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Contents

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8082-01, Session 1

Assistant systems for efficient multiscale measurement and inspection

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Optical inspection systems constitute hardware components (e.g. measurement sensors, lighting systems, positioning systems etc.) and software components (system calibration techniques, image processing algorithms for defect detection and classification, data fusion, etc.). Given an inspection task choosing the most suitable components is not a trivial process and requires expert knowledge. For multiscale measurement systems, the optimization of the measurement system is an unsolved problem even for human experts. In this contribution we propose two assistant systems (hardware assistant and software assistant), which help in choosing the most suitable components depending on the task considering the properties of the object (e.g. material, surface roughness, etc.) and the defects (e.g. defect types, dimensions, etc.). The hardware assistant system uses general rules of thumb, sensor models/simulations and stored expert knowledge to specify the sensors along with their parameters and the hierarchy (if necessary) in a multiscale measurement system. The software assistant system then simulates many measurements with all possible defect types for the chosen sensors. Artificial neural networks (ANN) are used for pre-selection and genetic algorithms are used for finer selection of the defect detection algorithms along with their optimized parameters.

A simple language parser has been implemented to translate the user specifications into machine readable instructions (C++ functions). These instructions are further used for selecting and optimizing the components. The optimization criteria can be freely assembled in the user specifications. Up till now, first assistants for fringe projection, video microscopy, and confocal microscopy have been implemented using C++. Comparisons of the results from the hardware assistant and from human experts are presented. For the software assistant, it is important to properly train the ANN to obtain reliable pre-selection. For genetic algorithms the parameters like population size, crossover rate, mutation percentage and the fitness functions should be chosen correctly. In this contribution we will show the general architecture of the assistant systems and results obtained for the detection of typical defects on technical surfaces in the micro-scale using a multiscale measurement system. We also present the ANN training methodologies, and the problem representation to genetic algorithms. Genetic algorithm parameter optimization methodologies will be presented in detail.

8082-02, Session 1

Multi-sensor technology based on a laser focus probe for nanomeasuring applications over large areas

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The range of measurement tasks in micro- and nanotechnology is becoming ever more varied and multifaceted. This development is mainly determined by the progress of manufacturing and production capabilities. The 2½ dimensional structures found in silicon technology are becoming more complex with smaller and smaller structure widths and increasingly larger surface areas. The demands on point-to-point measurement uncertainty are increasing as well. Currently established measurement methods such as AFM and SEM technology are very limited with respect to measurement field size and measurement speed. Also, side-wall measurements are becoming more important.

Similar tendencies can be observed in micro-system technology, optical precision manufacturing or micro-processing technology. The micro- and nanogeometries produced are becoming more complex and the aspect ratios larger.

In order to solve the problems arising within this application spectrum a multi-sensor platform based on a laser focus probe was developed. This platform is integrated in the Nanopositioning and Nanomeasuring Machine developed at the Institute of Process Measurement and Sensor Technology at the Ilmenau University of Technology with a measuring range of 25 mm x 25 mm x 5 mm and subnanometre resolution.

Therefore, optical probing systems, like the laser focus probe, CCD microscope and white light interference microscope, can be used for most measurement requirements. Large area scans, high precision stitching procedures as well as the measurement of steep edges up to 80° and 5 mm step heights are possible.

The tactile probes - a stylus sensor and an atomic force microscope - are based on the laser focus probe too. Thus, tactile high-precision profile measurements as well as the measurement of nanostructures are possible.

The various tactile and optical probes are constructed on the basis of a microscope tube and can be screwed into a microscope revolver. The laser and receiver part as well as the CCD camera are mounted above of the microscope revolver. Thus, the user can toggle between the various probes by rotating the revolver. This multi-sensor tool was integrated into the Nanopositioning and Nanomeasuring Machine. The different probes were compared with the aid of calibrated step height standards in the range from 7 nm to 700 nm in the Nanopositioning and Nanomeasuring Machine. The measurement deviation and uncertainty of all sensors are mostly less than one nanometre.

Finally we developed first approaches for multi-sensor procedures for the measurement of nanostructures in large areas (25 mm x 25 mm) for example for detecting defects on wafers (1”). Structures less than 500 nm can not be detected by optical microscopy (λ = 650 nm, NA = 0.55). However, an area scan with an AFM-probe with a line spacing of < 500 nm even at a scanning velocity of 100 µm/s is not feasible.

Therefore,the first step of the approach is to acquire a full image of the wafer with maximum lateral optical resolution by stitching around 2000 single CCD-microscope images together with the nanometre precision of the NPM-machine. The size of this image data file is around two gigabyte. By an automatic segmentation procedure areas of interest can be extracted. The nanostructures in these relatively small areas, which are distributed on the entire wafer, can be measured with the AFM-probe by well-aimed, nanometre-precise scans in a manageable time.

Further approaches to use the multi-sensor tool in combination with the NPM-machine especially of real 3D-micro and nanostructures are based on additional fiducial points on the object to be measured or on the measuring table.

Due to the multi-sensor approach the combination of several sensing principles opens up new possibilities of measuring of complex structures over scales from the nanometre up to the centimetre range.

8082-03, Session 1

Optical metrology for in-line process control

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Optical metrology is a widely used technique in quality control and it´s application is still growing, because the requirement for fast quality inspection is increasing. Additionally there is a trend of shifting monitoring and measurement from the standards laboratory to the shop floor. However today’s optical sensors are often not robust enough to be used in the factory. Therefore already in the development of the concept for new optical measurement systems the implementation near the production facility has to be considered. In this contribution the impact of different parameters of a typical shop floor environment on the measurement result is presented.

At first a classification of monitoring systems regarding their level of process integration is given. In a second step there will be a description of relevant parameters for the characterization of an exemplary drill process. Furthermore a description and specification of parameters of the environment of the machining process that possibly impact the measurement result is given. We consider vibrations and temperature variation. To estimate their impact a simulation model is build that mimics the behavior of different optical sensor systems when these disturbances occur. With this model the performance of chromatic confocal microscopy, spectral interferometry and chromatic confocal spectral interferometric microscopy within the environment of a drill process is investigated. Concluding the considerations, a guide to estimate the measurement error due to the process influences will be given.

8082-04, Session 2

Some figures of merit so as to compare digital Fresnel holography and speckle interferometry

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Optical techniques using speckle pattern have been widely used for many years. In particular these techniques give a fruitful contribution to the analysis of mechanical structures under strain by providing whole field information on displacement. According to the optical configuration of the experimental set-up, speckle interferometry SI (or electronic speckle pattern interferometry) [1-3] is able to measure in plane or out of plane displacement of the object under study, or simultaneously both in plane and out of plane displacements [4,5]. ESPI interferograms can be processed by phase shifting techniques [6] or by Fourier transform [7]. The latter require only one recording whereas the other one requires at least three recordings. Nearly at the same moment, digital holography was experimentally demonstrated [8, 9]. Digital holography can now be used advantageously to image objects. Lately, many fascinating possibilities have been demonstrated: focusing can be chosen freely [10], a single hologram can provide amplitude-contrast and phase-contrast microscopic imaging [11], image aberrations can be compensated [12], digital color holography and time-averaging are also possible [13,14]. The processing of digital hologram is generally based on the discrete Fresnel transform [8] which is applied on a single digital hologram [11, 14] or after a pre-processing based on phase shifting [13]. Note that digital holography exhibits various architectures such as: Fresnel holography, Fraunhofer holography, Fourier holography, Lens-less Fourier holography and image plane holography.

Methods of digital holography and ESPI find their interest in contactless metrology with application in mechanical strain, vibration, displacement field or surface shape measurements of objects. There exist some strong similarities between both methods, especially concerning data processing. However, some figures of merit explicating advantages and drawbacks of the methods have not been discussed in literature. These figures of merit must indicate, most objectively, differences and advantages. This paper proposes to analyse both methods on the basis of 5 criteria: number of recordings, digital processing of data, spatial resolution, photometric efficiency and decorrelation noise. We focus on the case where only one spatially phase-biased interferogram is recorded [7]. For digital Fresnel holography, the configuration is off-axis and the object reconstruction is based on a direct calculation using the discrete Fresnel transform [14].

