth map.

The imaging system comprised a Raytrix R11 camera (Raytrix GmbH, Kiel, Germany) and a light source placed adjacent to each other orientated in the same direction. A plain featureless sheet was positioned in front of the system at a number of different angles in relation to the cameras sensor plane, from 0 degrees to 45 degrees at intervals of 15 degrees. The sheet was illuminated first with unstructured white light and then with several different patterns including, but not exclusively, a regular grid of both densely and sparsely packed dots, stripes of varying width, spacing and orientation, and random binary projections. Depth maps were computed using software supplied with the Raytrix plenoptic camera. The results are presented in the form of line plots which show the mean and standard deviation of the computed depth for the points lying at the same physical depth. The computed surface angle is calculated from the relative differences in the values of the depth map between adjacent pixels.

The results of the experiment show clearly that when illuminated with unstructured white light, virtually no depth information is present, as when the scene was at 15 degrees to the sensor plane, the calculated angle from the plenoptic camera was -4.86 degrees, and at 30 degrees the plenoptic camera calculated the depth to be -7.71 degrees. However, when illuminated with a pattern, the difference between the actual and calculated gradient is significantly decreased. The results when the scene was illuminated with a densely packed regular grid of dots were as follows. At 15 degrees to the sensor plane the plenoptic camera calculated the angle to be 17.22 degrees, and at 30 degrees the calculated angle was 23.29 degrees. These results correlate with the initial hypothesis that the depth calculation in Raytrix R11 plenoptic camera strongly relies on registration between adjacent microimages. If there is no texture in the scene, the depth recovery algorithms produce erroneous results. This work also conclusively demonstrates that depth estimation from a plenoptic camera can be improved significantly with the projection of texture. Future work will involve the optimisation of the illumination pattern to further improve accuracy of results and include an investigation of depth recovery from more complex scenes.

9528-10, Session 2

3D measurement with active triangulation for spectacle lens optimization and individualization

Julia Gehrmann, Hochschule für Angewandte Wissenschaften München (Germany); Markus Tiemann, Peter C. Seitz, Rodenstock GmbH (Germany)

We present for the first time an active triangulation technique used for video centration. The newly developed technique requires less manual interaction compared to current methods and thus enables faster measurements while providing the same resolution.

With video centration the position of a spectacle lens in front of the human eye is measured. The measured parameters are the basis for individualized high-end progressive lenses, enabling best visual performance for the wearer. The tilt of the lens and the positioning to the visual axis is used in calculation and production of free-form lenses as well as subsequent assembly to a spectacle frame.

In our study the suitability to measure physiological parameters is demonstrated in a measurement series. We show the measurement sequence and analysis with an evaluation of the results. Furthermore, we discuss the optical setup and its calibration.

The active triangulation technique uses a laser line for illumination which is positioned such that it intersects with the pupils of the subject to be measured while being imaged by a camera. For the illumination of human eyes, the wavelength and output power were carefully investigated to ensure photobiological safety at all times and reduce irritation of the subject being measured. The camera imaging the subject is placed in a fixed orientation to the laser line. The exact position is determined using an optical calibration method.

The measurement consists of two images acquired sequentially. The first image is optimized for laser line detection, while the second illuminates mainly the subject. For the acquisition time required for two images, the measurement scene can be considered static, allowing the overlay of the two images. Physiological features on the subject and the frame are then selected in the second acquired image yielding directly a 3D position if lying on the illuminated laser line, which is automatically extracted from the first image. Distances to points off the laser line can be estimated from a scaling at the same depth. The measurements focused on two parameters: interpupillary distance (PD) and corneal face form angle (FFA). For the PD measurement, the pupil centers have to be selected. For the FFA the reflections on the frame have to be selected. On each side a nasal and a temporal reflection occur. Those four points are projected vertically to a horizontal plane to determine the FFA between the lines through the temporal and nasal points.

In our study we examined the repeatability of the measurements and the effects of variations in calibrating the setup. We found an excellent repeatability with small deviations to the reference value. Furthermore a physiological study was carried out with the setup showing the applicability of this method for video centration measurements. A comparison to a reference measurement system shows only small differences.

9528-11, Session 2

Detection of defects in a transparent polymer with high resolution tomography using white light scanning interferometry and noise reduction

Audrey Leong-Hoï, Rémy Claveau, Manuel Flury, Wilfried Uhring, Univ. de Strasbourg (France); Bruno Serio, Univ. Paris Ouest Nanterre La Défense (France); Freddy Anstotz, Univ de Strasbourg (France); Paul C. Montgomery, Univ. de Strasbourg (France)

Transparent layers such as polymers are complex and can contain defects which are not detectable with classical optical inspection techniques. With an interference microscope, tomographic analysis can be used to obtain initial structural information over the depth of the sample by scanning the fringes along the Z axis and performing appropriate signal processing to extract the fringe envelope. By observing the resulting XZ section, sub-μm sized defects can be lost in the noise which is present in images acquired with a CCD camera. It is possible to reduce temporal and spatial noise from the camera by applying image processing methods such as image averaging to reduce random noise of the camera, dark frame subtraction to correct “hot pixels”, or flat field division to overcome the non-homogenous illumination, pixel response non uniformity of the CCD camera, and vignetting problems and remove eventual errors from optical imperfections such as dust particles on the optical components. In this paper, we present some first results obtained by this means with a white light scanning interferometer on a Mylar polymer of 3 μm thickness, used currently as an insulator in electronics and micro-electronics. The system is an adapted Leitz-Linnik interferometric microscope with x50 objectives (NA = 0.85) and a Basler avA1000-100gc GigE camera. We show that structures of about 1.5 μm contained in the layer, initially lost in noise and barely observable, can be detected by applying a combination of image processing methods to each of the scanned XY images along the Z-axis. In addition, errors from optical imperfections such as dust particles on the lenses or mirrors of the system can be compensated for with this method and reduced in size by about 1 μm. We thus demonstrate that XZ section images of a transparent sample can be denoised by improving each of the XY acquisition images. Our technique allows noise reduction and improvement of axial detection sensitivity of internal details in the tomographic section of transparent layers. A quantitative study of the noise reduction is presented in order to validate the performance of this technique. Image averaging increases the stability of the acquisitions by reducing temporal noise, while dark frame and flat field corrections are involved in the spatial noise reduction of images. The last two corrections allow a lateral resolution improvement of at least 100 nm.

9528-12, Session 2

3D reconstruction with single image pairs and structured light projection for short-term ultra-high-speed applications

Christian Bräuer-Burchardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Stefan Heist, Patrick Dietrich, Fraunhofer IOF (Germany); Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Gunther Notni, Technische Univ. Ilmenau (Germany)

3D reconstruction based on optical surface measurements using structured light becomes more and more importance in high-speed applications such as in the automobile production and for dynamic processes. Recently, new developments of hardware components provide the possibility of scene observation using cameras with frame rates of some kHz. Additionally, new projection techniques allow the generation of structured light patterns such as statistical binary patterns, band-limited stochastic patterns, or fringe patterns. Here, laser speckle and array-projection are new projection techniques. Besides fringe projection profilometry the processing of sequences of statistic patterns provides good 3D reconstruction results with high accuracy and precision at the measurement of static scenes. However, the accurate measurement of dynamic processes using image sequences is a nontrivial task because of the necessary motion compensation or the achievement of an ultrafast measurement, where the objects motion is small in the time of the image sequence recording.

We introduce a new approach for a 3D reconstruction algorithm using a single pair of a stereo-camera setup and a structured light projection. In contrast to existing methods we achieve a relative high 3D-reconstruction quality by the iterative application of correspondence finding and filtering operators even in the case of low resolution images of ultra-high-speed cameras. This provides the advantage of using the fastest camera mode for quickly moving objects. Other advantages of the new technique regarding high-speed applications are, that no synchronization between projection and cameras is necessary, and single patterns instead of pattern sequences can be used for moving objects. This provides the possibility of pattern optimization according to measurement object properties, e.g. smoothness, texture, and color.

The introduced approach does not achieve the high measurement precision of an image sequence based measurement of a static scene, but it provides a robust rough measurement for the purpose of 3D object movement determination. The algorithm is based on a spatial image correlation analysis of image pairs of calibrated cameras. The typical outliers of such correlation based measurements are consecutively removed by iterative application of probability driven seed point selection, adaptive filters and intelligent filling operators.

The method has been tested at measurement objects with various surface properties using image pairs and sequences of stereo image pairs observing static and dynamic scenes of several sensor setups. Different kinds of projected patterns such as statistical binary patterns, band-limited stochastic patterns, laser-speckle patterns and aperiodic fringe pattern have been applied. The obtained results are analyzed concerning achievable accuracy in comparison to reference measurements using image sequences of different lengths. Because of the relative high image processing effort of the evaluation, filling, filtering, and outlier removing operators the favored application scenario of the new method is the rough 3D reconstruction and motion tracking of quickly moving objects in short-term processes (few seconds), e.g. in the analysis of crash-test situations.

9528-13, Session 2

Handheld underwater 3D sensor based on fringe projection technique

Christian Bräuer-Burchardt, Matthias Heinze, Ingo Schmidt, Lichun Meng, Roland Ramm, Peter Kühmstedt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Gunther Notni, Technische Univ. Ilmenau (Germany)

3D sensors based on fringe projection technique as handheld, mobile measurement devices become more and more importance. Whereas many sensors can be applied well in a laboratory environment, their field of application under bad outside conditions is limited. Especially in the case of underwater use fringe projection based 3D scanners are rarely developed, although there are a series of possible application fields such as the underwater archaeology for documentation of sunken objects, the surface measurement of pipeline systems, the inspection of boat parts such as propellers of ship, or the measurement of biological objects.

At Fraunhofer IOF a new, handheld 3D surface scanner was developed especially for underwater use until a diving depth of about 30 meters. Additionally, the sensor is suitable for the outdoor use under bad weather circumstance like splashing water, strong wind, and bad illumination conditions. The optical components of the sensor are two cameras and one projector. The measurement field is about 250 mm x 200 mm. The depth resolution is about 50 μm and the lateral resolution is approximately 150 μm. The weight of the scanner is about 10 kg. The housing was produced of synthetic powder using a 3D printing technique. The measurement time for one scan is between 200 and 800 milliseconds. The computer for measurement control and data analysis is integrated into the housing of the scanner. A display on the backside graphically shows the results of each measurement for a real-time evaluation of the user during the recording of the measurement data.

Because of the optical properties of the media water the common pinhole camera modeling is not suitable for underwater use. Nevertheless, it can be used as an approximation leading to some error in the 3D measurement result. However, intrinsic and extrinsic camera parameters are then considerable different between application under water and at use outside water (in air). For the underwater use an adapted calibration methodology was developed. Initially, the intrinsic and extrinsic parameters of the air calibration were modified according to the law of refraction. Distortion effects have been treated as well. Then these new parameters of the underwater calibration are corrected using certain evaluation measurements under water. Final check measurements confirm the calibration parameter modification and estimate the maximum and average 3D reconstruction error.

First measurements of selected specimen were performed in order to obtain values for the accuracy and the noise of the 3D measurement data over and under water and the evaluation of the underwater calibration procedure. Additionally, the completeness of the measurement value acquisition was checked using several measurement objects. The standard deviation of the 3D measurement points was between 8 and 20 μm in air and between 15 and 50 μm in clear water.

Future work will be addressed to the comparison of the new developed underwater calibration methodology with classical stereo camera calibration under water. Extensive experimental underwater measurements should provide more data concerning longtime stability of the sensor parameters and the measurement accuracy also depending on the water properties (water depth, degree of contamination, salt water).

9528-14, Session 2

Profilometry of discontinuous solids by means of co-phased demodulation of projected fringes with RGB encoding

Jose Moises Padilla, Manuel Servin, Guillermo Garnica, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Fringe projection techniques have been extensively applied in optical metrology thanks to their flexibility, high accuracy and full-field operation. With the fast evolution of digital display and acquisition technology, three-dimensional (3D) shape measurement by means of fringe projection has become very accessible for both academic and industrial fields.

The projection of sinusoidal open-fringes is a well-known example where, assuming a non-zero angle between the projection and observation direction, the fringe pattern becomes phase-modulated proportionally to the 3D object under study. The phase-modulated pattern may contain open or closed fringes depending on the frequency of the projected fringes, the geometry of the experimental set-up and the surface slope of the digitizing object. The so-called Fourier method allows the phase demodulation of open fringes from a single image, thus having low

sensibility to environmental vibrations and to study dynamic phenomena. On the other hand, a multiple-step phase-shifting approach is preferred when the fringe pattern contains closed fringes. (It is important to note that there are several methods for estimating the modulated phase in closed-fringes interferograms without spatial or temporal carriers, but reviewing such methods is not in the scope of this work.) Unlike classical phase-shifting techniques that involve slowly moving parts in order to change the optical path-difference modulated in phase within the fringe pattern, computer-generated synthetic fringes can be phase-sifted before being projected and multichannel operation, for instance using color encoding with red-green-blue (RGB), enable simultaneous modulation and acquisition allowing the study of dynamic phenomena with phase-shifting techniques.

In general, the modulating phase in a fringe pattern has a 2pi-ambiguity so phase demodulation methods cannot estimate it directly: when applying the Fourier method or a phase-shifting algorithm we obtain its principal value, or wrapped phase, within the intervals (-pi,pi) or (0,2pi). Thus, as final step of the phase estimation we require to apply some phase unwrapping algorithm. The phase unwrapping process is trivial assuming the fringe pattern has low-noise and good contrast in the entire region of interest. In fringe projection techniques the low-noise condition is easily meet but the geometry of the 3D object may generate self-occluding shadows (particularly in discontinuous surfaces) where the contrast falls to zero and the modulating phase became undefined. This drawback can be compensated with multi-camera or multi-projector setups since the resulting fringe patterns will have complementary phase information.

In this work we will discuss a single-camera setup for profilometry of discontinuous solids by means of co-phased demodulation of projected fringes with RGB channels encoding. This approach takes advantage of the analytical character of the output signals in phase demodulation algorithms to straightforwardly generate a single phase-map for the entire area where fringes' data is well-defined; it is noteworthy that heavy computational operations (such as image stitching) are not required. This multichannel operation approach also reduces the acquisition time respect to one at a time gray-scale fringes projection, making it suitable for the study of dynamic phenomena.

9528-6, Session 3

Development of orientation method with constraint conditions using vector data

Takashi Fuse, Keita Kamiya, The Univ. of Tokyo (Japan)

Recently, visualization of urban scenes with various information attracts attention. For the transmission of urban scenes, virtual reality has been widely used. Since the virtual reality requires comprehensive and detailed three dimensional models, the manual dependent modelling takes a lot of time and effort. On the other hand, it has been tackled that various data is superimposed on the scene which the users see at the time instead of comprehensive modelling, which is well known as augmented reality (AR). In order to superimpose 3D models on the images, ground control points are basically necessary. The setting of the GCPs takes a lot of time and effort. Besides the GCPs, auxiliary information can be available. Various kinds of vector data such as CAD, CG, or GIS have been widely used. Images as raster data also became popular, and then applications using the vector data and images simultaneously attract more interests. Such applications require registration of those data in a same coordinates system. This paper proposes an orientation method combining the vector data with the images based on bundle adjustment.

The method using only sequential image is according to normal image-based method, namely the method consists of feature points consists of feature points extraction / tracking, three dimensional coordinates estimation of the feature points, and orientation factors update based on bundle adjustment. The SURF algorithm is applied to feature points extraction / tracking. Even if the SURF is applied to feature points extraction / tracking, incorrect tracking points are still exist. The feature points tracking are refined by using RANSAC algorithm and thresholding. With the result of the tracking, three dimensional coordinates of the feature points can be calculated. Once initial value of the orientation factors and three dimensional coordinates of the feature points are acquired, the orientation factors update are conducted by bundle adjustment.

Since the vector data can be regarded as constraint condition, the bundle adjustment can be extended to constrained non-linear optimization method. The constraint conditions are coincidence between lines extracted from images and the corresponding ones of vector data. For formulation, a representative point is set as midpoint of a projected line of vector data on the image. By using the representative points, the coincidence condition is expressed as distance the point and the lines extracted from the image. According to the conditions, the proposed method is formulated as Lagrange's method of undetermined multipliers.

The proposed method is applied to synthetic and real data (compared with laser scanner data). The experiments with both synthetic and real data show that the proposed method is more accurate to errors caused by low accuracy of coordinates of feature points or GPS values than a method without constraint condition. In the case of synthetic data with low accuracy of coordinates of feature points, differences 3d coordinates of feature points decreased half. Accuracy (variances of estimated parameters) of 3d coordinates of feature points and baseline increased greatly in the same case. In the case of real data, numbers of constraint conditions were changed. The result of the proposed method with 3 lines was much better than ones of others.

As conclusion, this paper develops a method combining vector data with images based on bundle adjustment. Since the vector data can be regarded as constraint condition, the bundle adjustment can be extended to constrained non-linear optimization method. Through experiments with synthetic and real data, the accuracy improvements were confirmed. According to the experiments, the significance of the proposed method is confirmed. As a further work, integrated method with other sensors will become challenging investigation. As a result, promising method can be constructed, and then more impressive visualization will be accomplished.

9528-7, Session 3

Development, comparison, and evaluation of software for radial distortion elimination

Alexandra I. Papadaki, Andreas Georgopoulos, National Technical Univ. of Athens (Greece)

The constant development of technology has opened new perspectives in the field of Photogrammetry and Computer Vision, making it possible to carry out complex procedures, reduce the computational time while, at the same time, increasing the accuracy. In this context, it has been attempted to automate many processes in order to facilitate the procedures and to reduce the computational cost. A characteristic example of such a phenomenon that has preoccupied the scientific community from the perspective of automation is the radial distortion in digital images [1-4].

In particular, the interest has been focused on the automation of the processes of identification and elimination of the radial distortion, with the aim to correct the image coordinates and finally to obtain digital images with reliable geometric information. This effort has reached the point of development of commercial or free image processing software, claiming that it can automatically identify and remove the radial distortion of a digital image. In fact, this software requires only that the user supplies the image [5-7]. It is therefore clear that if this software provides the required accuracy for photogrammetric or other applications, it can be a very quick and affordable alternative to complex processes of correction of this deformity. However, the question arises as to how accurate are ultimately these software and what applications can be supported?

In this paper in depth research has been conducted about the radial distortion and the methods of its identification and elimination. In specific, it has been attempted to evaluate software as the aforementioned about its effectiveness, accuracy and applicability on the relief of a digital images from the radial distortion. For this purpose, characteristic samples of such software are investigated namely: DxO [8], Adobe Photoshop CS [9], Adobe Photoshop Lightroom [10], PTLens [11, 12] and GML Undistorter [13]. The greatest advantage of this software is that it offers the ability of automatic elimination of radial distortion and correction of a digital image. The automation of this process is based on two properties of the software. First of all, the software is automatically informed about the features of the optical system which is used for the specific capture, through the metadata file of the image. Nevertheless,

in case that such a file is not available, the updating is possible to be performed manually by the user. Secondly, this type of software affords a wide database for a variety of camera-lens models, which includes all the data that are required for each piece of software for the elimination of the radial distortion. However, each one of this software utilizes a different way of modeling for radial distortion and a different calibration method for the identification of the parameters of the optical system which is used. Consequently, the kind and size of the required data depends on the applied software. In any case, this software defines the required parameters, for the elimination of the radial distortion and the production of a distortion-free image, according to the chosen radial distortion model and the offered database [5-7].

For the attainment of the desired aim, four different methods of comparison and evaluation of the performance of the software, respecting the correction of a digital image, have been employed. The applied methods are the optical evaluation of the produced digital images, the subtraction of the images, the comparison of the curves of the remaining radial distortion in the images and the comparison of the results from the orientation of an image pair. However, it was really important to have a benchmark for the evaluation, in order to ensure the objectivity and accuracy of the comparison. Therefore, a new reliable algorithm has been developed, which was of known and controllable accuracy.

Thus, conclusions have been drawn, which were used in order to answer the question posed above, regarding the accuracy and applicability of the various software that are examined, with respect to removing the radial distortion and producing a geometrically correct, i.e. distortion free, image.

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9528-8, Session 3

Relevance of ellipse eccentricity for camera calibration

Waldemar Mordwinzew, Burkhard Tietz, Frank Boochs, i3mainz (Germany); Dietrich Paulus, Institute for Computational Visualistics, Universität Koblenz (Germany)

Optical metrology nowadays plays a significant role in the industrial production, especially when it comes to improving the productivity and quality of the output. This development is mostly reinforced by the constant progress of sensor development and corresponding photogrammetric calibration methods, which are able to utilize the new technology.

In most cases plane, circular targets are used in the field of close range calibration. The main reason for this choice is rooted in the simplicity of mathematical description, geometrical and radiometric design of circular targets.

However, with a prior given lens and sensor setup, the usage of circular targets may introduce systematic errors, which occur when a plane circle target is mapped into the sensor plane using projective transformation. Common ellipse detection algorithms like Hough transform, center of gravity or best-fit ellipse using the outline in the image space won't yield the geometric circle center of the object space. The difference between the circle center and its shifted counterpart in the image plane is mostly referred as ellipse eccentricity.

This effect has already been subject of discussion in various works. The causes and the overall quantitative effect on the target positions in the images have been shown in DOLD [1] and LUHMANN [2]. We will focus on the exact effects of two common calibration fields and find other suggestions to reduce the effect ellipse eccentricity. The most common and practical suggestions to lower this systematic error is to keep the target diameter and the inclination angle between the target and image plane as small as possible. These pointers may not be suitable for every task, especially not during calibrations where the usual intention is to find the best, systematically-non-biased values for the interior and exterior orientations. By putting aside the knowledge about the eccentricity a good geometric calibration should be carried out under different, wholly or partially contrary and therefore unfavorable conditions to the prior suggestions. The optimal geometric setup in this case implies the aim for 90° intersections - the best possible intersection angle between bundle rays. Also the target diameter has to be preferably big to ensure that enough boundary points (>50) can be used to fit the ellipse.

The intention of the research presented in this paper is to investigate the eccentricity influence and its role in the calibration process using the most common calibration field-designs, ~2D plane and 3D box. In the first step a pure numerical simulation is discussed. In this simulation the eccentricity and its impact on the bundle parameters is quantified in complete isolation from other physical and mathematical influences that cannot be avoided in real life calibration scenarios. While doing this, suggestions to avoid common bundle adjustment pitfalls will be proposed. In a second step real world calibrations will be carried out under approximately equivalent conditions as the simulation setup. Finally the achieved results and observed behavior will be compared to the numerical simulations carried out beforehand. Differences and similarities will be outlined and discussed.

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9528-9, Session 3

Self-calibration of a structured light based scanner for use in archeological applications

Adam V. Jahraus, Derek D. Lichti, Peter Dawson, Univ. of Calgary (Canada)

In archaeology, it is commonly necessary to measure and record cultural features and artifacts found in the field during excavations. For cultural features like dwellings, this is commonly done by hand using basic tools such as rulers and plumb bobs before they are irreversibly altered by

further excavation. For artifacts, they are typically collected, cleaned and stored until the excavation concludes, when they are then shipped to a laboratory or museum for analysis and long term storage. Each of these steps put the artifacts at risk of becoming damaged or lost before meaningful analyses can be performed. In both the case of artifacts and cultural features, it would be very beneficial to be able to produce a complete three-dimensional model to more accurately preserve the data, enabling new forms of analysis. Also, three dimensional models increase the availability of the data to different interested parties. This would enable research to be performed on the same data set simultaneously, or for discoveries to be more easily shared with the general population. Particularly in the case of structures, digital models enable a much more detailed analysis of the entire structure than a hand drawn map, which are necessarily limited in detail and accuracy due to time and labour constraints.

However, in spite of the highly desirable nature of three dimensional models, the data necessary are rarely collected in the field. There are many reasons why this is the case. One of the principal reasons is the cost of shipping the equipment necessary to the often remote and inaccessible locations is prohibitively expensive. Another major factor is that these devices are often complicated to operate and require specialized training. Very few archeologists have the necessary training, and hiring a non-archeologist to collect this data may be difficult and expensive. Even after the data have been collected, it takes a different set of skills to turn the raw data into a useful model. Given these factors, many archeologists find that three dimensional models are more effort than they are worth.

A new three dimensional scanner, the Dot Products DPI-7, has recently entered the market. It is a structured light scanner and has many characteristics that make it very attractive for archaeological applications. First, the scanner and all its peripherals weigh only a few kilograms, meaning shipping the device requires minimal cost. The scanner is also simple to operate, requiring only a brief warm-up period before it's ready to start collecting data, which are stored internally on the device. The data that are collected are viewable in real time, so any occluded or insufficiently covered areas can be addressed immediately. The scanner specifications indicate a "Typical Accuracy (RMS)" of 0.5% for ranges between one to two meters.

It has been observed that there are systematic biases present in the data collected with the Dot Products DPI-7 over a target field in an indoor laboratory. The target field comprised 42 spherical (40mm diameter) targets glued to a 91cm x 122cm plywood base. The target centres were scanned with a FARO Focus 3D scanner (Range noise of 0.6mm at 10m) to serve as the reference for the testing. The target field was scanned at a distance of 2m, approximately normal to the planar base, so that the entire field of view was filled with spheres. After registration by Horn's method, the difference vectors in the target centre locations were analyzed to quantify the scanner's quality. Clearly there exist large (up to 11mm) systematic errors even after the error compensation that results from loading a calibration file provided by the manufacturer before data are collected.

Figure 2 shows the differences between the DPI-7 data and the FARO Focus 3D data expressed in terms of error magnitude versus distance from the centroid of the target field, and the error direction as a function of the direction to the target. The trends in these figures suggest that a low-order polynomial modelling approach may permit more accurate co-ordinate determination. This paper reports the development of an analytical error model for the distortions found in a single frame of the scanner. This will be accomplished by using a self-calibration method, comparing the apparent change in position of common targets between changes in position of the scanner. By capturing targets across the entire field of view from many different perspectives, a model will be developed to describing the errors inherent in this system, and therefore improve its overall performance.

9528-15, Session 4

Optical metrology with low-cost camera systems for advanced manufacturing *(Invited Paper)*

Stuart Robson, Univ. College London (United Kingdom)

No Abstract Available

9528-16, Session 4

Assessment of the accuracy of 3D models obtained with DSLR camera and Kinect v2

Elise Lachat, Hélène Macher, Tania Landes, Pierre Grussenmeyer, Institut National des Sciences Appliquées de Strasbourg (France)

3D modelling of objects such as statues, moldings or ornaments, answers to a need of conservation and restoration in the field of cultural heritage.

Several sensors based on different technologies are used to obtain information on the geometry of an object in form of point clouds: laser scanners, digital cameras and more recently RGB-D cameras. The new Kinect v2 sensor, even more than the Kinect v1 sensor (Microsoft), looks promising for 3D close range measurements. The quality of the meshed model produced using the acquired point cloud is obviously correlated to the quality of the point cloud. Therefore the result is more or less faithful to the reality.

We will analyze the use of different types of sensors in the field of cultural heritage documentation for 3D modelling of a complex object. The objects under study are a limestone fragment from a Roman Theatre already studied by (Alby et al., 2009) and a part of a sandrock balustrade from the Strasbourg Cathedral. These objects were acquired by three types of sensors: the new Kinect v2 sensor (Microsoft), scan arm (Faro) and digital camera EOS 6D (Canon).

In the first part of our paper, the sensors will be presented and their benefits and drawbacks will be listed. We will consider criteria based on a) the captured object (material, size, complexity of the shape); b) the sensor (range measurement technology, accuracy, acquisition time, price, ease of use, need of post-processing); c) the local environment (ambient brightness, distance sensor-to-object). Regarding these criteria, the acquisition protocol as well as the different post-processing steps will be detailed.

Secondly, different comparisons will be realized in order to assess the accuracy of the point clouds and consequently the models obtained by photogrammetry and with RGB-D camera. Because of its accuracy and its high density, the point cloud obtained with the scan arm will be taken as a reference. In the literature, the most common inspection solutions are based on point-to-point, cloud-to-cloud or cloud-to-mesh (Charbonnier et al., 2013; Girardeau-Montaut et al., 2005; Mémoli and Sapiro, 2004).

Finally, regarding the results of the comparisons, we will be able to conclude about the reliability of photogrammetry and RGB-D camera for 3D modelling of complex objects.

9528-17, Session 4

Improving automated 3D reconstruction methods via vision metrology

Isabella Toschi, Erica Nocerino, Fondazione Bruno Kessler (Italy); Mona Hess, Univ. College London (United Kingdom); Fabio Menna, Fondazione Bruno Kessler (Italy); Ben Sargeant, Lindsay W. MacDonald, Univ. College London (United Kingdom); Fabio Remondino, Fondazione Bruno Kessler (Italy); Stuart Robson, Univ. College London (United Kingdom)

The 3D reconstruction problem is a fundamental issue of vision systems and refers to the process of recovering 3D information about a surveyed scene from two or more images taken from different viewpoints. Several methods have been developed in order to address the same basic question, i.e. how to compute the 3D position of an object point, given two (or more) corresponding image points. Literature in this field can be divided into two general approaches:

(i) vision metrology (VM) systems, that aim to derive 3D coordinates of few sparse object points;

(ii) dense image matching methods, that are designed to produce dense point clouds for surface representation.

The first approach is based on well-known principles that have gained widespread acceptance for industrial measurement and inspection applications. Its priorities have remained essentially constant over the years, i.e. very high accuracy with a high degree of measurement automation. As a consequence, VM systems adopt carefully designed image networks, coded targets, calibrated cameras and scale bars in order to measure specific features on the object of interest. On the other hand, several image-based software solutions have recently been developed to automatically retrieve dense point clouds from a set of un-oriented and un-calibrated images. This second approach covers extremely varied applications and image scales, thus becoming very popular for both professional and amateur end-users. The metrological consistency of the resulting 3D measurements is highly dependent on the quality of the imaged surface, on the image network configuration and on the matching algorithm. Furthermore, the large degree of automation is normally counter-balanced by an absence of statistical and evaluation parameters. Nevertheless, its promising outcomes together with the availability of many open-source or low-cost software systems, have raised the expectations of the scientific and industrial communities for a metrological-oriented use of these automated techniques for dense 3D reconstructions. Clearly, this requires a narrowing of the accuracy gap between the industrial sector and the more relaxed amateur or heritage sector.

The aim of the paper is to demonstrate a step towards bridging this gap by testing the metric performance of the automated photogrammetric 3D reconstruction procedure. In order to enhance the accuracy of the final results and obtain statistical indicators of the quality achieved in each step, the well-established algorithms implemented in classical photogrammetric packages for accurate measurement of single points are also adopted. The VM tool Vision Measurement System (VMS) is thus exploited to integrate its main functionalities (computation of image resections and intersections for target location, photogrammetric network adjustment, etc.) into the pipeline of 3D dense reconstruction. Geometric analyses and accuracy evaluations are performed on the raw output of the matching (i.e. the point clouds) by adopting a metrological approach. The latter is based on the use of known geometric shapes and quality parameters which are derived from VDI/VDE guidelines. Tests are carried out by imaging the calibrated Portable Metric Test Object, designed and built at UCL CEGE , UK. The object supports the evaluation of several geometric parameters, such as sphere spacing error, sphere diameter error, plane spacing error, angular error and structural resolution. The assessment procedure is carried out using GOM Inspect V8, a certified software currently freely available.

9528-18, Session 4

Determining the coordinates of lamps in an illumination dome

Lindsay W. MacDonald, Univ. College London (United Kingdom); Ali H. Ahmadabadian, Univ. of Tehran (Iran, Islamic Republic of); Stuart Robson, Univ. College London (United Kingdom)

Three techniques were employed for the geometric calibration of flash light positions in a dome illumination device for digital photography: (1) the shadow cast by a vertical pin onto graph paper; (2) multi-image photogrammetry with retro-reflective targets; and (3) multi-image photogrammetry using the flash lights themselves as targets. The precision of the coordinates obtained by the three techniques was analysed, and it was found that although photogrammetric methods could locate individual targets to an accuracy of 20 microns, the uncertainty of locating the centroids of the flash lights was approximately 1.5 mm.

The UCL Dome is an acrylic hemisphere of nominal diameter 1030 mm, fitted with 64 flash lights, arranged in three tiers of 16, one tier of 12, and one tier of 4 lights at approximately equal intervals. A Nikon digital camera is mounted on a rigid steel frame at the 'north pole' of the dome pointing vertically downwards with its optical axis normal to the horizontal baseboard in the 'equatorial' plane. It is used to capture sets of images in pixel register for visualisation and surface reconstruction.

1) Pin shadows The first calibration method used an imaging technique, based on the coordinates of the shadow cast onto graph paper by a vertical steel pin when illuminated by each light, analogous to determining the position of the sun in the sky from the shadow on a sundial. The coordinates were calculated by trigonometry.

2) Retroreflective targets The Vision Measurement System (VMS) was applied to determine the coordinates in the dome of retro-reflective targets stuck onto four well-defined positions around each of the 64 flash lamps. The locations of these targets on the inside of the hemispherical surface were estimated relative to the baseplane, but the photographs had to be taken with the dome raised on its hinges. The coordinates of the flash lamp were calculated as a weighted mean of the centroids of the four targets.

3) Flashes as targets VMS was used with the flashes of the lamps themselves as targets in the images. After running bundle adjustment, the coordinates of lamps were obtained with different levels of precision: 80.91 microns for the tier 1-2 image set and 43.60 microns for the tier 3-4-5 image set. The error ellipsoids of the targets show that the biggest errors occurred for the flashes in tier 1.

The objective of the study was to quantify the relative accuracy with which the lamp coordinates could be determined. With normal close-range photogrammetry it is expected to be able to locate all target positions to an accuracy of better than 10 microns. Although each individual image is limited in its pixel resolution, the use of relatively large retro-reflective target spots (diameter in range 2 to 5 mm) ensured that each spot had a diameter in the image of 6-15 pixels, and the centroid-fitting algorithm could locate the geometric centre of each spot to an accuracy of 0.1 pixel.

The poor accuracy of the first method, using pin shadows, was a consequence of mechanical movement of the structure and the assumption of a perfect hemisphere. The overall uncertainty measure was 11.37 mm for the accuracy of the lamp positions estimated by the pin shadow technique. For the second method, using four reflective targets around each lamp, the uncertainty arose from the characteristics of the circuit boards and the processing steps applied to the VMS results, giving an overall uncertainty measure of 1.17 mm. For the third method, using the flashes themselves as targets, the overall uncertainty measure was 1.22 mm. This was consistent with the distribution of differences between the X,Y,Z coordinates estimated by the target and flash methods.

In conclusion, this study proved the ability of the photogrammetric technique with the VMS software to estimate the lamp centroids in a complex structure to an accuracy of approximately 1.5 mm, i.e. 0.3% of the dome radius. This result is considered satisfactory for the purposes of using the dome for photometric imaging, and in particular for the visualisation of object surfaces by the polynomial texture mapping (PTM) technique.