The experimental configuration is adapted according to each method. The interferometer is based on a Mach Zehnder configuration in which a lens can be added to image the object onto the sensor (8 bits CCD camera with M×N=980×1289 pixels sized 4.65 m×4.65 m2). The laser is a continuous frequency doubled NdYAG laser (Verdi V2, 2W) and the object is a small loudspeaker (40mm in diameter). The loudspeaker membrane is localized at d0=1090mm from the sensor area. In the case of ESPI, there is an imaging lens associated to a variable aperture close to the lens. In the classical method [5], the aperture is placed at the focal plane of the lens. Figure 1 illustrates the experimental setup (left: Fresnel holography, right: ESPI).

The paper proposes a detailed analysis of the 5 figures of merit based on experimental results. In particular we propose a theoretical analysis of the influence of the aperture and lens in the case of ESPI. Compared to digital Fresnel holography, this element is a critical point that influences several aspects of the reconstruction process: Shannon conditions, spatial resolution, spatial filter and photometry. Moreover conditions for optimal filtering and image recovering are established. From this follows that digital holography is quite more adapted to simple and automated processing. However, advantages of using the lens associated to the aperture are related to the photometric efficiency. We present a theoretical modelling including all the physical parameters (object albedo, pixel surface, aperture number, transversal magnification, object diameter and laser power). The theoretical analysis is then validated by the experimental results. Influence of the speckle decorrelation is estimated for the case of mechanical deformation measurement. Therefore we have applied the same mechanical loading in both experimental configurations and then estimated the probability density of the noise map [15]. Fitting of the curve according to the theoretical analysis [1] enables an objective comparison of the decorrelation degree, given keys to compare the decorrelation sensitivity of the methods. This is a fruitful tool for e.g. high speed acquisition and processing of interferograms.

REFERENCES

[1] Dainty, J.C. [Laser Speckle and Related Phenomena], Springer Verlag, Berlin (1984).

[2] West, C. M. [Holographic Interferometry], John Wiley & Sons, New York (1979).

[3] Jones, R., Wykes, C. [Holographic and Speckle Interferometry], Cambridge University Press, Cambridge (1989).

[4] Slangen, P., De Veuster, C., Renotte, Y., Berwart, L., Lion, Y. F., "Computer-aided interferometric measurements of drift and phase shifter calibration for digital speckle pattern interferometry", Optical Engineering 34(12) 3526-3530 (1995).

[5] Schedin, S., Pedrin, G., Tiziani, H. J., Santoyo, F. M., "Simultaneous three-dimensional dynamic deformation measurements with pulsed digital holography", Applied Optics 38(34), 7056-7062 (1999).

[6] Creath, K., "Phase shifting speckle interferometry", Applied Optics 24(18), 3053-3058 (1985).

[7] Saldner, H. O., Molin, N. E., Stetson, K. A., "Fourier-transform evaluation of phase data in spatially phase-biased TV holograms", Applied Optics 35(2), 332-336 (1996).

[8] Schnars, U., Jüptner, W., "Direct recording of holograms by a CCD target and numerical reconstruction", Applied Optics 33(2), 179-181 (1994).

[9] Kreis, Th. [Holographic Interferometry - Principles and Methods], Akademie Verlag series in Optical Metrology Vol. 1, Akademie Verlag Gmbh, Berlin (1996).

[10] Yamaguchi, I., Kato, J., Ohta, S., Mizuno, J., "Image formation in phase shifting digital holography and application

8082-05, Session 2

Reference wave adaptation in digital lensless Fourier holography by means of a spatial light modulator

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Holography is a well suited method for recovering the complex amplitude of a wave field. This is done by superimposing an object wave field in the sensor plane by a known reference wave field and subsequently recording the resulting interference pattern by means of a sensor. The complex amplitude can be recovered from this interference pattern for an arbitrary reconstruction plane parallel to the recording plane, by solving the diffraction integral. This reconstruction consists of the zero diffraction order, the real image of the captured object and the conjugated twin image. However, the undisturbed real image will only be observable, if it is separated from the zero diffraction order and the twin image. For accomplishing this the off-axis capturing configuration has to be applied. This is realized by either tilting the incident angle of the reference wave relative to the incident angle of the object wave or by changing the object position. Both procedures result in a lateral shift of the real image in the reconstruction plane.

In Digital Holography the reconstruction plane is defined by the sensors band which is limited by the space bandwidth product of the sensor, i.e. the number of pixels. Since a part of the sensors band is used for reconstructing the zero diffraction order and the twin image, just a limited area of it is useable to reconstruct the real image without overlap. Furthermore, in contrast to holographic film, aliasing will occur, if the Nyquist-Shannon criterion is not satisfied.

In this regard, Digital Lensless Fourier Holography is an advantageous scheme for minimizing the recorded signals band, because both the real image and the twin image are reconstructed in focus. This scheme is based on a spherical reference wave whose origin has to be located in or close to the object plane, which means that it depends on the position of the captured object.

Since the object position may vary in consecutive measurements, e.g. in industrial mass production of micro parts, an overlap between the real image and the twin image respectively the zero diffraction order and also alias frequencies may occur.

To solve this problem, we present an experimental off-axis Digital Lensless Fourier Holography setup which allows for adapting the reference wave to any position of the object along and perpendicular to the optical axis in the measuring volume without the requirement of mechanical adjustment. The adaptation is solely realized by means of an electrically addressed phase only liquid crystal Spatial Light Modulator (SLM), which acts as programmable optical device allowing for manipulating the phase distribution of the reference wave field.

The reference wave originates from a fiber tip located on the optical axis in a fixed distance to the SLM. In order to adapt the reference wave to the object position it is modulated by a complex transmittance generated by the SLM. This results in a modified spherical reference wave which appears to originate from a virtual source point shifted along and/or lateral to the optical axis. The adaptation is limited to a finite measuring volume in which the object has to be located. It is shown that his volume depends on the distance between the sensor and the object, the object size, the wavelength and the pixel pitch of the SLM.

The adaptation of the reference wave is verified by capturing a digital hologram of a scene in two different ways: On the one hand a hologram of an object whose position does not fit to the useable sensors band is captured without the SLM. The resulting numerical reconstruction of the hologram is blurred and alias frequencies appear. On the other hand a digital hologram of the same scene is captured using the electronic adaptation of the reference wave by means of the SLM. Here, the scene appears to be both, in focus and shifted, so that no alias frequencies occur any more.

8082-06, Session 2

Self interference digital holographic microscopy approach for inspection of technical and biological phase specimens

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Interferometry-based quantitative phase contrast techniques enable high-resolution topography inspection of reflective surfaces, label-free minimally invasive live cell analysis and quantitative tomographic imaging. However, a drawback of many experimental arrangements is the requirement for a separate reference wave which results in a phase stability decrease and the demand for a precise adjustment of the intensity ratio between object and reference wave. Thus, a self interference digital holographic microscopy (DHM) approach was explored which only requires a single object illumination wave. The advantage of the proposed setup is that in difference to other self interference or common path-based approaches no additional components like temporal phase shifting devices, lenses or customized reflective surfaces are required. Furthermore, no optical elements like diffractive optical elements (DOEs) or spatial light modulators (SLMs) are used, which may be expensive or possibly affect the object wave by spatial filtering and thus decrease the lateral resolution. Due to the Michelson interferometer design of the proposed experimental setup two wave fronts with an almost identical curvature are superimposed. This results in a nearly ideal pattern of spatial off-axis carrier fringes and a constant interferogram contrast in the hologram plane. Moreover, the hologram evaluation with spatial phase shifting reconstruction algorithms [1,2] and Fourier transformation-based spatial filtering methods [3] as well as the integration of DHM in common research microscopes is simplified. To characterize the Michelson interferometer approach comparative investigations to a modular DHM system based on a Mach-Zehnder interferometer with a fiber optic reference wave (see detailed description in [4]) were performed. The obtained results demonstrate that due to the small optical path length difference within the interferometer an up to five times increased temporal phase stability is achieved. The increased interferometric stability also results in a significant reduction of reconstruction artefacts like unwrapping errors which is important for the automated evaluation of digital holograms obtained from time-lapse series. Furthermore, it is demonstrated that the use of low cost laser light sources with a short coherence length in the experimental setup is possible. The applicability of the proposed self interference principle is illustrated by data from the topography and refractive index analysis of several technical and biological phase specimens. This includes results from test charts, from different kinds of micro particles and optical fibers as well as from adherent and suspended cancer cells. In summary, the method prospects to be a versatile tool for quantitative phase contrast imaging as simplification is important for the establishment of digital holography in technical inspection and life science metrology applications.

[1] D. Carl, B. Kemper, G. Wernicke, and G. von Bally, "Parameter optimized digital holographic microscope for high-resolution living cell analysis," Appl. Opt. 43, 6536-6544 (2004).

[2] B. Kemper, D. Carl, J. Schnekenburger, I. Bredebusch, M. Schäfer, W. Domschke, and G. von Bally, "Investigation of living pancreas tumor cells by digital holographic microscopy," J. Biomed. Opt. 11, 034005 (2006).

[3] C. J. Mann, L. F. Yu, C. M. Lo, and M. K. Kim, "High-resolution quantitative phase contrast microscopy by digital holography," Opt. Express 13, 8693-8698 (2005).

[4] B. Kemper, D. Carl, A. Höink, G. von Bally, I. Bredebusch, J. Schnekenburger, "Modular digital holographic microscopy system for marker free quantitative phase contrast imaging of living cells," Proc. SPIE 6191, 61910T (2006).

8082-07, Session 2

Stokes holography for recording and reconstructing objects using polarization fringes

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Seminal work of Gabor for wavefront reconstruction started a new field called 'Holography'. Since then holography has been used as a tool in recording and reconstructing of the wavefront/object. Recording and reconstruction of an object is performed by encoding the object in-terms of modulation in intensity fringes and it helps to reconstruction of total field in form of amplitude and phase. Gabor's work is based on on-axis coherent recording and reconstruction of the intensity fringes. This is achieved using suitable coherent reference beam simultaneously with light scattered from object. Reconstruction of such fringes results into burial of object into high background. Later off-axis geometry of recording and reconstruction of fringes revolutionized the holography technique. This geometry modulates intensity fringes with properly selected carrier frequency in such a way that reconstructed objects get separated from the central high intensity background or dc. Reconstruction process in the holography is also performed with digital technique rather than using photographic plates or chemical process. This digital reconstruction, called 'Digital Holography' has drawn attention in recent years due to revolutionary progress in charge couple device (CCD) technology. Importance of holography has been realized in broad areas ranging from security applications to real world 3D objects. Recently a new un-conventional technique, called coherence holography, of imaging is also investigated. The technique is based on incoherent illumination of coherently recorded intensity fringes and reconstruction of object in terms of spatial distribution of coherence function.

Although term holography represents full reconstruction of the field but it is not complete in vectorial sense. Reconstruction of only amplitude and phase can be termed full reconstruction in scalar regime. However, this is not adequate in vectorial regime where a polarization characteristic of the object is significant. Extension of holography technique to vectorial regime has promising feature for various applications. Some of these are polarization imaging of biological samples, smart card for security purpose and in industrial applications.

Recently digital holography technique has been used in polarization imaging of objects. Technique is extended to vectorial regime by recording and reconstructing two interference fringes for orthogonally polarization components. This results into reconstruction of total field of the objects. It is well-known that interference of two point sources in vectorail domain for transverse field leads to modulation in all four Stokes parameters on the detector plane. Contrast and modulation of polarization fringes depend on the field correlation on the point sources.

Holographic reconstruction is also possible by using these polarization fringes, which will be referred to as Stokes holography. In more general way, all four components of Stokes fringes or polarization fringe can be exploited for this purpose. An intensity fringe is one of out of four polarization fringe modulation. In this paper, we discuss application of polarization fringes in recording and reconstruction of the total field. Polarization fringes are considered between coherently illuminated object and reference field. For this purpose, we consider interference of x polarized object and spatially separated y polarized reference beam. Interference of optical fields from these two sources results in modulation of only last two Stokes parameters (S2(r) and S3(r)), and no modulation in first two Stokes parameters such as in S0(r) and S1(r). These two modulated Stokes fringes help to reconstruct the object. Polarization holograms are incoherently illuminated and object is reconstructed into corresponding components of generalized Stokes parameters. Scalar counterpart of this technique is equivalent to coherence holography. As we know that space averages replace ensemble averages for Gaussian field, and experimental scheme can be devised accordingly. This is achieved by direct scattering of polarization fringes through static random glass plate and consequently space averaging of the scattered field. Object encoded into polarization holograms are reconstructed into their corresponding spatially averaged generalized Stokes parameters. It has been found that polarization modulation is well preserved even in case of random scattering or stochastic process, and this information is reconstructed in their generalized Stokes parameters. This technique provides promising tool for polarization imaging in random media.

8082-08, Session 2

An algorithm for the estimation of the in-focus distance for speckle holograms

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We investigate the possibility to estimate the in-focus distance d of speckle holograms. There are several algorithms that realize the estimation of in-focus distance. Cumulated edge detection is used as a method for the quantification of the image sharpness. Therefore, the total sum of the gradient or the Laplacian and the variance of gray values distribution of the image are calculated for the quantification. Threshold-based algorithms have been found to be not applicable for autofocusing in digital holographic microscopy, as the peak position of the focus function (threshold video-signal pixel count) or its width (threshold video-signal content) depends on the threshold value and therefore inhibits a robust focusing.

We propose an estimation process based on the Tamura model and we show that the Tamura estimation algorithm is the best method to estimate the in-focus distance for speckle holograms. To quantify the reliability of our algorithm, we consider a sequence of holograms deformed by means of a stretching algorithm. In fact, if an affine geometric transformation, consisting of a simple stretching, is applied to the original recorded hologram, we obtain the deformed holograms. Such simple stretching applied to the hologram has a very interesting impact on the numerical or even on the optical reconstructions. In fact, the in focus distance d before the stretching and the in-focus distance D after the stretching are related by the square of the stretching factor α.

Therefore, through subsequent reconstruction of the same hologram, stretched with a variable stretching factor, it is possible to create an in-focus reconstruction at any distance from the hologram plane. We use the Tamura model and the other methods for the distance recognition to investigate on the mathematical relationship between the in focus distance d before the stretching and the in-focus distance D after the stretching. The simulations show that the Tamura model is the best method for the in-focus distance estimation since it shows a more smoothed trend and a single global maximum value. In fact, it is compared with other known techniques for this context, where these last present several local maxima, with the drawback of easily reaching incorrect local maxima when blindly scanning the search range of the in-focus distance. This will results in noticeable estimation errors.. On the contrary, the concavity of the Tamura coefficient with respect to the variable d, assures the existence of a single global maxima as will be shown in the results. In addition, the existence of a global maxima of the Tamura model will allow us to use a classical gradient ascent search for the correct in-focus distance value, instead of using complex stochastic searches.

8082-09, Session 3

Synthetic aperture engineering for superresolved microscopy in digital lensless Fourier holography

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When considering an imaging system in digital lensless Fourier holographic configuration, the maximum achievable resolution is mainly limited by both the restricted CCD size acting as the limited imaging system aperture and by the presence of a beam splitter cube in front of the CCD for reference beam insertion defining a low numerical aperture imaging system value. Such limitation prevents high resolution microscopy considering digital lensless Fourier holography.