9528-19, Session 5

Tracking of object deformations in color and depth video: deformation models and applications

(Invited Paper)

Andreas Jordt, Stefan Reinhold, Reinhard Koch, Christian-Albrechts-University Kiel (Germany)

No Abstract Available

9528-20, Session 5

Comparison between single and multi-camera view videogrammetry for estimating 6DOF of a rigid body

Erica Nocerino, Fabio Menna, Fondazione Bruno Kessler (Italy)

The estimation of the 6DOF (Degree-Of-Freedom) is a common task in many fields of application such as machine vision, navigation, industrial measurements, and medicine. Different non-contact technologies and methods for 6DOF determination of an object exist [1]: (i) inertial navigation systems (INS), (ii) GNSS/IMU for airborne camera orientation,

(iii) laser triangulation with multiple transmitters (Indoor-GPS), (iv) laser tracking with photogrammetric pose estimation (e.g. Leica Absolute Tracker T-Mac, T-Scan, T-Probe[2]), (v) laser tracking with CCD array and tilt sensors (e.g. Automated Precision Inc. API [3]), (vi) photogrammetric stereo and multi-image point tracking, (v) photogrammetric single camera object tracking.

Advantages/disadvantages of the above mentioned methods mainly depend on the budget, required accuracy, frequency and velocity of the dynamics, set up and location restrictions, expertise of personnel using the system.

Among optical-based methods, videogrammetry, i.e. multi-epoch photogrammetry, is the most flexible solution as it allows satisfying requirements from a broad field of applications. Indeed in many cases, a same system can be used for many applications with an appropriate set up and configuration [4].

Among optical methods three main approaches are used to track a rigid body: (i) multi-camera view photogrammetry (ii) multi view from mirror systems and (iii) single or sequential space resections. Methods (ii) and (iii) are not affected by synchronization issues therefore they are especially suited for high speed motion analysis applications where the cost of high frequency cameras is not negligible.

In a previous work [5] the authors presented an off-line low cost system based on multi-camera view photogrammetry synchronized exploiting the audio signals recorded by the consumer grade video cameras (three full HD interlaced Sony HDR CX106E) used in the experiments. An audio signal with known frequency was generated by an electronic device and matched on the three video cameras using cross correlation to measure the synchronization delays.

The system was used for a 6DOF motion analysis of ship models in a towing tank. A towing tank or naval basin is a pool where tests on scaled ship models are carried out to assess the performances of the ship in both calm and rough sea conditions. In the experiments presented [5], the scaled ship model was secured to the tank sides and several sea states were generated Some high contrast retro illuminated coded targets were positioned on the hull model and measured with an estimated accuracy ?XYZ of 0.1 mm using photogrammetry. The coded targets were tracked during the trials in the towing tank and a similarity transformation used to estimate the 6DOF of the boat with respect to a reference epoch. The accuracy of the method was evaluated using the RMSE of the rigid transformation.

The proposed method proved submillimeter accuracy in 3D point positioning for an object moving at a speed of 0.35m/s.

In this paper a single camera method, which does not require any synchronization, is used to track the 6DOF of the same ship model and towing tank trials of the previous work, using the results achieved as reference for accuracy evaluation of the single camera method. The ship model is regarded as a rigid body and the 5 coded targets used as GCPs to execute successive resections over the entire trial. The 6DOF of the boat is computed form exterior orientation parameters of the camera using the inverse motion. Commercial and in house developed software are used for the processing. Statistical parameters from least square adjustment are used to estimate quality parameters of computed motion. A comparison between the multi view and single camera 6DOF, advantages and disadvantages are also reported.

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9528-21, Session 5

Fast instantaneous center of rotation estimation algorithm for a skied-steered robot

Vladimir V. Kniaz, GosNIIAS (Russian Federation)

Skid-steered robots are widely used as mobile platforms for machine vision systems. However it is hard to achieve a stable motion of such robots along desired trajectory due to an unpredictable wheel slip. It is possible to compensate the unpredictable wheel slip and stabilize the motion of the robot using visual odometry. This paper presents a fast optical flow based algorithm for estimation of instantaneous center of rotation and angular and longitudinal speed of the robot. The feedback from the visual odometry is fused with the data from the wheel encoders to achieve the desired quality of robot dynamics.

Skid-steered robots use two pairs of differential driven motors to perform both longitudinal motion and rotation. The drawback of such system is the unpredictable motion of the robot during the rotation due to unknown amount of wheel slip. It is hard to stabilize the motion of the robot during the rotation even using the inertial navigation system because the real slip of each wheel remains unknown. However it is possible to recover the dynamics of the robot using the visual odometry.

The proposed algorithm is based on Horn–Schunck variational optical flow estimation method. The computational cost of the regularization term of the original Horn–Schunck method was reduced by estimation of an optical flow derivative by high pass filtering in frequency domain. This technique is used to achieve a rough optical flow estimation in real time. The instantaneous center of rotation is estimated by back projection of optical flow field to the ground surface. The divergence of the resulting vector field gives the instantaneous center of rotation.

The algorithm was developed and tested using the Hercules skid-steered mobile platform. The platform includes two pairs of differential driven wheels, motor controller, single-board computer and low cost webcam. To estimate the quality of the visual odometry data provided by the algorithm an external motion capture system was used. The motion capture system includes four calibrated industrial cameras operating in synchro mode at 100 FPS and a number of targets. The trajectory of the robot estimated by the algorithm was compared to the ground truth provided by the motion capture system.

The paper consists of four parts. The first part presents the equation of dynamics of four-wheel skid-steered robot. The exact transfer functions of the motors were measured using the motion capture system and used to design the basic motor controller.

The second part describes the proposed algorithm. The computationally optimized implementation of Horn–Schunck variational optical flow estimation method is presented. The constrained model of optical field used for optimization of minimization of the energy is based on the desired dynamics of the mobile platform and a-priori information about the ground surface.

In the third part the results of the external and internal orientation of the mobile camera are presented. The calibration was performed using a coded target field. The internal orientation parameters are based on Brown–Conrady distortion model.

The fourth part presents the results of drive testing of the algorithm using the Hercules mobile platform. The mobile platform was controlled to drive along the basic trajectories: circle, ellipse, rectangle, sine wave. The longitudinal and angular navigational errors of the robot were measured using the motion capture system.

The paper is concluded with the comparison of the developed algorithm with modern optical flow based visual odometry algorithms. The evaluation of the developed algorithm and comparison with the data from the motion capture system proved its accuracy and robustness. The desired quality of control during the motion along the basic trajectories was achieved.

9528-23, Session 5

Investigating influence of UAV flight patterns in multi-stereo view DSM accuracy

Dimitrios P. Skarlatos, Marinos Vlachos, Cyprus Univ. of Technology (Cyprus); Vasilis Vamvakousis, Cyprus Univ of Technology (Cyprus)

Current advancements on photogrammetric software with the implementation of computer vision algorithms as well as the affordability and wide spreading of Autonomous Unmanned Aerial Vehicles (AUAV), allow for rapid, timely and accurate 3D modelling and mapping of small to medium sized areas. Although the importance of flight patterns and large overlaps in aerial triangulation and Digital Surface Model (DSM) production from large format aerial cameras is well documented in literature, this is not the case in AUAV photography, with high overlaps and Multi View Stereo (MVS) processing software. This paper assess the DSM accuracy of models created using different flight patterns and comparing them against Lidar data.

The test site has 130m height difference and the average flying height was 215m, with an average pixel size of 8.5cm. Three UAV flights took place, all from same flying height, with 70/50 overlaps, with West-East (WE), North-South (NS) and Northwest-Southeast (NwSe) directions. The aerial triangulation assessment is not part of this work, hence a common aerial triangulation, with all photos took place, with all ground control points being measured in all visible photos. After the finalization of the aerial triangulation with 0.06 m horizontal and 0.14 m vertical residuals, five separate blocks were created by removing photos from the combined block; WE, NS, NwSe, WE+NS, NwSe+WE+NS. Each block was processed to create a DSM with 0.25m ground pixel size using MVS.

The test site was selected because of the existence of aerial Lidar data which could act as reference data, as well as the morphology of the site with a variety of land use and large height differences. The available Lidar data in LAS format, with 2mspacing, were processed to produce a DSM using first response, hence creating a DSM compatible to the one produced by aerial photos. For each DSM a difference map was created and statistical measures were calculated in order to in order to evaluate its overall accuracy. Accuracy analysis against different land cover such as ground and tree canopy is presented, analysed and discussed. Height accuracy against slope is also analysed in particular and discussed.

Overall, the combined scenario, with all available photos performed better that the rest. Particular samples of objects and vegetation are selected and discussed in particular to highlight differences between data sets. Because of their lower spatial resolution, Lidar data prove to be an inadequate reference data set, although according to their internal vertical precision they are superior to UAV DSM. Therefore, in order to compensate for that, the UAV DSMs were downsampled to be made equivalent to Lidar ground pixel size and compared again. Moreover discussion and comparison is extended among passive and active sensors, based on the findings of this work. Another apparent difference among the data sets is the noise of the image DSM in contrast to pre-processed Lidar data, which due to the down sampling of UAV DSM is almost completely eliminated. A Lidar data set from a lower flying platform such as helicopter might have been a better match to low flying UAV data.

9528-24, Session 6

Multi-image semi-global matching in object space

Folkmar Bethmann, Thomas Luhmann, Jade Hochschule (Germany)

Semi-Global Matching (SGM) has proven to be a powerful stereo matching algorithm which is used for a variety of applications and measurement tasks, ranging from close-range and real-time applications to aerial image matching. It has become widespread especially due to several advantages compared to other matching algorithms: It is very robust and reduces large outliers in low or no-textured areas while preserving edges and sharp object boundaries. It allows for the use of pixel-wise cost functions and is therefore able to resolve fine spatial structures on the object surface. Further on, it is almost independent of task dependent parameter settings and therefore reduces efforts for the adaption of matching parameters for a special measurement task, avoids unsuccessful test runs and can be used in black box solutions. Finally, it can be implemented very efficiently in terms of computing time by using hierarchical matching strategies and techniques of parallelization on special hardware (GPU, FPGA). All in all SGM can be regarded as a good compromise between high accurate but less robust image matching techniques and robust but time-consuming global matching methods.

Originally, SGM has been developed to perform stereo image matching. Moreover, it is often used in Multi-View Stereo (MVS) approaches for solving complex 3D reconstruction tasks by using more than two images. Typically, MVS approaches consist of several processing steps, beginning with the selection of appropriate image pairs for stereo image matching, the rectification of all image pairs, the pairwise stereo image matching and the fusion and filtering of all resulting disparity maps to create the final solution.

The matching process is always performed in stereo images because the original SGM method do not allow for multi-image matching. Further on, SGM is usually performed by using rectified image pairs according to the normal case of stereophotogrammetry, aiming at the simplification of the semi-global optimization to a 2.5D problem with 2D image coordinates and one disparity for each pixel. Hence, for a bundle of n images (n?(n-1)) images have to be rectified to create (n?(n-1))/2 image pairs (e.g. with n=5, twenty images have to be rectified) which may increase the computation time significantly.

Within this paper we propose an alternative solution for Semi-Global Matching which avoids these disadvantages while preserving the above mentioned advantages of SGM. Our approach is especially well-suited for typical 2.5D applications e.g. like aerial image matching but, in general, it is extendable for 3D applications as well. Altogether, it yields to an essential simplification of the matching process compared to MVS approaches.

The new approach differs in two main aspects from SGM. Firstly, cost calculation is formulated in object space instead of image space (figure 1, left hand side). Therefore, the object space is subdivided into a voxel raster in a first step. Each voxel may be a cube or a cuboid and the size of the cuboids defines the resolution in object space.

For each voxel matching costs can be calculated by using the corresponding grey or colour values either of selected image pairs or of an arbitrary number of images. Therefore, it is principally possible to perform real multi-image matching instead of stereo matching if appropriate cost functions are used.

Secondly, the path-wise (semi-global) cost aggregation is also performed in object space (figure 1, right hand side). The smoothness constraints of SGM, which are controlled by the two penalties P1 and P2, then effectuate a smoothing with respect to a defined axis in object space, e.g. the Z-direction of the global coordinate system. The semi-global optimization finally results in one Z-coordinate for each X/Y-position of the grid. Consequently, 2.5D point clouds are directly generated in a defined (local or global) coordinate system instead of one disparity map for each image pair like in common SGM. This approach has several advantages. Firstly, if pairwise matching is performed, consistency checks for the resulting Z-coordinates can easily be performed and the number of remaining outliers can be reduced significantly. Secondly, it is possible to subdivide the whole voxel grid into smaller parts and the size of each part can be adapted to the existing working memory. Hence, it is possible to implement the algorithm for the usage of very large datasets very easily and large datasets can be processed principally even with standard hardware. Thirdly, there is no need for further transformations and fusion strategies for the transformation of the results into a global coordinate system. Finally, as already mentioned, instead of stereo image matching multi-image matching can be performed. Moreover, the new approach can as well be used for 3D applications by combining multiple 2.5D solutions by using strategies related to those of MVS approaches.

Within the paper the new method is described in detail, including strategies for a RAM-efficient implementation, parallelization for multi-threading on CPU and hierarchical matching to speed up the performance. Further on, matching results for close-range applications and aerial image matching (figure 2 and 3) will be presented and discussed.

9528-25, Session 6

3D city models completion by fusing lidar and image data

Lazaros Grammatikopoulos, Ilias Kalisperakis, Elli Petsa, Technological Educational Institute of Athens (Greece); Christos Stentoumis, National Technical Univ. of Athens (Greece)

Today, 3D city models are of course an essential tool in a variety of applications, such as urban planning, tourism, real estate as well as asset and utility management, since they provide a more realistic representation of urban environments compared to traditional 2D maps and orthophotos. A crucial task in generating geometrically accurate and visually detailed 3D models of buildings, and urban areas in general, is the acquisition of high fidelity 3D data, which is usually performed by airborne Lidar scanners. However, in densely built areas these elevation data are often incomplete, due to failures, adverse geometries or occlusions, which are more severe on building facades. Hence, an interesting task is the fusion of Lidar data with those generated from image-based procedures in order to enhance or complete them. The work presented here is part of an ongoing research project which aims to create accurate 3D city models by combining various types of geospatial data, such as Lidar, orthomosaics along with vertical and oblique aerial imagery.

In particular, we primarily focus on the automatic registration of the images with the existing Lidar data and digital orthophotos. Then, dense matching algorithms allow the generation of a highly detailed point cloud and its integration with the Lidar model, thus finally leading to a more complete 3D mesh model. Our dataset covers a neighborhood of Athens, Greece, and includes an orthomosaic with spatial resolution of 20 cm, provided by the National Cadastre & Mapping Agency of Greece (Figure 1), a DSM generated from Lidar with spatial resolution 1 m and aerial overlapping images (both vertical and oblique) with average resolution of 15 cm.

The image-to-Lidar registration is carried out in multiple steps. First, all available images are relatively oriented through a hierarchical structure from motion scheme implemented by our team. Image pairs are identified among unordered sets of images; sparse matching is then performed employing state-of-the-art features with their descriptors (SIFT, SURF) at multiple image scales. Image matches are thus established across different stereo-pairs leading to multi-image point correspondences. By means of closed-form algorithms, image orientations are initialized, and finally exterior and interior orientation parameters are refined through a typical self-calibrating bundle adjustment solution. In this way, a 3D point can be assigned to every extracted feature.

On the other hand, features with descriptors are also detected on the available orthophoto and assigned to 3D points via height interpolation on the Lidar DSM. Descriptor matching with robust outlier detection (by applying RANSAC to 3D similarity transfomation) is performed among these two point sets, and then a new bundle adjustment solution is carried out, in which the features from Lidar and orthophoto are treated as control point observations with appropriately tuned weights. Additionally, tie points may be constrained to follow the DSM elevations (soft constraint). In this way an optimal registration of all data is achieved.

In the last step, state-of-the-art dense matching algorithms are applied in order to complete the Lidar data, acquiring the final triangulated 3D model (3D mesh). The overall accuracy of the described approach is evaluated by comparing a new orthomosaic created from the generated data against the available orthoimage. Additional comparisons are also made between the DSMs. Preliminary results on our dataset show that, with this implemented approach, image-based modeling can indeed significantly improve the quality of acquired 3D data.

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9528-26, Session 6

DTM generation from STC-SIMBIO-SYS images

Cristina Re, INAF - Osservatorio Astronomico di Padova (Italy); Emanuele E. S. Simioni, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Gabriele Cremonese, INAF - Osservatorio Astronomico di Padova (Italy); Riccardo Roncella, Gianfranco Forlani, Univ. degli Studi di Parma (Italy); Vania Da Deppo, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and INAF - Osservatorio Astronomico di Padova (Italy); Giampiero Naletto, Univ. degli Studi di Padova (Italy) and CNR-Istituto di Fotonica e Nanotecnologie (Italy) and INAF - Osservatorio Astronomico di Padova (Italy); Giuseppe Salemi, Department of Cultural Heritage: Archaeology and History of Art, Cinema and Music (Italy)

The development of advanced techniques in data acquisition and processing for the mapping of Solar Systems bodies are becoming more and more important and interesting for the scientific community. In this context the research group with the responsibility of the STereo Camera (STC) for the ESA BepiColombo mission to Mercury realized an innovative and compact camera design in which the light, collected independently by two optical channels at ±20° with respect to the nadir direction, converges on the same off-axis portion of a modified Schmidt design and on unique bidimensional detector. Moreover, STC adopts a novel stereo acquisition mode, based on the push-frame concept, never used before on a space mission.

STC, integrated in the SIMBIO-SYS suite, will provide a three-dimensional reconstruction of Mercury surface, acquiring images from two different perspectives. The new stereo push-frame concept, due to the low resources allocated to support the mission instruments design, needs a pre-flight verification of the actual accuracies in obtaining elevation information from stereo couples. To this aim, a stereo validation setup, based on the used of two rotational stages to get an indoor reproduction of the flight observing condition of the instrument, has been developed in order to give a much greater confidence to the novel instrument design. Since in-flight STC will have to deal with source/target placed at infinity, an auxiliary optical system (collimator lens) that collimates the light rays coming from the target has been necessary to realize the indoor acquisition of the images. In doing so, a target projected at infinity by about 1-m focal length collimator corresponds to a representation of the Mercury surface at 400 km distance.

The stereo-pairs of a series of rock samples (anorthosite and basalt stones have been specifically collected as they represent a good analogue of the hermean surface) and of a modelled piece of concrete, acquired in laboratory, have been introduced in the photogrammetric pipeline that consider the Dense Matcher as image correlator for the final 3D model generation. Once run the program, the stereo validation has been performed by comparing the STC DTMs (Digital Terrain Models) produced by Dense Matcher software and the DTM produced by an high resolution laser scanning system as reference data. The latter has a much higher precision (ca. 20 micrometer) of the expected in-lab STC photogrammetric image network (ca. 190 ?micrometer).

A series of different parameters and conditions have been changed in order to test their influence on the accuracy of the DTMs produced by the STC-stereo images as different illumination angles (in order to reproduce the acquisition conditions according to the Sun position) and different image compression rates. The main aim is to define the best stereo-pairs and acquisition configurations to obtain the best DTMs in terms of accuracy, considering the compromises between the mission constraints and the specific matching aspects that could affect the mapping process.

9528-27, Session 6

Stereo matching based on census transformation of image gradients

Christos Stentoumis, National Technical Univ. of Athens

(Greece); Lazaros Grammatikopoulos, Ilias Kalisperakis, Technological Educational Institute of Athens (Greece); George I. Karras, National Technical Univ. of Athens (Greece); Elli Petsa, Technological Educational Institute of Athens (Greece)

Image-matching is essential for providing geometric and radiometric information required for many tasks addressed in photogrammetry and computer vision. Full automation of the 3D extraction process implies accurate dense image matching. Advances in the past decade have proven image-based methods to be indeed comparable to active methods (e.g. terrestrial laser scanners). Although multiple-view matching provides certain advantages regarding accuracy, occlusion handling and radiometric fidelity, stereo-matching remains indispensable for a variety of applications. In several scenarios when image acquisition requires fixed geometry, limited number of images or speed, stereo-matching is necessary. Such instances include robotics, autonomous navigation, reconstruction from a limited number of aerial/satellite images, industrial inspection and augmented reality through smart-phones. As a consequence, stereo-matching is a continuously evolving research field with a growing variety of applicable scenarios. In this paper, a novel multi-purpose matching cost is proposed, which is based on Census transformation on image gradients and is evaluated within a local, hierarchical, adaptive scheme.

The cost is the Hamming distance of the widely used non-parametric Census transformation of stereo-images, which however is here applied to image gradients. Census transformation depends on how pixels relate to their surroundings; hence, it is robust against changes in brightness and contrast which do not upset the ordering of intensity values. Our modification exploits the representational potential of image gradients. The size of the binary vector, which represents the census transformation, is doubled, without noticeable drop in process speed. It is shown here that when the census transformation is applied on gradients the invariance of the cost function to exposure and illumination changes is strengthened. The complete Middlebury dataset 2006 is used here to experimentally verify the above, as it includes images with different exposure settings and illumination changes.

The calculated cost values are aggregated through adaptive support windows, based on cross-skeletons. These are computed on both the left and right images based on colour similarity and their distance from the reference pixel in image space. Both basic rectangular support windows and adaptively weighted support windows are also used as an aggregation strategy, in order to verify that the census transformation on image gradients indeed results in a more robust cost function, regardless of the cross-skeleton-based support windows.

Matching is addressed through a hierarchical matching scheme, in order to improve computational complexity (reduced running time and memory consumption). The support windows are exploited to indicate the neighbouring pixels, which define the range of potential disparities of each pixel, via their estimated disparity in the coarser level. Left-right matching consistency is used to prevent errors in coarser scales from accumulating in the full resolution scale. The matching strategy is then finalised by estimating sub-pixel values for disparities through curve interpolation to the cost function values of potential disparities for each pixel. Disparities have not been refined here, as in previous works, mainly because the core matching algorithm is to be evaluated, but also because the effectiveness of the refinement process does not match the computational cost.

The described approach is evaluated on the widely used Middlebury stereo vision evaluation platform, with both the 2006 offline dataset and the 3rd (beta) version of the online dataset, presented only a few months ago (http://vision.middlebury.edu/stereo/eval3/). The 3rd version of Middlebury evaluation platform consists of high resolution images of complicated real-life indoor scenes; hence it is more suitable for assessing the performance of each algorithm. These stereo-pairs include images with different exposure (Fig.2, above) and illumination settings, as well as stereo-pairs with epipolar rectification errors, in order to allow evaluation of these parameters. In Fig.1, the effectiveness of census transformation on image gradients is visualized; the average matching error percentages on the 21 stereo-pairs of the 2006 dataset are presented with respect to combinations of exposure and illumination changes (i.e. three exposures modes [0 to 2] and three illumination modes [1 to 3]). In Fig. 2, the results for two stereo pairs from the new Middlebury training set are presented. The MotorcycleE (MotorE) stereo pair yields the best matching results (excluding the older and simpler Teddy dataset), having 10.4% erroneous disparities above 2 pixels for non-occluded regions (5th position). On the contrary, the Shelves (Shelvs) stereo pair gives the poorest matching results with 49.7% erroneous disparities above 2 pixels (13th position). The preliminary results are promising (although they are inferior to those for the previous version of the Middlebury evaluation dataset, as the new dataset is clearly more challenging), and the algorithm (simplified LAMC-DSM) performs satisfactorily when compared to other well-known algorithms, e.g. SGM and ELAS (Fig. 3).

9528-28, Session 7

Single-plane versus three-plane methods for relative range error evaluation of medium-range 3D imaging systems

David K. MacKinnon, Luc Cournoyer, Jean-Angelo Beraldin, National Research Council Canada (Canada)

Within the context of the ASTM E57 committee, we compare to methods for evaluating the relative range measurement performance of medium-range (2 m to 150 m) lidar systems: a single-plane method and method involving three mutually non-orthogonal planes. Both methods are evaluated for their utility in calculating the relative range error of medium-range lidar systems. Based on experimentation, we determined that there is no significant difference in relative range error values generated by either method so conclude that both methods produce equivalent results for purposes of measuring relative range error. A drawback of the single-plane method proposed by the ASTM E57 Committee is that the plane boundaries must be manually selected in order to location a common center despite there being known issues around lidar measurement of edges. The three-plane method uses the intersection of planes to locate a common center so avoids this problem. Residual dispersion and ease of use were also assessed and were found to be comparable.

9528-29, Session 7

Extracting the MESA SR4000 calibrations

Sean A. Charleston, Adrian A. Dorrington, Lee Streeter, Michael J. Cree, The Univ. of Waikato (New Zealand)

Time-of-flight range imaging cameras operate on the principle that the precise knowledge of the speed of light can be used to determine the distance to an object. In practice, the range is inferred indirectly, using Amplitude Modulated Continuous Wave (AMCW), due to the high electronic demand required to directly measure the flight time. In AMCW systems, the transmitted light is modulated, and the phase change of the received signal is measured to infer distance. These cameras require at least three captures (known as phase steps), in order to produce a single phase/amplitude image combination.As with any optical system, calibration is a key step to produce accurate results. Time-of-flight cameras introduce a variety of additional sources of noise and error compared to standard 2D cameras, due to a number of complications, including the transmission/reception of modulated light. The MESA SR4000 is an industrial grade time-of-flight camera, which is regarded to have a relatively high quality calibration.The SR4000 has a number of built in calibrations, which are unavailable when using the camera in `raw mode' (acquiring only the raw phase steps). The main application includes an upcoming motion correction algorithm, which is the main motivation for this work. It is also applicable to other techniques requiring either raw data, or data captured at other (uncalibrated) frequencies. In this paper, we investigate the calibrations of the SR4000 in order to determine the calibration necessary for correct use of data acquired in `raw mode' from the camera. BACKGROUND. Time-of-flight cameras using the AMCW technique determine the phase (hence range) of a returning modulation waveform, by correlation with the original modulation waveform. At least three phase steps, with additional phase offsets added, are required to resolve the phase, amplitude, and background level of the returning modulation waveform. Four phase steps are typically used, as it simplifies the calculations, particularly for hardware implementation. There are a number of noise and error sources related to time-of-flight cameras. The first error source, fixed in time and independent of range, is a global phase offset. This constant phase offset is due to fixed propagation

delays in the electronics, and is corrected by applying a constant phase correction to all pixels. Secondly, there is a gradual phase offset across the sensor, caused by clocking propagation delays. Finally, there is a phase fixed pattern noise (PFPN), likely due to additional fixed per-pixel delays. These three phase offsets can be combined into one constant phase correction per pixel.

Phase offsets that are dependent on the range to the scene can be caused by harmonic distortion, which is a result of harmonics (odd harmonics only if four phase steps are used) of the modulation signal (due to square wave modulation and/or non-linearities) aliased onto the fundamental. The error presents as a calibratable oscillation on the true phase. There are also two sources of amplitude error. The first is a gain fixed pattern noise (GFPN), where each pixel responds slightly differently to the same number of arriving photons. Secondly, there is a dark current amplitude offset per pixel. This is due to the sensor reporting some level of signal in the absence of light. Typical calibration techniques involve imaging a planar target, or a checkerboard pattern to attempt to correct the image to some ground truth. One of the downsides of this technique is the fact that the cameras measure the radial distance to the scene, hence a transformation is required if the calibration is to be compared to a plane. METHOD. The key novelty in retrieving the SR4000 calibrations is in acquiring the data. The SR4000 is set up on a precision linear translation stage. A retro-reflector is set on the stage, and positioned from 0.5 m up to 3.5 m from the camera. The purpose of the retro-reflector is that at distance, it approximates a point source, and generates a near planar wave at the sensor. Diffusers are added to the system, to distribute the light evenly across the sensor, and prevent saturation due to the use of the retro-reflector. Images were then acquired from the calibrated SR4000, both in normal operation and in `raw mode'. Analysing these images, each portion of error discussed above can be modelled in turn, providing look up tables for each error source. RESULTS. To verify the calibrations, new data was captured of a flat plane at various angles and distances. In this case, the MESA calibrated data is treated as a calibrated reference. The modelled calibrations are then applied to the `raw mode' data, and these are compared to the reference. The RMSE and SD between these data sets were calculated at a number of angles and distances. The average RMSE for the modelled calibration was measured to be 6.5 mm, with the average SD 3.5 mm. To gauge the improvement compared to using the `raw mode' data, the RMSE between `raw mode' and the ground truth data shows an RMSE 57.8 mm, with SD 38.4 mm.

We introduce a novel technique to extract and model the calibrations built into the MESA SR4000. These calibrations can then be applied to the `raw mode' data, which is required for running custom algorithms. The calibration showed a significant improvement in using the retrieved calibrations, rather than the `raw mode' data by itself. The main limitation of the technique lies in the fact that it is using the MESA calibrations as its calibration reference. There is a temperature calibration required, which is currently being investigated further, as well as the consideration of the integration time. Future work will see this work applied to motion correction, as well as other algorithms requiring the manipulation of `raw mode' data.

9528-31, Session 7

Enhancing swimming pool safety by the use of range-imaging cameras

Dave Geerardyn, Sven Boulanger, Maarten Kuijk, Vrije Univ. Brussel (Belgium)

Drowning is the cause of death of 372.000 people, each year worldwide, according to the latest report of the World Health Organization. Currently, most swimming pools only use lifeguards to detect and rescue drowning people. In some modern swimming pools, camera-based detection systems are nowadays being integrated. These camera-based systems are expensive, bulky and suffer from occlusions if not enough cameras are installed. Moreover, they have to be mounted underwater, mostly as a replacement of the underwater lighting, since otherwise they are not able to distinguish swimming from drowning people. We are interested in range imaging cameras mounted on the ceiling of the swimming pool, since they would allow to distinguish swimmers at the surface from drowning people underwater, while keeping the large field-of-view and minimizing occlusions. However, to obtain a qualitative image, we have to take into account that the water surface of a swimming pool is not a flat surface, but mostly rippled, and that the water is completely transparent for visible light, but not for infrared light. We first experimentally and theoretically investigated the use of different types of commercially available 3D cameras to detect objects underwater at different depths and with different amplitudes of surface perturbations. Specifically, we performed measurements with time-of-flight cameras and a structured-light depth camera. To minimize the limitations of these low-cost commercial cameras, we designed, created and tested our own time-of-flight system. Our developed time-of-flight system uses a different operation principle and works at a different wavelength than the commercially available system. It uses pulsed time-of-flight instead of continuous-wave time-of-flight and emits light of 785 nm instead of the more generally used 850 nm. Moreover, in contrast to the commercial vendors, we are able to easily adjust the system parameters of both the software and hardware. For all three tested systems, our measured distances between the camera and the object are influenced through the perturbations on the water surface. Nevertheless, our own system shows a better performance when measuring distances behind a semi-transparent surface, which causes confusing reflections. Due to the ripples on the water surface, the incoming light is refracted and reflected in various directions dependent on the position and angle of the wave, in accordance to Snell's law. As a consequence, this also causes more direct reflections than with a flat surface. However, due to the timing of our time-of-flight camera, our system is able to minimize the influence of these reflections. The detectable object depth of our camera is limited through the absorption of the infrared light into the water, but is larger than the commercial systems due to the use of a light source with a shorter wavelength. Furthermore, the performed characterization of the camera system allowed us to define low-cost improvements for the current depth-camera systems. The combination of a post image-acquisition filter compensating for the perturbation and the use of a light source with smaller wavelengths to enlarge the depth range can significantly improve the current commercial cameras. As a result, we can conclude that low-cost range imagers can increase swimming pool safety, by inserting a post-processing filter. Moreover, through the use of another light source, with a higher optical power and shorter wavelength, the camera would show an improved performance for deeper swimming pools or soiled water. With this work we hope to pave the way towards an improved and low-cost solution for drowning-people detection systems for swimming pools.

9528-32, Session 7

Evaluating the capability of time-of-flight cameras for accurately imaging a cyclically loaded beam

Herve D. Lahamy, Derek D. Lichti, Mamdouh El-Badry, Xiaojuan Qi, Ivan Detchev, Jeremy Steward, Mohammad Moravvej, Univ. of Calgary (Canada)

Concrete beams are used in the construction of civil infrastructure. Years of traffic overloading and insufficient maintenance have left some civil infrastructure systems such as bridges in a poor state of repair. Therefore, the structures have to be strengthened. Many options for their reinforcement exist such as adding fiber-reinforced polymer composites and steel plates to the structural elements. The efficacy of such methods is evaluated through fatigue load testing in which cyclic loads are applied to individual beams under laboratory conditions. The deflection of a beam in response to the applied loads is measured in order to examine the efficiency of the particular reinforcement. Many optical modalities such as digital cameras, laser scanners and displacement transducers have been used for the measurement of the beam deflection.

The SR4000 range camera has also been used to estimate concrete beam deflections due to its ability to provide 3D data in real time with up to 54 frames per second using one single camera. Several experiments implemented in the structures laboratory in the University of Calgary have shown the capability of the SR4000 range cameras to recover the deflection measurements with half-millimeter accuracy at a loading frequency of 1 Hz and 3 Hz. However, in the past this deflection was measured from several thin plates attached to the concrete beam. Since the previously used spreader beam occluded almost half of the top surface of the concrete beam, thirteen thin aluminum plates were attached to the side of the concrete beam at uniform increments along its length. Even though the surface of interest was the top surface of the

concrete beam, the deflections were measured from the thin plates. In the current experimental setup (see Figure 1), no spreader beam has been used and the actuator only covers about 25 cm of the 3-metre beam. This allows for the top surface of the beam to be imaged. The objective of the current paper is twofold. First, reconstruct the 3D movement of the top surface of the beam after correction of the random and systematic errors generated by the time-of-flight cameras and evaluate the motion accuracy. Secondly, this paper intends to compare the 3D surface obtained from the range cameras with the one extracted from the laser scans.

The methodology used consists first in calibrating the range cameras in order to estimate their interior orientation parameters. The two SR4000 range cameras used to cover the beam surface are then synchronized using a signal generator. As the common field of view of the cameras is nearly non-existent, the data sets from the cameras are registered using several circular black and white targets pasted on the laboratory floor (Figure 1). Since none of the targets overlap, the HDS 6100 terrestrial laser scanner is used to scan the targets and the object space coordinates of the centers of the targets are obtained after fitting an ellipse to their circumferences. Using the object space coordinates as well as the pixel coordinates of the target centers, a photogrammetric resection is applied to extract the exterior orientation parameters of each camera. The scattering effect induced by the spreader beam in the range images is corrected using a polynomial function. The 3D point cloud of the top surface of the beam is then segmented from the registered data (Figure 2) and compared to the corresponding reference segment extracted from the scanned data.

The preliminary results from the data analysis of the deflection measurement indicated that periodic deflection can be recovered with sub-millimeter accuracy at 1 Hz and 3 Hz loading frequency.

9528-33, Session PS

Hand-eye calibration method based on Schur Decomposition

Jinbo Liu, National Univ. of Defense Technology (China)

Approach

In this paper, we address the hand-eye problem of a theodolite mounted video camera. We propose a more accurate and robust two-step hand-eye calibration linear method based on schur matrix decomposition. In a first time, we prove that the schur decomposition of orthogonal matrix has two important special characteristics. These allow a matrix analysis that usual approaches do not consider. In a second time, we extend these special characteristics into a hand-eye calibration method. This method allows to get rid of outliers, which is a basic problem unsolved in all methods. In a third time, we prove minimal configuration for hand-eye calibration from another view and also drive the same conclusion. The main innovative points are as follows:

(1)Obtain the general solution from one observation and decrease the degree of freedom from 3 to 2, which improves method's efficiency.

(2)Deduce judge equation of outlier and improve observation quality by input data selecting, which makes method more robust.