In this contribution, we present a method capable to improve the resolution limit of an imaging system in digital lensless Fourier holographic configuration allowing microscopic imaging in the range of 1 micron. The method is based on angular- and time-multiplexing of the spatial frequency object information in order to generate a synthetic aperture higher than the conventional limited imaging system aperture. On one hand, angular multiplexing is implemented by using tilted beam illumination in order to diffract on-axis a different spectral frequency band of the object's spectrum when comparing with of on-axis conventional illumination case. And, on the other hand, time multiplexing is needed to cover full two-dimensional spatial frequency domain in order to generate a synthetically expanded aperture in every Fourier domain direction. Such illumination procedure (combination of angular and time multiplexing) in addition with holographic recording allows the complex amplitude recovery of the on-axis diffracted wavefront generated by the object and incoming from the used tilted beam. Finally, an expanded synthetic aperture can be generated by coherent addition of the different set of recovered elementary apertures. Such synthetic aperture expands up the cut-off frequency limit of the imaging system when only on-axis illumination is considered and allows getting a superresolved image of the input object. Moreover, if a priori knowledge about the input object is available, customized synthetic aperture shaping is possible by considering the addition of those elementary apertures corresponding with only the directions of interest and, thus, reducing the full consuming time of the approach.

The experimental setup is based on a classical Match-Zehnder interferometric configuration where the input object is placed in one branch (imaging branch) and the another one (reference branch) serves for reference beam introduction in Fourier transform holographic configuration. In the imaging branch, an illumination stage composed by a set of tilted beam illuminations in sequential mode and incoming from the rotation and translation of a prism provides the angular- and time-multiplexing working principle. Thus, a set of digital holograms are recorded in time sequence and stored in the computer's memory. From the set of recorded holograms we compute a set of band pass images by simple digital processing operations (fast Fourier transformation, and filtering and centering over the area of interest). Finally, the set of band pass images containing different spatial frequency information is carefully managed in order to provide a high quality final superresolved image. Such process can be conducted either automatically guided by correlation operation with the overlapping areas between elementary apertures, or visually by adding phase factors in order to match the spatial frequency shifts at the Fourier domain and the global phase

differences and the amplitude ratios between elementary apertures with pixel accuracy.

We present experimental results in concordance with theoretical predictions for two different resolution test objects (spoke target and USAF resolution target), for different synthetic aperture shapes, and considering different resolution gain factors. Starting from a numerical aperture value of around 0.11 and 0.08 in the horizontal and vertical CCD directions, the first off-axis illumination angle allows a resolution gain factor of 2.5 and 3, respectively, and a synthetic numerical aperture value equal to 0.28 and 0.25, respectively. When considering the second illumination angle, the new resolution gain factors and the synthetic numerical aperture values are approximately improved to 4 and 5 and 0.45 and 0.42, respectively, for the horizontal and vertical directions. In the former case, the superresolution limits are improved from 5.74 microns and 7.72 microns to 2.26 microns and 2.53 microns, for the horizontal and vertical CCD directions when using He-Ne laser wavelength, while in the latter one the new superresolution limits arrive until 1.41 microns and 1.51 microns, respectively.

8082-11, Session 3

Dual-wavelength holographic shape measurement with iterative phase-unwrapping

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In order to measure the shape of a large number of identical components in the manufacturing industry we propose a method where dual wavelength digital holography is used to capture a phase representation of the object and iterative phase unwrapping is performed using information about the CAD-model. The aim of the work is to adapt the measurement method for on-line purposes; hence the process must be fast and reliable.

The holographic recording of the object is done using a single mode laser diode. The diode is temperature and current controlled which makes it possible to tune the wavelength between 638 and 645 nm. We have chosen to work with the wavelengths $\lambda 1$ = 640.5 nm and $\lambda 2$ = 641.6 nm which give a synthetic wavelength of Λ = 395.1 µm according to the equation

$$\Lambda = \lambda 1\lambda 2/|\lambda 1-\lambda 2|. \quad (1)$$

The phase intervals in the map represent a depth distance on the object of

$$\delta = 0.5\Lambda \quad (2)$$

which in our case correspond to a distance of about 0.2 mm.

A drawback with this approach is that we use only one laser diode, thus the holographic recordings are done in sequence after a change of wavelength. This means that in our work this is the time consuming step. We have however previously shown that it is possible to capture both holographic recordings in the same image using two different light sources[1].

To find the shape of the object the phase map has to be unwrapped. Since the surface contains discontinuities we use information from the CAD-model of the measured object. The fundamental problem is then reduced to that of finding the correct position and orientation of the measured object in relation to the CAD-model.

In order to save time in an online process we start by pre-processing the CAD-model. This is time saving since the same CAD-model can be used for a large number of identical objects in the manufacturing industry. The pre-processing consists of finding a sampled point representation of the model surface, i.e. model points.

To unwrap the phase map we use an algorithm that iteratively matches the object points to the model points and at the same time unwraps the phase map and finally finds the correct object points. This algorithm starts by constructing initial object points; that is finding the starting position of the algorithm. After that the algorithm matches the position and orientation of the measurement object to the position and orientation of the CAD-model. This is done using one iteration of the iterative closest point (ICP) algorithm[2], which means that a rigid body transformation, i.e. a rotation and a translation, of the object points is performed in order to find a "best" fit in space between the model points and the object points. When the best fit is found the phase values, ϕ_model, that the model points should have had if it were the CAD-model that had been measured are calculated. This makes it possible to compare the wrapped phase values in the phase map from the measured object, ϕ_w, with these wrapped phase values on the CAD-model according to

$$\Delta\phi = \phi\_w-\phi\_model. \quad (3)$$

Using this phase difference and measurement setup parameters the object points can be reconstructed. The reconstructed object points are then transformed again using the ICP-algorithm which is then followed by a new calculation of the phase difference and object point reconstruction. The algorithm is performed until all the phase differences are within the interval $[-\pi,\pi)$. After that it is possible to perform more iterations of the ICP-algorithm in order to align the object points even better to the model points, this is then done without reconstruction of the points.

The final result becomes a digital point representation of the measured surface that can either be used just as a description of the object shape or as a way to describe how well the object has been manufactured compared to the CAD-model.

For the iterative phase unwrapping algorithm to work the measurement object cannot deviate more than $\delta/2$ from the CAD-model, thus it depends on the synthetic wavelength in the holographic recording. Also the accuracy in the measurement depends on the synthetic wavelength; a shorter wavelength gives better accuracy.

[1]P. Gren, "Four-pulse interferometric recordings of transient events by pulsed tv holography," Optics and Lasers in Engineering, vol.40, no.5-6, pp.517 - 528, 2003, recent Developments in Digital Speckle Pattern Interferometry.

[2]P. Besl and N. McKay, "A method for Registration of 3-D Shapes." IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI), vol.14, no.2, pp.239 - 256, 1992.

8082-12, Session 3

Infrared digital holography for large object investigation

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Holography and, more generally, interferometry are commonly used for non-destructive testing of mechanical structures, stress analysis and quality control. The replacement of analog recording devices with digital ones, for example CCD and CMOS sensors, in the procedures has strongly simplified these kinds of dynamical investigations allowing much faster measurements and information retrieval. However, when the analysis In the visible range of an object larger than a few centimeters is required, the measurement is complicated by the inherently high sensitivity to seismic noise of the interferometric set up and by the relatively low power of available laser sources. By means of the far infrared radiation (10.6 µm) produced by a high power (110 W) CW CO_2 laser, we managed to overcome these problems. Thanks to its lower sensitivity to sub micrometric vibrations and to its high output power, we were able to perform digital hologram recording and reconstruction of objects up to about 2 meters. In previous works we demonstrated that working with a typical CCD sensor and a radiation source in the visible region, in order to obtain the same reconstruction resolution, we should put the sample at about one order of magnitude longer distances with consequent problems of inadequate irradiation density power on the sample surface. At any distance, however, one of the peculiar difficulties in recording a large object digital hologram consists in irradiating effectively the entire surface of the sample. In order to obtain the most homogeneous irradiation over the sample, we tested different holographic recording configurations. In the simplest set up we used a single object beam, enlarged by means of a ZnSe lens, to irradiate the sample; in this configuration, however, the peripheral part of the beam is characterized by a lower intensity and therefore an non-uniform irradiation of the object surface is obtained; furthermore, the object beam dimension is limited by the focusing power of the lens and, consequently, only a portion of the sample can be fruitfully irradiated. With long and narrow objects it is possible to exploit more efficiently the available beam energy replacing the spherical lens with a cylindrical one. To obtain a more uniform irradiation of the sample and a larger irradiated area it is possible to split the object beam into two or more beams of comparable intensity and cover, with each of them, a different portion of the object. A different approach consists in using a single object beam, expanded by a lens, and changing its propagation direction by means of a motorized mirror, in order to scan the whole object surface; with this technique it is possible to capture the entire scene at a rather small (couple of meters) working distance.