Results

It is very expensive to obtain real transformation between robot gripper and camera. Most of references adopt the following program: camera moves 2N times, in which preview N times is called calibration procedure and last N times is called verification procedure. Calibration procedure is to calculate the transformation between robot gripper and camera. Verification procedure is to verify the methods' accuracy by comparing the predicting rotation and translation with real rotation and translation. We adopt the program that uses camera's rotation, translation and fixation relationship to predict theodolite's rotation and translation. Also we can use theodolite's rotation, translation and fixation relationship to predict camera's rotation and translation. The Leica RTS with angle-measuring accuracy of 0.5" simulates robot and eyepiece sleeve simulates robot gripper. Camera is fixed on the eyepiece sleeve. At the time i, rotation and translation of camera and eyepiece sleeve can be obtained by extrinsic calibration and encoder.

(Experiment 1)Predict Leica RTS's rotation and translation based on camera

Experiment 1 is mainly for robot, whose vision sensor is fixed on gripper. Based on the feedback of vision sensor, gripper can do some precise operation.

Table1 Statistical results of experiment 1?terror: mil ?error?mrad?

N Proposed method Tsai method Inria method Navy method Quaternion method

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2 2.95 5.49 2.95 7.06 2.95 6.23 2.96 5.25 2.97 8.70

3 2.94 4.63 2.94 6.21 2.95 6.20 2.95 5.10 2.95 7.08

4 2.93 4.06 2.94 5.77 2.94 4.74 2.94 4.97 2.95 6.18

5 2.86 3.94 2.93 4.15 2.93 3.79 2.93 4.62 2.94 4.17

6 0.28 2.46 0.28 3.67 0.38 3.61 0.63 3.54 1.11 3.98

7 0.13 1.57 0.15 3.51 0.15 3.60 0.15 1.87 0.52 3.64

8 0.11 1.15 0.11 2.76 0.12 2.51 0.13 1.77 0.13 2.27

9 0.02 1.01 0.08 2.47 0.10 2.27 0.12 1.19 0.12 1.82

(Experiment 2)Predicting camera rotation and translation based on Leica RTS

The essence of experiment 2 is the same as experiment 1. However, the application is different. The preview one aims at hand-eye coordination and the last one mainly aims at optical measurement. Phototheodolite is important optical equipment, fixing camera on a theodolite's eyepiece sleeve. It can supply the gap of fixed viewing field and simplify measurement equipment. Extrinsic prediction is an important factor of measurement accuracy. Hand-eye calibration method can also be applied to solve this problem. We evaluate method's precision using target's reprojection error on image.

Table 2 Statistical results of experiment 2 (pixel)

N Proposed method Tsai method Inria method Navy method Dual quaternion method

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2 4.89 7.21 5.90 6.48 7.36

3 3.71 5.03 4.02 4.78 7.06

4 3.36 4.61 3.68 4.55 6.47

5 3.03 3.69 3.09 3.62 4.52

6 2.94 3.54 2.98 3.48 4.37

7 2.52 3.50 2.58 3.11 4.27

8 1.65 2.25 2.10 2.12 3.45

9 1.50 1.99 1.87 1.94 2.06

9528-34, Session PS

Precise deformation measurement of prestressed concrete beam during a strain test using the combination of intersection photogrammetry and micro-network measurement

Rudolf Urban, Jaroslav Braun, Martin ?troner, Czech Technical Univ. in Prague (Czech Republic)

The prestressed thin-walled concrete elements enable the bridge a relatively large span. These structures are advantageous in economic and environmental way due to their thickness and lower consumption of materials. The bending moments can be effectively influenced by using the pre-stress. The experiment was done to monitor deformation of the under load. During the experiment the discrete points were monitored. To determine a large number of points, the intersection photogrammetry combined with precise micro-network were chosen.

The strain tests are very important for the prediction of the concrete structure. There are many different concrete elements for the construction, but usually the deformation properties of the structure are determined only by numerical computations. For better understanding of the deformation of concrete beam an actual experiment was planned. There were many points on the beam therefore the photogrammetric method was chosen.

The prestressed thin-walled concrete beam was 7.7 m long and 0.6 m

high. There were about 220 discreet points on the beam and about 40 points on stable objects for better comparison of the stages. The whole experiment was divided into 20 stages. The photogrammetric points were represented by special circular reflective targets for sub-pixel marking. Six of these photogrammetric points in each stage were measured by total station. The time to measure one stage was only 7 minutes. The press machine was precisely programmed and when 7 minutes passed, it started in further deformation of the beam regardless to the state of the measurement.

The images were made from four standpoints (about 2.5 meters from the beam) and the total station was placed about 4 meters from the beam. From each standpoint 7 images were made shooting only from hand orientation and parameters of the camera were calculated in software (full field calibration). The scale of the photogrammetric model was determined using only the distance of two points on the images.

For photogrammetry (method) the digital camera Canon EOS 5D Mark II with the Canon 40 mm fixed focus lens was used. The camera has 21 Mpix resolution (W: 5616 pixel and H: 3744 pixel). Before taking pictures the lens was focused automatically on the concrete beam and then the focus has been fixed for the whole stage. The fixation was realized by sellotape, after that the focus was switched to manual. For sufficient depth of field the aperture of number 22 was chosen, also for the photogrammetric reflective targets the external flash was used.

Geodetic measurements has been done using the total station Trimble S6 High Precision Robotic (standard deviation of direction and zenith angle is 0.3 mgon, standard deviation of distance is 1 mm + 1 ppm D). The concrete beam was quite near to the standpoint and therefore the standard deviation in direction was changed to 0.7 mgon for analysis of accuracy.

The photogrammetric model is a composition of 28 images in each stage and processing was done in PhotoModeler Scanner 6 software.

The full field calibration was used in each stage. For good determination of the parameters of the camera (principal points, focus length and distortion) it was necessary to take turned images. The beam was very thin and therefore many photogrammetric points were added for a better coverage of images.

For each stage the photogrammetric project was founded. The marking of points was done automatically by sub-pixel method. One pixel on the sensor corresponded to circa 0.5 mm in reality. The highest value of RMS from all stages was 0.15 pixel and the maximum residue on point was circa 0.7 pixel. Photo coverage was at least 97 percent. The average accuracy of an individual point in the model was about 0.1 mm.

The micro network was chosen to determine the scale of the photogrammetric model. Around the measured beam there were three standpoints and five reflective targets (40 mm x 40 mm) on the wall, and other stable objects were installed. The standpoints were realized using heavy tripods. During the experiment the tripods were absolutely stable. The good stability of tripod was controlled by measurement on reflective targets on the wall. The standpoints and the reflective targets in three groups were measured for basic determination of the micro network. During the strain test the eight points were measured (two points from micro network and six on concrete beam) in one set.

From the accuracy model of the micro network expected spatial standard deviation of about 0.1 mm was detected. This assumption was subsequently confirmed after making an adjustment. The points on the concrete beam were determined with spatial standard deviation of 0.5 mm in all stages.

During the strain test of the concrete prestressed beam the photogrammetric method was used. To get a correct size of the model the micro network was set up. The accuracy of the points from photogrammetric model was controlled by the spatial polar method from network. The experiment was divided into 20 stages. The results show that the photogrammetric model is very precise, about 0.1 mm in the middle of the beam. On sides of the beam the accuracy was worse. The 3D transformation of all the stages based on the zero stage was determined with standard deviation of 0.2 mm. About 30 points around the beam were used for the transformation. The average difference between shifts determined by the photogrammetry and micro network was circa 0.10 mm (position on the beam). The accuracy of relative position changes of individual points was circa 0.3 mm.

9528-35, Session PS

A simple and flexible calibration method of non-overlapping camera rig

Guan B. Lei, National Univ. of Defense Technology (China); Yang Shang, National University of Defense Technology (China); Qifeng Yu, National Univ. of Defense Technology (China); Zhi hui Lei, National University of Defense Technology (China); Xiaohu Zhang, National Univ. of Defense Technology (China)

A simple and flexible method for non-overlapping camera rig calibration that includes camera calibration and relative poses calibration is presented. The cameras haven't overlapping fields of view, and their internal parameters and relative poses of each camera do not change over time. There is a variety of applications for non-overlapping camera rig: mobile robotics, scene reconstruction and deformation measurement.

Applications using non-overlapping camera rigs demand for an accurate calibration of the device which includes intrinsic parameters measurement and identification of the relative poses of the coupled camera with respect to each other. The conventional techniques of non-overlapping camera rig calibration where camera intrinsic parameters and relative poses of the coupled camera are computed separately, i.e., first performing camera calibration and then carrying out the relative poses calibration based on the calibrated parameters of cameras. In this paper we propose a joint algorithm that combines the camera calibration and the relative poses calibration together. The proposed algorithm gives the solutions of the cameras parameters and the relative poses simultaneously by using nonlinear optimization. Both simulations and real experiments show the feasibility of our algorithm.

First, the intrinsic and extrinsic parameters of each camera in the rig are estimated individually. Each camera observes a calibration plane, the calibration planes are unified in a global coordinate system, the cameras are assumed to be synchronized, a few images of the calibration planes are took by corresponding cameras simultaneously under different orientations by moving the camera rag, the intrinsic and extrinsic parameters apart from the distortion coefficients are estimated with a closed-form solution which examines planar homographies between the images of the calibration plane as originally proposed by Zhang's method. The solution is afterwards refined iteratively by a non-linear optimization method regarding the distortion parameters subject to minimizing the reprojection errors, the trajectory of each camera is computed separately.

Second, a linear solution derived from hand eye calibration scheme is proposed to compute an initial estimate of the relative poses inside the camera rig. It is an essential property of the camera rig that relations between coordinate frame of cameras are considered by Euclidean transformations, Each Euclidean transformation is represented with a rotation and a translation. The camera rig model proposed above is a straightforward generalization of the hand-eye model, so an estimate of the relative poses can be obtained linearly from the trajectory of each camera. We opt for a two-step solution: solve first the rotations, then the translations, using a set of corresponding poses of all cameras from the moving rig.

Third, combined non-linear refinement of all parameters is performed, which optimizes the intrinsic parameters, the extrinsic parameters and relative poses of the coupled camera at the same time. Our proposed method do not make the assumption that the intrinsic and extrinsic parameters computed separately for each camera are globally consistent, because the previous non-linear optimization in the frist step are the maximum-likelihood estimators for each camera separately, but not for the non-overlapping camera rig. In order to improve the accuracy, the camera parameters and relative poses computed in the initialization step are also refined by a standard bundle adjustment algorithm. If the bundle adjustments are considered independently, the whole system is over-parametrized. In our case, the cameras are rigidly linked. Thus a more minimal parametrization is advisable, only one camera pose is expressed relative to the global coordinate system, the other cameras are expressed relative to the front camera. The algorithm is initialized with the camera parameters and the linear estimate of the relative poses, expressed in the same coordinate system.

We develop and test a novel approach for calibrating the parameters of non-overlapping camera rig using camera calibration and hand-eye calibration method. The method was inspired by Zhang's method and

Tsai's method, the advantage of our approach is the fact that the cameras parameters and the relative poses are calibrated simultaneously by using nonlinear optimization. The method was designed inter alia for the purpose of deformation measurement using the calibrated rig. In the application of deformation measurement, there is a need for simple and flexible calibration approaches for non-overlapping camera rig in advance. Compared the camera calibration with hand?eye calibration separately, our joint calibration is more convenient in practice application. Experimental data shows our algorithm is feasible and effective. Further studies will be made on increasing the robustness and accuracy of the method.

9528-36, Session PS

Performance of a 3D scanner based on structured light projection

Dalia N. Mahmoud, Abdallah M. Khalil, Mohammad A. Younes, Alexandria Univ. (Egypt)

3D scanning methods have gained a good reputation in industry over the past few decades. That is due to their versatility and their ability to cope with various ranges of applications. 3D scanning techniques can be classified into either contact or non contact techniques. Non contact techniques are known to be relatively less accurate but are favorable due to the considerably shorter time needed to obtain a full 3D scan of test objects. One of the most commonly used non contact 3D scanning techniques is structured light projection. Unlike stereo vision methods, structured light systems require only one camera with a projector replacing the second camera.

This work investigates the performance of a proposed structured light scanning system. Surfaces of three different objects have been reconstructed using the proposed structured light system. The same test objects have also been measured using a Coordinate Measuring Machine (CMM).The results obtained from both measurement methods are investigated and compared. The structured light system used in this study is based on the stepped three phase shift algorithm, and a flood fill phase unwrapping algorithm. The structured light system is empirically calibrated, in both the transverse and longitudinal directions.

The selection of the three test objects was aimed to examine and demonstrate the ability of the proposed structured light system to accurately reconstruct parts with various sizes, shapes and surface textures. Firstly, surface of a spherical object with known diameter was reconstructed to investigate the accuracy of the system and optimize system parameters such as; algorithms parameters, calibration methods and captured images quality. Secondly, the free form profile of a spur gear tooth was reconstructed to examine the system's ability to measure parts with special profiles. And thirdly a part with a shiny free form surface was reconstructed to investigate the effect of surface reflectance on the system's performance.

Measurement deviations are investigated in all cases, and differences are studied. A deviation of nearly 0.02 mm was observed in case of the spherical object reconstruction. While in the case of spur gear tooth profile, vertical deviation errors between two section profiles reached a maximum of 0.6 mm. Effect of different process parameters on the overall system performance is also investigated.

A straightforward and effective experimental procedure is presented to overcome the noisy reconstruction originally obtained when evaluating the shiny free form object. The reconstruction has significantly been enhanced after applying the proposed procedure and measurement errors were considerably reduced

Experimental results show the effectiveness of the demonstrated structured light reconstruction system. A major advantage of the structured light reconstruction system is the reduction of time needed to obtain the three dimensional coordinates of the measured object when compared to traditional contact methods. The proposed system proved to be capable of reconstructing surfaces both with predefined geometrical profiles and with free form profiles at reasonable level of accuracy. With proper procedure, shiny surfaces can also be accurately reconstructed. The system provides a versatile and cost effective tool for reconstructing a wide range of surfaces with reasonable accuracy.

9528-37, Session PS

The phase correlation algorithm for stabilization of capillary blood flow video frames

Konstantin A. Karimov, Mikhail V. Volkov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Blood flow parameters recovery methods are widely demanded in biomedicine for monitoring of human health. Changes in the circulation of blood in microvasculature are played an important role in the pathogenesis of psoriasis, arthritis, rheumatism, hypertension and others [1–2]. Video capillaroscopy is a convenient and non-invasive method of blood flow parameters recovery in the capillaries.

Video capillaroscopy method is based on registration of capillary blood flow with using microscope and high-speed video camera. The obtained video sequences are distorted by frame-shifts which are caused by tremor of living objects and inability of their rigid fixation relative to the optical axis of the camera. In this case, video sequences processing is required ? methods of video frames stabilization.

Generally, most of the existing software for video stabilization use difference between neighboring frames only [3–5]. Using in this software algorithms allows to improve visual perception of video sequences, but do not guarantee static position of the capillary at the entire sequence.

It is known the full-frame superposition which is the correlation method for each pixel and all frames of the sequence. This method is highly accurate but requires more of computational resources and time. Besides, stabilization method based on the detection of key points can be applied [6, 7]. This method can provide reducing of the computational complexity. However, it decreases the amount of useful information necessary for effective stabilization by reducing the number of considered points. As a result, this approach has low robustness to noise and low quality of stabilization. Video frame stabilization of capillary blood flow by phase correlation method is also described in [5].

In this research the advanced methods of video sequence stabilization based on described methods [3–7] with using reference frames with shift compensation between these frames and whole sequence are proposed. This allows to increase the quality of video sequence stabilization.

The results of experimental capillary blood flow video processing and comparative analysis of the efficiency of stabilization methods are presented. All methods were tested using experimental video sequences of human capillaries and computer-simulated video sequences. The results of methods comparison are obtained. It is shown that full-frame method provides high-quality stabilization of video sequence, but it required significant computational resources. The method based on the detection of key points is fast, but provides low quality stabilization for video capillaroscopy. The phase correlation method is most effective for stabilization of the considered source video sequences. It provides high-quality stabilization of video sequence with using low computing resources.

In this research the advanced methods of video sequence stabilization are compared and discussed. It is shown that the advanced phase correlation method is most useful for stabilization of video sequences of capillaries blood flow. The research results can be used in software for biomedical diagnostics.

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9528-39, Session PS

Efficient estimation of orthophoto images using visibility restriction

Hiroyuki Miura, Aero Asahi Corp. (Japan); Hirofumi Chikatsu, Tokyo Denki Univ. (Japan)

The orthophoto image which is generated using an aerial photo is used in river management, road design and the various fields since the orthophoto has ability to visualize land use with position information. However, the image distortion often occurs in the ortho rectification process. This image distortion is used to estimate manually by the evaluation person with great time. The image distortion should be automatically estimated from the view point of efficiency of the process.

With this motive, angle V between view vector at exposure point and normal vector at center point of a patch area was focused in this paper. In order to evaluate the relation between image distortion and angle V, DMC image which were acquired 2000m height were used and angle V for 10m?10m patch was adopted for computing visibility restriction. It was confirmed that image distortion occurred for the patch which show rather than 69 degree of the angle V. Therefore, it is concluded that efficient orthophoto mapping is able to perform using the angle V as visibility restriction.

Moreover, relationship between angle V and view angle, focal length were investigated using DMC?140,DMC?230,UltraCamD,UltraCam-X,UltraCam-Xp,RC30 (f=150mm) ,RC30 (f=210mm) with different altitude respectively in this paper.

9528-40, Session PS

Action cameras and low-cost aerial vehicles in archaeology

Martina Ballarin, Caterina Balletti, Francesco Guerra, Univ. Iuav di Venezia (Italy)

The last few years have seen an exponential growth in the use of UAV photogrammetry. This evolution has opened new possibilities and new scenarios for close range surveying, due to the combination of aerial and terrestrial techniques and relatively low-costs compared with traditional aerial techniques.

The growing use of software for extracting point clouds from images has obtained great attention not just from the “geomatic” scientific community, but also by users from other disciplines including archaeologists. It is easy to understand this success: the various software packages combine high quality results, both in qualitative and quantitative terms, with ease of use. The spread of these products also coexists with a growth in the market of low cost off-the-shelf cameras, able to acquire high quality and high-resolution images.

The research developed from several experiences, carried out in the Laboratory of Photogrammetry of Iuav University, on the use of micro UAVs for close range photogrammetry. Though a number of case studies, we used and analyzed many different configurations of these systems, regarding both the type of cameras used and the type of vehicles on which the cameras were mounted. This technique was used in different fields and on objects with different morphologies, from the archaeological survey to the survey of Cultural Heritage more generally.

From the experiences gained during these years, and after the development of amateur aerial vehicles on one side and lighter cameras on the other, the research began to focus on the analysis of the potentials of a system integrating those two components in the archaeological field. In this field economic considerations are often an issue and the metric aspect of the data is frequently subordinated to its interpretative value.

A particular group of cameras are the so-called “action cameras”, which are very light-weighted, small and have good performance even under extreme conditions. Their use for photogrammetric purposes has not had a great development because the images acquired by the first sensors had a quality and resolution that were insufficient to obtain the accuracies of a photogrammetric survey. Nowadays, however, compact cameras can acquire high-resolution images even in extreme activities, such as free fall, underwater swimming and diving.

This research is concerned with testing these cameras and the analysis of the results they can achieve when mounted on non-professional aerial vehicles: in particular we analysed the Go Pro Hero3 Black Edition and the Parrot Ar.Drone 2.0. This camera allows the acquisition of images up to a resolution of 12MP (4000x3000) and its weight and dimensions (76 g – camera with battery - 60x40x20 mm) allow them to be mounted on non-professional aerial vehicles, such as the Parrot Ar.Drone 2.0. These vehicles are made for recreational purposes and for this reason are cheap and easy to pilot as they can be controlled via tablet or smartphone through specific applications. In this way, we are able to obtain a low cost easy-to-use system, suitable for archaeologists and for archaeological documentation.

The main limits of this system are two and they are related to both the instruments used. In fact, the photograms acquired by these cameras have a great level of distortion and consequently raise problems in the calibration process. The limit of the vehicle is the difficulty in maintaining an adequate flight route for photogrammetric purposes especially under adverse environmental conditions.

For these reasons, during this research we performed a number of calibration tests using different software products (free, low-cost and implemented ad hoc in the University) and different methodologies (test field calibration; self calibration) to calculate the interior parameters of the camera. We also performed a number of tests to analyze the whole acquisition system and test the accuracy of the results we could reach on different typologies of objects and with different network geometries.

This system was used during an intensive surveying campaign in an archaeological site in Molise, the ancient city of Altilia. There, we performed a number of acquisitions on different objects and following different workflows. The data obtained was compared with that acquired through more traditional close range photogrammetric systems (calibration cameras on professional drones) and laser scanner.

In this paper we will analyze one of the possible products of these systems: the orthophoto, which is very interesting in the archaeological field, especially in situations – such as the excavation – where there usually are only a few structures still standing. In these cases, aerial photography have great value, as it allows a full readability of the elements and it is fundamental for recording shape and position of each single layer.

The system proposed has demonstrated to be an accessible solution for the production of aerial documentation, which combines a very high quality of the results to a metrical content of which we know the precision.

9528-41, Session PS

Miniaturized 3D microscope imaging system

Yung Sung Lan, Chir-Weei Chang, Hsin-Yueh Sung, Yen-Chang Wang, Cheng-Yi Chang, Industrial Technology Research Institute (Taiwan)

As concern for obesity and diabetes grows, the need for automated and accurate methods to monitor nutrient intake becomes essential for managing dietary. The challenging problem of the image-based dietary assessment is the accurate estimation of food portion size from a photograph taken with a camera. Measuring accurate dietary intake is considered to be an open research problem in the nutrition and health fields. In this work, we present a novel application for food volume calculation which is based on light-field technology. We describe a method to automatically calculate size of foods through volume estimation by using depth information from a plenoptic camera. The design of the camera approach to the novel digital imaging system by using commercial optical software ZEMAX merged with MATLAB based on image processing software for the joint digital-optical design

process. An array of micro-lenses captures information that one can refocus images after acquisition, as well as shift one's viewpoint within the sub-apertures of the main lens, effectively obtaining multiple views, which contains depth information. The micro-lenses have a plano-convex shape and are arranged in a square grid with a lens pitch of 200 μm. The distance is 0.649 mm between micro-lens and CMOS. The focal length of main lens is 8 mm. These lenses are formed by using diamond-turning technique which is 4-axis Ultra-precision machine for allowing uniformity in the shape and position of each micro-lens. The depth information is available simultaneously in a single capture. The light field pre-processing image convertor executes color correction, calibration, and image rendering for obtaining 2D image and light field image. The food volume estimated after depth map function acquired. The depth (Z) resolution in the system is smaller than 20 mm. The resolution of X and Y in transverse plan can be obtained by substituted the distances of object and image, size of pixel in COMS and magnifying power into lens equation. In the case, the resolution X and Y are smaller than 0.25 mm. The minimum unit of cuboid volume multiplied by X*Y*Z is equal to 1.25 mm3 by using upper-plan of a table as a reference plan. The cuboids stacked together to fit the shape of food for estimating the food volume. We demonstrate to estimate volume of an apple, the real volume of the apple is approximate to 340 cm3, and predicted volume of the apple is approximate to 300 cm3. The major error of this estimation comes from opacity part of the apple. By learning from empirical training of human and building up a database of different kinds of food for list a lookup table providing a factor for obtaining more accurate estimation volume of foods. A key innovative feature of the system is to predict opacity part of the food by food recognition module, which is based on image and spectrum technologies for distinguish between foods to provide a correction factor for obtain more accurate volume. The spectrum module is hyper-spectrum with wave length range from 600 nm to 1000 nm. Furthermore, this prototype system is a first step in designing an overall framework to support a realistic evaluation; collection of dietary data by mobile device is feasible, acceptable for better health data management.

9528-43, Session PS

Frequency-spatial cues based sea-surface salient target detection from UAV image

Xiaoliang Sun, Xiaolin Liu, Qifeng Yu, Yan Liu, National Univ. of Defense Technology (China)

Unmanned Aerial Vehicles (UAV) have achieved great progress and play more and more important roles in civilian and military applications, e.g. aerial reconnaissance, surveillance, rescue, etc. The automatic detection of visually salient target in video captured by UAV has great significance for manual analysis and decision, object recognition, tracking, etc. However, the analysis of the video is always a challenging task due to narrow view field, rapid platform motion, image instability, etc. Focusing on applications on the sea-surface, this paper proposes a frequency-spatial cues based sea-surface salient target detection from UAV image.

1. Frequency domain analysis for sea-surface salient target in UAV image

Based on the analysis of UAV images captured on the sea-surface, this paper treats sea-surface backgrounds as non-salient components and targets as salient components in UAV images. The non-salient components are modeled as spikes in the amplitude spectra in the frequency domain and can be suppressed via filtering the spectrum with a Gaussian kernel of an appropriate scale. A 1D signal is used to illustrate the suppression of the non-salient components. As shown in Fig. 1, the non-salient backgrounds (repeated cycles) are suppressed effectively and the salient components (labeled by green boxes in row 1 of Fig. 1) are highlighted. However, the salient components are not highlighted uniformly (labeled by green boxes in row 4 of Fig. 1).

2. Frequency-spatial cues based sea-surface salient target detection from UAV image

The method described in this paper intends to highlight sea-surface salient target accurately and uniformly by fusing cues in the frequency and spatial domains. Firstly, as illustrate in section 1, we suppress sea-surface background via filtering the spectrum with a Gaussian kernel of an appropriate scale. Secondly, the input image is segmented into regions using a graph-based algorithm in the spatial domain. Thirdly, the sea-surface background suppressed result and segment result are fused using a probabilistic framework to highlight salient targets uniformly. At last, sea-surface salient targets are located precisely using region growth and cluster. The main contributions of this paper are as follows:

- Present a thorough theoretical analysis of suppressing the sea-surface background in the frequency domain.

- Propose a frequency-spatial cues based method for sea-surface salient target detection from UAV image.

3 Experiments

This paper collects large numbers of UAV images captured on the sea-surface to evaluate the performance of the proposed method. The collected images cover most of occasions in practical applications. Some representative results are listed in Fig. 2. The detected sea-surface salient targets are labeled by red rectangles. Experiment results indicate that the proposed method can detect sea-surface salient target automatically and precisely in various occasions.

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9529-1, Session 1

Continuous morphology and growth monitoring of different cell types in a single culture using quantitative phase microscopy

Björn Kemper, Jana Wibbeling, Lena Kastl, Jürgen Schnekenburger, Steffi Ketelhut, Westfälische Wilhelms-Univ. Münster (Germany)

The minimally-invasive quantitative observation of different cell types in a single culture is of particular interest for the analysis of the impact of pharmaceuticals, pathogens or toxins on different cellular phenotypes under identical measurement conditions and to analyze interactions between different cellular specimens. Quantitative phase microscopy (QPM), provides high resolution detection of optical path length changes that is suitable for quantitative tomographic imaging and stain-free minimally-invasive live cell analysis (see for example [1] and included references). Due to low light intensities for object illumination, QPM minimizes the interaction with the sample and thus is in particular suitable for long term time-laps investigations on cells in which for example morphology alterations due to toxins [2], drugs [3] or genetical modifications [4] are studied. We studied the feasibility of QPM, for the analysis of mixed cell cultures and explored if quantitative phase images provide sufficient information to distinguish between different cell types and to extract cell specific parameters. For the experiments quantitative phase imaging with digital holographic microscopy (DHM) was utilized as described in [5,6]. Mixed cell cultures with different cell types were continuously observed with quantitative DHM phase contrast up to 80 h. The obtained series of quantitative phase images were evaluated by adapted image segmentation algorithms. From the segmented quantitative phase images the area covered by the cells, the cellular dry mass as well as the mean cell thickness and volume were determined as described with details in [7] and used as parameters to quantify the reliability of data acquisition. The obtained results demonstrate that it is possible to characterize the growth of cell types with different morphology features separately in a single cell culture. This prospects new application fields of quantitative phase imaging in drug and toxicity testing in vitro.

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9529-2, Session 1

Quantitative phase imaging by wide field lensless digital holographic microscope

Adamou Adinda-Ougba, Ruhr-Univ. Bochum (Germany); Nektarios Koukourakis, Technische Univ. Dresden (Germany); Aissam Essaidi, Ruhr-University Bochum (Germany); Nils C. Ger?hardt, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Wide field, lensless microscopes have been developed for telemedicine and for resource limited setting[1]. They are based on in-line digital holography which is capable to provide amplitude and phase informations resulting from numerical reconstruction. The phase information enables achieving axial resolution in the nanometer range. Hence, such microscopes provide a powerful tool to determine three-dimensional topologies of microstructures.

In this contribution, a compact, low-cost, wide field, lensless microscope is presented, which can be changed from transmission to reflection mode.

The transmission mode is based on in-line holography. One of the usual key concepts of this setup is the use of an LED with a pinhole of size ~ 50-100 μm as point source. We use instead a laser diode operated below lasing threshold to emit low coherence light like an LED. In this case, a pinhole is not necessary as the laser diode is already a point source. Holograms of micro-objects are recorded on a CMOS-sensor which is placed directly behind the sample. A wide field of view of ~24 mm? corresponding to the entire sensor area is achieved. Moreover, amplitude and phase information with lateral resolution of ~2 μm are obtained from the numerical reconstruction of the holograms. The reconstructed amplitude and phase suffer from the so called twin image effect. Using a phase retrieval algorithm together with the angular spectrum propagation method, amplitude and phase information free from the twin image effect are obtained and topography information of a highly transparent micro-object is achieved from the phase data. Here, we characterize focused laser beam written microstructures in transparent material (such as waveguides, transparent conductors). A reliable characterization is crucial for their functionality. White light interferometer based measurements of such structures usually fail due to their transparency and require reflective coating before. We record holograms of lines with different depths written by a focused laser beam on an ITO coated PET film. Our results show that our system is indeed capable to determine topological profiles of microstructures in transparent material.

In reflection mode the lensless microscope is changed to off-axis digital holography, which leads to a reduced field of view as the sample has to be placed in a considerable distance from the sensor due to geometrical reasons. This Michelson Interferometer based setup consists of a laser diode, a beam splitter, a mirror and the CMOS-sensor as main components. The magnification is provided by the laser diode´s divergent beam. Amplitude and phase images have been obtained using the angular spectrum propagation method and the phase unwrapping algorithm. We evaluate our setup by recording holograms of reflective microstructures. Our results confirm the possibility of performing three-dimensional topography measurements of microstructures such as MEMS.

In conclusion, our lensless digital holographic microscopes are low cost imaging devices suitable for fault detection, roughness and shape measurement of microstructure in transparent as well as on reflective material. In addition the transmission mode presents the advantages of wide field of view and tomographic imaging.

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9529-3, Session 1

Influence of sample preparation and reliability of automated numerical refocusing in stain-free analysis of dissected tissues with quantitative phase digital holographic microscopy

Björn Kemper, Westfälische Wilhelms-Univ. Münster (Germany); Philipp Lenz, Dominik Bettenworth, Universitätsklinikum Münster (Germany); Philipp Krausewitz, Westfalische Wilhelms Univ Munster (Germany); Dirk Domagk, Steffi Ketelhut, Westfälische Wilhelms-Univ. Münster (Germany)

Digital holographic microscopy (DHM) has been demonstrated to be a versatile tool for high resolution non-destructive quantitative phase imaging of surfaces and multi-modal minimally-invasive monitoring of living cell cultures in-vitro [1-4]. DHM provides quantitative monitoring of physiological processes through functional imaging and structural analysis which, for example, gives new insight into signaling of cellular water permeability and cell morphology changes due to toxins and infections. As quantitative phase imaging with DHM is based on the detection of optical path length changes the method is label-free and only requires low light intensities for object illumination. This minimizes the interaction with the sample. Also the analysis of dissected tissues quantitative DHM phase contrast prospects application fields by stain-free imaging and the quantification of tissue density changes. We show that DHM allows imaging of different tissue layers with high contrast in unstained tissue sections. As the investigation of fixed samples represents a very important application field in pathology, we also analyzed the influence of the sample preparation. The retrieved data demonstrate that the quality of quantitative DHM phase images of dissected tissues depends strongly on the fixing method and common staining agents. As in DHM the reconstruction is performed numerically, multi-focus imaging is achieved from a single digital hologram. Thus, we evaluated the automated refocussing feature of DHM [2] for application on different types of dissected tissues and revealed that on moderately stained samples highly reproducible holographic autofocussing can be achieved. Finally, it is demonstrated that alterations of the spatial refractive index distribution in murine [5] and human [6] tissue samples represent a reliable absolute parameter that is related of different degrees of inflammation in experimental colitis and Crohn's disease. This paves the way towards the usage of DHM in digital pathology for automated histological examinations and further studies to elucidate the translational potential of quantitative phase microscopy for the clinical management of patients, e.g., with inflammatory bowel disease.

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9529-4, Session 1

Fourier Ptychography: Using computation to address physical optical challenges *(Keynote Presentation)*

Changhuei Yang, California Institute of Technology (United States)

Microscopes are complex and fussy creatures that are capable of delivering limited image information. This is because physical optical lenses are intrinsically imperfect. The perfect lens we draw in high school ray diagrams simply do not exist. I will discuss our recent work on Fourier Ptychographic Microscopy - a computational microscopy method that enables a standard microscope to push past its physical optical limitations to provide gigapixel imaging ability.

9529-5, Session 1

Spatial light interference microscopy (SLIM) for histopathology applications *(Invited Paper)*

Gabriel Popescu, Univ. of Illinois at Urbana-Champaign (United States)

Recent work has shown that refractive index measurements from the quantitative phase imaging (QPI) modalities can offer very competitive medical diagnosis results compared to those from Hematoxylin and Eosin (H&E) stained images. We demonstrate the first time to our knowledge, the use of QPI images obtained from the Spatial Light Interferometry Microscopy (SLIM) to do label-free automatic prostatic cancer diagnosis in biopsies.

9529-10, Session 2

A new twist on light sheet imaging *(Invited Paper)*

Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

The last decades have seen the emergence of propagation invariant ('non-diffracting') light fields and complex beam shaping. Propagation invariant light fields keep their transverse intensity profile upon propagation. Bessel light fields and Airy light fields are prime examples of such beams. In terms of imaging, single plane illumination (light sheet) microscopy (SPIM) offers a key advantages of fast acquisition and low phototoxicity. Orthogonal detection allows rapid imaging of large, three-dimensional, samples of living tissue. This talk will describe the perhaps surprising and powerful route of using Airy light fields in light sheet imaging. Despite the parabolic trajectory and asymmetric beam profile, this approach is well suited to this imaging modality.

9529-11, Session 2

Optomechanical properties of cancer cells revealed by light-induced deformation and quantitative phase microscopy

Lena Kastl, Björn Budde, Michael Isbach, Christina E. Rommel, Björn Kemper, Jürgen Schnekenburger, Westfälische Wilhelms-Univ. Münster (Germany)

There is a growing interest in cell biology and clinical diagnostics for label-free optical techniques which minimize the interaction with samples and reduce side effects of substances like dyes or fixatives. Such techniques include digital holographic microscopy (DHM) [1] and the optical stretching by fiber optical two beam traps [2]. DHM enables quantitative phase contrast imaging and thereby the determination of the

cellular refractive index, dry mass and the volume [3], whereas optical cell stretching reveals the deformability of cells.

Since optical stretching strongly depends on the optical properties and the shape of the investigated material we combined the usage of fiber optical stretching and DHM for the characterization of pancreatic tumor cells such as PaTu 8988S and PaTu 8988T [4]. The major reason for pancreatic tumor malignancy is their potential to metastasize, spread through the bloodstream and build distal tumors/metastases. The grade of dedifferentiation in which cells lose their cell type specific properties is a measure for this metastatic potential. The less differentiated the cells are, the higher is their potential to metastasize. Our results demonstrate that pancreatic tumor cells, which were derived from the same tumor but vary in their grade of differentiation, show significant differences in their deformability. The retrieved data show that differentiated cells have a higher stiffness than less differentiated cells of the same tumor. Even cells that differ only in the expression of CDH1, a tumor suppressor gene encoding the cell-cell adhesion protein E-Cadherin, can be distinguished by their mechanical properties. Additionally, the results of the DHM measurements showed differences in the volume and the dry mass of the tumor cells, whereas the refractive index showed only few variations, indicating that it does not significantly influence the results of the optical cell stretching. Thus, we could identify different populations of cell lines by parameter sets that were retrieved by the combined usage of these two techniques.

The obtained results show a promising new approach for the phenotyping of different cell types, especially in tumor cell characterization and cancer diagnostics.

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9529-12, Session 2

Monitoring cell morphology during necrosis and apoptosis by quantitative phase imaging *(Invited Paper)*

Martina Mugnano, Alejandro Calabuig, Simonetta Grilli, Lisa Miccio, Pietro Ferraro, Consiglio Nazionale delle Ricerche (Italy)

Cellular morphology changes and volume alterations play significant roles in many biological processes and they are mirrors of cell functions. In this paper, we propose Digital Holographic microscope (DH) as a no-invasive imaging technique for a rapid and accurate extraction of morphological information related to cell death. In particular, we investigate the morphology variations that occur during necrosis and apoptosis. The study of necrosis is extremely important because it is often associated with unwarranted loss of cells in human pathologies, such as ischemia, trauma, and some forms of neurodegeneration, then a better elucidation in terms of cell morphological changes could pave the way for new treatments. Also apoptosis is extremely important because it’s involved in cancer, both in its formation and in medical treatments. The inability to initiate apoptosis enhances tumor formation, and current cancer treatments target this pathway.

Within this framework, we have developed a transmission off-axis DH apparatus integrated with a micro incubator for investigation of living cells in a temperature and CO2 controlled environment. We employ DH to analyse the necrosis cell death induced by laser light (wavelength 473nm, light power 4mW). We have chosen as cellular model NIH 3T3 mouse embryonic fibroblasts because their adhesive features such as morphological changes, the time needed to adhere and spreading have been well characterized in literature. We have monitored cell volume changes and morphological alterations in real time in order to study necrosis process accurately and quantitatively. Cell volume changes were evaluated from the measured phase changes of light transmitted through cells. Our digital holographic experiments showed that after exposure of cells to laser light for a couple of hours, they firstly swell then they are subjected to balloon-like shape until the plasma membrane ruptures and finally the volumes decrease. Furthermore, we present a preliminary study on the variation of morphological parameters in case of cell apoptosis induced by the exposure to 10 μM cadmium chloride. We employ the same cell line monitoring the process for 18 hours. In the vast group of environmental pollutants, the toxic heavy metal cadmium is considered a likely candidate as a causative agent of several type of cancers. Widely distributed and used in industry, and with a broad range of target organs and a long half-life (10–30 years) in the human body, this element has been long known for its multiple adverse effects on human health, through occupational or environmental exposure. In apoptosis we measure cell volume decrease and cell shrinking.

Both data of apoptosis and necrosis were analysed by means of Sigmoidal Statistical Distribution function, which allows to establish several quantitative data like swelling and cell death time, flux of lacked material outside from the cell, initial and final volume vs time. In addition, we can study quantitatively the cytoplasmatic granularity that occurs during the necrosis. As future application, DH could be employed as no-invasive and label-free method to distinguish between apoptosis and necrosis in terms of morphological parameters.

9529-13, Session 2

Off-axis digital holographic microscopy by updating a regular upright microscope

Vicente Micó, Carlos Ferreira, Univ. de València (Spain); Zeev Zalevsky, Bar-Ilan Univ. (Israel); Javier García, Univ. de València (Spain)

In this contribution we present a low cost, extremely simple, and highly stable scheme to update a standard microscope into a holographic microscope. The proposed architecture is named as SMIM (incoming from the initials of spatially-multiplexed interferometric microscopy) and it is based on a common-path interferometric configuration which is adapted into a conventional microscope with some specific constraints to allow off-axis holographic recording. The main layout modifications are three: i) the use of a coherent light source instead of the broadband one included in the microscope illumination module, ii) the insertion of a properly placed one-dimensional diffraction grating needed for the holographic recording at the output plane of the microscope, and iii) the use of spatial multiplexing at the input plane to allow reference beam transmission in a common light-path with the imaging branch.

As consequence of the input plane spatial multiplexing, the field of view provided by the used microscope objective is reduced in comparison with the field of view reported by the same objective lens in conventional white light illumination mode. However, complex amplitude distribution of the inspected sample is retrieved after off-axis holographic recording and conventional digital image processing of the recorded hologram (direct digital fast Fourier transform, spatial filtering of one of the hologram diffraction orders at the Fourier plane, and inverse digital fast Fourier transform of the filtered spectrum).

The proposed update is experimentally validated in a regular Olympus BX-60 upright microscope by using coherent illumination incoming from a commercial grade laser diode, by inserting a one-dimensional precision Ronchi ruling grating in the microscope embodiment, and by dividing the input plane into the spatially multiplexed areas. Here we present an experimental implementation that proposes three spatially multiplexed regions: one containing the sample under inspection (imaging beam), one as a clear region for reference beam transmission (reference beam), and another one to be blocked in order to avoid multiple replicas at the recording plane.

Finally, experimental results are provided for the different microscope objectives included in the Olympus microscope showing calibration (USAF resolution test) as well as biological (red blood cells and sperm cells) images containing complex (amplitude and phase) information. Recovered phase values are then contrasted against conventional Mach-Zehnder interferometric configuration for quantitative comparison in order to validate the proposed SMIM approach.

9529-14, Session 2

Multi-illumination Gabor holography recorded in a single camera snap-shot for high-resolution phase retrieval in digital in-line holographic microscopy

Martin Sanz, Jose Angel Picazo-Bueno, Javier García, Vicente Micó, Univ. de València (Spain)

Lensless holographic microscopy (LHM) supposes a digital implementation of the Gabor's concept implemented for electron microscopy at the middle of the past century and adapted to the optical range by Rogers a few years later. Aside of other restrictions (mainly, coherent noise and weak diffraction assumption), Gabor's concept of holography is affected by the twin image problem. The presence of the misfocused twin image is a direct consequence of the in-line configuration and provides disturbances in final image quality when imaging at the sample plane. Twin image can be eliminated in Gabor-like layouts by using essentially two different strategies: phase-shifting and phase retrieval procedures. However, both of them imply the recording in time sequence of multiple (more than two) in-line holograms before applying the phase recovery digital processing cycle.

In this contribution, we present a new concept and design of a lensless holographic microscope based on wavelength multiplexing, single hologram acquisition and digital image processing. The technique, named as MISHELF (initials incoming from Multi-Illumination Single-Holographic-Exposure Lensless Fresnel) microscopy, involves a new concept of LHM for quantitative phase imaging. This compact microscope is based on the simultaneous illumination and recording of multiple diffraction patterns in the Fresnel domain. In combination with a novel and fast iterative phase retrieval algorithm, MISHELF microscopy is capable of high-resolution (micron range) phase-retrieved (twin image elimination) biological imaging of dynamic events (video rate recording speed) since it avoids the time multiplexing needed for the in-line hologram sequence recording when using conventional phase-shifting or phase retrieval algorithms.

MISHELF microscopy proposes a LHM layout involving 3 simultaneous illumination wavelengths in addition with a conventional (Bayer filter array) color CCD camera in classical digital in-line holographic configuration. Here, we present MISHELF microscopy experimental validation for two different cases. In the first one, we illuminate the sample with 3 wavelengths tuned with the 3 color channels of the camera, that is, illumination using R-G-B wavelengths (633, 532, and 405nm). And in the second case, we report on the use of IR-R-B wavelengths (780, 660 and 405nm) which are not tuned with the detection channels. In the former, the illumination point source is implemented by properly combining the 3 laser beams (He-Ne, green-diode pumped and violet diode lasers) before impinging directly onto a 1 ?m diameter pinhole while in the latter we directly use a diode can containing the 3 diode lasers inside (illumination source included in PS3 optical assembly) in addition with a high numerical aperture (0.6NA) molded glass aspheric lens. The RGB scheme takes the advantages of providing a single spatially-located triple-wavelength illumination source and minimization of the crosstalk resulting from the Bayer color filter array, thus resulting in a relatively simple digital image processing. And the IRRB scheme permits layout miniaturization and cost reduction while improves the complexity of the digital processing since the 3 illumination wavelengths are not neither spatially placed at the same point (thus providing slightly different magnification and lateral shift in the recorded holograms) nor tuned with the detection channels (thus requiring a calibration stage to avoid crosstalks). In both experimental cases, the information contained in the 3 CCD channels is digitally processed to finally obtain a high-resolution image without twin image contribution. The digital processing involves a customized and fast convergence phase iterative algorithm. Experimental results are provided for both experimental layouts using synthetic object (USAF resolution test target) and biological samples (swine sperm sample and micro beads).

9529-6, Session 3

Wavefronts matching: a novel paradigm for three-dimensional holographic particle tracking

Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Lisa Miccio, Francesco Merola, Istituto di Cibernetica Eduardo Caianiello (Italy); Paolo A. Netti, Istituto Italiano di Tecnologia (Italy); Pietro Ferraro, Istituto di Cibernetica Eduardo Caianiello (Italy)

Recently, several approaches to track micro-objects in 3D environment [1-4], using digital holography (DH) in microscopic configuration, have been proposed, gaining credits as one of the most effective techniques for these applications. In fact, DH in microscopy allows to retrieve in an accurate way the spatial coordinates of multiple particles performing 3D tracking of the sample in the entire field of view. In particular, a posteriori quantitative multi-focus phase-contrast imaging, suitable for 3D tracking of micro-objects, is one of the main features of the holographic approach. Holographic-based tracking method is typically composed by two steps: (i) numerical refocusing [5,6], through amplitude reconstruction's contrast analysis, in order to find the position of the targets along the optical axis, and (ii) evaluation of lateral displacements of refocused micro-objects through quantitative phase map segmentation methods [2]. In the last years, many contributions have been proposed to investigate increasingly accurate refocusing strategies as well as suitable 2D localization approaches for quantitative phase contrast images. However, the need to decouple amplitude and phase contributions of the complex wavefronts to calculate target positions in 3D represents a limitation, due to the fact that the lateral displacements can be calculated only after refocusing step. In order to overcome this limitations, recently, a novel method of the simultaneous calculation of both axial and lateral coordinates of moving particles has been proposed [4]. This is based on the novel concept of wavefronts matching, i.e. the 3D positions of micro-object, moving in 3D volume, are obtained by aligning wo subsequent holographic complex reconstructions, calculated at the same distance. By this way, 3D displacements (lateral and axial) can be directly retrieved. The proposed method is tested for studying the Brownian motion of particles when they are trapped by using optical tweezers [3], and for particles flowing in a microfluidic channel.

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9529-7, Session 3

Cells characterization in microfluidic flows by small angle light scattering and 3D holographic technique

David Dannhauser, Istituto Italiano di Tecnologia (Italy); Pasquale Memmolo, Istituto Nazionale di Ottica (Italy) and Istituto Italiano di Tecnologia (Italy); Domenico Rossi, Istituto Italiano di Tecnologia (Italy); Francesco Merola, Lisa Miccio, Istituto Nazionale di Ottica (Italy); Filippo Causa, Univ. degli Studi di Napoli Federico II (Italy); Pietro Ferraro, Istituto Nazionale di Ottica (Italy); Paolo A. Netti, Univ. degli Studi di Napoli Federico II (Italy) and Istituto Italiano di Tecnologia (Italy)

The light scattering profile of single micrometric sized particles provides a fast and accurate characterization of morphological particle properties (refractive index, size, shape, etc.). By combining a camera-based small angle light scattering apparatus with a microfluidic-induced particle

migration technique, it becomes possible to characterize particles in microfluidic flows. The light scattering profile of a single particle can be fully characterized in a continuous scattering range from 2° up to 30° by an optimized optical light collection system, thanks to the narrow incident beam collimation of our apparatus [1]. Viscoelastic-induced particle migration by a polyethylene oxide solution has been successfully implemented in a single low-cost device composed of a particle alignment section and a particle measuring section. The passage of the single particle through the incident laser beam in the microfluidic observation area allows for the precise label-free single particle analysis in microfluidic flows. This simple combination of particle alignment and observation area has been used to study polystyrene particles as well as living cells in microfluidic flows by our small angle light scattering apparatus and by a digital holographic microscope system [2]. The precise 3D position tracking, obtained from our holographic microscope measurements, points out the accurate microfluidic alignment, which has been achieved by varying the viscoelastic polymer concentration and particle velocity in our ad hoc microfluidic device. We applied this approach to living cells under physiological measurement conditions. The results confirm an accurate cell alignment even in multiple particle conditions of varying particle or cell sizes.

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9529-8, Session 3

Optical analysis of nanomaterial-cell interactions: flow cytometry and digital holographic microscopy

Sarah Mues, Jan Antunovic, Rainer Ossig, Björn Kemper, Jürgen Schnekenburger, Westfälische Wilhelms-Univ. Münster (Germany)

Engineered nanomaterials are tested for potential hazards by various toxicity testing approaches. The assessment of in vitro cytotoxicity of nanoparticles commonly involves the measurement of different cellular endpoints like the short term formation of reactive oxygen species, or mid term effects on cell viability or cell death [1]. Usually these parameters are determined by optical readouts of enzymatic transformation of specific substrates, which often interfere with the tested nanomaterials [2]. A more precise and specific nanomaterial toxicity testing requires a deeper understanding of the underlying cellular mechanisms and cell uptake pathways as well as screening methods which allow a dosimetry up to Low Effect Levels (LOEL).

We have investigated cytotoxic effects of spherical (NM 300) and rod shaped (NM 302) silver nanoparticles with a matrix of four cell lines representing different functions like lung epithelial cells, macrophages and fibroblasts on two different endpoints: cell viability (WST-8) and cell death (LDH) [3|. In addition we have used a flexible flow cytometer system to investigate the best detector-laser combination for analyzing cell-particle interactions and uptake by increased side scatter signals. Furthermore, we have applied digital holographic microscopy (DHM) for multimodal label-free analysis of nanomaterial toxicity [4, 5]. Phase images were analyzed for cell thickness, cell volume and dry mass.

Our results demonstrate a dose dependent increased cell interaction of NM 302 analysed by flow cytometry, which differed significantly from spherical particles. Testing other lasers and optical configurations will optimize the interaction analysis. The resulting system will be applied to mechanistic studies of NM302 cell interactions.

Furthermore, parameters like cell thickness and dry mass monitored over time (24 h) were indicators of cell death and viability. This method was compared to commonly used toxicity endpoint assays.

Our results demonstrate both optical methods as valuable tools for toxicity and toxicity mechanistic studies. These optical technologies overcome limiting problems in current nanomaterial characterization and toxicity testing. Optimized flow cytometry for nanomaterial cell interaction provides a rapid screen for industrial materials without fluorescent or radio labeling. DHM will detect simultaneously different cellular endpoints without nanomaterial assay interference therefore allowing the detection of LOEL of nanomaterials with weak cellular effects.

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9529-9, Session 3

Single image correlation for blood flow mapping in complex vessel networks *(Invited Paper)*

Giuseppe Chirico, Laura Sironi, Univ. degli Studi di Milano-Bicocca (Italy); Margaux Bouzin, Univ. degli Studi di Milano Bicocca (Italy); Laura D’Alfonso, Maddalena Collini, Univ. degli Studi di Milano-Bicocca (Italy); Nicolo’ G Ceffa, Univ. degli Studi di Milano Bicocca (Italy); Cassia Marquezin, Univ. degli Studi di Milano Bicocca (Italy) and bUniversidade Federal de Goiás, Instituto de Física, Goiânia (Brazil)

Microcirculation plays a key role in the maintenance and hemodynamics of tissues and organs also due to its extensive interaction with the immune system. A critical limitation of state-of-the-art clinical techniques to characterize the blood flow is their lack of the spatial resolution required to scale down to individual capillaries. On the other hand, despite recent developments of novel fluorescent dyes and genetically encoded proteins for intravital optical microscopy, the study of the blood flow through auto- or cross-correlation methods fail to correlate the flow speed values with the morphological details required to describe an intricate network of capillaries.

Here we propose therefore a novel technique (FLICS, FLow Image Correlation Spectroscopy) that, by employing a single raster-scanned xy-image acquired in vivo by confocal or multi-photon excitation fluorescence microscopy, allows the quantitative measurement of the blood flow velocity in the whole vessel pattern within the field of view, while simultaneously maintaining the morphological information on the immobile structures of the explored circulatory system. Fluorescent flowing objects produce diagonal lines in the raster-scanned image superimposed to static morphological details. The flow velocity is obtained by computing the Cross Correlation Function (CCF) of the intensity fluctuations detected in pairs of columns of the image. This powerful technique finds its emblematic application in the characterization of the intricate murine hepatic microcirculatory system, where the blood flow speed has been mapped in several capillaries from a single xy-image and followed in time at high spatial and temporal resolution.

9529-15, Session 4

Digital holographic micro-interferometry of nonradiative transitions in biological specimens

Andrey V. Belashov, Ioffe Physico-Technical Institute (Russian Federation) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Irina V. Semenova, Ioffe Physical-Technical Institute (Russian Federation); Oleg S. Vasyutinskii, Ioffe Physical-Technical Institute (Russian Federation) and Saint-Petersburg State Polytechnical Univ. (Russian Federation)

Methods of digital holography are widely used nowadays for studies of various objects and processes. However peculiarities of objects under study often imply difficulties in digital holograms recording, reconstruction and further processing. One of the major factors is the existence of a large amount of nonuniformities that cause singularities and low signal to noise ratio. Therefore the development of new algorithms for processing of phase distributions especially conformed for studies of biological objects are of the utmost interest.

The paper presents a novel approach aimed to calculate a phase difference from two digital off-axis holograms, providing noise filtration and omitting the unwrapping procedure. The technique is suitable for evaluation of phase variations from highly noisy digital holograms. The suggested algorithm simulates an interferogram in finite width fringes, by analogy with classical double exposure holographic interferometry. Such an interferogram carries information on phase difference of two object waves corresponding to the two recorded holograms. Thus the suggested algorithm allows to simulate the procedure of classical holographic interferometry. In this case substantial phase breaks caused by the object speckle structure are cancelled at the subtraction. The obtained interferogram is then processed as a digital hologram using the reconstruction technique with adjustable smoothing being defined by the size of processing window at the reconstruction. Although this smoothing procedure reduces somewhat the spatial resolution, an adjustment of the algorithm parameters allows to find a balance between the degree of filtration and the required spatial resolution. After noise and phase wraps elimination the phase distribution may be easily unwrapped. It was shown that the suggested approach allows obtaining a difference of highly noisy phase distributions with much lower losses of spatial resolution than those provided by other algorithms, e.g. by sin-cos filtration. Besides that the application of regulated smoothing allows phase unwrapping even under the conditions when traditional methods such as Goldstein's branch-cut technique fail.

The algorithm is promising for studies of dynamic processes in biological media due to some specific features of such objects. First, the sought value in these studies is phase retardation caused by the object disturbance, which is directly connected to phase distribution difference. Second, micrometer size objects in these media may be a source of speckle structures in the wave front, which are cancelled in phase subtraction process. Third, studies of biological objects occur usually at low signal to noise ratio. Besides that phase distributions of wave fronts passed through biological media are usually smooth surfaces. Thus regulated smoothing provides noise elimination with almost no distortions in the reconstructed wave front.

The suggested algorithm was applied to detection of nonradiative deactivation of singlet oxygen in an aqueous solution of Radachlorin photosensitizer. Photosensitizer molecules were excited by diode laser radiation at 405 nm and transferred then their energy to oxygen molecules. Since the radiative transition from the singlet to the ground triplet state of the oxygen molecule is forbidden most part of energy was released through nonradiative transitions producing thermal gradients in the surrounding medium. These thermal gradients resulted in refractive index variations and phase retardations of the wave front passed through the water cell with the solution. The photosensitizer phosphorescence at 680 nm caused noise and additional phase wraps rendering difficulties in phase unwrapping procedure. In course of the algorithm performance interferograms in finite width fringes were simulated and then processed as digital holograms using reconstruction technique with adjustable smoothing. After noise elimination and phase unwrapping the inverse Abel transform had been applied and spatial distributions of temperature gradients and phase retardation were reconstructed.

9529-16, Session 4

Extended field of view space-time digital holograms for lab-on-a-chip microfluidic imaging

Vittorio Bianco, Melania Paturzo, Valentina Marchesano, Pietro Ferraro, Istituto Nazionale di Ottica (Italy)

The study of biological specimens onboard Lab-on-a-Chip (LoC) platforms is well assessed and raises growing interest for point-of-care diagnostics [1,2]. In this framework, great effort has been spent to develop compact chips with embedded imaging functionalities [3]. Label-free techniques are preferred for non-invasive ex-vivo inspection of the samples. Among them, Phase shift Interferometry (PSI) and Digital Holography (DH [4]) have been proved to yield quantitative phase-contrast mapping as well as flexible numerical refocusing [5]. In PSI a phase shift between multiple interferograms has to be provided, e.g. by piezoelectric actuators, to synthesize the whole complex object field. Here we show an interesting imaging modality, named Space-Time Scanning Interferometry (STSI) which exploits a lateral displacement between the object and the detector, provided by a translational stage, to synthesize a new space-time interferogram with interesting features [6]. Indeed, a single linear sensor array is sufficient to build up a synthetic interferogram with unlimited Field of View (FoV) along the scanning direction and improved Signal-to-Noise Ratio (SNR). Besides, if a small subset of lines of the detector are selected, synthetic interferograms can be obtained, shifted each other of the desired phase step for phase retrieval purposes. The theoretical formulation and experimental proofs of the STSI method applied to different and complex shaped pure-phase objects (e.g. polymeric drops) are reported [6]. PSI is applied to properly shifted synthetic interferograms (PS-STSI) to demonstrate the capability of estimating the whole complex object field. Noteworthy, the STSI principle is well-suited to be adopted in all the cases where the object motion is an intrinsic feature of the system, such as in case of microfluidics, so that the advantages of STSI have no cost associated with. Starting from these considerations, we discuss the application of the STSI method to in-flow on-chip microscopy. By performing out-of-focus recordings with a single line detector, a Space-Time Digital Hologram (STDH) could be synthesized carrying full-field information of the flowing samples. A so built STDH still maintains all the advantageous capabilities of DH microscopy, i.e. quantitative phase-contrast mapping and flexible numerical refocusing. Moreover, a re-focusable STDH with unlimited FoV along the flow direction can be created adopting a single linear detector and with no need for hologram stitching. Promising first-cut results, obtained using polystyrene beads as test samples, will be reported. Hence, it could be possible to move a step toward the integration of the imaging functionalities onboard chip for high-throughput rapid diagnostics.

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9529-17, Session 4

Imaging with multimode fibers *(Keynote Presentation)*

Demetri Psaltis, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Holography and phase conjugation were proposed in the middle 1960's for correcting the distortions in imaging systems due to aberrating or scattering media. These early methods have been revisited in recent years and successful experimental demonstrations have been reported with digital holographic methods in which the recording and reconstruction of the hologram is done with the help of a digital computer. Digital holographic methods offer a lot more flexibility and control compared to the all-optical methods of the past making holographic imaging much more practical. In addition, adaptive wavefront shaping techniques have been recently developed providing a set of related and synergistic methods for imaging in complex media. In this presentation we will focus primarily on the application of the modern tools of holography to the control of light transmission through multi-mode fibers. The modal dispersion that severely scrambles images propagating through multi-mode fibers can be compensated allowing us to exploit the many degrees of freedom available in the multi-mode fiber for imaging and sensing.

9529-18, Session 5

Photonics-enhanced polymer lab-on-chips : from high-tech prototyping platform to applications *(Invited Paper)*

Hugo Thienpont, Vrije Univ. Brussel (Belgium)

In this presentation we will highlight the technological capabilities of our state-of the art polymer platform for the design, prototyping,measurement, and proof-of-concept demonstration of photonics-enhanced lab-on-chips and their mass-manufacturing on 300 mm polymer wafers, and illustrate these capabilities with applications in the domain of medicine, food-safety and authentication, and chemistry.

9529-19, Session 5

Red blood cell three-dimensional morphometry by quantitative phase microscopy

Francesco Merola, Istituto di Cibernetica Eduardo Caianiello (Italy); Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Lisa Miccio, Oriella Gennari, Martina Mugnano, Istituto di Cibernetica Eduardo Caianiello (Italy); Paolo A. Netti, Istituto Italiano di Tecnologia (Italy); Pietro Ferraro, Istituto di Cibernetica Eduardo Caianiello (Italy)

Quantitative evaluation of three dimensional (3D) morphometric parameters is an important aspect in different fields, from bio-technologies to medicine. In particular, 3D shape and biovolume are fundamental for diagnostic purposes of flowing and not-adherent cells at Lab on Chip scale. Diagnostics tools need to be accurate, reliable and, as much as possible, no-invasive. In bio-inspired experiment a central problem is the quantitative evaluation of the phase-shift introduced by the sample and, for this reason digital holography (DH) has been improved to be considered as suitable diagnostic method in biology. A simple holographic approach based on DH [1-3] and shape from silhouette (SFS) algorithm, has been demonstrated for accurate calculation of cells biovolume and for 3D shape display [4]. Such approach has been adopted in combination with holographic optical tweezers and successfully applied to cells with convex shape. Unfortunately, the method failed in case of specimen with concave surfaces. Here, we propose an effective approach to achieve correct 3D shape measurement that can be extended in case of cells having concave surfaces, thus overcoming the limit of the previous technique and avoiding the high computational load of tomographic algorithms. By decoupling thickness information from refractive index ones and combining this with SFS analysis, 3D shape of concave cells is obtained. Specifically, the topography contour map is computed and used to adjust the 3D shape retrieved by the SFS algorithm. We prove the new procedure for healthy red blood cells having a concave surface in their central region. Experimental results are compared with theoretical model. We prove the new procedure for healthy red blood cells (RBCs) (i.e., discocytes) having a concave surface in their central region [5]. Moreover, the method can be also useful to classify, in terms of morphology, different kinds of RBCs.

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9529-20, Session 5

Imaging and characterization of surface relief gratings on azopolymer by digital holographic microscopy

Alejandro Calabuig, CNR - ISASI Institute of Applied Sciences & Intelligent Systems "E. Caianiello" (Italy); Carmela Rianna, Department of Chemical, Materials and Industrial Production Engineering, University of Naples (Italy) and Center for Advanced Biomaterials for Health Care@CRIB, Istituto Italiano di Tecnologia (Italy) and Interdisciplinary Research Center on Biomaterials, University of Naples Federico II (Italy); Vito Pagliarulo, CNR - ISASI Institute of Applied Sciences & Intelligent Systems "E. Caianiello" (Italy); Maurizio Ventre, Department of Chemical, Materials and Industrial Production Engineering, University of Naples (Italy) and Center for Advanced Biomaterials for Health Care@CRIB, Istituto Italiano di Tecnologia (Italy) and Interdisciplinary Research Center on Biomaterials, University of Naples Federico II (Italy); Silvia Cavalli, Center for Advanced Biomaterials for Health Care@CRIB, Istituto Italiano di Tecnologia (Italy); Simonetta Grilli, CNR - ISASI Institute of Applied Sciences & Intelligent Systems "E. Caianiello" (Italy); Paolo Antonio Netti, Center for Advanced Biomaterials for Health Care@CRIB, Istituto Italiano di Tecnologia (Italy) and Department of Chemical, Materials and Industrial Production Engineering, University of Naples (Italy) and Interdisciplinary Research Center on Biomaterials, University of Naples Federico II (Italy); Pietro Ferraro, CNR - ISASI Institute of Applied Sciences & Intelligent Systems "E. Caianiello" (Italy)

Azopolymer materials belong to family special materials with specialized optical properties, which are subject to trans-cis-trans photoisomerization when illuminated by appropriate light wavelength. They give rise to three different motions: in molecular, micro-domain and macroscopic levels. Specifically, the third photoinduced motion involves large amount of polymeric material, which produces deformations on the surface. The interference lithography is an excellent tool to trigger the

isomerization reaction on the material realizing the so calling SRGs that have applications in the field of biotechnology, photonic elements, molding templates, etch masks and micro-nanochannels. In this work, the interference lithography (IL) setup is based on the Lloyd's mirror scheme. The laser source is a He-Cd laser operating at lambda=442 nm with a total power of about 50 mW. A p-polarized light is switched and then split in two coherent beams by a Lloyd mirror, interfering at the same position to create a regular line pattern. A He-Ne source is used to monitoring the SRG formation thought the visualization of the diffraction pattern. After the lithographic process is always necessary, a morphological characterization often archived with the use of an AFM tool.

The motivation of the present paper is to show the performances of Digital Holographic Microscope (DHM) realized in situ to acquire 3-dimensional images of the SRGs with a resolution comparable to that of different techniques. This holographic setup has also potentially interesting applications thanks to low costs and to the ease of use. In particular, DHM allow to achieve high resolution and phase information in microscopic level that consents to study some of such movements. Nowadays, the origins of photoinduced SR deformation are not completely understood. With this work, we want to use the DHM benefits to give further explanation on the formation of SRG's.

Moreover, preliminary results of the employment of these materials as functionalized substrate for study into the cell mechanics field are shown. Cell-topography interaction has proven to be an important element in controlling biological features and guiding cell responses. Micro patterned polymers are suitable supports to analyze cell mechanotransduction and contact guidance cues. In particularly, we report an early study of NIH-3T3 cell line on reversible light-induced patterned azopolymers. Light was used to write and erase azo-patterns in order to sort a biological feedback to photo-induced topographical changes. Cell elongation, orientation and focal adhesions morphology were investigated.

9529-21, Session 5

Optical characterisation of complex structures, from engineering composites to biomaterials *(Invited Paper)*

Roger M. Groves, Technische Univ. Delft (Netherlands)

Bio-materials and engineering composites share many common features, such as complex anisotropic structures and mixtures of materials with different properties. Engineering composites are typically composed of fibres in a resin matrix. Examples are Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Plastic (GFRP). These materials are used to make high performance structures such as the body and chassis of a Formula 1 race car and the blades of a wind turbine, respectively. Further, these composites way be combined with metals to form hybrid materials including fibre metal laminates (FMLs), such as GLARE (GLAss REinforced aluminium) which was developed at TU Delft and is used in the Airbus A380 fuselage. An important structural biomaterial is wood, which can be considered to have a structure analogous to engineering composites. For example, softwood is a fibrous material composed of tracheids and parenchyma cells. Tracheids are axial cells, typically 100 longer than wide, and parenchyma cells are darker, radiating perpendicular to the growth rings. These cell types and the resulting material density and structure determine the moisture transport properties of the wood. Wood has many structural uses from the construction of furniture, buildings, early aircraft and as a support for panel paintings.

Bio-materials and engineering composites are challenging materials for structural characterisation due to their anisotropic structure and behaviour. Optical measurement techniques for these materials can be characterised into 2D surface metrology, 3D volume imaging and photomechanics techniques to measure the response of materials under an applied load. The surface profile of an object can be measured by using fringe projection, photogrammetry or white light interferometry. These techniques provide data at typically better than 50 ?m depth resolution. Structural applications of natural and manufactured composite materials commonly employ coatings for protection of the material from moisture, heat, scratches, and for aesthetic purposes. Coatings may respond to both structural changes by delamination and cracking, after which they no longer fulfil their purpose of protecting the underlying material. This damage accumulation is often accelerated by chemical aging of the coating and underlying bio-materials or manufactured composite. Optical techniques can provide information on damage accumulation. For example optical coherence tomography (OCT) can measure the thickness of semi-transparent coatings and hyperspectral imaging can measure the spectral, and hence chemical, properties of the materials.

3D volume imaging is more challenging as many materials are not transparent. A range of techniques, some optical, are used to determine the internal structure of materials at different spatial and depth resolutions. Semi-transparent materials such GFRP may be structurally characterised by refractive index changes between fibres and resin using OCT. Using this technique it is possible to determine fibre position and direction and the presence of cracks and delaminations. Dry wood is partially transparent to terahertz radiation and internal structural features, such as a knot, may be assessed by their different absorption characteristics. However wood containing a high moisture content is strongly absorbing to terahertz radiation due to the water content. One challenging aerospace composite to measure optically in 3D volume imaging is CFRP. The presence of carbon disturbs the propagation of electromagnetic waves in the material. The material is typically measured using ultrasonic waves (1 to 10 MHz frequency) and techniques such as pulse-echo and phased-array can be used to reconstruct the internal structure. Ultrasonics can also be used to characterise biomaterials. In both cases the measurement resolution is in the mm range, due to the ultrasonic wavelength in these materials.

Photomechanics, the development and application of optical techniques for solid mechanics, is an active and growing topic for a wide range of materials. Composites of both bio-material and manufactured origin are anisotropic and as such have a non-uniform response to loading. This is partially at the materials level where different materials, wood cell types, fibres and resin have different Young's modulus, Poisson ratio, thermal conductivity, expansion coefficients, densities etc. Also as these materials chemically age, their properties vary over time. The second factor is the interfaces between materials, where stress concentrations form giving adhesive failure. Materials may also vary in density, modulus, moisture content, etc. due to environmental conditions, such as temperature, relative humidity, light. Solid mechanics employs a number of optical techniques, most of which are non-contact. Commonly used techniques are digital image correlation (DIC), holographic and speckle interferometry and Moiré. These techniques can measure with a displacement resolution down to 50 nm or a strain resolution down to 20 ??. Spatial resolutions are typically in the range 100 ?m to 1 mm for camera based techniques.

This paper will review the field of optical measurements for complex anisotropic structures and mixtures of materials with different properties. Parallels will be drawn between applying these techniques to bio-materials and engineering composites. Examples will be given from engineering, bio-materials testing and cultural heritage. In particular, examples of bio-material and engineering composite examples from aerospace engineering will be included.

9529-22, Session 5

Characterization of piezoelectric materials and the biocompatibility ferroelectric lithium niobate *(Invited Paper)*

Brian J. Rodriguez, Univ. College Dublin (Ireland)

Piezoelectric biomaterials, including collagen, organic peptide nanomaterials, deoxyribonucleic acid nucleobase crystals, and transparent biocompatible ferroelectric crystal substrates have numerous potential applications in sensing, energy harvesting, and tissue engineering. Recent progress in understanding the origin and role of piezoelectricity and possible ferroelectricity in such functional biomaterials using a scanning probe microscopy technique called piezoresponse force microscopy (PFM) will be discussed. The role of pH and moisture content on electromechanical coupling in type I collagen and the observation of piezoelectricity in type II collagen, thymine nucleobase microcrystals grown from solution during evaporation, and dried self-assembling peptide hydrogels will be presented. At the heart of piezoelectricity is the presence of a non-centrosymmetric crystal structure, highlighting the potential for characterizing such materials by complementary

scanning probe (i.e., PFM) and optical techniques such as second harmonic generation imaging. Furthermore, the widely used nonlinear optical material, lithium niobate (LN), exhibits piezoelectric properties that are proportional to the spontaneous polarization. Thus, the piezoelectric response can be considered as providing insight also into the nonlinear optical coefficient, as will be demonstrated on periodically proton-exchanged crystals. The optical and electronic properties of such periodically-patterned LN crystals further enables their use as a template for Raman scattering-based biosensing applications. Lastly, the biocompatibility and proliferation of osteoblast cells on LN will be discussed, which may facilitate the exploitation of nonlinear optical properties for biomaterials characterization.