8082-13, Session 3

Remote laboratory for digital holographic metrology

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The idea of remote and virtual metrology has been reported as early as in 20001, 2 with a conceptual illustration by use of comparative digital holography. However the concept of remote and virtual metrology can go much further beyond this. For example, it does not only allow for the transmission of static holograms over the Internet, but also provides an opportunity to communicate with and eventually control a remote metrology system. This will open up many novel opportunities in industrial inspection such as virtual remote testing and controlling.

With the development of broadband Internet and software for remote control, now we are able to make a real pace toward this aim: to build a remote metrology system based on digital holography. Our remote experimental system can perform deformation measurement of small objects such as MEMS under various loads in nanometer scale, and 3D holographic microscopic imaging of (biological) samples in micron scale by providing accessibility from all over the world through Internet connection. The system is built for scientific research, in particular for international collaboration in joint experiments. Nevertheless, as a side consequence, the system can be also used for the education of digital holography. To access the remote experimental system a remote user needs to register to the system to obtain a user name and password, book his or her schedule. There are many security issues and information technology involved in building a practical remote experimental system. However in this presentation we will limit our discussion on the technology directly related to the metrology system.

The system architecture for the remote lab is schematically shown in Fig. 1. At the heart of the architecture is the digital holographic microscopic system, which is hidden behind a proxy server for the sake of security and can be directly accessed only by a coordinator. The proxy is connected to a user database in which all the user registration information together with the corresponding IP addresses are stored. The proxy is also connected to an external repository so that the user can store the experimental data together with the metadata during or after performing the experiment. The repository is also accessible by a generic user so that he or she can search for information of interest with respect to the subject of digital holography.

[1] W. Osten, “Holography and virtual 3D-Testing,” in Proceedings of the International Berlin Workshop HoloMet 2000, W. Osten and W. Jüptner Eds., (Bremen Institute of Applied Beam Technology, Bremen, Germany, 2000), 14, pp. 14-17.

[2] W. Osten, T. Baumbach, and W. Jüptner, “A new sensor for remote interferometry,” SPIE. 4596, 158-168 (2001)

8082-14, Session 3

Simultaneous out-of-plane and in-plane displacements measurement by using digital holography around a hole or indentation

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A measurement prototype based on digital holography for the simultaneous measurement of out-of-plane and radial in-plane displacement fields is shown. This prototype enables recording two holograms at the same time with a single image taken by a digital camera and evaluating separately in-plane and out-of-plane displacement components. An axis-symmetrical diffractive optical element (DOE) is used for the illumination of the object, which causes radial sensitivity vectors. Blind holes as well as spherical indentations were preformed over a welded steel plate (containing residual stresses). By using the digital holography device, characteristic out-of-plane and in-plane displacement fields generated when the hole was introduced into the stresses material were measured and compared with theoretical ones. Good agreement was found between them. In addition, a mature digital speckle pattern interferometry (DSPI) setup was used to measure only one the in-plane component around the hole. Good agreement between both systems was also found. Finally, displacements fields were measured around indentation marks. In this case, preliminary results show that out-of-plane displacements are larger than in-plane ones, enabling its use for residual stress computation or maybe material properties determination.

8082-15, Session 3

Measurement of temperature of axi-symmetric gaseous flames using digital holographis interferometry

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A large number of optical techniques classical interferometry, holographic Inteferometry, moiré deflectometry, speckle photography, speckle shearing interferometry, Talbot interferometry, and shearing interferometry have been investigated to measure the temperature and temperature profile of gaseous flames [1]. Further addition this direction was the use of Lau phase interferometry [2]. Digital holographic interferometry is relatively new imaging and measurement technique [3]. It records the hologram electronically on a CCD/CMOS sensor and reconstructs the hologram by numerical method. This process avoids chemical processing of the hologram, thus, providing greater flexibility, speed and also the potential for almost real time implementation of holographic process. Advances in the performance of the computer and electronic image acquiring devices have made digital holography a potential tool in measurement technology and in several other industrial applications. For digital holographic interferometric applications a real image is numerically reconstructed from the hologram by calculation of the diffraction of the reconstructed wave associated with the microstructure of the hologram. In this case the reconstruction plane of the real image is not restricted because digital holographic reconstruction process is having capability to yield images at arbitrary required positions. The transverse resolution of the reconstructed image decreases as the observation plane is moved further from the recording plane. This places a limitation on the position of the observation plane. Sometimes back X. Xiao and I. K. Puri [4] investigated digital holographic interferometry for optical diagnostic of combustion. These people evaluated the efficiency of digital holographic interferometry for making temperature measurement in flames and assess its applicability through simulation.

In this paper we are presenting the experimental investigations and theoretical analysis to measure the temperature and temperature profile of axi-symmetric gaseous flames using lensless Fourier transform digital holographic inteferometry (LLFrTrDHI). The temperature at different points in the flame is calculated by evaluating the interferogram obtained by LLFrTrDHI and using Lorentz-Lorenz relation applied to ideal gas with index of refraction air n0 =1 [5].

Using digital holographic set-up experiments are conducted on candle flame and Bunsen burner flame. Interferograms are made using digital holographic interferometry. Experimentally obtained interferograms are evaluated. The experimental results are in good agreement with the measurements done by Pt-Pt-Rh thermocouple and data logger. The evaluation of experimental results reveals that the accuracy, sensitivity, and spatial resolution of the technique are better than its counterparts.

REFERENCES

[1] Shakher, C. and Nirala, A. K., “A review on refractive index and temperature profile measurements using laser based interferometric techniques,” Opt. Lasers Eng. 31, 455-491 (1999).

[2] Thakur, M., Vyas, A. L. and Shakher, C., ‘’Measurement of temperature profile of an axi symmetric gaseous flames using Lau phase interferometer with linear gratings,” Opt. Lasers Eng. 36, 373-380 (2001).

[3] Schnars, U. and Juptner, W., P., O, “Digital recording and numerical reconstruction of holograms,” Meas. Sci. Tech. 13, R85-R101 (2002).

[4] Xiao, X. and Puri, I. K., "Digital recording and numerical reconstruction of holograms: an optical diagnostic for combustion," Appl. Opt. 41, 3890-3899 (2002).

[5] Born, M. and Wolf, E., "Principles of optics," 4th Ed., Pergamon Press, New York, Chapter 3, 122, (1978).

8082-79, Session 3

Optical characterization of phase gratings written by a UV femtosecond laser in PMMA

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We report on the characterization of optical Bragg type phase gratings created in polymethyl methacrylate (PMMA) substrates by means of a femptosecond Ti: Sapphire laser. A spatially resolved microscopic interferometric technique is used to investigate the two-dimensional distribution of the refractive index changes produced by the irradiation process. With this technique it is possible to obtain a direct and quantitative two-dimensional measurement of the refractive index profile in irradiated PMMA, providing information on how the fabrication process depends on the laser irradiation.

In order to investigate the refractive index changes induced in the irradiatied region of the sample, we performed a three-dimensional visualization and spatially resolved optical analysis of the induced refractive index profile by using a digital holographic technique. The advantage of this technique is the possibility of numerically reconstructing both amplitude and phase of the complex wavefield transmitted by the sample under investigation. The experimental set up consists in a Mach-Zehnder inteferometer employing a He-Ne laser and a microscope objective in the object arm near after the sample (see Fig.1).

FIG. 1. Mach-Zehnder interferometric system in microscopic configuration. BS1 and BS2 are beam splitters. NDF1 and NDF2 are neutral density filters; BE1 a spatial filter and beam expander for the incident laser light; BE2 a spatial filter and beam expander to generate a plane wave front reference beam, MO a microscope objective 10 .

The refractive index changes are obtained from the phase change profile by the relationship where λ= 633 nm is the wavelength of the probe beam and d the thickness of the sample. The three dimensional visualization of the refractive index of the phase gratings are shown in Fig. 2(b) and Fig. 2(d). The maps are numerically retrieved from the corresponding digitized interferograms shown in Fig. 2(a) and Fig 2(c). The periodicity of the structure is quite evident from the reconstructed 3D maps and it is related to the periodicity of the laser writing process.

The measurements show that femto-second laser pulses induce localized optical phase variations along the laser scanning direction resulting in positive refractive index changes with average peak values nmax of the order of 1.4 10-3 and 2 10-3, for a sample written with 0.102 µJ (laser pulse energy), 5 overscans and for a sample written with 0.105 µJ, 32 overscans, respectively.

FIG. 2. 3D visualization of the spatial distribution of the index of refraction calculated from the interference patterns: (a) and (b) digitized interferograms of UV written phase gratings in PMMA with scan speed 1.25 mm/s and (b) and (d) corresponding refractive index maps

These results are consistent with the expectation that, if the material is repeatedly exposed, the refractive index changes increase owing to the accumulated laser fluence.

The spatial resolution of the technique is limited by the probe beam wavelength, the microscope objective numerical aperture and the pixel size of the recording detector array. The results suggest that efficient modification of the material can be accomplished for a regime of repeated pulses of 250 fs and low laser fluence.

References

A.Baum et al. " Phase gratings in bulk polymethyl methacrylate written by a UV femtosecond laser" sub. to Appl. Phys. Lett.

8082-82, Poster Session

Measurement of surface resistivity/ conductivity of carbon steel in 5-20ppm of KGR-134 inhibited seawater by optical interferometry techniques

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Optical interferometry techniques were used for the first time to measure the surface resistivity/conductivity of carbon steel samples in blank seawater and in seawater with different concentrations of a corrosion inhibitor, without any physical contact. The measurement of the surface resistivity/conductivity of carbon steel samples was carried out in blank seawater and in seawater with a concentration range of 5-20ppm of KGR-134 corrosion inhibitor, at room temperature. In this investigation, the real-time holographic interferometry was carried out to measure the thickness of anodic dissolved layer or the total thickness, U_{total}, of formed oxide layer of carbon steel samples during the alternating current (AC) impedance of the samples in blank seawater and in 5-20 ppm KGR-134 inhibited seawater, respectively. In other words, the surface resistivity/conductivity of carbon steel samples was determined simultaneously by holographic interferometry, an electromagnetic method, and by the Electrochemical Impedance (E.I) spectroscopy, an electronic method. In addition, a mathematical model was derived in order to correlate between the AC impedance (resistance) and to the surface (orthogonal) displacement of the surface of the samples in solutions. In other words, a proportionality constant (surface resistivity (ρ) or surface conductivity (σ=1/[surface resistivity (ρ)] between the determined AC impedance (by EIS technique) and the orthogonal displacement (by the optical interferometry techniques) was obtained. Consequently the values ρ and σ of the carbon steel samples in solutions were obtained. Also, the value of ρ from other source were used for comparison sake with the calculated values of this investigation. This study revealed that the oxide film of the carbon steel sample has been removed from the surface of the sample, in the blank seawater. Therefore, the corresponding value of the resistivity to such layer remained the same as the value of the resistivity of the carbon steel sample in air, around $1x10^{-5}$ Ohms-cm. On the contrary, the measured values of the resistivity of the carbon steel samples were $4.91x10^7$ Ohms-cm , $5.1x10^7$ Ohms-cm, and $4.2x10^7$ Ohms-cm in 5ppm,10ppm, and 20ppm KGR-134 inhibited seawater solutions, respectively. Furthermore, the determined value range of the   of the formed oxide layers, $1.9x10^7$ Ohms-cm to $4.91x10^7$ Ohms-cm, is found in a reasonable agreement with the one found in literature for the Fe Oxide-hydroxides, i.e., Goethite(α-FeOOH) and for the Lepidocrocite (γ-FeOOH), $1x10^9$ Ohms-cm. The ρ value of the Goethite (α-FeOOH) and of the Lepidocrocite (γ-FeOOH), $1x10^9$ Ohms-cm, was found slightly higher than the ρ value range of the formed oxide layer of the present study. This because the former value was determined by a DC method rather than by an electromagnetic method,i.e., holographic interferometry, with applications of EIS, i.e., AC method. As a result, erroneous measurements were recorded due to the introduction of heat to Fe oxide-hydroxides. This led to higher value of the resistivity of the Goethite (α-FeOOH) and for the Lepidocrocite (γ-FeOOH)), $1x10^9$ Ohms-cm, compared to the determined value range of the resistivity of the formed oxide layers, $4.2x10^7$ Ohms-cm to $5.1x10^7$ Ohms-cm.

8082-83, Poster Session

Reconstruction of 3D refractive index distribution across the graded index optical fibre using digital holographic interferometry

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Digital holographic interferometric phase shifting method is used to calculate the refractive index profile of graded index (GRIN) optical fibre and the 3D refractive index distribution across the GRIN fibre. GRIN optical fibre sample is immersed in a suitable liquid and then Mach-Zehnder-like arrangement phase shifting digital holographic system is used. The optical phase difference due to the graded index optical fibre can be extracted by digital holographic interferometric phase shifting technique. The problem of the tilted GRIN optical fibre with respect to the reference axis is solved. Since, the fibre must be perpendicular to the reference axis according to symmetry considerations. The optical phase difference map along the GRIN optical fibre is used to calculate the mean values of the optical phase difference across the fibre. The refractive index profile of GRIN optical fibre is calculated using the multilayer mathematical model, where, the refraction of the incident rays through the fibre layers is considered. The shape parameter of the investigated optical fibre is determined. The mode field distributions can be analyzed for the used GRIN optical fibre. The calculated refractive index profile is used to reconstruct the 3D refractive index distribution across the fibre sample.

8082-84, Poster Session

Characterization of a waveguide written by an UV- laser into a planar polymer chip by digital holographic interferometry

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The optical- functional properties of an integrated-optical strip-waveguide in a planar polymer chip are presented in this article. The waveguide was directly written into the surface of a planar polymer chip by UV-laser irradiation. Digital holographic interferometric phase shifting method is used to calculate the refractive index profile of the waveguide. This profile contains one or two regions according to the parameters of UV-laser. The mode field distribution and the effective mode indices for each region are obtained. The study shows that the optical-functional properties strongly depend on the UV-irradiation parameters. Several mostly independently occurring photochemical processes competing with one another are proposed to explain the formation and shape of the refractive index distribution.

8082-85, Poster Session

Influences of Colorful LED Emissions on Spectrophotometric Properties of a LED Based White Light source

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A LED based white light source is designed and constructed to determine the color characteristics of the samples having specular and diffuse reflectance properties at the standard measurement conditions of 0/45 and d/8. The light source is composed of high power cool white (HPCW) and ultraviolet (UV) light emitting diodes (LEDs) which are operable in adjustable current levels. In order to combine the light beams emerging from two LED sources, a 1x2 fiber optic combiner is used. Optical characterizations of the light source designed and influences of several colorful LEDs called Royal-Blue, Blue, Cyan, Green, Amber, Red-Orange and Red on spectrophotometric properties of the light source are investigated.