9529-23, Session 6

Three-axis digital holographic microscopy for high-speed volumetric imaging of swimming cells *(Invited Paper)*

Roberto Di Leonardo, National Research Council of Italy (CNR) (Italy) and Dipartimento di Fisica, Sapienza Università di Roma (Italy); Silvio Bianchi, Filippo Saglimbeni, Alessia Lepore, Dipartimento di Fisica, Sapienza Università di Roma (Italy)

Digital Holographic Microscopy allows to numerically retrieve three dimensional information encoded in a single 2D snapshot of the coherent superposition of a reference and a scattered beam. Since no mechanical scans are involved, holographic techniques have a superior performance in terms of achievable frame rates. Unfortunately, numerical reconstructions of scattered field by back-propagation leads to a poor axial resolution. Here we show that overlapping the three numerical reconstructions obtained by tilted red, green and blue beams results in a great improvement over the axial resolution and sectioning capabilities of holographic microscopy. A strong reduction in the coherent background noise is also observed when combining the volumetric reconstructions of the light fields at the three different wavelengths. We used our technique to record the 3D motions of individual bacteria swimming in optical traps. We find that most cells possess two run states characterised by different propulsion forces, total torque and bundle conformations. Our method is naturally multi-particle and opens up the way towards controlled hydrodynamic studies of interacting swimming cells.

9529-24, Session 6

Investigation on cytoskeleton dynamics for non-adherent cells under point-like stimuli

Lisa Miccio, Istituto Nazionale di Ottica (Italy); Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Francesco Merola, Istituto Nazionale di Ottica (Italy); Martina Mugnano, Sabato Fusco, Antonio Paciello, Istituto Italiano di Tecnologia (Italy); Pietro Ferraro, Istituto di Cibernetica Eduardo Caianiello (Italy); Paolo A. Netti, Istituto Italiano di Tecnologia (Italy)

Cytoskeleton is a dense interpenetrated biopolymeric network able to adapt itself to cellular tensional state. It plays a key role in cell-force sensing/production and cell mechanics. Understanding cell mechanics requires knowledge of the magnitude and distribution of forces throughout the cell. Generally, force transmission is via the focal adhesions (FA) acting as structural connection between external substrate and cytoskeleton. FA are the primary pathway for intracellular force transmission that influence different cascade pathways of biochemicals signals that regulate short and long term cellular responses and behaviors. A quantitative determination of transmitted forces will contribute significantly to shed light on mechano-transduction mechanism. A variety of different methods have been used to mechanically manipulate cell, including micropipette aspiration, microplate cell manipulation, optical and magnetic tweezers. Usually, experimental campaigns have been conducted on adherent cells averaging the generated forces, and consequently the mechano-transduction on the contact points with substrates. In order to better correlate the transmitted forces to the cell deformations and definitely decouple substrate influence, Optical Tweezers (OT) allow to manipulate cells directly in suspension. Indeed, OT is an high-throughput and effective tool for micro/nano manipulation in a contact-less and non-invasive manner. In biological field, OT is particularly suited for studying single cell behavior making the possible applications endless. Recent studies have been devoted to confine or constrain cells, for sorting, assembling, and patterning. OT have undergone an improved interest when computer addressable spatial light modulators made possible the creation of multiple traps that can be steered individually. The method, named Holographic Optical Tweezers (HOT), enables the generation and independent high-precise control of an arbitrary number of 3D optical traps.

Here, we use the capabilities of HOT to generate different numbers and configurations of trapping sites, in order to trap and manage functionalized micrometric latex beads with the aim at probing the cellular response. We exploit the HOT arrangement to induce mechanical deformation in suspended NIH 3T3 fibroblast cells. Our investigation is devoted to understand the inner cell mechanism when it is mechanically stressed by point-like stimulus without the substrate influence. In our experiment, cell adhesion is prevented and the stimulus is applied through latex beads trapped by HOT and positioned externally to the cell membrane. Our aims are devoted to analyze cell response during the transition from an homogeneous and isotropic structure (as it's in suspension) to a mechanically stressed state. To analyze the cell material interaction we combine the HOT arrangement with two imaging systems: a Digital Holography (DH) setup in microscope configuration that is an investigation method useful for quantitative and label-free and full-field analysis of low contrast object and a fluorescence modulus. HOT are exploited to induce cellular response to specific stimuli while DH allows to measure such responses in a quantitative, label free and not invasive way. Finally, fluorescence imaging is added to discriminate the inner cell structures.

9529-25, Session 6

Photovoltaic tweezers an emergent tool for applications in nano and bio-technology *(Invited Paper)*

Mercedes Carrascosa, Angel Garcia-Cabañes, Mariano Jubera, Iris Elvira, Héctor Burgos, José L. Bella, Fernando Agulló-López, Univ. Autónoma de Madrid (Spain); Juan F. Muñoz-Martínez, Univ. Politecnica de Madrid (Spain) and Univ. Autónoma de Madrid (Spain); Angel Alcázar de Velasco, Univ. Politécnica de Madrid (Spain)

The field of trapping, patterning and manipulation of micro- and nano-objects, including, molecules, living cells or bacteria and micro- and nanoparticles, is very active and offers interesting possibilities in a variety of applications ranging from nano-technology to photonics, biology and biomedicine. A number of different approaches have been proposed and explored including conventional optical tweezers or electrokinetical methods. In the last years a new optoelectric technique for particle manipulation, the so called photovoltaic (PV) tweezers (or photorefractive tweezers), has been proposed and demonstrated. It relies in the bulk photovoltaic effect (PVE), a singular phenomenon which appears in some crystalline ferroelectric materials (doped LiNbO3 clearly highlighting) when properly doped (mainly with Fe). It allows the photo-generation of very high internal electric fields (1-3x105 V/cm) for moderate or low light levels (~mW/cm2). The field extends to the proximity of the crystal surface (evanescent field) and can trap either charged particles via electrophoretic (coulombian) forces or neutral particles via dielectrophoretic forces.

The novel technique has a number of key advantages over conventional optical tweezers and/or electro-kinetical methods such as parallel manipulation on many particles, flexibility and versatility of the light-induced patterning without the need of electrodes or voltage suppliers, operation at low light intensities (several orders of magnitude smaller than conventional optical tweezers) and reconfiguration capabilities.

However, in spite of its potential, the technique is still in an emergent stage and both its possibilities and its potential applications are in continuous expansion.

In this contribution we present an overview of the work recently developed by our group on the development and applications of PV tweezers, including the analysis of the physical basis of the method and the main achievements in the theoretical description and experimental implementation. Particular attention will be also paid to the main potential applications and first demonstrations of its use in nano- and bio-technology. Specifically: i) effects of PV fields of LiNbO3 in tumour cells, ii) manipulation and patterning (1D and 2D) of micro and nanobjects, either particles or bio-objects (spores, pollen...), iii) development of diffractive gratings and integrated optical components and, iv) fabrication of metallic nanoestructures for plasmonic applications.

9529-26, Session 6

Controlling self-propelled nanobiorobots by optical micromanipulation *(Invited Paper)*

Alvaro Barroso Peña, Florian Hörner, Shirin Landwerth, Cornelia Denz, Westfälische Wilhelms-Univ. Münster (Germany)

Microscopic arrangement, patterning, and organization of biomolecular motors prospect exciting applications from microbiology to nano-engineering and biomedicine. In this respect, the rotary nanomotors of flagellated bacteria are the most exploited biological motors for the actuation and powering of micro-systems because of their high efficient mechanism for motion in the low Reynolds number regime, where viscous forces dominate over inertial forces. In particular, chemotactic bacteria convert chemical energy to mechanical energy directly from the surrounding medium in order to address a driven motion in direction of favorable nutrients. This on-board actuation enables to eliminate the challenge for miniaturization of the energy power source, leading to the development in the last years of novel, dynamic hybrid nano- and micro-devices. For instance, motile bacteria attached on solid surfaces (bacterial carpets) have been used for microfluidic applications to pump liquid or to enhance mixing in microfluidic systems. In addition, self-propelling bacteria have been used to actuate moving microparticles, reaching from conventional microspheres to more complex abiotic objects which were transported to specific locations, and to rotate microscopic gears. A prerequisite for reasonable utilization of such biological motors in general and efficient cooperative behavior in particular is a method to attach, i.e. adhere or tether a single or a multitude of individual biological cells to a an specific surface or microparticle in a defined way that gives the best possible control over the location and state of every single cell. Traditional fabrications and bonding techniques for the micro-assembly of bacterial-based micro-devices rely on the site-selectively functionalization of the abiotic object surface such that the biological specimen attach only where the surface has been modified. However, the process of micro-patterning and micro-assembly requires a relatively high effort, suitable material know-how and equipment. Moreover, fine control over individual bacteria is very limited and the approach lacks flexibility and re-configurability with respect to new arrangements. The aim of this contribution is to present and elaborate a generalized scheme based on holographic optical trapping to create microsystems that are actuated by self-propelling bacteria. The holographic approach of conventional optical tweezers extends the concept of confining transparent microparticles near the focal spot of a tightly focused laser beam to multiple optical traps by holographically tailoring the trapping light field using a spatial light modulator (SLM). It is a flexible, reconfigurable method, which allow the dynamic control of tens of non-spherical particles and allow arranging the different parts of the assembly in any desired configuration. We demonstrate the feasibility of the method by showing the fabrication of flow micromixers made of tens of bacteria attached to a homogeneous, polystyrene-coated surface [1] and the assembly of bio-hybrid micro-robots consisting of only one self-propelling bacterium with zeolite nanocontainers [2] which can be envisioned for drug release applications.

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9529-27, Session 7

3D phase imaging with computational illumination *(Invited Paper)*

Laura Waller, Lei Tian, Zachary F. Phillips, Univ. of California, Berkeley (United States); Chenguang Ma, Univ. of California, Berkeley (United States) and Tsinghua Univ. (China); Ziji Liu, Univ. of California, Berkeley (United States) and Univ. of Electronic Science and Technology of China (China)

This talk will describe new methods for achieving 3D and high-resolution images in a commercial microscope. Our setup involves replacing the illumination unit of the microscope with a programmable LED array for computational illumination. Using a combination of optical hardware and post-processing software, we achieve real-time darkfield, 3D and phase imaging via light field methods. By rapidly coding illumination angles on the LED array and employing computational coding in time, we further show that 3D and super-resolution results (6x better resolution than the objective allows) can be achieved in real time. The result is a high-resolution gigapixel image of both phase and absorption information in 3D with fast capture times. Such computational approaches to optical microscopy add significant new capabilities to commercial microscopes without much cost or hardware modification.

9529-28, Session 7

Computational imaging with phase-structured illumination: application in scattering *(Invited Paper)*

Enrique Tajahuerce, Lluís Martínez-León, University Jaume I (Spain); Yutaka Mori, Wakayama University (Japan); Pere Clemente, Vicent Climent, Jesús Lancis, University Jaume I (Spain)

We describe several approaches for computational imaging with single-pixel detection. Images are obtained by sampling the scene with microstructured patterns, implemented onto a spatial light modulator, and recording light intensity fluctuation with a simple photodiode. With this technique we have demonstrated image transmission through scattering media, such as biological tissue, even with dynamic scattering. We will emphasize the extension of these ideas to phase retrieval by using interferometric techniques and phase-structured illumination. Preliminary experimental results are shown.

9529-29, Session 7

Label-free coherent microscopy through blood by digital holography

Vittorio Bianco, Melania Paturzo, Francesco Merola, Lisa Miccio, Istituto Nazionale di Ottica (Italy); Pasquale Memmolo, Istituto Italiano di Tecnologia (Italy); Oriella Gennari, Pietro Ferraro, Istituto Nazionale di Ottica (Italy)

Label-free optical imaging of biological samples onboard Lab on a Chip (LoC) platforms is a highly demanded capability in all fields of biology and medicine for point-of care diagnostics. LoCs are compact low-cost devices allowing to manipulate small amounts of liquid, yielding sample counting and sorting, and to study cell mechanics and adhesion to functionalized substrates [1]. Whenever the specimen is dipped inside a

transparent medium, Digital Holography (DH) microscopy is one of the preferred imaging techniques as it provides non-invasive quantitative phase-contrast mapping as well as flexible numerical refocusing of samples acquired in lens-based or lensless conditions. However, a challenging issue has to be faced when the samples are immersed inside a dynamic turbid medium, as biological occluding objects, out of interest, that provoke severe light scattering or unpredictable time-variable phase delays which scramble the object information, so that in many cases the sample is not visible at all. Here we show a simple technique, named Multi-Look Digital Holography (MLDH), able to fully recover the useful signal of the specimen of interest dipped inside the turbid liquid phase. Multiple hologram recordings are incoherently combined to synthesize the whole complex field carrying the useful information, thus revealing the hidden objects. MLDH is proved to accomplish such optical task by microscopy imaging of different targets and biological samples through different turbid media made of inanimate objects (i.e. milk colloids), living species (i.e. bacteria colonies) or scattering layers [1,2]. Noteworthy, in our experiments we studied fibroblast cells settling down the inner wall of a microfluidic chip, previously functionalized in order to favorite the cell adhesion mechanism, while letting a multitude of Red Blood Cells (RBCs) flow along the channel. In such condition conventional imaging techniques cannot yield any qualitative or quantitative information. On the contrary, MLDH provides both clear amplitude imaging and phase-contrast mapping of the fibroblasts despite the severe image distortion introduced by the RBCs [3], paving the way for the holographic blood vessel inspection (e.g. to detect blood clots or cholesterol). Besides, qualitative comparison and quantitative evaluation show a remarkable improvement with respect to the image captured when the cells were immersed in a transparent medium. In other words, the RBCs have been demonstrated to accomplish an optical task, acting as a speckle noise de-correlation device [3]. Thanks to the suppression of coherent speckle artifacts, we obtained by DH an image quality comparable with the quality achievable with an incoherent light microscope.

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9529-30, Session 7

Superresolution imaging system on innovative localization microscopy technique with commonly using dyes and CMOS camera

Varvara V. Dudenkova, N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation); Yuri Zakharov, N.I. Lobachevsky State University of Nizhni Novgorod (Russian Federation)

Optical methods for study biological tissue and cell at micro- and nanoscale level step now over diffraction limit. For the most part one or another property of fluorescent emission (stimulated depletion, photoactivation, photoswitching, etc.) is used to reach superresolution. Nobel Prize 2014 awarded an achievement of one of the many techniques in this field. Really it is single molecule localization techniques that achieve the highest spatial resolution, but photoactivation is not the only phenomenon possible for this method. One of the other techniques, called bleaching/blinking assisted localization microscopy (BaLM) relies on the intrinsic bleaching and blinking behaviors characteristic of commonly used fluorescent probes [1]. All fluorophores blink: at some instant of time they are exited and begin to shine and early or late they are bleached. And they do it independently of one another. This fact is the base of BaLM image series acquisition and data analysis (gSHRImP [2], 3-B [3]). Alike mentioned in our work appearance or disappearance of single fluorescent spot against a background of others comes to light by subtraction of time series successive frames. Then digital estimation gives the center of the spot as a point of fluorescent molecule presence. This point transfers to other image with higher resolution as a Gaussian cupola that width is equal to accuracy of the center localization (sensitivity and accuracy of the localization of the blinking and bleaching molecule mainly depends on camera dynamic range and signal/noise ratio). It is a part of image with improved resolution. In contrast to STORM (PALM) method this approach allows overlapping fluorophores and not requires single photon sensitivity, so unlike above we use 8,8 megapixel CMOS camera with smallest (1.55 um) pixel size. This instrumentation on the base of Zeiss Axioscope 2 FS MOT allows image transmission from object plane to matrix on a scale less than 100 nm/pixel using 20x-objective, thereafter the same resolution and 5 times more field of view as compared to EMCCD camera with 16 um pixel size. To optimize excitation light power, frame rate and gain of camera in order to achieve best results we have made appropriate estimations taking into account fluorophores behaviors features and equipment characteristics. Finely we have clearly distinguishable details of the sample in the processed field of view, though primary they weren’t resolved directly by microscope optics during the study of cell motility, morphological and functional evolution.

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9529-31, Session 7

Multiple angle of incidence, spectroscopic, plasmon-enhanced, internal reflection ellipsometry for the characterization of solid-liquid interface processes

Peter Petrik, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pannonia (Hungary); Emil Agocs, Benjamin Kalas, Peter Kozma, Research Institute for Technical Physics and Materials Science (Hungary); Balint Fodor, Judit Nador, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pécs (Hungary); Csaba Major, Research Institute for Technical Physics and Materials Science (Hungary); Miklos Fried, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pécs (Hungary)

A semi-cylindrical lens in Kretschmann geometry combined with a flow cell was designed for a commercial rotating compensator ellipsometer to perform internal reflection spectroscopic ellipsometry measurements, while allowing the use of multiple angles of incidence. A thin glass slide covered with a gold thin film was mounted between the half-cylindrical lens and a small-volume flow cell ensuring an improved sensitivity for protein adsorption experiments. The performance of the system was investigated depending on the angle of incidence, wavelength range and thickness of the gold films for surface plasmon resonance enhanced ellipsometric measurements, and a sensitivity increase of up to two orders of magnitude was revealed compared to ellipsometric measurements with standard flow cells, depending on the measurement parameters and configuration. The sensitivity of our system was found to be in the range of 1E-5-1E-6 for refractive index changes. Additionally, by focusing the light through the semi-cylindrical lens to the plasmonic thin layer, a measurement spot size down to a few hundred microns was achieved. Using a compensator rotating with 20 Hz, a temporal resolution of 50 ms can be reached. [Acknowledgement: Support from the ENIAC E450EDL project is greatly acknowledged.

9529-32, Session 7

Measurement of nanofluids absorption coefficient by Moiré deflectometry technique

Khosro Madanipour, Amirkabir Univ. of Technology (Iran, Islamic Republic of); Ataollah Koohian, Univ. of Tehran (Iran, Islamic Republic of); Shahrzad Shahrabi Farahani, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Cancer therapy is strongly depended in understanding of cancer biology, specifically microenvironment functions, signaling pathways and metastasis evolution. To avoid drug resistance development during long period cancer therapy, using drug combinations is necessary. In addition, in some cases higher doses of single drugs could be useful to prevent resistance mechanisms in vitro.

Nanoparticles exhibit many unique and interesting physical and optical properties making them an excellent candidate for drug delivery system in cancer treatment. Nanoparticles are capable of targeting diseased tissue, carrying imaging agents for detection, and delivering multiple therapeutic agents for combination therapy simultaneously.

One of the most important properties which affect the performance of NPs as drug deliverers is absorption coefficient. Strong absorption plays a key role in colorimetric detection of cancer cells where changes in the refractive index of the environment of the NPs is measured. Absorption coefficient is also used to calculate the nanoparticle concentration or estimate the nanoparticle size, important factors in higher therapeutic index for the therapeutic agent. On the other hand absorption coefficient is related to heat transfer coefficient which is an effective factor in laser treatment.

In this work, by using Moiré deflectometry technique, the absorption coefficient of a nanofluid is measured. The studied nanofluid is Au nanoparticles in water. It has many applications in laser cancer therapy and some diesis diagnostic. The proposed method is based on the evaluating of beam divergence instead of intensity measurement. Two beams are used to measure the absorption coefficient set up. The first beam is a comparatively high intensity laser beam with a wavelength in absorption spectrum range of the sample. This beam interacts with the sample and absorbed by the NPs. A wide beam with low intensity as a probe beam is radiated to the first beam vertically.

The fringe pattern which is used as reference data is taken without high intensity laser absorption. Then by turning on the laser, energy is absorbed by NPs and the probe beam is deflected consequently. So the Moiré fringes are deflected. It is shown that by measuring the deformation of Moiré fringes, absorption coefficient can be measured.

9529-48, Session PS

Diffraction phase microscopy with transmission and reflection illumination for refractive index measurements

Natalya A. Talaykova, Alexander L. Kalyanov, Vladimir P. Ryabukho, N.G. Chernyshevsky Saratov State Univ. (Russian Federation)

Biological tissues are the important system and characterized by a complex structure and non-stable optical properties. One of the most significant properties is refractive index. Measurements of refractive index of biological tissue and its individual parts is the one of the topical problems of the tissues optics. But information about refractive index insufficiently total although studies are conducted for a long time. Purpose of this work is red blood cells (RBC's) refractive index measurements by diffraction phase microscopy with transmission/ reflection illumination.

Diffraction phase microscopy (DPM) is new and rapidly developing method of optical microscopy. Its advantages are stable interferometric system to vibration, useful with any illumination source (He-Ne laser, semiconductor laser, LED, halogen lamp), one-shot information about investigation object. Layering scan, contrast agents and complex procedures preparation object don't use in this method. All of them allow performing DPM to real-time investigation of rapidly changing objects, for example in vitro human blood flow and in vivo blood flow after skin optical clearing.

We employ both transmitted light and reflected light illumination modes simultaneously. To separate the signals we use light sources with different central wavelengths. We employ He-Ne laser with wavelength ?0=632.8 nm for transmitted light and green semiconductor laser for reflected light (?0=532 nm). The radiation from light sources is registered by different colour channels of a detector (ac2500gc, Basler, Germany) since their spectra difference. This allows us to employ single shoot mode for capturing both reflected and transmitted light.

Diffraction phase microscope is an optical microscope, in which the diffraction phase module installed in image space of the microscope. The module is a 4f-system with a diffraction grating in an input plane, which is conjugate with output plane of the microscope. Image detector is situated in an output plane of the module and in a Fourier plane the spatial filter is employed. Image of the object, resulting in the microscope, combined with the image of the interference picture produced by the diffraction phase module in the plane of the detector matrix. Light passed through diffraction grating generate diffraction orders. Only two orders passed through the spatial light modulator (SLM) and interference in detector plane. One of them filtered by SLM is reference beam. The first diffraction order save full information about object and can use as object beam. A light wave passing through a phase object, such as human blood cells, undergoes a phase change, which is caused by the difference in refractive indices between the object and the environment and is shown in the curve of the interference fringes. Phase map turns out interference picture after Hilbert transforms.

The analysis of the interference image is carried out in LabView. Investigations were done with human capillary blood smears and flow. All the morphological characteristics of the optical thickness can be calculated from the quantitative information obtained from the phase object map. Other parameter of cells, such us refractive index and volume, is measured by optical thickness and microrelief.

Result of this work can be use for investigation administering drug in blood cell to transfer in the body and drugs influence on internal organs.

9529-49, Session PS

Study of optical waveguide sensor using metamaterial as buffer layer with non-linear cladding and substrate

Santosh Kumar, Anamika Kumari, DIT Univ. (India); Sanjeev K. Raghuwanshi, Indian School of Mines (India)

In this paper, dispersion equation of optical waveguide using metamaterial as buffer layer with non-linear cladding and substrate is pointed. The sensitivity of TE and TM mode in metamaterial optical waveguide sensor are computed mathematically and results are analyzed using MATLAB. The impacts of buffer layer with non-linear cladding and substrate on metamaterial optical waveguide sensor are also tried out.

9529-50, Session PS

Applicaton of speckle dynamics for studies of cell metabolism

Alexander P. Vladimirov, Ural Federal Univ. (Russian Federation); Alexey Baharev, Research Institute of Viral Infections (Russian Federation); Alexander Malygin, Julia Mikhailova, Irina Novoselova, Dmitry I. Yakin, Ural Federal Univ. (Russian Federation)

The features of metabolism in cultivated cells are conventionally studied using a variety of biochemical techniques which are mostly invasive and destructive. Appplication of biospeckles is a promising tool for interaction-free diagnosis of the processes occurring in the cells of live systems. Biospeckles were used to study the biological activity of seeds, fruit, to measure the bloodstream velocity in the human retina and extremities.

Earlier, a speckle interferometry technique and a device for quantitative assessment of metabolic activity in cultivated cells were theoretically grounded and experimentally tested. A time averaging speckle technique for separation and studies of processes occurring in cells at various velocities was proposed. The application of the technique for upgrading the device enabled us to obtain well-reproducible results. It was demonstrated that the upgraded device allows timely interaction-free detection of herpes virus in cultivated cells.

The parametre characterising the metabolic activity of cells was determined by averaging over a large number of cells. Along with that, application of biospeckles to study the processes occurring in separate cells is of vital scientific and practical interest. Research of this type is possible with devices providing high optical magnification.

The objective of this reseach was comparing the parametres of speckle dynamics used to assess metabolism in the cells averaged in areas of various sizes. The areas within the speckle image of the cell as well as those in the image plane areas containing various numbers of cells were averaging regions.

The target of the research was L-41 cells placed into a special optical tray with a nutrient solution immediately after defrosting. The experiments were conducted in a thermal chamber at 36.7 ± 0.1???. We used the following parametres characterising changes in the speckle fields: 1) the digital intensity value of the radiation into the TV camera pixels averaged over the time period ?, 2) the correlation coefficient of two digital images ?. The digital images corresponded to the same frame section at two time points.

The observation of the speckle dynamics film showed that the cells are densely set at the bottom of the tray. The cells are in interaction with the adjacent cells resulting in their migration. At certain time intervals the cells can be considered immobile, and the (t) dependences can be regarded as stationary. Typical (t) dependences and temporal value spectra for inracellular areas are provided. It was demonstrated that within the cell, the distribution of the metabolic activity parametre conforms to certain regularity. With the T time increase the detected regularity stabilises.

It is demonstrated that in an area containing hundreds of cells the ?(t) dependence levels off. From the theoretical viewpoint, this fact speaks for the stationarity of the random value . The stationarity is also confirmed by a good coincidence of the ?(t) dependences obtained in various temporal areas. Comparison of the temporal spectre deduced using the ?(t) autocorrelation function with the spectra of the signals recorded in separate pixels is provided.

The features of the ?(t) dependences obtained by averaging over large and a small cell numbers are discussed. The obtained data are compared with the materials of earlier research done by different authors. Recommendations on selecting the sizes of the regions for averaging physical values to be used in studies of a variety of cell proceses were formulated.

9529-51, Session PS

Dynamic speckle-interferometer for intracellular processes analyses at high optical magnification

Alexey Baharev, Research Institute of Virus Infections (Russian Federation); Alexander P. Vladimirov, Alexander Malygin, Julia Mikhailova, Irina Novoselova, Dmitry I. Yakin, Ural Federal Univ. (Russian Federation); Alexey Druzhinin, Institute of Metal Physics (Russian Federation)

The method of recording the dynamics of laser speckles and biospeckles is a promising tool for studying microscopic processes occurring in biological media. Currently, biospeckles are successfully used in studies of the activity of various biological objects.

At present work dynamic of biospeckles is used for studying processes occurring in cells which arranged in the one layer. The basis of many diseases is changes in the structural and functional properties of the molecular cells components as caused by the influence of external factors and internal functional disorders. Purpose of work is approbation of speckle-interferometer designed for the analysis of cellular metabolism in individual cells.

The assembly of installation for speckles dynamics registration at high magnifications of cells was carried out in the laboratory of Research and Education Center “Nanomaterials and Nanotechnologies” (NOU) of Ural Federal University. Basic elements of the installation - liquid thermostat, an optical microscope with a monochrome television camera type Videoscan, the semiconductor laser module. The radiation from the module falls on matte scatterer and further to the cuvette with the sample. The optical system allows to visualize individual cells. Signals from the camera via USB-port came on the laptop 8 type Aspire 3692 WLMi of company Acer.

With the help of the program «Viewer», the dynamics of speckle was studied by comparing of two images taken at different times. This resulted in the data on the correlation coefficient change over time at specific temperature in the installation. Signals in the individual pixels were also recorded and analyzed.

Cell cultures L-41 CD / 84 were selected as objects of research. Cell culture A-41 is cancerous culture.

As a parameter characterizing the metabolic activity of cells used the value of the correlation coefficient (?) of optical signals proportional to the radiation intensity I, recorded at two points in time t. At 320x magnification for the cell diameter of 20 microns value ? can be determined in the area size of 6 microns.

Typical film frames of speckles dynamics illustrating changes in the speckle images of cells are shown. Typical dependences of ? (t) and I (t) for areas within the cell are analyzed. Dependences ? (t) and I (t), obtained by averaging over many cells and time are discussed.

It is shown that the installation and method allows distinguishing the processes occurring in the nutrient solution and the cells. It can be used to study the cells responses on external influences, in particular for studying the interaction of cells with viruses. In operation, the design has been optimized to improve its mechanical stability.

9529-52, Session PS

Parameter optimization of phase microscope with the interferometer as a spatial phase modulator

Olga A. Izotova, N.G. Chernyshevsky Saratov State Univ. (Russian Federation); Vladimir P. Ryabukho, N.G. Chernyshevsky Saratov State Univ. (Russian Federation) and Institute of Precision Mechanics and Control (Russian Federation)

One of the most widespread cells in the human organism are red blood cells (RBC). They play significant role on the all organism’s functions because of their responsibility for carrying oxygen to the body tissues. Various diseases generally affects to the microcirculatory blood system, so the structure of RBC is changing. Monitoring of these changes can provide useful information about the disease.

There are several methods for investigation the internal microstructure of biological objects, such as interference microscopy, holographic microscopy, phase contrast microscopy, diffraction phase microscopy, and etc. All these methods have different techniques for getting the result images, and their own advantages, and drawbacks.

In this paper we use method of interference microscopy with spatial modulation of optical field - spatial light interference microscopy (SLIM) for visualization cell structure and measurement its dynamics. SLIM is based on the principles of phase contrast microscopy and holographic microscopy and provides the high contrast imaging of cell structures. The idea of phase contrast microscopy is to introduce a phase shift between two components of the object wave field – undiffracted and diffracted. Such phase shift provides the contrast images of the transparent structure of the sample. The holographic principles are used for the reproducing quantitative phase image of the investigated object.

The distinctive feature of SLIM technique is introducing the additional spatial phase modulation of optical field in system of phase contrast microscope. In the currently known optical schemes of phase microscope the additional phase modulation is created by the liquid crystal spatial phase modulator (LCPM). Such modulation is generated in the Fourier

plane of the optical system which is coincide with the back focal plane of the microscope objective. LCPM introduces the phase shift equal to ϖ/2 between undiffracted and diffracted light from the sample, which leads to the formation of phase contrast images.

In our work we use the Michelson interferometer type optical system as LCPM. The phase shift is produced by micro displacement of one of the mirrors of the interferometer with the help of the piezoelectric element. The CCD camera recorders the image of interference between sample and reference arms of the interferometer. Such modification allows setting the path difference of fraction of the wavelength between the undiffracted and diffracted components of the optical field. This modernization of standard scheme of SLIM improves its performance due to higher speed of piezoelectric element comparing with the speed of LCPM. Also, it makes the price of such scheme more reasonable. The quantitative phase images of the object are formed by the phase shift method. In this work the phase images of RBC at four phase shift values are obtained. The quality of result images of the investigated object depend on technical parameters of the optical scheme of microscope, including the size of illumination system aperture. The purpose of this work is to calculate the optimal diaphragm size for better phase image quality of RBC, studied in this paper, which will be used further for the measurement RBC parameters and its dynamics.

9529-53, Session PS

Simple method of microorganism detection by using optical transmission and scattering techniques

Takeshi Ishiyama, Ayata Takami, Toyohashi Univ. of Technology (Japan)

Development of food testing system is important for food hygiene. In particular, microorganism testing in foods is essential to prevent food poisoning because food poisoning is generally caused by microorganisms. The flow cytometry technique is one of the most popular techniques to detect microorganisms using light scattering and florescence. However, the flow cytometer is very expensive and sophisticated system. Therefore, a simple testing technique is needed for microorganism testing in foods. We have developed a microorganism detection system by using optical transmission and scattering techniques. In this work, we constructed the simple detection system which was composed of a light emitting diode (LED), a photodiode, and a quartz cell. The radiated light from the LED (OSR5XME3C1S, Optosupply) with center wavelength of 625 nm was shuttered by the first iris diaphragm and converted into parallel light with a planoconvex lens. After the parallel light was narrowed to 5.0 mm diameter by the second iris diaphragm, it was irradiated to the quartz cell (width; 10 mm, optical pass length; 5 mm) where sample solutions were dispensed. We used polystyrene particles (30 and 1.6?m in diameters) and microorganisms (Bio Ball; 410106, sysmex biomerieux) which were dispersed in pure water, as the sample solutions, which are previous step for detection of microorganisms existing in foods. Transmitted and scattered light was measured with a PIN photodiode (PD; S3071, Hamamatsu Photonics). Light receiving surface of the PD is 5 mm diameter. We measured transmitted light intensity and angular dependence of scattered light intensity from polystyrene-particles-dispersed aqueous solutions with different concentrations and particle diameters. Transmitted light intensity decreased with increasing in the concentration of the particles and the threshold concentrations for the decay of the transmitted light intensity increased as the diameter of the particles decreased. In general, the transmitted light intensity I is given by following equation (1),

I=I0 exp(-Qext NL) (1)

where I0 is intensity of light source, Qext is the extinction cross-section per particle, N is the particle concentration and L is the optical path length. By fitting the transmitted light intensity using equation (1), Qext was evaluated. In addition, scattered light intensity per particle (Iscat) was evaluated from the integrated scattered light intensity. The Qext of the BioBall corresponds to those of polystyrene particles. In contrast, Iscat of the BioBall was stronger than that of the polystyrene particles. These indicate that the scattering light measurement is more effective than that of transmitted light. The detection limit concentrations were 9.0?10-3 mL-1 at 30-μm-diameter and 7.0?10-5 mL-1 at 1.6-μm-diameter, respectively.

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9529-54, Session PS

Investigation of surface irregularities of laser-treated metallic biomaterials based on light scattering measurement

Sepehr Razi, Mahmoud Mollabashi, Iran Univ. of Science and Technology (Iran, Islamic Republic of); Khosro Madanipour, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Success or failure of metallic biomaterials is in a direct relation with their surface characteristics. Surface irregularities such as roughness or waviness are among the most important and effective characteristics in this regard. Not only mechanical properties such as wear resistance but also biocompatibility features such as implant surface wettability or osseointegration are the sensitive functions of the surface irregularities. So the surface irregularities measurement is one of the essential quality control processes.

The statistical parameter which is used frequently for roughness is Root Mean Square (RMS) height. However, the surface irregularities cannot be specified only by the RMS roughness. In the other words the height distribution is insufficient to categorize a surface but another parameter which is named correlation length “T” is also needed to distinguish surface smoothness. T can be considered as the average value of the spacing of the adjacent crests and sometime is called “surface spatial wavelength”.

Numerous contact stylus-type inspections such as DEKTAK profilometer, Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) are more common for the calculation or measurement of these surface irregularities. In some cases they lack lateral resolution due to the tip geometry and they may also cause surface damage due to the forces exerted on the surface. On the other hand none of them is capable of being used in on-line measurement processes. Optical techniques which are mainly based on Total Integrated Scattering (TIS), Angular Distribution (AD), interferometery and speckle pattern recognition also offer quick measurement of surface features without the surface contact or damage.

In this paper, we suggest a method for roughness and correlation length measurement of metallic implant surfaces based on light scattering and Beckmann formulation. Metallic biomaterials that were laser treated in specified conditions are selected for the investigation. A laser and a CCD camera are the main elements of the experimental measurement set up. The laser source and camera are located symmetrically around the surface normal .The intensity distribution of the scattered light is captured by the CCD camera and the recorded intensity is analyzed using MATLAB software.