8082-86, Poster Session

Experimental study of the heat transfer process of air around atmospheric arc plasma

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The experimental investigation of thermodynamic properties such heat and mass transfer of plasmas has many applications in different industries. Laboratory atmospheric arc plasma is studied in this work. Spatial distribution of refractive index and temperature of air around atmospheric arc plasma have been measured by moiré deflectometry.

Moiré deflectometry is a technique of wave front analysis which in both Talbot effect and moiré technique is applied for measuring test phase objects or reflection surfaces. Deflection of light beam passing through the inhomogeneous medium is utilized to obtain the different parameters distribution. when coherent collimated light beam propagates through a phase object as the probe beam and the beam is deflected due to refractive index gradient in the object, so the self imaging lines of grating G1 on grating G2 is displaced equals . Ultimately moiré pattern displaces in each point with respect to equals . The ray deflection angle can be calculated by knowing and are the pitch of gratings and moiré fringes, is -th Talbot distance given by where is the wavelength of probe beam and moiré pattern displacement.

According to Fermat's principle, light traverses between two points in smallest optical path length and by using Euler equations under paraxial approximation, the ray deflection angle which is productive of moiré pattern can be calculated for an inhomogeneous medium.

Deflection of light beam passing through the inhomogeneous medium is utilized to obtain the refractive index distribution. In experimental set-up, an expanded collimated He-Ne laser propagate through the arc plasma and the around air. The deflected light beam analyzed by a moiré deflectometer. By this method the spatial distribution of refractive index of air around atmospheric arc plasma have been measured. The temperature distribution is obtained by use of thermo-optic coefficient of air. , the thermo- optic coefficient, depends on wavelength of probe light and different properties of air around the plasma. To calculate the thermo- optic coefficient and the refractive index of air for a given wavelength of light and given atmospheric conditions (air temperature, pressure, and humidity), the modified Edlén equation is used.

The sensitivity of moiré deflectometry is selectable to measuring the deflection angle and can be increased by optimizing the pitch of gratings and Talbot distance and by increasing the moiré spacing.

The refractive index of the air around the plasma is changed because of convection phenomena. When the convection creates the air flowing around the plasma, the density of air is distributed symmetrically. The convective heat transfer coefficient is obtained by calculating the temperature gradient on the plasma border. Also the heat transfer coefficient is proportional to air thermal conductivity calculated by semi- experimental equation. This technique is simple and not sensitive to noise. Also, the measurement setup is not complicated and expensive. The probe light wavelength does not affect the measurement results and just the test object should be transparent with respect to probe light. The advantage of moiré deflectometry with respect to interferometry is evaluation of refractive index gradient directly and simplicity of this method.

8082-88, Poster Session

Coherence effects in Makyoh topography

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Makyoh topography is an optical tool for the flatness testing of specular surfaces, based on the defocused detection of a collimated light beam reflected from the tested surface. The reflection image is related somehow to the surface relief pattern of the tested surface due to the focusing/defocusing action of the surface irregularities. The main application of the method is the assessment of the polishing quality of wafers in semiconductor technology. In this contribution, the effects of the coherence of the illumination on the Makyoh imaging is analysed. Makyoh is usually considered as a geometrical optical technique, and coherence effects have received limited attention. It is shown that coherence effects are expected even for white-light illumination because of the small source size. Under optimum imaging conditions, coherence is manifested as (1) diffraction patterns around isolated defects and at sample edges, and (2) as speckle due to the surface roughness. These phenomena are analysed as a function of surface roughness (for speckle), illumination coherency and wavelength, light source size and instrumental geometrical parameters. Since speckle is a quasiperiodic pattern, it is easily mistaken for an image of a periodic surface morphology. The characteristic signature of speckles in Makyoh images is therefore determined, thus allowing its recognition. The effects of speckle on the sensitivity of MT imaging is analysed as well. The findings are illustrated with experimental images of various semiconductor samples.

8082-89, Poster Session

Optical characterization of three-dimensional structures within a DRAM capacitor

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Non-intrusive and non-destructive Fourier Transform Infrared Spectroscopy has been chosen to enable an inline characterization chain for DRAM manufacturing as an alternative to common destructive and mostly very time consuming methods. This characterization chain comprises the mold oxide - stacked capacitor - etch profile and depth control, control over the bottom electrode separation and the step coverage control of high-k deposition. In our case Hafnium Aluminium Oxide and Zirconium Aluminium Oxide deposited by Atomic Layer Deposition were evaluated high-k dielectrics. The characterization of the different process steps was carried out by either absorption parameters based on molecule vibrations or optical path differences calculated from oscillations in the infrared spectra. First absorption parameter like the silicon dioxide-, silicon nitride- and other molecular compound- vibrations and/or the combination of various vibrational modes visible in the infrared were used to characterize several geometry parameters. For verification purposes a statistical comparisons between Fast Fourier Transformation (FFT) Analysis data and several absorption parameters from the infrared spectrum were done which showed a good correlation between several absorption parameters and the FFT analysis. First very good results for certain absorption parameter could be achieved by describing the mass loss after capacitor etch pre-determined by scale measurements. Also the top critical dimension (CD) could be described with high accuracy. Further higher grade geometry descriptions of the stacked capacitor etch profile were achieved by dividing the high ratio capacitor structure into three parts: the top, middle and the bottom part of the capacitor. The first necessary to monitor a possibly existing overetch profile could be described in a similar manner to the top CD. The last one, which was a highly sophisticated region to describe for, needed already a combination of at least two absorption parameters and was necessary to verify the etch depth. The ratio between the top and the bottom part was also used to characterize the potential taper of the etched structure. For comparison and validation of the results both cross-sectional SEM method as well as simulations has been used. The simulated spectra have been carried out for a pre-determined capacitor geometry stack with several varied parameters like the top or bottom CD or the height of the stack. Afterwards the absorption parameters and various combinations of them were used to describe the before precise specified stack shape.

For the successful characterization of the step coverage of high-k deposition, a combination of two independent optical measurements was established. Therefore a volume-related FTIR-measurement in a DRAM array and an ellipsometric thickness determination of a two-dimensional layer in a support area were combined. This support area consists of well defined planar, not structured layers, where the film thickness could be determined with high accuracy for every die. This information delivered likewise the thickness on the top of the structure. As against the FTIR-measurements were focused on the complex three-dimensional structures in the middle of the array and delivered thus the information of the whole amount of deposited dielectrics. The ratio of both, the ellipsometric support area measurement and the FTIR array measurement delivered the searched step coverage parameter. This method showed a highly complicated deposition parameter dependence, like pulse time, precursor flow and deposition temperature as well as tool geometry dependence on the step coverage behavior. By the use of 300 mm mapping techniques a full characterization including spatial maps over the whole 300 mm wafers was possible.

8082-90, Poster Session

Spatial phase-shift interferometry: implementation of an effective phase-recovery algorithm

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Thanks to its robustness with respect to vibrations and air turbulence, spatial phase-shift interferometry (SPSI) is a measuring technique of particular value in industrial environments. Making use of a commercial CCD camera with USB connection to a PC we have set up an essential system that acquires and processes the fringe pattern, extracting the relevant features of the phenomenon being observed. The basic algorithms for phase recovery are available from the literature. Here we present a variant of one of such algorithms and describe in detail its implementation in our SPSI system. Experimental results are presented, showing the effectiveness of the overall measuring chain.

8082-91, Poster Session

Inexpensive 3-D laser scanner system based on a galvanometer scan head for high temperature applications

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Obtaining information about the position, size and form of an object is a common problem in industrial settings. There exist many solutions to this problem ranging from photogrammetry, via LIDAR scanning, to range imaging cameras. Each of these techniques has its own preferred application areas, where its advantages are emphasized and challenges conveniently avoided. However, there exist specific applications where none of the above techniques seem to fully satisfy the right combination of demands. For example, in the challenging offshore environment there is a need for gathering information quickly, with high accuracy and without interaction with the object of interest. At the same time, the instruments need to be kept simple and robust. They need to be cheap, tolerate the harsh environment and require minimal maintenance. They must not interfere with the rest of the equipment and, last but not least, have no negative EH&S implications.