The theoretical approach that was suggested by Beckmann correlates the intensity of scattered light with surface parameters i.e. RMS roughness ?q and correlation length T. Thus in order to determine both the ?q and T parameter the experiments are realized for two different incident laser angles. Then by inserting the intensity data of the two experiments in the Beckmann formula, two mathematical relations are obtain that the surface ?q and T could be extracted from them. STM microscopy is also assessed to evaluate the accuracy of the determined values. Due to the simplicity this setup could be even used for the on-line investigations.

9529-55, Session PS

Manual wavefront holoscopy for inspection and visualization of engraved marks in progressive addition lenses

Beatriz Perucho, Jose Angel Picazo-Bueno, Carlos Ferreira, Vicente Micó, Univ. de València (Spain)

Progressive addition lenses (PALs) are marked at standardized locations at the PAL with two types of marks for layout, power verification, dispensing, and identification purposes. On one hand, removable marks are inked on and permits the identification and verification of the lens zones (essentially, distant, near and corridor zones). And on the other hand, permanent marks are engraved upon the surface at different stages in the manufacturing line and provide the model identification and addition power of the PAL, as well as to serve as locator marks to re-ink the removable marks again if necessary.

Because of their durable characteristic, permanent marks are the most important ones. However, aalthough those permanent marks should be visible by simple visual inspection, they are often faint and weak on new lenses providing low contrast, obscured by scratches on older lenses, and partially occluded and difficult to recognize on tinted or anti-reflection coated lenses. Due to this, visualization and identifying of permanent marks could be impossible with the naked eye and particularly for the less experienced technician. Aimed to that, there are several PALs marking readers in the market allowing identification and visualization of several PALs characteristics such as the initials of the manufacturer of the lens or company logo, fitting reference points, the addition power, the identifying symbol of the lens model, any customized mark, the material code, etc.

Permanent engraved marks can be understood as a sandwich of two layers of different materials having different refractive index values and thicknesses. Under this perspective, the phase of the wavefront transmitted by the PAL is distorted (advanced or delayed) according to this two-layer sandwich. Thus, the engraved marks are one of the best Gabor-like objects one can imagine. Since the PAL's engravings are essentially transparent (weak diffractive sample), the in-line hologram highly approaches to a Gabor hologram where the powerless imaging wave caused by diffraction at the PAL mark interferes with the strong non-diffracted light passing through it. And thus, in-line holography is perfectly suited for inspection and characterization of these engravings.

In this contribution we present an extremely simple visualization and inspection system for permanent marks in PALs based on manual wavefront holoscopy (an application of digital in-line holography). The digital implementation of this technology has been recently reported where not only visualization and identification but also quantitative phase profile of the mark are allowed [B. Perucho and V. Micó, J Biomed Opt. 19(1):16017 (2014)]. Here, we present a simplification of such concept by avoiding digital elements in the setup. The layout is extremely simple and defines a new concept of marking reader for visualization and identification of engraved marks in PALs. Light emitted by a diode laser is used to provide spherical divergent illumination in this ophthalmic instrument. The PAL is then manually placed in the proximity of the laser point source and when the engravings are properly positioned, they will provide a magnified diffraction pattern of the mark projected at a given distance. By placing a translucent screen, the magnified diffraction pattern of the mark can be visualized on it, thus allowing the user to identify and properly read the engraving. Experimental results are reported using different progressive addition lenses as well as two different laser diode wavelengths.

9529-57, Session PS

Low-cost digital holographic microscope using webcam sensor and laser pointer

Arun Anand, The Maharaja Sayajirao Univ. of Baroda (India); Prachi Shah, Sardar Vallabhbhai National Institute of Technology (India); Swapnil Mahajan, Vismay Trivedi, Vani K. Chhaniwal, The Maharaja Sayajirao Univ. of Baroda (India); Bahram Javidi, Univ. of Connecticut (United States)

Digital holography microscopy has been widely used to improve the contrast without labeling and also to gain information about the cell morphology. Digital holographic 3D microscopes are based on the principle of optical interference. The holograms/interference patterns are generated using a laser source and are recorded on digital sensors. These holograms are processed in computers to yield high contrast images of the cells as well as its thickness information.

Implementation of two-beam digital holographic microscopes is usually achieved by the use of high end laser sources, high quality optics and expensive charged coupled detectors (CCD). These make them expensive and bulky. Nowadays, cheap, off the shelf, small diode laser modules are available. Also low cost digital sensors, including webcams are widely obtainable. In the present study an effort is made towards the development of low cost, filed portable digital holographic microscope using low cost optics, laser pointers and webcams. In this paper we investigate different digital holographic microscope configurations, employing different sensors, and optics and laser sources. The setups were compared based on the SNR, three dimensional imaging capability, temporal stability and cost. From the obtained results it was observed that a digital holographic microscope using webcam and a laser pointer provides accurate reconstructions with spatial and temporal stability comparable to that of a digital holographic microscope implemented using a He-Ne laser and an expensive CCD sensor. The cost of the setup using the laser diode and webcam is very low compared to the one involving high end optics and sources. Also the setup becomes more compact, since the laser diode module could be integrated into the box containing the optics, making the form factor of the setup small. This makes the equipment field portable. The prototype of the microscope was tested on an array of micro-object including microspheres and red blood cells to asses it capabilities and was found to provide accurate 3D profile of the objects under investigation. As the digital holographic microscope has the potential to be a tool for label free automatic identification of micro-objects, a compact, low cost, field portable device will be a boost especially for disease diagnosis applications as well as for dynamic studies of micro-objects.

9529-58, Session PS

Design of rigid GRIN-endoscope with sapphire window and improved image quality

Grzegorz V. Fluder, Warsaw Univ. of Technology (Poland) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Anna Voznesenskaya, Alexey Bakholdin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

A lot of medical diagnostic and microsurgical procedures apply rigid endoscopic systems of different types. Results of such manipulations depend generally on quality of an endoscopic system. From the optical point of view it means that such a system should be diffraction-limited, with decreased off-axis aberrations. Miniaturization requirement makes the design of GRIN endoscopes protected by a sapphire window perspectiveGRIN lens has superior ability to reduce geometrical aberrations in comparison to ordinary lenses. However, in general case GRIN lenses with flat ends show unsatisfactory field curvature and coma which cause the extension of spots. Distortion should be less than 5%. This paper concentrates on ways to decrease significantly off-axis aberrations for an endoscope consisting of a GRIN lens (objective), relay system and eyepiece for visible range applications with field of view 250 and nominal working distance 125 mm. It is presented that GRIN lenses with spherical surfaces allow decreasing of off-axis aberrations and in consequence spot sizes. Influence of working distances on image quality is shown. Also we have proposed an optimum gradient profile and length of the GRIN lenses that provide excellent imaging qualities and large enough image size.

9529-59, Session PS

Novel design of a refractive index sensor based on a dual-core micro-structured optical fiber

George N. Tsigaridas, National Technical Univ. of Athens (Greece); Vassilis Karvouniaris, Peter Persephonis, Univ. of Patras (Greece); Alexander-Panagiotis A. Serafetinides, National Technical Univ. of Athens (Greece)

In the present work a new model of a refractive index (RI) sensor based on a dual core micro-structured fiber is presented. It is well known that in a dual core fiber coupling between the propagating modes in the two cores occurs, because of their interaction through their evanescent fields. This coupling can also be described using a pair of super-modes, a symmetric (even) and an anti-symmetric (odd) one [1-3]. However, a major disadvantage of these systems is that the core interaction is generally weak and consequently the dimensions of the sensor should be very small, in the micrometer scale. This causes several problems regarding the practical use of the sensor, especially regarding the filling of the fiber holes with the fluid under study. Therefore, a major modification is proposed, by introducing a hole in the center of the fiber cores. This way the mode profile is extended providing the opportunity to increase the dimensions of the fiber sensor

For studying in detail the behavior of this system as a refractive index sensor two useful parameters are introduced, namely the coupling length and the sensitivity. The first one is defined as the propagation distance where the optical power is completely transferred from one core to the other, given by the formula Lc=λ0/(2Δneff), where λ0 is the free space wavelength and Δneff is the difference between the effective refractive indices of the even and odd super-mode propagating in the dual core fiber. Obviously, the strength of the interaction is inversely proportional to the coupling length.

On the other hand, the sensitivity is defined either as the rate of change of the transferred mode power between the fiber cores with the refractive index of the liquids under study (dT21/dn), or as the rate of change of the wavelength for maximum transmittance with the refractive index of the liquids under study (dλmax/dn). The two different definitions of the sensitivity correspond to the two different ways that the system can be used as a refractive index sensor [1-2]. In the first scheme, the transmittance of the mode power through a selected fiber core is monitored as a function of the refractive index of the substance under study, while in the second one, the measured quantity is the wavelength for maximum transmittance through a selected fiber core. It is proven that in both cases the sensitivity is proportional to the quantity [d(Δneff)/dn]/Δneff, where Δneff is the difference between the effective refractive indices of the even and odd super-mode propagating in the dual core fiber.

The influence of the core separation and the diameter of the central hole on the coupling length and the sensitivity of the sensor is studied through numerical simulations. Three different models were studied with different values of the core separation, namely 2 Λ - one hole between the cores, 3 Λ - two holes between the cores, and 4 Λ - three holes between the cores, where Λ is the distance between adjacent holes. The results have shown that, when no hole is introduced at the center of the cores, the coupling length and the sensitivity also increase as the core separation increases. This is expected because as the core separation becomes larger the interaction between the modes propagating in the two cores of the fiber becomes weaker and consequently the refractive index difference Δneff reduces.

As mentioned previously, the introduction of the central holes enhances the core interaction, reducing the coupling length and the sensitivity of the system. However, in this case the dimensions of the system can be increased. indeed, the numerical simulations have shown that by proper selection of the central hole diameter, the dimensions of the sensor can be increased by a considerable factor, up to 10, providing values of the sensitivity similar to the case of the original sensor, without the central holes.

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9529-33, Session 8

Dynamic speckle interferometry of intracellular processes: theory and features of application

Alexander P. Vladimirov, Ural Federal Univ. (Russian Federation) and Research Institute of Virus Infections (Russian Federation)

At the present time speckle dynamics is used to study processes occurring in grains, fruits, for studying bloodstream features on the retina and extremities of patients. However, the logic of development of speckle optics and practical necessity have a goal to study the features of the speckles dynamics as a result of processes that occur within a single cell of alive systems. In particular, this problem arises in the development of a methodology and a device designed for the selection of the drug for the individual patient.

The purpose of the work was the link establishment between the parameters characterizing the change phase difference of the wave pairs, passing through the cell and the parameters of the dynamics of speckle. It was assumed that the change in wave phases is caused by microscopic and macroscopic processes in the cell.

Optical system is considered in theoretical part. It is consist of the source of coherent radiation, thin transparent diffuser, thin transparent biological object and thin lens which forms an image of the object. It is assumed that the diffuser consists of randomly located scattering point centers. Also, it is assumed that optical path length of single wave: a) changes with time t randomly due to the microscopic processes on the structure level, and b) is determined for the translational movement and shape change (deformation) of the thin object.

Expressions for the intensity I of the scattered radiation at some point in the image plane of the object at a fixed time and Î - by averaging for some time T are given. It is shown that the expression for Î contains the time-average value and the dispersion of the difference between the paths of waves pairs located in the vicinity of the conjugate point on the object. Situation when the random variation of the wave's phase's difference can be considered in terms of the interference of two speckle fields is analyzed. From the viewpoint of many waves interference, deterministic changes in the optical paths are analyzed. It is shown that the last two effects lead to a quasi-periodic change in the value Î.

An expression for the time autocorrelation function of the radiation intensity ?(t) at some point in the observation plane is given, the time spectrum of the radiation intensity is discussed. Function ?(t) type for stationary and non-stationary change in the path difference of the waves is discussed. The results obtained in theory from the viewpoint of their application possibilities for quantitative assessment of cell metabolism are analyzed. The examples of using this theory for the analysis of the processes occurring in the cells cultured in the absence and in the presence of the herpes virus are considered.

Typical experimental dependences Î(t) and ?(t) are shown. It is shown that a focused selection of averaging time T allows creating the conditions for obtaining reproducible results, highlighting and analyzing processes occurring in cells at different velocities.

9529-34, Session 8

In situ quantitation of collagen fibrils diameter using absolute measurements of second harmonic generation signals

Stéphane Bancelin, Ecole Polytechnique (France) and Ctr. National de la Recherche Scientifique (France) and INSERM (France); Carole Aimé, UPMC Sorbonne Univ. (France) and Ctr. National de la Recherche Scientifique (France); Ivan Gusachenko, Ecole Polytechnique (France) and Ctr. National de la Recherche Scientifique (France) and INSERM (France); Laura Kowalczuk, UPMC Sorbonne Univ. (France) and INSERM (France); Gaël Latour, Ecole Polytechnique (France) and Ctr. National

de la Recherche Scientifique (France) and INSERM (France); Thibaud Coradin, UPMC Sorbonne Univ. (France) and Univ. Pierre et Marie Curie (France) and Ctr. National de la Recherche Scientifique (France); Marie-Claire Schanne-Klein, Ecole Polytechnique (France) and Ctr. National de la Recherche Scientifique (France) and INSERM (France)

Type I collagen is a major structural protein in mammals. This biopolymer is synthesized as triple helix, which self-assembles into fibrils (diameter: 10-300 nm) and further forms various 3D organizations specific to each tissue. In recent years Second Harmonic Generation (SHG) microscopy has emerged as a powerful technique for the in situ investigation of the fibrillar collagen structures in matrices or tissues. However, as an optical technique with typically 300 nm lateral resolution, SHG microscopy cannot resolve most of the collagen fibrils. Moreover, in contrast to incoherent fluorescence signals that scales linearly with the chromophore concentration, SHG is a coherent multiphoton signal that scales quadratically with the density of collagen triple helices aligned in a parallel way in the focal volume. Consequently, quantitative SHG measurements have been limited so far to averaged phenomenological measurements [1].

In this study, we correlated SHG and transmission electron microscopies to determine the sensitivity of SHG microscopy and calibrate SHG signals as a function of the diameter of the collagen fibril [2]. To that end, we synthesized in vitro isolated fibrils with various diameters and successfully imaged the very same fibrils with both techniques. The smallest fibril observed in SHG images had a diameter of 30 nm. This value gives the sensitivity of our setup, and provides an order of magnitude of SHG sensitivity for any SHG setup, which was never reported so far. We observed that SHG signals scale as the fourth power of the fibril diameter, as expected from analytical and numerical calculations. It validated our quantitative bottom-up approach used to calculate the non-linear response at the fibrillar scale and demonstrated that the high sensitivity of SHG microscopy originates from the parallel alignment of triple helices within the fibrils and the subsequent constructive interference of SHG radiations.

As a proof of feasibility, we applied this SHG calibration to a diabetic rat cornea. Indeed, some hyperglycemia-induced collagen fibrils were recently evidenced in the Descemet's membrane of diabetic rats, while in control rats this membrane is mainly composed of nonfibrillar matrix that exhibits no SHG signal [3]. We successfully determined the diameter of these hyperglycemia-induced fibrils without having to resolve them. Averaged measurements of fibril diameter by TEM in ultrathin sections of the same region of the cornea validated these results.

Note that this calibration is not based on a super-resolution technique, so that it is limited to low-density matrices or tissues, where the distance between two fibrils is larger than the optical resolution, with only one fibril in the focal volume. Nevertheless, complementary approaches may be used to quantify dense collagen distributions in tissues or matrices, by combining numerical calculation and measurements sensitive to the collagen organization within the focal volume.

In conclusion, this study represents a major step for advanced biomedical studies that require in situ quantification of collagen fibrils in collagen matrices or tissues. It also demonstrates the unique sensitivity of SHG microscopy that detects fibrils with diameter as small as 30 nm within any labeling.

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9529-35, Session 8

Time domain diffuse optical spectroscopy: in-vivo quantification of collagen in breast tissue *(Keynote Presentation)*

Paola Taroni, Antonio Pifferi, Giovanna Quarto, Andrea Farina, Politecnico di Milano (Italy); Francesca Ieva, Università degli Studi (Italy); Anna Maria Paganoni, Politecnico di Milano (Italy); Francesca Abbate, Enrico Cassano, European Institute of Oncology (Italy); Rinaldo Cubeddu, Politecnico di Milano (Italy)

Time-resolved diffuse optical spectroscopy (TR-DOS) provides non-invasively the optical characterization of highly diffusive media, such as biological tissues. Short (<100 ps) light pulses are injected into the medium and the re-emitted pulses (either in reflectance or in transmittance geometry) are detected. The effects of light propagation (on pulse shape and time delay) are then interpreted with a suitable theoretical model, most often the diffusion approximation to the radiative transport theory, to simultaneously assess the absorption and reduced scattering coefficients of the medium. When measurements are performed at several wavelengths, information on the medium composition and structure can be derived applying the Beer law to the measured absorption and a simple empiric approximation to Mie theory to the reduced scattering.

Breast cancer is a leading cause of death in women. The cumulative false positive rate in breast screening is >30%, leading to frequent unnecessary biopsies with related patient morbidity and high costs for the health systems.

Breast density (i.e. fibrogladular tissue fraction) is a strong independent risk factor for breast cancer. Nowadays, it is estimated from mammographic images, implying the use of ionizing radiation. Its non-invasive assessment would allow the early identification of high-risk subjects that could undergo dedicated screening and preventive paths.

Collagen is involved in tumor onset and progression. Different collagen type and higher amount have been detected in breast cancer as compared to healthy tissue, suggesting that collagen could provide useful information for the discrimination between malignant and benign lesions. Collagen is also a major constituent of stromal tissue that determines breast density, and its optical assessment might provide a non-invasive measurement of breast density and related cancer risk. For its involvement in cancer development, collagen might also represent an independent risk factor.

Thus the absorption spectrum of collagen powder was preliminarily measured (600-1700 nm) using a unique portable set-up for TR-DOS, which relies on a super-continuum source, advanced detectors, and time-correlated single photon counting to assess the absorption and scattering properties of highly diffusive media that can hardly be characterized by conventional means.

A clinical study was then performed acquiring optical projection images at 7 wavelengths (635-1060 nm) in compressed breast geometry on 218 subjects, either healthy or bearing malignant or benign breast lesions.

For all subjects, tissue composition was estimated in terms of oxy- and deoxy-hemoglobin, water, lipids, and collagen. The scattering parameters were also assessed to provide information on tissue microscopic structure.

Good correlation was obtained between mammographic density (BIRADS categories) and an optical index based on collagen content and scattering power (that accounts mostly for tissue collagen). Moreover, subjects at high risk for developing breast cancer for their high breast density could be effectively identified fitting a logistic regression model to TR-DOS data. The best model turned out to depend only on collagen content and scattering parameters.

Finally, applying a perturbative approach, tissue composition was assessed in 46 malignant and 40 benign breast lesions, showing that collagen and hemoglobin content are significantly higher ($p<0.01$ and $p<0.04$, respectively) in malignant lesions than in benign ones.

9529-37, Session 9

FF-OCT as imaging tool for material, biochip- and microfluidic applications

Bettina Heise, Boris Buchroithner, Paul J. Wagner, Johannes Kepler Univ. Linz (Austria); Mario Kanka, Rainer Riesenberg, Alexej Grjasnow, Leibniz-Institut für Photonische Technologien e.V. (Germany); David Sifter, Johannes Kepler Univ. Linz (Austria)

Full field optical coherence tomography (FF-OCT) - similar to its close relative, optical coherence tomography (OCT) as a scanning version - has its origin in the field of medical and micro-biological optical imaging, developed some decades ago [1]. Supporting there medical diagnosis in particular in the field of ophthalmology [2] (FF)OCT became over the years also widely used for diagnostic tasks in other medical areas [3].

As a tendency observed during last years, the introduction and continuous transfer of these low-coherent interferometric imaging techniques, OCT and FFOCT, into the field of material sciences and inspection should be recalled [4, 5]. Here, these techniques have been applied e.g. for optical quality inspection of semi-transparent composites or layered materials containing structures at microscopic scale in the sub-surface region. Visualizing and characterizing delamination, inclusions, spatial distributions of fillers or defect structures should be named as examples. But also the application for in-line monitoring of technological processes in pharmacy, such as tablet coating should be mentioned [6].

Nowadays, the circle between material sciences and life sciences gets closed for imaging applications in the field of biomaterials or bio-chip components. (FF)OCT as an imaging tool suitable for evaluating the quality of bonded interfaces at mesoscopic scale, or visualizing internal defects therein, provides access to validate such micro-channel devices in a non-destructive way. Additionally, polarization-sensitive versions of FF-OCT provide information about optical anisotropies and birefringence [7]. These birefringent material properties may result from internal stress-strain fields in polymer-based micro-chip devices. They can be introduced during the manufacturing process; injection moulding or curing processes should be called as examples, which can cause such internal stress fields.

Recently, FF-OCT as well as digital in-line holographic microscopy (DIHM) [8] found entrance into the realm of microfluidics. Under the aspect of gaining depth-resolved information, also FF-OCT may act as a valuable tool providing insights about the flow field of micro particles injected and moving within the microfluidic channels. Furthermore, visualization and characterization of flow fields are not restricted to the particles themselves, but also the ‘flow’ occurring within a (scattering) polymer material, subjected to external loading, can be visualized by the (FF) OCT imaging techniques [9]. These techniques, realized in conventional and polarization-sensitive way, deliver hints about internal defects and fracture front propagation, as well.

In this contribution, we will show diverse applications coming from the field of material sciences, bio-materials, and bio-chip inspection. The FF-OCT technique demonstrates potential to be exploited for micro-fluidics applications in the future as well, extended by features derived from the field of DIHM.

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9529-38, Session 9

Full-field swept-source optical coherence tomography with phase-shifting techniques for skin cancer detection

Johann Krauter, Tobias Boettcher, Klaus Körner, Marc Gronle, Wolfgang Osten, Institut für Technische Optik (Germany); Nicolas Passilly, Luc Froehly, Stéphane Perrin, Christophe Gorecki, Institut FEMTO-ST (France)

The optical coherence tomography (OCT) is an optical measurement technique that has been developed for ophthalmological applications at first. However, in dermatology the default analysis technique of malign tissues is still the traditional biopsy, whose drawback is a long diagnosis time and its invasiveness. Recent, OCT systems are also emerging in the traditional field of dermatology and permit non-invasive 3D optical biopsies of skin. In the research project VIAMOS (Vertically Integrated Array-type Mirau-based OCT System) an approach for a new generation of sensor systems for the skin analysis is developed. MOEMS technologies enable a low-cost, miniaturized and hand-held OCT device. This concept combines swept-source OCT, full-field detection, phase-shifting interferometry and MOEMS technologies, providing 3D tomograms of the human skin from a volume of 8 x 8 x 0.5 mm? with an axial and transverse resolution of 6 μm. The key component of this system is a wafer stacked 4 x 4 array detector. Each measurement channel consists of an active Mirau interferometer with an oscillating reference mirror, which introduces an additional phase shift between the reference and object path.

This paper presents the study of the signal detection and evaluation of the VIAMOS OCT system. The algorithms are based on Fourier-domain OCT signal evaluation in combination with phase shifting algorithms. By using phase shifting techniques, the complex conjugate artifacts of the Fourier transform are strongly reduced. The OCT image becomes visible without DC-, Autocorrelation- and mirror image artifacts and the measurement range is doubled. Then it becomes possible to set the zero-path length at the center of the total measurement range, whose absolute size can therefore be doubled. Different algorithms are evaluated and compared.

A prototype OCT setup is developed in a laboratory environment based on the same design parameters as the final VIAMOS system. This reference setup uses a Linnik interferometer microscope with a swept-source, operating in the 850 nm range with a full-tuning range of 50 nm and a minimal linewidth of one single wavelength of 0.05 nm. In the illumination part, a multi-mode fiber is used for a field illumination. Due to the high spatial coherence of this light source, speckle noise will occur which obviously reduces the signal to noise ratio. Therefore means for speckle reduction are implemented in the illumination path of the interferometer. The Linnik interferometer uses two equal infinity-corrected microscope objective lenses, where the reference path is mounted together with a Piezo-driven actuator for phase shifting. A tube lens is implemented to image the object and reference path onto the camera. The performance of the phase shifting algorithms is compared with the suppression ratio of the complex conjugate artifact and the OCT system sensitivity. First experiments with biological samples are shown.

9529-39, Session 9

3D quantitative phase imaging techniques for the study of pathophysiology of cells and tissues *(Invited Paper)*

YongKeun Park, KAIST (Korea, Republic of)

Due to its strong correlation with the pathophysiology of many diseases, three dimensional refractive index distributions of individual biological cells and tissues can provide unique advantages for the study of various functions of cells and tissues and related diseases. Recent developments in quantitative phase microscopy techniques enables non-invasive and quantitative imaging of optical phase images of biological samples and three-dimensional refractive index distributions of the samples (1, 2). These three dimensional refractive index maps provides information about morphological, chemical, and mechanical properties at the

individual cell levels.

In this talk, we will discuss about the recent technical developments for measuring three dimensional refractive index distributions of individual biological cells and tissues. In particular, we will present a precise and sensitive optical holographic technique, referred to as Common-path diffraction optical tomography (cDOT) (3) and an optical technique which convert an existing optical microscopy into a quantitative phase microscopy by adding simple optical elements, referred to as Quantitative phase imaging unit (QPIU) (4, 5). We will also present the biomedical applications using the cDOT and QPIU. In particular, we will discuss (i) the quantitative three-dimensional refractive index imaging of human red blood cells and the correlation analysis of morphological, chemical, and mechanical properties of individual red blood cells (6), (ii) the pathophysiogy of mouse red blood cells infected by babesia parasites (7), and (iii) the non-invasive imaging of lipid droplets in hepatocytes. We envision the non-invasive investigation of biological cells using quantitative phase imaging techniques will be one of the important approach to unlocking the secrets of a number of diseases, as well as to opening up new possibilities for diagnosing diseases in their earlier stages.

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9529-40, Session 10

Raman spectroscopy in the diagnosis of acute leukemia

Stefano Managò, National Research Council (Italy); Anna Chiara De Luca, Carmen Valente, Consiglio Nazionale delle Ricerche (Italy); Peppino Mirabelli, Istituto di Ricerca Diagnostica e Nucleare (Italy)

Acute lymphoblastic leukemia (ALL) is a heterogeneous group of malignancies characterized by a proliferation of immature bone marrow-derived cells (leukemic cells). ALL presents varying clinical, morphologic, immunologic, and molecular characteristics. Many distinct types are known to carry predictable prognoses and warrant specific therapy. Therefore, a firm diagnosis of hematological malignancies requires the identification and classification of leukemic cells.

This is routinely achieved by morphological and immunophenotypic characterization of the cells sample from bone marrow or peripheral blood [1,2]. Anyway morphological approaches are, in some situations, of low sensitivity [3] and, it is currently impractical to perform a comprehensive, undirected molecular analysis of hematolymphoid malignancies owing to the myriad different genes involved [4].

Advanced photonic techniques may play a pivotal role in early leukemia detection and classification because they are non-invasive, offer single molecule detection sensitivity, and allow functional imaging at micro- or even nano-scale resolution. In terms of a label-free method, RS is more attractive than fluorescence because it provides specific biochemical cellular information and does not require any labeling. In Raman technology, a laser light of a certain wavelength shines on a sample, which causes molecules in the sample to vibrate and emit a Raman spectrum. From that spectrum, scientists can identify protein, lipid, and other chemical concentrations, as well as distinguish normal cells from cancerous ones [5,6].

In this work we demonstrate the use of Raman spectroscopy to identify normal B cells, collected from different healthy patients, and three ALL cell lines (RS4;11, REH and MN60). The cell lines RS4;11 and REH are two cellular model system derived from human immature B cell acute lymphoid leukemia and both models are classified as L2 in the FAB classification system. Conversely, the MN-60 cell line is more differentiated and, due to the surface expression of immunoglobulin and other B cell activation antigens, it is classified as FAB-L3. As all four cell types belong to the human B lymphoid lineage, they look very much alike. However, since they show different membrane protein expression and differentiation level they vary in their composition and therefore also in their Raman spectra. More precisely, we observed an increase in RNA and protein concentration and a decrease in cellular DNA concentration in leukemic compared to normal cells, due to an increase of transcription and replication and, consequently, de-condensation of the chromatin structure in cancer cells.

In order to quantify the capability of our system to sort leukemia/normal cells, we performed Principal Component Analysis (PCA) and a sorting accuracy of 97% for differentiating between three leukemia cell lines has been obtained.

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9529-41, Session 10

Spermatozoa quality assessment: a combined holographic and Raman microscopy approach

Annalisa De Angelis, Maria Antonietta Ferrara, National Council of Research (Italy); Giuseppe Di Caprio, The Rowland Institute at Harvard (United States); Stefano Managò, National Research Council (Italy); Luigi Sirleto, Giuseppe Coppola, Anna Chiara De Luca, National Council of Research (Italy)

Semen analysis is widely used as diagnostic tool for assessing male reproductive health, controlling and pre-selecting the progeny sex. The most important parameters measured in a semen analysis are the morphology and biochemical alterations, and the sex-sorting of the sperm. For obtaining such information, some non-invasive, label-free, non-destructive techniques have to be used. For this reason, the optical approach is deeply investigated.

In the morphological characterization studies, Digital Holography (DH) represents a powerful technique, allowing quantitative, non-invasive and fast morphological sperm cell analysis, also providing the advantage of directly observing spermatozoa in their native environment. When combined with Raman Spectroscopy (RS), a non-invasive and very specific technique, provides biochemical information of cellular component with a spatial resolution in the sub-micrometer range.

In this study, we used a DH-RS combined set-up for a complete morphological and biochemical characterization of single bovine spermatozoa.

High-resolution images of bovine sperm have been obtained by DH microscopy from the reconstruction of a single acquired hologram, highlighting in some cases morphological alterations. Quantitative 3D reconstructions of sperm head, both normal and anomalous, have been studied and an unexpected structure of the post-acrosomal region of the head has been highlighted. Such anomalies have been also confirmed by Raman image, suggesting the protein vibrations as associated Raman

marker of the defect.

Finally, the same set-up has been used to separate X and Y-chromosome-bearing sperm cells. DH imaging sex-assessment, entirely based on a possible difference in sperm head size and volume due to the size difference in X- and Y-chromosomes, does not allow the unequivocal identification of the two cell populations. On the other hand, the label-free identification of DNA content, plasma-membrane proteins or biochemical signatures achieved with RS allowed to non-invasively discriminate between X- and Y-chromosome-bearing sperm cells with a high accuracy (>90%).

9529-42, Session 10

Design and validation of a multimodal low-budget Raman microscope for liquid and solid phase applications

Hanna Koch, Kristina Noack, Stefan Will, Lehrstuhl für Technische Thermodynamik (Germany) and Erlangen Graduate School in Advanced Optical Technologies (Germany)

Confocal Raman microscopy is a powerful tool for analyzing small liquid sample volumes, solids, macromolecules or single cells. The great resolution of a microscope and the application of a pinhole for confocal measurements lead to an increase in the signal-to-noise ratio of Raman spectra. This is especially important for applications on a single cell level and for x-,y-,z-mapping of a sample. This method leads to the reception of detailed information about the sample. Nevertheless, to improve the flexibility and to reduce the costs compared with a commercial Raman microscope, we built up a low budget multimodal Raman microscope. This innovative set-up is characterized by higher signal intensities and flexibility due to a multimodal design of excitation and detection line. It is possible to select different excitation wavelengths and measure samples in the liquid and solid phase in different planes. For validation of the multimodal microscope we, first, compared the Raman spectra of our 785 nm-microscope line with those obtained by a commercial one. Here, we found, that by using the same laser power and similar objectives, the signal intensities are the same in both set-ups. Moreover, the signal intensities in the stretching region were improved by a factor of around 70 based on an optimization of the optical arrangement. Another important feature of our low budget multimodal Raman microscope is the increased flexibility. On the one hand, the set-up can be easily adapted to varying applications, since the set-up is multimodal and the optics are not fixed in place. On the other hand, by choosing different laser wavelength, the most suitable laser wavelength for the applications can be applied. For example, a laser with 785 nm for biological samples can be used, and one with a wavelength of 532 nm for measuring solids. Moreover, the laser power can be selectively regulated. Changing the orientation of our excitation pass enables us to adapt our microscope to the system under investigation. For example, for measurements with a cuvette, a horizontal (parallel) excitation path is preferred, while in cases of cells or microorganisms, a vertical, i.e., perpendicular arrangement may be favored. Furthermore, this set-up enables the mounting of different commercial or home-built objectives. This is especially important for increasing the working distance and focus the laser beam, for example, in big sample vessels. Finally, regarding different applications, especially for measurements on a single cell level, the installation of an optical tweezers can be included to keep one cell or particle in focus.

Summing up, our multimodal low-budget Raman microscope offers great advantages over commercial Raman microscopes and offers improved measurements due to fast application-oriented variations of the excitation and detection line and plane.

9529-43, Session 10

Multiscale mechanical characterization of biological materials *(Invited Paper)*

Luciano Lamberti, Politecnico di Bari (Italy)

The detailed knowledge of the constitutive behavior of materials is mandatory in all engineering applications. In fact, design procedures often include less or more severe safety factors and correction factors which assess to what extent materials can be "utilized" without incurring into catastrophic failures. The strength of the material hence is the most important parameter to characterize the load bearing capacity and the risk of failure. Mechanical tests can provide values of material properties in a "closed form" way if there are few unknown material parameters and the specimen is homogeneous and isotropic. In general, several independent testing protocols must be run independently and the corresponding results have to be processed on a statistical basis.

Mechanical characterization of biological materials is a very complex subject as these materials represent very special specimens. In fact, we try to characterize matter which by most part we do not know in terms of inner structure and constitutive behavior, usually characterized by a high level of non-linearity. Furthermore, biotissues require specially designed experimental set ups and testing protocols to gather realistic data.

Optical Techniques (OT) are well suited for mechanical characterization of biological materials because they provide high-resolution full-field data. This turns very useful both in the case of small specimens where it may be very difficult to find sensors able to be physically applied onto the object surface and in the case of large objects where it may be too expensive to place many sensors onto the specimen. Another important advantage is that the state of the surface and the inner structure of the material is not altered by the execution of experimental measurements. This is at least true at the macro/micro-level. Third, the quality of the signal from which displacement/strain information are extracted can be optimized with very little intervention of the analyst. The resolution of OT can be increased either optically and/or numerically: for instance, higher orders can be selected by properly masking the interfering wavefronts or/and super-resolution techniques can be utilized by processing signals at the sub-pixel level. Last, it is possible to perform measurements at different scales without losing accuracy by using non-conventional illumination.

There are several approaches to the mechanical characterization of biological materials:

1. "Closed form" property determination with standard tests;

2. Hybrid techniques at macro/micro/nanoscale;

3. OT-based analysis of "images" provided by other techniques.

The paper reviews some examples of mechanical characterization of biological materials carried out with the above mentioned approaches. Hard and soft biotissues as well as cell membranes will be considered. Special emphasis will be put on the discussion of hybrid methods where the displacement field experimentally measured is compared with numerical results. The difference between experimental data and numerical results is the error functional depending on the material properties to be determined. Global optimization is utilized to solve the highly non-linear and non-convex problem of the minimization of the error functional. The relationships between the degree of anisotropy of the material to be characterized and the nature of the numerical algorithms used for processing experimental data and extract material properties will be analyzed. The influence of the measurement scale on the reliability of the characterization process also will be analyzed. The global-local approach merging information gathered at different scales will be discussed. Finally, we will show the correspondence between OT and diagnostic tools used in medicine.

9529-44, Session 11

Microgels for multiplex and direct fluorescence detection *(Invited Paper)*

Filippo Causa, Univ. degli Studi di Napoli Federico II (Italy); Anna Aliberti, Angela Cusano, Edmondo Battista, Istituto Italiano di Tecnologia (Italy); Paolo A. Netti, Univ. degli Studi di Napoli Federico II (Italy)

Blood borne oligonucleotides fragments contain useful clinical information whose detection and monitoring represent the new frontier in liquid biopsy as they can transform the current diagnosis procedure. For instance, recent studies have identified a new class of circulating biomarkers such as s miRNAs, and demonstrated that changes in their concentration are closely associated with the development of cancer and other pathologies. However, direct detection of miRNAs in body fluids is particularly challenging and demands high sensitivity -concentration

range between atto to femtomolar- specificity, and multiplexing. Furthermore, cost effectiveness, simplicity of procedures for handling, workflow and reading must be carefully considered in a context of point-of-care testing for large screening.

Here we report on engineered multifunctional microgels and innovative probe design for a direct and multiplex detection of relevant clinical miRNAs in serum. Polyethyleneglycol-based microgels have a core-shell architecture with two spectrally encoded fluorescent dyes for multiplex analyses and are endowed with fluorescent probes for miRNA detection. Encoding and detection fluorescence signals are distinguishable by not overlapping emission spectra. Tuneable fluorescence probe conjugation and corresponding emission confinement on single microgel allows for enhanced target detection. Such suspension array has indeed high selectivity and sensitivity with a detection limit of 10-15 M and a dynamic range from 10-9 to 10-15 M, with higher accuracy than qRT-PCR.

We believe that sensitivity in the fM concentration range, signal background minimization, multiplexed capability and direct measurement in serum of such microgels will translate into diagnostic benefits if compared to other biosensing technologies such as direct microarray and qRT-PCR. The robustness, flexibility and versatility of microgel assay open up new roots toward liquid biopsy in the context of point-of-care testing through an easy and fast detection of sensitive diagnostic biomarkers directly in serum.

9529-45, Session 11

All optical indentation probe for endoscopic diagnosis of ostheoarthritis

Gabriele Marchi, Michael Jost, Albrecht Steinkopff, Hochschule für Angewandte Wissenschaften München (Germany); Carina Prein, Hochschule für angewandte Wissenschaften (Germany); Attila Aszodi, Ludwig-Maximilians-Univ. München (Germany); Hauke Clausen-Schaumann, Johannes Roths, Hochschule für Angewandte Wissenschaften München (Germany)

A novel kind of a miniaturized, all optical probe concept to measure the elasticity of biological tissues is presented. Possible applications are the diagnosis of arthrosis and its use in surgical treatment of degenerated cartilage. The probe is based on fibre Bragg grating sensor elements inscribed in an optical single mode optical fibre (SM28) using a 248nm Excimer laser in combination with a phase mask. The measurement procedure happens with a contact between tissue and fibre, exploiting the well-known strain sensitivity of the Bragg grating and using a low power infrared laser to interrogate the fibre sensor. Advantages of this approach are related to its small dimensions and flexibility, its immunity to electromagnetic fields, which make it apt to be used during magnetic resonance analysis, and the biological neutrality of the material. Details on the construction of a conceptual testbed and on the steps which have been done to optimize the design are given. Furthermore, studies on the reproducibility, reliability, and resolution of the sensor are presented. Silicone samples have been used as reference material for these studies because of their homogeneity and the possibility to produce samples which mimic closely the elastic modulus of the tissues under investigation. The problem of noise sources related to optical as well as thermal effects have been investigated and solutions are proposed. A first measurement on bovine cartilage tissue is reported. A linear elastic model of the cartilage has been used to analyse the data and the results indicate a good agreement with previous values given in the literature for micro indentation.

9529-46, Session 11

Differential self-mixing interferometry for micro-cantilever motion sensing

Francisco J. Azcona Guerrero, Ajit Jha, Carlos R. Yañez, Santiago Royo, Univ. Politècnica de Catalunya (Spain)

Force sensing is a common practice used for the characterization of matter physical properties and in particular of biomaterials. Typically, a force sensor is comprised by a mechanical mass spring element at which a force is exerted and an electronic transducer that acquires the deformation of the spring. By relating the spring's elastic constant with the sensed deformation, it is possible to retrieve the applied force and further relate it with a physical property. At micro and nano scales the same principle has been applied for the design of well-known scanning probe microscopy (SPM) techniques, in which a micrometric size cantilever is used as a spring mass element and the deflection at the cantilever tip is related to the measured force.

In order to measure cantilever deflection on micro force systems, different sensing techniques have been proposed. From these techniques, optically based sensing methods are often preferred since they allow measuring with high resolution while preventing the change of cantilever properties, such as the quality factor Q, and the natural resonance frequency λ0 caused by the mass increase of contact sensors.

Typically, two optical setups can be applied for cantilever deflection measurement: interferometry based setups and the optical lever method. In both cases, the system sensor requires a careful alignment of several elements in the setup increasing the cost and complexity of the sensor. In order to solve this problem, we propose the use of differential self-mixing interferometry (DSMI).

DSMI is an interferometric technique based on the principle of self-mixing interferometry (SMI). In SMI, the backscattered laser light from a moving target interferes with the light inside of the laser cavity causing small fluctuations in the laser optical power which, in appropriate feedback conditions (1< C<4.7) acquires saw-tooth form in which each transition corresponds to a λ/2 displacement where λ is the laser wavelength. Therefore, SMI sensors are characterized for having a simple setup consisting only of a laser diode and a focusing lens making them self-aligned, compact and cost effective. DSMI sensors inherit SMI characteristics while increasing the theoretical resolution to a level of λ/2000 and λ/200 for practical applications.

In order to test the DSMI sensor, a rectangular cross section cantilever was placed on a piezoelectric stage (PZT) PI-LISA with a maximum travel of 25?m which contains a capacitive sensor with a 2nm resolution. The obtained DSMI measurements are compared with the PZT sensor in order to test the feasibility of the method. A discussion of the potentials, limitations and future applications of the method is also presented.

9529-47, Session 11

Feasibility test of line sensors for optical tissue thickness estimation

Patrick Stueber, Tobias Wissel, Benjamin Wagner, Achim Schweikard, Floris Ernst, Univ. zu Lübeck (Germany)

To achieve the highest possible localisation accuracy during radiation therapy, optical tracking sys-tems have become more and more popular. Unfortunately currently available systems neglect both optical and physiological properties of human tissue. Therefore, accuracy in the submillimetre range is not yet achievable.

Previously, we have developed a marker-less and non-invasive optical localisation system for the cranium based on tissue-thickness labelled point clouds of the forehead. We designed a laser scan-ner setup working at 850nm for a point-grid projection on the forehead of a subject. Each point is triangulated and an HDR image is acquired. From these images we determine optical features in concentric regions-of-interest (ROIs) around the spot centre. By applying a machine learning algo-rithm and using high-resolution MRI scans as ground truth, we transform the optical features into a 1D tissue thickness estimation. The RMS error (RMSE) of this estimation can be used to evaluate the quality of the learning process. By combining the triangulated 3D point cloud and the 1D tissue thickness estimation, a 4D tissue-labelled point cloud of the forehead results.

Since the HDR camera (Andor Zyla) is limited in its speed and has an imperfect quantum efficiency in the near-infrared range, replacing this device is desirable. Line sensors provide one alternative approach. They are cheap, fast (up to multiple kHz readout rates) with excellent quantum efficien-cy in the near-infrared spectrum with high signal-to-noise ratio.

Based on data acquired from three volunteers (three scans for each of three head poses, 27 data sets), we simulated replacing the HDR camera by a line sensor: Since the size of commonly available line sensors vary, we performed the following experiment: From the HDR images stripes with a variable width ranging from 1 to 137 pixel rows were extracted corresponding to different line sen-sor widths ranging from 6.5 to 890.5μm. Pixels were accumulated in orthogonal direction to the simulated line sensor axis to form the equivalent of a single line sensor image. This single line image was partitioned into ROIs yielding characteristic features. Similar to the post-processing done previ-ously, a machine learning algorithm was trained on the data and the RMSE for tissue thickness es-timation was determined.

We found that the orientation of the extracted stripes relative to the longer semi-axis of the pro-jected laser spot has a strong influence on the RMSE. This is due to the majority of spot ellipses orientated into one predominant direction. This is typically entailed by a necessary subject pose within the scanning system. Lines extracted along the longer spot axis have a worse RMSE com-pared to lines oriented orthogonal to this direction. The influence of the incident angle of the laser on the spot is stronger in this first direction. Second, with increasing stripe width the RMSE de-creases because the algorithm has more information to train a model and noise is averaged out. In the worst case we found estimation errors of 0.4mm for the narrowest sensor. For the widest sen-sor we found an RMSE of 0.18mm. For comparison, the classical HDR-based circular ROI approach delivers an RMSE of 0.17mm.

Concluding, it can be seen that even though the RMSE is higher when using line sensors than when using area sensors, they can be used for optical tissue thickness estimations.

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9530-11, Session PS

New opportunities of pegmatites enrichment by optical sorting

Aleksandr N. Chertov, Elena V. Gorbunova, Artem A. Alekhin, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Lyubov S. Skamnitskaya, Tatiana P. Bubnova, Institute of Geology (Russian Federation)

Extraction of minerals from mica pegmatites for use them as a multipurpose raw material is possible with help of complex technology. It must provide obtaining the feldspars (microcline, plagioclase, quartz and muscovite) of a given quality in accordance with the requirements of consumers and with minimum loss of indicated mineral products.

Intensive development of radiometric sorting methods opens new opportunities for enrichment of mineral raw materials. Such methods are based on different physical phenomena occurring in the interaction of minerals and their constituent chemical elements with different types of radiation. In recent years, the mining industry began to use actively the optical (also called are digital or color) sorters. Their working principle is based on determining the color difference between the mineral components of original ore and following isolation of the useful fraction through a system of pneumatic valves.

However optical method is often ineffective in sorting ore characterized by the low color contrast of mineral components. At the same time, optical sorters are based on machine vision technologies. It means that their potentiality is much wider than analysis of only the color information about the object.

Group of authors studied pegmatites from the mines “Plotina” and “Khetolambino” that contains muscovite, biotite, microcline, plagioclase and quartz. The research aim was to define objective (measurable) differences in the optical characteristics of mentioned minerals which can be used to select them from initial mixture.

The studies were conducted by setting for color analysis of static objects at the Department of Optical-Electronic Devices and Systems (ITMO University). Color analysis was performed using a modified HLS color system.

The analysis of color parameters of representative ores sample allowed to establish following:

- Microcline can be identified in the total mixture by the value of the H channel;

- A pair of “quartz and plagioclase” can be identified in the total mixture by the value of the L channel;

- For separating a mixture of muscovite and biotite from the total mixture you can use the summation of the H and S channels;

- Quartz and plagioclase are not distinguishable from each other by color.

As a result of performed studies the new algorithm for quartz and plagioclase separation was proposed. It’s based on these minerals differences of the degree of transparency and of the internal and surface structure.

Also the 3-step enrichment scheme of initial feldspar mixture was proposed.

9530-14, Session PS

Modeling and analysis of the two-dimensional polystyrene aggregation process

Krzysztof Skorupski, Wroclaw Univ. of Technology (Poland); Imre Horvath, Maria Vetrano, Von Karman Institute (Belgium)

Small particles tend to aggregate and create large fractal-like structures which can be analyzed using microscopy techniques. However, images obtained this way are very difficult to process manually. Mostly because of the fact that even a few thousands particles might be present on a single image. In this work we present an algorithm capable of measuring the basic morphological parameters of two-dimensional polystyrene layers, i.e. the number of aggregates, their size and their fractal dimension. Our study consisted of two separate parts. The first one was to create polystyrene particle monolayers. Their purpose was to allow for monitoring of the two-dimensional aggregation process by means of optical microscopy. The liquid phase consisted of a 1.5mm water film containing 1M NaCl. In our study 1?m polystyrene particles, which represent the smallest resolved particle size by the available optical microscope, were used. They were initially dispersed in water and stabilized by electrostatic repulsive forces. The particle monolayer was created using a spreading technique. The initial particle suspension was diluted in a 20% aqueous ethanol solution. Then, a spray of fine droplets was created. The particles impacted the water-air interface with a low vertical velocity. Upon impact the suspension droplets spread quickly on the water-air interface due to the low interfacial tension between ethanol and water. The particles, initially enclosed in the suspension droplets, remained trapped on the water-air interface, which is assumed to be the most energetically favorable position. The resulting two-dimensional particle layer was stable for ca. 10 minutes. Afterwards, small clusters started to form leading finally to an almost continuous particle network. In the next step of our study the microscopy images were analyzed in more detail. To remove artifacts caused by measurement conditions the background pattern, based on fifteen randomly selected images, was generated. Its features were removed from every other element of the investigated image set and the noise was reduced using standard morphological operations. Next, shapes smaller than a single particle were excluded. Finally, the size distribution function and the total number of particles were calculated. When a structure was larger than a specified size its fractal dimension was approximated using the box-counting technique. After retrieving the morphological parameters models for different stages of the polystyrene aggregation process were created using the most common tunable algorithms, including: DLA (Diffusion Limited Aggregation) and RLA (Reaction Limited Aggregation). Our study proved that real structures resemble to models created with Cluster-Cluster aggregation techniques. Initial clusters, i.e. those generated during early stages of the aggregation process, are characterized by a relatively large fractal dimension. However, its value decreases along with the aggregation time and finally reaches values estimated for the DLA (Diffusion Limited Aggregation) process. The next step is to improve our algorithm even further and use it in a fully automatic on-line monitoring process. Generated fractal-like aggregate models will be used in light extinction simulations what will hopefully results in an aggregation monitoring technique based on the optical properties of investigated polystyrene monolayers.

9530-19, Session PS

Fast interframe transformation with local binary patterns

Boris V. Vishnyakov, Vladimir S. Gorbatsevich, Sergey V. Sidyakin, GosNIIAS (Russian Federation)

In this paper, we propose the solution to a problem of transformation calculation of two consecutive frames taken from image sequence. The described approach is applicable both to the image stabilization problem in video surveillance systems and to the image stitching problem in the field of aerial photography. Stabilization of an image sequence obtained from various video optical sensors, as well as stitching of a set of images are important tasks of computer vision. The main requirement of the

image sequence stabilization algorithm in surveillance systems is speed, because usually dozens of channels must be processed in parallel. Linear camera motion model is often unacceptable when perspective distortions arise, so we have to consider affine or projective transformations for both stabilization and stitching tasks.

The proposed algorithm belongs to a group of algorithms based on search and comparison of the feature points. We use found feature point pairs for calculation of an affine or projective transformation matrix of the first image to the second one.

At the first step of the algorithm, we use a modified version of DoG (Difference of Gaussians) algorithm [1]. We try to find feature points that are stable to scale change, calculating them for various values of the Gaussian mixture variance. Found feature points are local maxima of the DoG detector response (absolute difference of two convolutions). We also apply recurrent filters [2] for fast image convolution calculation. We select filter coefficients empirically to minimize the mean square error between the recurrent filter impulse response function and the approximated Gaussian function. Proposed approach provides a quick search of feature points, while the stability of these feature points is almost identical to the stability of the points found by the direct method of the convolution calculation.

At the second step, we calculate descriptors with various radii to make them less sensitive to affine transformations. We consider only best feature points in some neighborhood to increase reliability and decrease computation speed. We decided to operate with simple descriptors of feature points, for example, LBP (local binary patterns) with various radii, considering that shooting conditions between consecutive frames change slightly.

At the last step we determine the affine transformation parameters using modified RANSAC [3] algorithm. We use a combination of the Hamming distance (between binary codes) and the difference between the DoG feature point responses for the feature points matching.

The described approach is computationally efficient (over 150 fps) and can be used in difficult shooting conditions (camera noise, low visibility) for arbitrary camera movement (jitter, shift, rotation, scale change).

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9530-20, Session PS

The algorithm for generation of panoramic images for omnidirectional cameras

Vasiliy P. Lazarenko, Sergey N. Yarishev, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The omnidirectional cameras are used in areas where large field-of-view is important. Omnidirectional cameras can give a complete view of 360° along one of direction. But the distortion of omnidirectional cameras is great, which makes omnidirectional image unreadable. In our previous work we focused on creation of distortion-free perspective images from omnidirectional images. Another way to view omnidirectional images in a readable form is the generation of panoramic images.

Generally a panorama is an image depicting a wide angle view. Panoramas can be described as projections onto cylinders, spheres, cubes, or other surfaces that surround a viewing point. In practice, the most commonly used cylindrical, spherical and cubic panoramas.

The algorithm for creating panoramas from omnidirectional images consists of several steps. First we describe panoramas field-of-view by creating virtual surface (cylinder, sphere or cube) from matrix of 3d points in virtual object space. Then we find coordinates of image points for those 3d points on omnidirectional image by using projection function. At the last step we generate panorama pixel-by-pixel image from original omnidirectional image by getting of color information of corresponding pixels.

In order to find the projection function of omnidirectional camera we used the calibration procedure, developed by Davide Scaramuzza. Omnidirectional Camera Calibration Toolbox for Matlab allows the user (also inexpert users) to calibrate any central omnidirectional camera. After the calibration, the toolbox provides two functions which express the relation between a given pixel point and its projection onto the unit sphere.

9530-21, Session PS

Automatic online laser resonator alignment based on machine vision: analysis

Lizhi Dong, Wenjin Liu, Ping Yang, Shuang Wang, Xing He, Bing Xu, Institute of Optics and Electronics (China)

Misalignment of a laser resonator would increase the diffraction loss, leading to degraded output power and beam quality. Under very poor alignment conditions, there will be no laser output at all. In order to maintain sufficient performance of laser systems, it is very important to guarantee proper alignment of laser resonators. Although laser resonators could be finely adjusted to achieve high precision alignment before operation, misalignment of resonator mirrors is still inevitable in operation for many reasons, for example, temperature fluctuations, shocks and vibrations of the environment, and the heat from pumping sources of lasers. Therefore many applications require online automatic alignment of laser resonators. The key of automatically aligning a laser resonator is how to detect misalignment. Existing methods generally introduce reference beams into laser resonators with some auxiliary mirrors and equipment. However, these mirrors must be removed before laser operations, thus it is not practical to automatically online align laser resonators with these methods. In this paper we present online laser resonator alignment based on machine vision. In this method, a camera is placed behind the rear mirror of the laser resonator to detect the displacement of the laser beam spot on the rear mirror from a predefined reference point. When the resonator mirrors tilt, the laser beam spot location on the rear mirror will also change. We use the displacement of this spot to indicate the misalignment of the cavity mirrors, and the resonator could be automatically aligned using the displacement as feedback. No reference beam or auxiliary mirrors are required, thus this method could conveniently online align the resonator when the laser is operating. We first give a detailed analysis of the relation between tilt of resonator mirrors and the beam spot location on the rear mirror. This analysis is implemented by calculating the transverse modes of resonators with a two-dimensional matrix method, so that the intensity distributions and locations of the beam spot on the rear mirror could be figured out. Three different types of resonators are analyzed, including a plane-parallel resonator running with multiple modes, a resonator designed to operate with a single high-order mode, and an unstable resonator intended for TEM00 mode. Calculation results show that the displacement of the beam spot on the rear mirror continuously grows with misalignment of the resonator mirrors under all the three conditions, indicating that the displacement can effectively denote resonator misalignment. As the intensity distribution of the spot on the rear mirror with a misaligned resonator is quite different from conventional Gaussian distribution, we also analyzed the accuracy of several methods to calculate the location of the beam spot for the three types of resonators, including first moment, convolution, weighted first moment and adaptive threshold, and determined the most appropriate method for each case. Finally an experimental system with an Nd: YAG laser and a plane-parallel resonator is built. Experimental results show that the presented method is effective.

9530-22, Session PS

Control system of warehouse robots' position

Ivan Maruev, Eugene G Lebedko, Anton V Nikulin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Currently robotic systems are widely used in such fields as conveyor sortation, automated inspection in industrial production, measurement and control applications and other fields. In all the applications it is necessary to control spatial position of the robotic systems. The task could be rather sophisticated in the case of mobile robots, which parts are permanently moving in 3D space. Precise control of robotic systems position can be implemented by different methods developed for automated inspection of moving objects.

The purpose of this work is to develop a setup for spatial position control of robotic vehicles based on machine vision system.

Setup is a table 800 ? 2000 mm with the layout of vehicle is the carrier of objects of observation (LEDs). The layout of the vehicle on the platform Rover 5 Chaises was developed for monitoring the position of the robot. On the vehicle the reference mark was fixed. The mark consists of four LEDs. Configuration of LEDs were represented as vertices of a cube.

To determine a structure of the system different mathematical methods for extractions of inspected objects' coordinates from images were considered and the most robust and accurate method was determined. It was shown that accurate 3D measurement is possible when just one camera is used in conjunction with cubic LED reference mark. To implement acquisition setup different parameters of optics (focal length, aperture and field angle), illumination (spectral characteristics and intensity of LEDs) and size of cubic reference mark were calculated. For covering of blind zones of the setup, two cameras were used.

A circuit diagram of an infrared transmitter for control the setup, was developed.

3D model of the setup was developed, for immobility for improve the precision of the setup.

The results of complex software development are:

-provision of moving the reference mark in the space (pattern recognition in clutter environment + 3D spatial position control);

- control software setup;

Results of monitoring showed, that errors not exceeding 2-3 mm at the distance up to 2 m.

The calculations of the distance to influence value of the measured object, as well as the actual values of the focal lengths of the system to determine the error of the spatial coordinates of the object.

Increase of the precision of the setup can be provided by calibration and camera settings, but in this work this problem is not considered.

9530-23, Session PS

A novel regularization method for optical flow-based head pose estimation

Sebastian Vater, Guillermo Mann, Fernando Puente León, Karlsruher Institut für Technologie (Germany)

Three dimensional head pose estimation is an important component in human-machine interaction and visual surveillance. As a tracking algorithm or a preprocessing step, head pose estimation has many applications in machine vision, such as face detection, face recognition, facial expression analysis, image registration or gaze estimation. Head pose estimation is often achieved by using expensive, bulky or limiting hardware like head-mounted devices or infrared light sources. Here an approach that utilizes simple, off-the-shelf hardware like webcams is presented to process data obtained from video sequences to make head pose estimation widely applicable. In this context, image alignment techniques play an essential role. A method often used for image alignment and computation of optical flow is the Lucas-Kanade algorithm. In this article, the forward compositional algorithm based on the Lucas-Kanade algorithm is employed for optical flow calculation to estimate 3D head pose in low-resolution videos. The goal is to recover full motion from 2D image data while achieving real-time performance. We estimate the full head motion consisting of six degrees of freedom using a cylindrical head model. To improve the robustness and the accuracy of existing methods, we present a novel regularization approach for image alignment utilizing the Lucas-Kanade algorithm. To solve the non-linear optimization problem stated by the Lucas-Kanade equations a Gau{ss}-Newton approximation of the Hessian matrix is performed. Here the critical part of the calculation of the optical flow is the estimation of the inverse of the Hessian. Ambiguities due to the aperture problem as well as regions of small image gradients lead to an ill-conditioned Hessian. Singularities cause numerical problems when computing the inverse. To compensate for the high condition number as a result of the ill-conditioned matrix, a second order regularization term is proposed in the literature to limit the optical flow. However, previous approaches that regularize the Hessian matrix by weighting the regularization term in an iterative process do not utilize any knowledge about the actual state of the system when applying the weighting factor. To better link the system state to the regularization, we present an adaptive integration of the actual pose parameter into the scaling term providing direct coupling of the rigid motion parameters to the motion estimation itself. The new regulatory term, being dependent on the pose parameters, yields a suitable conditioning of the Hessian according to the actual change in pose by affecting translation and rotation separately, improving the parameter estimation. This leads to a robust algorithm allowing for noise and disturbances of the pose parameters. Experiments are conducted on the Boston University head pose dataset allowing for extreme poses and are compared to results of other researchers. Using well-defined parameters for the regulatory term, the proposed method outperforms existing methods in head-tracking scenarios.

9530-24, Session PS

Accurate invariant pattern recognition for perspective camera model

Mariya G. Serikova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Ekaterina N. Pantyushina, ITMO University (Russian Federation); Vadim V. Zyuzin, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Joel J. P. C. Rodrigues, Instituto de Telecomunicações (Portugal) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Pattern recognition remains important problem for machine vision application. Well known fact is that accuracy of object inspection strongly depends on accurate results of pattern recognition and estimation of its position on a sensor. Only accurate image processing techniques can give robust results on control an object position. But image perspective deformation can significantly reduce recognition performance of known techniques. Another great problem for automated inspection by machine vision systems is that frequently this process is performed in motion and illumination is not enough. These lead to significant noise and blur problems, which can lead to mistakes both in pattern detection and its position estimation.

In this work we compare performance of different pattern recognition methods (geometry, correlation and moment computing) in the case when noise, motion blur and perspective deformation are significant. The comparison addresses statistics of detection, accuracy estimation of pattern position on a sensor and algorithms' performance.

We implemented comparison of algorithms on simulated images with predictable deformations both in object and image domains (noise level, blur behavior, scale, linear displacement and rotation around different axes). For estimation of pattern detection quality we performed image simulation process with random size, intensity and spatial frequency of background clutter. For estimation of accuracy of pattern position we added both translational and rotational deformations in given pattern position.

Obtained results were experimentally examined by tests at a developed setup. The setup included a camera and a flat pattern, which orientation

varied both by angle (~30 degrees in every direction) and linear shifts (120x120x5000 mm). False match probability, standard deviation of position measurement and static characteristic linearity were used as criteria of quality estimation.

Implemented analysis showed that the most preferred strategy both from effectiveness of estimation and calculation speed is combination of different algorithms. Thus the most correct and fast results on the detection stage were archived by applying moment functions, which gave reliable recognition (detection probability is over 0,98) even when noise level is high (SNR no less than 7), motion blur presents (up to 10 pix at object's image size of 40 pix) and image has strong perspective deformation. In addition, algorithm performance is also impressive in the case of moment functions. Pattern position estimation can be calculated more accurate (accuracy up to 0.01 pix) by geometrical features. But development of measurement metrics in this case was a challenge when perspective camera is considered. Based on the achieved results we give practical recommendations on how to construct reliable invariant measurement metrics for different projective transformations and configurations of measurement system.

Furthermore, we propose development techniques for reference marks to be used in machine vision applications. We suggest splitting of detection and metrology features and show different approaches on how to make this features work better for corresponding algorithms. Those approaches are supported by analytical and experimental results.

9530-25, Session PS

Stereo sequences analysis for dynamic scene understanding in a driver assistance system

Boris V. Vishnyakov, Yury V. Vizilter, Vladimir A. Knyaz, Ivan K. Malin, Oleg V Vygolov, Sergey Y. Zheltov, GosNIIAS (Russian Federation)

Stereo vision seems to be extremely attractive for Driver Assistance Systems (DAS) applications due to possibility of robust and accurate 3D road modelling, obstacle detection and distance measurement. In this paper, we describe the improved scene understanding approach based on a combination of photogrammetric 3D scene analysis and computer vision tools for vehicle detection.

The input hardware of DAS system consists of two calibrated video cameras located on the windshield of the vehicle. The procedure of obstacles and objects detection consists of the following steps:

- Stereo system calibration (once at setting up)
- Road lane detection
- Road 3D model generation
- Photogrammetric obstacle detection
- Machine learning-based objects detection
- Object tracking

The proposed method of system calibration does not require 3D test field with high accuracy of reference points coordinates. The basic requirements to the test field is its planar surface and knowing of distances between some reference points with given accuracy. The result of the calibration procedure is an estimation of unknown parameters, including camera principal point, scales in x and y directions, the radial symmetric and decentering distortion.

The algorithm of road lane detection consists of three steps. The first step is preliminary lane marking segments detection. This procedure is based on statistical analysis of the image row intensity projections. A lane marking segment has a significant positive intensity contrast with the background and a sharp edge. At the second step, we perform monocular road marking lines detection, using a modified Hough transformation algorithm [1]. The third step is a procedure for stereo tracing of marking lines. A pair of left and right monocular lane marking lineaments forms a hypothesis about the 3D line segment (lineament). For all possible lineament pairs from different images we test the conditions on 3D line segment direction and height above zero plane. Lineament pairs, which satisfy these conditions, are put to the stereo lineament list. We perform this procedure iteratively in a sequence of searching zones at a number of distances from a vehicle. Such systematic stereo tracing of marking lines allows detecting the extremely curved and sloped lanes.

The road surface is represented by a four-parametric model, selected as a compromise between small number of reliably estimated parameters and flexibility in representation of lengthwise and lateral character of the road, particularly for highways.

For photogrammetric obstacles detection we use orthophotos obtained from left and right images of the stereo pair. Due to the properties of orthophoto the calculation of the difference of orthogonal projections results in appearance of characteristic geometric structures in the neighborhoods of 3D-objects that do not belong to the given surface. Thus, the problem of 3D-obstacle detection reduces to the problem of 2D corner-shaped structures detection. There is a computationally efficient algorithm for detection of such structures proposed in [2] based on orthophoto transformation in polar coordinate system (radial orthophoto). The occluded regions of the road in the radial orthophotos have a rectangular shape with vertical edges that can be easily detected using 1d search on the vertical projection of the image intensity first derivative.

To detect objects of known classes (vehicles and pedestrians) we use histograms of oriented gradients [3] as an image descriptor and SVM as the sliding window classifier. In the workflow of total scene analysis algorithm the object detection for each frame is performed just in the small region around the obstacle that was detected by the photogrammetric method. Photogrammetric detection algorithm allows computing an approximate distance to the obstacle, so for computational efficiency we can select a limited number of image pyramid levels to perform a search on. For more precise estimate of the distance, we find SIFT feature points [4] of the object both on left and right images, match them and perform a photogrammetric resection.

In addition, we publish the labeled dataset of selected road and car stereo sequences acquired by our vehicle-based laboratory – CSS Dataset (Car Stereo Sequences Dataset).

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9530-26, Session PS

Image restoration using aberration taken by a Hartmann wavefront sensor on extended object, towards real-time deconvolution

Ahmad Darudi, Hadi Bakhshi, Reza Asgari, Univ. of Zanjan (Iran, Islamic Republic of)

In imaging systems like telescope and microscopes a high image quality is desire and potentially a post processing image restoration method, for instance deconvolution, may improves the image quality. The main limitation is the high computational time required that is limiting its applications. However simple deconvolution algorithms are fast but typically yield poor results. In this paper, we are reporting the result of experimental and theoretical results that is used to select an optimized size for PSF and distorted image. The desire signal to noise on restored image is also an important factor on selecting a right deconvolution algorithm. The experimental setup consists of following components; a Hartmann pattern of 40?40 aperture on a CMOS chip of 1024?1280 pixels is the base of our Hartmann sensor (HS) which is operating at 50fps. And wavefront gradient is measured from the image motions of an extended object at each sub-apertures. The extended object of 30 arc minute in diameter is simulated by another optical system and a rotating glass plate in the light path distort the image in real time. The imaging lens is a doublet of 100mm in diameter and 500mm focal length. A beam splitter

reflect portion of the light toward a CCD camera and pass the rest to the HS for recording the distorted image of the object and measuring the aberration, respectively. Then Point Spread Function (PSF) of the system is simulated from the measured aberration and is deconvolved from corresponding distorted image. The total time of the image restoration process is affected mainly by the deconvolution algorithm which is also depends on the size of the matrix of the image and simulated PSF. Several deconvolution methods are investigated and compared for getting reliable and fast solution.

9530-27, Session PS

A FragTrack algorithm enhancement for total occlusion management in visual object tracking

Francesco Adamo, Pier L. Mazzeo, Paolo Spagnolo, Cosimo Distante, Consiglio Nazionale delle Ricerche (Italy)

In recent years, the framework called “FragTrack” [1], has been one of the most cited real–time algorithms for visual tracking of an object in a video sequence. In this framework, the target object is divided into several parts, called fragments or patches, which are determined in arbitrary way and not based on a model, as it happens in other tracking algorithms. Every patch of the template is compared, in term of histogram distance, with the corresponding patch of the object identified in the current frame. All these comparisons are inserted into a map of the votes to determine the location of the minimum and then the position of the target object on the current frame.

This algorithm fails when the object model is not present in the current frame or it is completely covered by other larger objects (such as trees, bridges, ...) and when the video sequence is not short. In the second case, the target object appearance is considerably modified during the execution of the sequence and then it is difficult to compare it with the template established in the first frame.

In this work we introduce improvements to the algorithm as the management of total occlusions of the object and the update of the target object template. We use a voting map generated by a non-parametric kernel density estimation strategy, that allows to determine a probability distribution for the set of data, represented by the distances of the histograms between template patches and object patches in the frame, without the need to make assumptions on the distribution form itself. The location of the object in the current frame is determined by the maximum in the voting map.

In order to automatically determine whether the target object is present or not in the current frame, an adaptive threshold is introduced. A Bayesian classifier (two classes and multivariate distributions) establishes, frame by frame, if the values, identified on the voting map, represent the template object in the current frame. The template is partially updated at every frame, through substitutions, for some patches, of the original histogram with the histogram of the corresponding patch in the current image [2].

We tested the algorithm on well known benchmark sequences, in which the object is always present in every frame, and on video sequences showing total occlusion of the target object to demonstrate the effectiveness of the proposed method.

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9530-1, Session 1

Camera series and parallel networks for deformation measurements of large scale structures *(Invited Paper)*

Qifeng Yu, Yang Shang, Bang lei Guan, Zhi hui Lei, Xiao lin Liu, National Univ. of Defense Technology (China)

No Abstract Available

9530-2, Session 1

Extending critical dimension measurement for optical microlithography with robust SEM image contours

Francois Weisbuch, GLOBALFOUNDRIES Dresden Module Two, GmbH & Co. KG (Germany)

Semiconductor micro-fabrication involves the patterning of structures whose critical dimensions are typically inspected with Scanning Electron Microscope (SEM) and measured by thresholding of high resolution top down greyscale images. Specific image processing algorithms are used to detect the edges of the structures and generate useful contours (see Fig 1). The challenge is to extract only the relevant information from the image with the best possible precision. For advanced microlithography patterning, one has to characterize structures printed inside a photoresist (see Fig.1a) which is a polymer very sensitive to electron beam and can shrink during the SEM image acquisition introducing a bias to the measurement. For this reason, low electron doses are used to minimize these side effects but consequently create very noisy images. Processing SEM images is a difficult task not only because of the poor image contrast and the noise responsible for high uncertainty in the recorded contours but also because of the complexity of the shapes to analyze. The challenge is to be able to generate high quality contour from single or sequence of images without suffering too much from rough contours or even improper edge detection (see Fig. 2b).

Getting high quality image contours is very important because many applications depend on the accuracy of critical dimension measurement. In line production control requires reliable measurement as well as specific tasks like process “hot-spot” characterization, lithographic Optical Proximity Correction (OPC) model calibration or process matching. The usage of contours has many advantages because they capture the most information from an image. As a consequence complex, 2D features can be fully characterized and inspection time is optimized.

Our approach is to develop specific methods to improve the quality of the contours extracted from the SEM images. A first possibility is to reduce the contour roughness by using a specific smoothing algorithm as illustrated in Fig.1 c,d. This works well to remove high frequency errors but cannot solve significant edge detection errors as shown Fig. 2b. The solution for edge detection errors is to acquire sequence of images and merge the corresponding contours in an appropriate way to perform a robust averaging almost insensitive to any outlier (see Fig. 2c).

The method has been successfully implemented to get reliable contours of complex and noisy SEM images containing critical structures of around 50nm width. The quality of any average contour can be assessed by computing the measurement error along it. In addition, it’s also possible to compare each average contour with a reference one generated by photolithography simulation. As a matter of fact, photolithography simulations can predict with high accuracy the shape of contours printed in the photoresist. We demonstrate that the information supplied by valuable contours can be efficiently exploited to generate statistics about the dimension variation of a given structure measured at different locations on the wafer or characterized at different process conditions.

9530-3, Session 1

Towards one trillion positions

Tobias Haist, Marc Gronle, Duc Anh Bui, Bofan Jiang, Christof Pruss, Frederik Schaal, Wolfgang Osten, Institut für Technische Optik (Germany)

The detection of position is of considerable importance for a lot of optical measurement techniques. Examples are triangulation, 2D image processing, Shack-Hartmann sensing. Position sensing diodes/devices are easy to control but cannot deliver high accuracies.

Interferometric systems, e.g. Laser tracers, are complex, expensive and typically not fast enough. Two dimensional image sensors (CCD or CMOS) are most often employed but are limited to accuracies (1 sigma) in the range of 1/10 to 1/100-th of a pixel. In addition, for high accuracies, the requirements for the optical system and the calibration are high.

We propose a non-expensive system that is able to measure 3D position and orientation of a small head in a measurement/fabrication machine with high speed (> 500 Hz) over a large volume (300 x 300 x 50 mm) with very high accuracy. Two 2D sensors will be used perpendicular to each other, measuring the exact positions of several LEDs mounted on the head.

In this contribution we concentrate on the 2D sensor. For the challenging measurement uncertainty (below 1 micron), telecentricity is required but leads normally to very expensive optics. The optical design has to achieve low distortion in combination with good telecentricity and sufficient imaging quality over a large field (300 mm). Conventional designs using large glass optics, therefore are very demanding. We circumvent these problems by using a large, thin diffractive optical front element in combination with two small standard off-the-shelf achromats.

Distortion and telecentricity optimization as well as PSF-optimization can be incorporated into the DOE and, therefore, a simple three-element telecentric objective lens can be realized.

In principle, the fabrication of the DOE can be made quite cheap if replication techniques are used.

Of course, the application of the optics is limited to quasi-monochromatic operation (LED). Due to fabrication errors there are also unwanted (defocused) diffraction orders present which lead to a loss of contrast. Still, for the envisioned sensing applications this is tolerable. The presented telecentric DOE-system might be also used for other measurement applications in industrial image processing.

Apart from the imaging, of course, the position detection is the main crucial point for achieving small measurement uncertainties for the position and orientation detection. We improve on the state of art by a simple idea, already presented in [1,2]: Before a spot is detected by the image sensor it is replicated N-times, currently using a binary computer-generated hologram. By this approach discretization errors and camera noise is reduced by a factor of sqrt(N) and position measurement uncertainties (1 sigma) in the range of 1/1000 of a pixel can be achieved on a cheap CCD sensor. For the 2D case we hope that the final system - including calibration - can measure more than one trillion (10^12) positions on one standard CCD.

The high speed operation of the system will be achieved using partial scan readout of the CCD.

We describe the system, present an extensive error modell and show experimental results for the DOE-based telecentric imaging and the position detection sensing.

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9530-4, Session 1

Application of a reflectance model to the sensor planning system

Tomá? Kouteck?, David Palou?ek, Jan Brandejs, Brno Univ. of Technology (Czech Republic)

This study describes a new sensor planning system for the automatic generation of scanning positions based on a computer model of the part for digitization of sheet metal parts. The focus of this paper is in the application of a reflectance model into this sensor planning system.

Manufacture and related inspection of sheet metal parts are closely connected to the automotive industry. Based on increasing general requirements on accuracy, there is also a requirement for accurate inspection of manufactured parts in serial-line production. Optical 3D scanners and industrial robots are used more often for that purpose. Measuring positions for accurate and fast digitization of a part need to be prepared as the manufacturing of the new part begins. Planning of such positions is usually done manually by positioning of the industrial robot and saving the positions. The planning of positions proposed by this system is done automatically. A methodology of sensor planning consists of positions planning, their simulation for true visibility of the part elements using a reflectance model, and a simulation of the positions for robot reachability. The entire methodology is implemented as a plug-in for the Rhinoceros software.

This study is focused on digitization of sheet metal parts that are characterized by specular surfaces. The system is designed for and tested with a stereo camera fringe projection 3D scanner, ATOS Triple Scan (GOM GmbH), but can be adapted to other stereo camera scanners. Compared to previous studies in the field of automated sensor planning, this study adds in the simulation phase the use of a reflectance model. By this model, actual visual properties of the scanned parts' surface can be precisely simulated.

A polygonal model generated from the CAD model of the part is used for the simulation process. The verification of visibility follows after testing for inclusion and occlusion of the portion of polygons of the whole part. The Nayar model is used as a reflectance model. This model has been previously used for inspection in another study and proved to be suitable for materials that are characterized by the combination of diffuse and specular reflections. The Nayar reflectance model uses three components of reflection: diffuse, specular lobe and specular spike. This paper describes the experimental determination of the Nayar model parameters and also the determination of limit gray values (from scanner camera images) for correct decoding of fringes and thus correct scanning of a sheet metal (steel) part. Using this model, the system can determine if the area on the part is both not too dark and not too bright (as a result of reflections) for decoding. For each sensor position an exposure time for scanning is determined based on simulation.

Results of the scanning that were obtained using an ATOS Triple Scan 3D scanner and a KUKA KR 60 HA industrial robot were compared to the simulation. The comparison based on the correspondence of the polygons area acquired in each sensor position (in simulation and in scanning) shows that in the performed measurements the median of differences between simulation and scanning is around 16%. High reduction of time in positions planning compared to the manual approach was observed in the performed experiments.

9530-5, Session 1

The application of vision measurement in aerodynamic testing combined with speckle correlation

Ding Chen, Jing-guo Zhang, Ye-hua Zhang, Wei Wang, Hong-qiang Ma, Shang-bin Zhang, Jia-bo Feng, China Academy of Aerospace Aerodynamics (China)

This paper presents a combination of visual measurement technique of speckle correlation method in aerodynamic test application. Modal analysis model of aerodynamic testing and deformation measurement is often very important but very difficult to achieve, fortunately, the development of modern optical measurement techniques made it

possible. First, we conduct the modal analysis on a airfoil model and its deformation analysis under certain conditions. Then, the above techniques was used to verified it. The results of the test results of the aerodynamic test and finite element analysis agree well, The novel of the new method is combining the speckle correlation and the model deformation in the aerodynamic testing. This method using the speckle correlation to process the data, combining sub-pixel correlation can make the results achieve very high precision and realized the real planar measuring. This non-contact full-field optical metrology shows a lot of abstracting potentials in aerodynamic test applications.

INTRODUCTION

The accuracy of aerodynamic testing simulation increased significantly, modal parameters of testing model and the deformation are important factors affecting the accuracy of the measurement data also. And often these would have a great effect on the practical application. Aeroelastic of the aircraft is interaction of the structure and its aerodynamic force which would coupling each other. Aircraft designers concerned these issues for it may lead to the deformation of the aircraft or the unstable of the aircraft, these factors are all fatal for the aircraft.

Vision measurement is a technique which combined with two cameras. Cameras acquired the same scene in the different position. We will obtain the 3D coordinates of the point value by calculating the spatial point in two images with parallax. Vision measurement technique directly simulated the processing scene mode of human eyes. It is very simple and reliable, and it has high application Potential in many fields. The basic problem of digital speckle correlation method is measure the two correlated speckle fields, namely reference field and deformation field. Digital speckle correlation method extract the displacement and strain signal from the speckle signal, it has many advantages such as simple optical path, the low requirement of the environment and so on. The light source can be used by laser even white light. Speckle can be some natural texture or artificial speckle.

This paper combined the vision measurement technique with speckle correlation method for certain airfoil model measurement. And the finite element analysis results verified the above technique. We carry out the modal analysis and the deformation analysis under the certain condition of a airfoil model.

We made sufficient number of speckle on the surface of the airfoil model, aerodynamic testing was conduct after that accompany with the deformation measurement. The testing used two cameras, and also used a 3D calibration target to calibrate the system. Because the environment of aerodynamic testing are very complexed, such as complicated light, the irregular vibration, and many other unstable factors . We made a calibrating measurement in the real environment before the testing.

RESULTS AND CONCLUSIONS

This paper present a technique using vision measurement for model deformation measurement, aerodynamic testing results verify the method and obtain higher measurement results. This method is different from the prevalent model deformation measurement for its speckle correlation. This method can realize the planar measurement, theoretically it can achieve arbitrary interval size. This method processing the data by using speckle correlation, combining sub-pixel correlation algorithm can make the measurement results achieve very high accuracy. This method is a method of non contact measurement, it can complete the measurement in the flow field of the aerodynamic testing without any interference. This method has wide application prospect in the aerodynamic testing, such as 3D measurement, aerodynamic model of attitude measurement, angle measurement and model of elastic displacement measurement. This non-contact full-field optical metrology shows a lot of abstracting potentials in aerodynamic test applications.

We need to do more work to improve this technique. Higher precision in automatic camera calibration, higher accuracy of feature recognition and higher sensitivity of the model deformation are our goals in the future.

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9530-6, Session 2

Research of the fuison methods of the multispectral optoelectronic systems images *(Invited Paper)*

Aleksandr S. Vasilev, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

This article is devoted to consideration of the issues relating to digital images fusion of the multispectral optoelectronic systems. The images fusion formation methods and methods are studied.

Theoretical analysis of the methods was completed in the course of the work, mathematical simulation model of the multispectral optoelectronic systems was developed. Effect of various factors on the result of fusion was demonstrated on the basis of the said model investigation. The paper also considers and suggests the objective assessment methods of the fusion image quality.

Currently development of the distributed multispectral optoelectronic systems plays the major role in many branches of the industry, in the security and counter-terrorism systems. They are extensively used in the military equipment due to the ability to detect and identify military units of a potential enemy by registration of its own emission in various ranges of the electromagnetic spectrum. However the modern multispectral optoelectronic systems could not be possible without images fusion method. It allows increasing essentially the system efficiency, simplify the perception and analysis process of the received image on the account of summing up of the objects information features in various spectral ranges.

The generalized structural diagram of the multispectral system includes the receiving optical system, spectral range division system, electronic unit, fusion system and the output device. The fusion system generates the integrated image which is realized on the basis of the registration of the information field of the surveillance object received by the measurement channels of various spectra. In this case fusion shall be understood as such combination of several images resulting in increase of the information value in comparison with the initial.

There are a lot of methods of images fusion with their advantages and disadvantages in specific tasks resolution. The paper describes the mostly widely used from the above: the averaging method, the masking technique fusion, the interlacing fusion, fusion of images Fourier spectrum. The mathematical synthesis method of the initial images of the various channels was realized to research the images' fusion methods under consideration based on the generalized structural diagram of the multispectral optoelectronic systems. The quality of the resulting image was assessed on the basis of the calculation of the cross entropy, brightness dispersion and excess of the Fourier spectrum function.

Based on the research findings we can state that the images obtained by the mask technique methods, by averaging and the Fourier spectrum integration methods have the highest information entropy. The interlacing fusion method allows increasing the information value versus the second initial image on the account of adding of the first image information features, however the resulting entropy value is significantly lower of the values obtained by other methods. The best quality feature, in terms of the brightness dispersion and excess of the Fourier spectrum function, was demonstrated by the averaging method. The method allows reducing noise components of an image on the account of smoothing of its local brightness variations smoothing thus the contrast is improved.

9530-7, Session 2

A new indicator in early drought diagnosis of cucumber with chlorophyll fluorescence imaging

Heng Wang, Haifeng Li, Liang Xu, Xu Liu, Zhejiang Univ. (China)

Crop population growth information can more fully reflect the state of crop growth, eliminate individual differences, and reduce error in judgment. But it is lack of effective means of the information measurement of the plants growth distribution in a large area. We have built a suitable plant population growth information online monitoring system with the plant chlorophyll fluorescence and spectral scanning imaging to get the crop growth status.

The system consists of three parts, chlorophyll fluorescence imaging detection module, spectral imaging detection module and scanning system module. Chlorophyll fluorescence detection module integrates LED excitation light source module and fluorescence imaging camera system. LED light source module includes 16 LED to form high brightness and high uniformity of the fluorescence excitation light intensity, whose total excitation power of 1600W. In order to achieve fluorescence measurements, we have developed the LED light pulse and the fluorescence camera synchronization circuit system. Spectroscopy system integrates a high-sensitivity camera and filter wheel, which can achieve 10-channel spectral imaging by the stepper motor drive.

In order to achieve the measurement of the plant growth state in a large area, we designed the measuring module scanning device, which includes the two-dimensional scanning by the horizontal, vertical and inclined rotation part. The horizontal scanning can cover a width of 2 m by the three measurements. Vertical scanning walks ways by the scanning system, whose distance is not limited. The vertical move and rotation is to better align the measurement area of plants.

In the detection of chlorophyll fluorescence, the modulated chlorophyll fluorescence measurement is applied widely. By a saturation pulse, we get the maximum quantum efficiency of photosynthesis of the plants (P) after dark adaptation. Then the actinic light is opened which simulates environment lighting, the chlorophyll fluorescence intensity of plants (S) will eventually be stable under the actinic light. By modulated chlorophyll fluorescence measurement, we can get a variety of chlorophyll fluorescence measurement parameters about plant physiological state. On the basis of the fluorescence image detection, we have studied the early drought diagnosis of cucumber. In the rapid detection of plant stress state, the maximum quantum efficiency of photosynthesis is an important indicator. However, the maximum quantum efficiency of photosynthesis in cucumber early drought diagnosis indicate limited extent, the effect is not significant. In practical applications, on the basis of modulated chlorophyll fluorescence measurement curve, we define a new indication parameter (DI) (maximum quantum efficiency of photosynthesis divided by the rate of change of chlorophyll fluorescence intensity). With the drought deepening, DI declines. Through experiments, this parameter enlarges the early manifestation of cucumber drought (3-5 days), the parameter DI in the early drought diagnosis of cucumber can indicate more significantly.

9530-9, Session 3

Spatial regularization for the unmixing of hyperspectral images *(Invited Paper)*

Sebastian Bauer, Florian Neumann, Fernando Puente León, Karlsruher Institut für Technologie (Germany)

For demanding sorting tasks, the acquisition and processing of color images does not provide sufficient information for the successful discrimination between the different object classes that are to be sorted. Instead of optical technologies, other technologies such as X-ray transmission measurement and others can be used for the successful discrimination. Sticking with light, an optical alternative to integrating three spectral regions of visible light to the three color channels is to sample the spectrum at up to several hundred, evenly-spaced points and acquire so-called hyperspectral images. Such images provide a complete image of the scene at each considered wavelength and contain much more information about the composition of the different materials. Hyperspectral images can also be acquired in spectral regions neighboring visible light such as the ultraviolet (UV) and near-infrared (NIR)-region. From a mathematical point of view, it is possible to extract the spectra of the pure materials and the amount to which these spectra contribute to material mixtures. This process is called spectral unmixing. Spectral unmixing based on the mostly used linear mixing model is a difficult task due to model ambiguities and distorting factors such as noise. Until a few years ago, the most inherent property of hyperspectral images, that is to say, the abundance correlation between neighboring pixels, was not used in unmixing algorithms. Only recently, researchers started to incorporate spatial information into the unmixing process, which by now is known to improve the unmixing results.

One approach of incorporating spatial information into the unmixing process is to add the constraint that the abundances of neighboring pixels should differ as little as possible from each other. This can be done in quite a few ways. One idea is to interpret the unmixing process as an optimization task and extend the objective function by a spatial regularization term. One example of such regularizers extends the famous Total Variation image denoising algorithm, which is known to preserve edges really well but approximating linear transitions by steps, to hyperspectral image unmixing.

For this reason, we recently investigated if the constraint of having linear image transitions can be enforced by minimizing the second spatial derivative. In this publication, we will build on these two approaches and describe the effect of incorporating different matrix norms into the regularizers on the unmixing result. Our investigation is similiar to one already conducted on conventional images, but we transfer the analysis to hyperspectral image unmixing.

9530-10, Session 3

Identification and sorting of regular textures according to their similarity

Pilar Hernandez Mesa, Johannes Anastasiadis, Fernando Puente León, Karlsruher Institut für Technologie (Germany)

Regardless whether mosaics, material surfaces or skin surfaces are inspected, in many cases their texture plays an important role. Texture is a property which is hard to describe using words but it can be easily described in pictures. Furthermore, a huge amount of digital images containing a visual description of textures already exists. However, this information becomes useless if there are no appropriate methods to browse the data. In addition, depending on the given task some properties of the texture like scale, rotation or intensity invariance are desired.

Many methods have been proposed to sort texture images according to their similarity. They can be roughly classified into approaches extracting features either in the spatial or in the spatial-frequency domain. However, they mostly have in common that the extracted features are evaluations of some functions applied to all the values in the domain being summarized in a histogram or a vector of moments. The visual characteristics of the pattern, like their type (regular, non-regular) or the texel's (fundamental unit of a texture) relative positions, are not taken into account directly. Furthermore, it is not possible to adapt the desired similarity measure easily to visual characteristics like the texture's scale or the texel's form invariance.

In this paper we propose to analyze texture images according to their characteristic pattern. First a classification approach is proposed to separate regular from non-regular textures. As mathematically perfect regular textures are rarely found in digital images due to lighting conditions and quantization, regular textures with small deviations will be classified as regular textures, too. To achieve the classification, a regular texture image will be generated containing the expected texel and the texel's positions extracted from the inspected texture from the frequency and the spatial domain. The classification is taken by comparing the synthesized texture with the original one. The second stage will focus on regular textures suggesting a method to sort them according to their similarity. Different features will be extracted from the texture in order to describe its scale, orientation, texel and the texel's relative position. Some of the features will be extracted from the spatial domain (e.g., the intensity-values used in the texel) and others from the frequency domain (e.g., the texel's arrangement pattern). Depending on the desired invariance of the visual characteristics, the comparison of the features between images will be weighted and combined to define a degree of similarity between them. Tuning the weighting parameters allows this search algorithm to be easily adapted to the requirements of the desired task. Not only the total invariance of desired parameters can be adjusted, the weighting of the parameters may also be modified to adapt to an application-specific type of similarity.

This search method has been evaluated using different textures achieving very promising results.

9530-12, Session 3

The influence of the design features on optical sorter effectiveness

Nikita A. Pavlenko, Valery V. Korotaev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The gradual depletion of mineral resources leads to the need of extraction ores with low content of valuable components. In this regard, the improvement of existing technologies for extraction, enrichment and complex processing of mineral raw materials, as well as the introduction of new, more advanced and progressive methods are relevant.

Optical sorting method is one of the most promising and environmentally friendly methods and attracts consumers by high-performance of enrichment. It's based on detection of differences of minerals optical characteristics such as color, transparency, reflectivity.

This method is universal, and is widely used not only in the mining industry, but also for sorting fruit and vegetables, the materials used in the construction industry, industrial and domestic waste, etc.

At the same time, optical sorters have a number of shortcomings including the followings:

- Difficulty or inability to sort the material with weak color tones of its components;

- Difficulty of adaptation (reconfiguring) of the optical sorter for sorting of a new type of raw material with the other color characteristic.

In addition, according to authors, producers of optical sorters pay insufficient attention to optimizing the parameters of sorters constructing schemes, as well as compensation of the impact of the used element base shortcomings on the results of the color analysis.

All this affects the sorting final efficiency and can be the potential obstacle to the optical sorting method development.

This paper deals with research of influence of the optical sorter key elements on the color characteristics of the analyzed object image obtained on the sensor of registration node, and, consequently, on the results of sorting process.

Research is conducted not only for finding ways of reducing the negative factors and impacts, but also for the development of evidence-based design techniques of optical sorters.

Research is conducted by device for analysis of moving objects, which is a laboratory prototype of an optical sorter. Its distinctive feature is the ability to change the mutual arrangement of the elements in order to simulate a specific situations of enrichment.

With this device we studied the effect of number of factors on the color of the analyzed object image. These factors are:

- Type of lighting devices and parameters of their work;

- Lens aberrations;

- The camera used, its operation modes and sensor calibration error.

The studies were conducted using multiple sets of mineral objects with particle size of 1-20 mm and different color characteristics.

9530-13, Session 4

Investigation into the use of smartphone as a machine vision device for engineering metrology and flaw detection, with focus on drilling

Vikram Razdan, Richard Bateman, Brunel Univ. (United Kingdom)

This study investigates the use of a Smartphone and its camera vision capabilities in Engineering metrology and flaw detection, with a view to develop a low cost alternative to Machine vision systems which are out of range for small scale manufacturers. A Smartphone has to provide a similar level of accuracy as Machine Vision devices like Smart cameras. The objective set out was to develop an App on an Android Smartphone, incorporating advanced Computer vision algorithms written in java code. The App could then be used for recording measurements of Twist Drill bits and hole geometry, and analysing the results for accuracy.

A detailed literature review was carried out for in-depth study of Machine vision systems and their capabilities, including a comparison between the HTC One X Android Smartphone and the Teledyne Dalsa BOA Smart camera. A review of the existing metrology Apps in the market was also undertaken. In addition, the drilling operation was evaluated to establish key measurement parameters of a twist Drill bit, especially flank wear and diameter. The methodology covers software development of the Android App, including the use of image processing algorithms like Gaussian Blur, Sobel and Canny available from OpenCV software library, as well as designing and developing the experimental set-up for carrying out the measurements.

The results obtained from the experimental set-up were analysed for geometry of Twist Drill bits and holes, including diametrical measurements and flaw detection. The results show that Smartphones like the HTC One X have the processing power and the camera capability to carry out metrological tasks, although dimensional accuracy achievable from the Smartphone App is below the level provided by Machine vision devices like Smart cameras.

A Smartphone with mechanical attachments, capable of image processing and having a reasonable level of accuracy in dimensional measurement, has the potential to become a handy low-cost Machine vision system for small scale manufacturers, especially in field metrology and flaw detection.

9530-15, Session 4

Range imaging behind semi-transparent surfaces by high-speed modulated light

Dave Geerardyn, Hans Ingelberts, Robin Deleener, Maarten Kuijk, Vrije Univ. Brussel (Belgium)

Range-imaging is a measurement technique able to generate an image which contains the distance information from the camera to all the points of a scene. This distance information can be captured by, amongst others, the time-of-flight principle measuring the time a light pulse needs to travel back and forth from the camera to the scene and converting this time into a depth. For a good operation of the time-of-flight principle, a high-power, fast-modulated light source is needed. Currently, consumer devices use laser diodes or LEDs, while industrial equipment sometimes also uses solid-state lasers. Commercially available high-power solid-state lasers are bulky, expensive and generate a narrow and collimated beam of light. For imaging however, the complete scene must be uniformly illuminated, indicating the need of high optical powers at large object distances. Most time-of-flight systems use square-wave modulation of the light source, requiring large bandwidths of the optical driver. The larger the bandwidth, the higher the resemblance between the amplitude of the optical modulated signal and the amplitude of the electrical source signal. We developed a large bandwidth, high power light source, capable of being integrated with a time-of-flight camera. Specifically, we designed and experimentally validated a new light source, based on 16 ultra-fast laser diodes, allowing an increased performance of the current time-of-flight cameras. In this paper, we discuss the development of a high-power illumination board (using lasers), with a large beam divergence and suitable for high-speed square-wave modulation with a chosen duty-cycle. We first characterized the optical power, modulation speed and pulse deformations of our developed light source. These measurements indicated that our light source could be modulated faster than 1GHz, which corresponds to optical pulses smaller than 500ps. Moreover, the pulses can be shifted in time with sub-nanosecond precision. Secondly, we integrated this light source into a time-of-flight setup, able to measure the distances of objects behind a semi-transparent surface. We performed time-of-flight measurements of a static scene of objects with and without semi-transparent surfaces, of which the results are displayed and discussed. Generally, we obtained an good image quality with a depth resolution of less than 5cm. Moreover, the resulting images are afterwards compared with the image quality of commercially available time-of-flight cameras. It became clear that the commercially available time-of-flight camera shows difficulties with semi-transparent surfaces and the distance to the objects behind it. When a continuous-wave time-of-flight sensor is displaying a scene with semi-transparent surfaces, the resulting distance is a weighted average of the distances of the semi-transparent surface and the object itself. We can conclude that our light source is suitable for

time-of-flight measurements and gives a low-cost alternative for imaging purposes. Moreover, through the combination of our light source with a time-of-flight camera, we are able to capture depth information of objects behind a disturbing surface. Consequently, this can be useful for drowning people detection in swimming pools. Our low-cost, compact light source and time-of-flight camera can be mounted on the ceiling of a swimming pool, allowing capturing an image of both the people at the water surface and underwater. As a results, this system would be a valuable help for the lifeguards and does not requires the expensive, underwater mounting of the camera. With this work we hope to pave the way towards an improved solution for the light source of commercial time-of-flight sensors, which could be used to increase the swimming pool safety.

9530-16, Session 4

Retroreflective microprismatic materials in image-based control applications

Mariya G. Serikova, Anton V. Pantyushin, Elena V. Gorbunova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrei G. Anisimov, Technische Univ. Delft (Netherlands)

This work addresses accurate measurement of reference marks position by machine vision systems in the case when mark is made of retroreflective microprismatic materials. Modern microprismatic technology implies tiny hermetically sealed pockets, which improves reflection intensity. The inherent drawback of the technology is the use of non-reflective preprinted netting pattern. This pattern affects the spatial distribution of retroreflected light that does not limit the material application for indicating (e.g. traffic sign applications). However, it was shown that the distribution irregularity becomes important when the material is used for reference marks for accurate position control by image-based techniques. Traditionally in such applications an opaque mask is applied to the top of microprismatic material and forms pattern for detection and measurement purposes. Despite the difficulties with pattern recognition caused by superposition of two patterns (preprinted netting and opaque measurement mask) microprismatic material shows good potential for automated inspection applications, because it is compact, technological and can provide high retroreflectivity. Due to this features this material has potential to replace traditional solutions used as a reference marks in machine vision applications (tetrahedral prisms, cat's eye reflectors, LEDs, etc.)

The main problem caused by superposition of netting pattern and opaque mask is a random deformation of mask border in a final image. This fact prevents accurate image coordinate extraction. Thus major authors' efforts were aimed at elimination of the netting structure affection on accurate image processing.

In this paper we provide survey of high reflection microprismatic materials and also results of our examination of their structure and retroreflectivity by special scanning apparatus for multispectral analysis of flat surfaces. This study gave information for reliable Zemax simulation of the reference mark. The mark containing both non-reflective netting pattern and opaque measurement mask was modeled in Zemax. Then examination of simulated images was made by developed key features extraction algorithm implemented by two different ways. First approach was based on median filtering while second one was developed by elimination in frequency domain. On the first stage of both approaches we made a rough estimation of image scale and orientation by large-scale features of the mask image. As a result an adequate correction for the filtering in both approaches was implemented. A comparison of the mentioned approaches for different reference mark orientation, illumination conditions and sensor noise level was made in order to identify algorithm boundary conditions.

Modeling results were verified experimentally with a developed setup consisting of a camera based on Sony ICX274 CCD, 25 mm lens, 800 nm LED lightning and high reflection microprismatic material with netting cells approximately 3 mm in diameter. The material was covered with a mask made of black industrial paint. Distance between reference mark and camera varied up to 5 m. The experiment showed that filtering in frequency domain demonstrates better accuracy (approximately 0.1 pix). The study confirmed simulation results and high potential of the material to be used in image-based control applications.

9530-17, Session 4

Object recognition in 3D point clouds with maximum likelihood estimation

Harshana G. Dantanarayana, Jonathan M. Huntley, Loughborough Univ. (United Kingdom)

This paper presents a novel technique of object recognition and localisation within a 3D point cloud by constructing a maximum likelihood (ML) function by comparing features in a model and features detected in a scene.

Using an optimisation algorithm, the maxima of the ML function was found, corresponding to the 6 degree of freedom (DOF) pose of the model within the scene.

1.0 Introduction:

Object recognition and localisation is a fundamental, yet a complex problem in machine vision. With 3D imaging, one is able to eliminate a?ne transformations usually present in 2D images. Yet, the problem still remains the same. Recent advances in 3D imaging has allowed one to obtain dense point clouds with high accuracy with techniques such as fringe projection scanning. When detecting machined parts, due to too little or too many unique interest points, one requires a classifier more powerful than random sample consensus (RANSAC).

In this publication, we present a probabilistic classifier based on maximum likelihood using surface features abundant in machined parts. We show that both rough estimation and pose refinement can be obtained by tuning the maximum likelihood function, obviating to need for costly refinement algorithms such as iterative closest point.

2.0 Maximum Likelihood Estimator

The localisation problem is essentially estimating the pose $\phi = \{x, y, z, \phi, \phi, \phi\}$ T of an object, given a set of features detected in a scene. The maximum likelihood of pose ϕ of object m with a feature set m within scene s with a feature set s, is directly proportional to the probability of observing features m in scene s, given pose ϕ of object m. When all features are independent, the probability of observing all features m is given by,

The probability of observing a feature m j in scene s given pose ϕ of object m is equal to matching parameters of feature m j in pose ϕ to those of all features s. Since there may exist features m j that does not match any feature in s, a base line probability is also added to prevent $P(m|\phi)$ being null.

where y j and x i are parameters of feature m j rotated and translated by pose ϕ and those of feature s i respectively.

We segment surfaces from a 3D depth map by performing a connected component analysis based on surface normals and 3D position allowing a fixed variance between neighbour surface normals to allow for free-form surfaces.

The detected surfaces are cut into smaller patches as shown in figure 1(a), where u ϕ v ϕ w are the principal axes of the surface. Each surface patch is then represented by a set of quadratic coefficients, a surface normal and a centre coordinate.

By considering these parameters, we obtain a probabilistic match between two surface patches by defining vertical and radial distances between patches and an angle between the surface normals as shown in fig 1(b).

where ϕ zj , ϕ rj and ϕ ϕj are the standard deviations in vertical distance, radial distance and surface normal, all of which are characteristics of model patch m j.

To build a gold standard model, we obtain multiple views of the object of interest annotated by circular markers with some overlap; hence, obtain the rigid transformation of all views relative to one view. Subsequent to segmenting all views, surfaces with no corresponding surfaces in other views are discarded, while corresponding surfaces are merged. The gold standard model derived using the above techniques are shown in figure 2.

3.0 Results

The optimisation algorithm starts with an initial pose and moves along the local gradient of the log likelihood function given in equation 1. To find a rough estimation, the log-likelihood function was broadened by scaling the standard deviations ϕ zj , ϕ rj and ϕ ϕj of model surface patches.

The log likelihood function was thresholded for object recognition. By

narrowing the log-likelihood function, the refined pose estimate was found.

The results of the refined pose is shown in figure 3. The error map shows the error between the scene and the rotated and translated model. The error in alignment of the model to the scene is less than 1.5 mm according to the error map.

4. CONCLUSION

We have presented a probabilistic matching technique by taking surfaces of machined parts into account. By tuning the model pose parameter variances, we have achieved both rough pose estimation and its refinement.

The technique has the potential to be more robust by including more feature sets such as interest points.

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9530-18, Session 4

Automatic detection system of shaft part surface defect based on machine vision

Lixing Jiang, Zhengzhou Institute of Surveying and Mapping (China); Kuoyuan Sun, Fulai Zhao, Zhengzhou Institute of Surveying and Mapping, China (China); Xiangyang Hao, Zhengzhou Institute of Surveying and Mapping (China)

Shaft part is common and important in mechanical industry. Its quality is core part of mechanical products. The size inspecting and surface detection are both important parts of shaft part quality inspection. The requirement for accuracy and speed of shaft part quality inspection becomes strong with the development of modern manufacturing technology. At present, the researchers have already realized rapid size inspecting of shaft part by image processing technology and the inspecting result is good. But the application of image processing techniques on surface detection is still on primary stage. Most manufacturing industry use sampling inspection to ensure the quality of shaft parts. And the detecting methods are mostly human eye identification. This kind of detection method has many disadvantages such as low efficiency, bad reliability, low detection accuracy, high cost, mistakable and so on. In order to improve the automation level of shaft part surface detection quality and apply machine vision to shaft parts detection, a controller system with SCM (Single Chip Microcomputer) was designed and realized the automatic surface detection of shaft part.

The designed system mainly contains three parts: image acquisition, image processing, encoding and marking.

In the image acquisition part, appropriate CCD camera and lens, image acquisition card and illuminant are used to acquire images of shaft part surface. The system adopt the monochrome line-scan digital camera to improve the detecting speed and use the co-rotating lighting way to acquire images with high equality.

Affected by the environment and the limitation of imaging system, the obtained image usually contains noise. In the image processing part, medium filter is used to preprocess the component image after studying and comparing classical image processing methods including image filtering and image enhancing. Automatic threshold-selecting image segmentation algorithm is adopted and defect information is extracted from image based on matched threshold. Finally, the position and size of the defect area in the image are got.

In the encoding and marking part, the rotate information of the shaft part being detected is recorded by the incremental encoder. The signal is transmitted to the microcontroller through the filter module. The upper computer receives and processes the data coming from the microcontroller and then send the point coordinate of the shaft part through the serial port. Finally, the microcontroller converts it into a code, used by marker pen to mark the location of the defect.

A device was manufactured to verify the designed system. Two 50cm long shaft parts (shaft diameters are 5cm and 10cm) were chosen as the test samples. Images were acquired and processed by adaptive program. The images of shaft part were clear and the accurate rate of defects detection algorithm was more than 98 percent, which was outclassed the level of manual work, the undetected error rate was 0.00 percent for which the width of the defects was larger than 0.1millimeter. The result showed that the designed system met the demand of shaft part on-line real-time detection and achieved non-contact, automated, standardized detection for shaft part surface.

Plenary Presentation

Extreme Computational Imaging: Photography, Health-tech and Displays

Ramesh Raskar, MIT Media Lab., United States

The Camera Culture Group at the MIT Media Lab aims to create a new class of imaging platforms. This talk will discuss three tracks of research: femto photography, retinal imaging, and 3D displays.

Femto Photography consists of femtosecond laser illumination, picosecond-accurate detectors and mathematical reconstruction techniques allowing researchers to visualize propagation of light. Direct recording of reflected or scattered light at such a frame rate with sufficient brightness is nearly impossible. Using an indirect 'stroboscopic' method that records millions of repeated measurements by careful scanning in time and viewpoints we can rearrange the data to create a 'movie' of a nanosecond long event. Femto photography and a new generation of nano-photography (using ToF cameras) allow powerful inference with computer vision in presence of scattering.

EyeNetra is a mobile phone attachment that allows users to test their own eyesight. The device reveals corrective measures thus bringing vision to billions of people who would not have had access otherwise. Another project, eyeMITRA, is a mobile retinal imaging solution that brings retinal exams to the realm of routine care, by lowering the cost of the imaging device to a 10th of its current cost and integrating the device with image analysis software and predictive analytics. This provides early detection of Diabetic Retinopathy that can change the arc of growth of the world's largest cause of blindness.

Finally the talk will describe novel lightfield cameras and lightfield displays that require a compressive optical architecture to deal with high bandwidth requirements of 4D signals.