Having these kinds of applications in mind, we will make an effort to address the problem of close range imaging of diffusely reflecting objects. This paper will look into the possibility of assembling a cheap 3-D scanning system based on a laser distance meter that can acquire 3-D information about an object placed 4-7 meters away fast and accurately. In order to meet the requirement for a cheap system, the solution considered will be based on commercial, off-the-shelf products. Commercially available 3-D laser scanners have the disadvantage of high cost and/or low accuracy and low sampling rate. Alternatively, 2-D laser line scanners can be incorporated into inexpensive systems and used for 3-D scanning if they are tilted with the help of mechanical devices. Unfortunately, attempting rapid scanning and movement of the sensors unavoidably compromises the demand for a robust system. Thus, scanning in the third dimension must occur relatively slowly. In addition, many of the commercial 2-D line scanners have either low accuracy, relatively low sampling rate and/or do not work well enough on targets with low remission coefficient.

In this paper, we have decided to set our focus on designing and characterizing a system based on a cheap and accurate 1-D laser rangefinder and a galvanometer scan head. Galvanometers and galvanometer scan heads are well-developed, highly accurate and reasonably cheap systems readily used in a wide variety of applications, for example in laser shows and welding. Galvanometer scan heads can position the laser beam with extreme accuracy, precision and speed. They offer more degrees of freedom by allowing scanning of the beam either in a continuous manner with raster positioning, in a step-and-hold positioning, or by vector positioning. However, to the best of our knowledge, there have been a very few attempts to use a galvanometer scan head to scan the beam of a laser distance meter.

The system that will be described is well-suited to scan an area where

the number of points needs to be minimized because of the demand for a high response time. The fact that the system can be used to measure independent points, and not necessarily whole lines, offers an advantage compared to commercial scanners, since it potentially reduces the time used to scan the object. Based on these points, different line and curve fitting algorithms can be used to find the size, the position, etc of the measured object. However, the use of these algorithms does require some prior knowledge of the shape of the object. Fortunately, in a variety of real-world applications this requirement is readily met.

The proposed system consists of a galvanometer scan head from Cambridge Technology and a laser distance meter from Acuity Laser Measurement Systems. The laser beam is angled in two dimensions, by two galvanometer mirrors, before it reaches its target. The light scattered from the target is sent back into detector through the same system of mirrors.

The scanning speed of the system is mainly limited by the sampling time of the laser, and the amount of data points needed. The accuracy, on the other hand, depends upon multiple factors. These factors include, among other things, the size of the galvanometer mirrors, the distance between the laser and the galvanometer, angular resolution of the galvanometer and the accuracy of the laser. Based on the accuracy and speed requirements for a specific application, the laser and/or galvanometer employed can easily, with some changes in the software, be replaced by a better suited laser and/or galvanometer.

This paper will look into and discuss some of the possible configurations. In particular, we will evaluate the effect of the galvanometer mirrors' size and the distance between the galvanometer and the laser on the accuracy of the measurement. The inaccuracy of the measurements caused by curve fitting algorithms, galvanometer control, laser measurement algorithms and software, and our own software will be discussed. The system performance will be tested on objects of different shape, made up of different materials with varying remission coefficients. However, the focus will be kept on curved surfaces.

8082-92, Poster Session

Dynamic concentricity measurement of large interval-diameter ratio holes with virtual annular quadrant method

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Dynamic concentricity measurement of small holes distributed in large room is valuable in assembling some big and complex optical facility. It's not feasible for the conventional measurement with portable CMM or laser tracker. A solution of dynamic concentricity measurement is put forward in this article, in which low power laser was selected as reference and camera &lens were used to acquire images of holes and laser spots. The relative orientation of hole and spot could be detected after image processing. To overcome the shortcoming that the edge of laser spot could not be detected for laser's Gaussian character with traditional method, a virtual annular quadrant (VAQ) method was proposed to determine the relative orientation between small holes and laser spot. With the simulation of VAQ method, the property was analyzed and the parameters of VAQ were optimized with the simulation results. Experiments were carried out to test VAQ method, and comparison of simulated and experimental results has confirmed the accuracy of VAQ method. A dynamical concentricity measuring system based on VAQ method is developed, which can perform one measurement in 5 seconds and has accuracy of about 0.015mm.

8082-93, Poster Session

High pressure measurement by fat long period garting sensor on a single mode optical fiber

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Optical fiber sensors based on fiber gratings have found increasing applications in different technological fields because of their many advantages such as their wavelengh-selective nature, small size, low cost, ease of use and fabrication. With respect to the wide range of applications of fiber optics in industrial application, a fat long period fiber grating (FLPFG) has provided an optical method for measuring the pressure in downhole.

The FLPFG consists of a periodical and slowly enlargement of the optical fiber diameter using fusion splicer. The spectral properties of the FLPFGs are determined by the mode coupling between the guided LP01 core mode and the LP0i cladding modes when a periodic perturbation of physical deformation of the fiber is introduced along the fiber. As the cladding modes are strongly attenuated, coupling of the guided mode to a cladding mode leads to the minima in the transmission spectra.

The behavior of the FLPFG with changes of pressure can be qualitatively explained using the fact that the propagation constant of a mode in a step index fiber. The pressure along the longitudinal direction will make the cladding diameter smaller but will not greatly affect the size of the core diameter because the core diameter is much smaller than that of the cladding. When the grating is forced to elongate, the core diameter becomes smaller, and the pitch becomes longer too. The former decreases the propagation constant of the core mode and in consequence decreases the effective core refractive index of that mode, but the latter increases the pitch of the grating. The core effective refractive index plays a major role and its decrease makes the grating output notch move toward the shorter wavelength. The pressure sensitivity of the bare optical fiber is low and many works have been done for increasing the pressure sensitivity which some of them can be applied to downhole application.

8082-94, Poster Session

Industrial surface inspection by wavelet analysis

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Industrial surfaces can be measured by manifold ways, especially by noncontacting optical methods. The aims of inspection range from shape measurement in reverse engineering to non-destructive testing and fault detection. Therefore one seeks for a common software tool to be utilized in all these fields.

Wavelet analysis is a signal processing method for the description of single- or multi-dimensional signals in multiple scales. Thus they are well suited for describing technical surfaces with variable resolution. In our presentation height data of optically measured surfaces are transformed along two dimensions using wavelet transformations with different objectives: One objective is the representation with only a few coefficients in the sense of an efficient data compression, the other objective is the reliable detection of defects, which can be regarded as a pattern recognition task. The speciality of the wavelet approach is the fact that no a-priori knowledge about the surface is needed, and that it is independent from the surface roughness and texture.

A systematic comparison of various wavelet families resulted in the choice of the biorthogonal pseudo-coiflets for representing the surfaces, and differentiating wavelets like Burt-Adelson-wavelet or short-range Daubechies-wavelets for solving the defect detection problem. It is shown that the representation can be improved by not taking the most significant wavelet-values which can be interpreted as low-pass filtered coefficients, but to maintain those with the largest weights. Thus the variance between the original surface and that reconstructed from the representation data is minimized by a factor up to 4. The found procedures are applied to different surfaces, like coin-surface, copper-mirror surface, or lacquered surface. The presented experimental results approve the suitability of the wavelet approach and demonstrate its versatility, robustness, and precision.

8082-95, Poster Session

Measurement of five-degrees-of-freedom error motions for a micro high-speed spindle using an optical technique

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The miniaturization of machine tools and cutting tools in recent years has led to an increasing need for spindles designed for high-speed rotation and reduced spindle size. In micromachining, the form accuracy and surface roughness of workpieces are extremely dependent on the rotational accuracy of the microspindle, and this development has led to an increasing demand to evaluate microspindle rotation errors. It is very difficult to evaluate five-degree-of-freedom error motions (one axial, two radial, and two angular motions) for high-speed microspindles using the conventional method, which simultaneously employs a master ball or cylinder and displacement sensors (for example, an electrostatic capacitance displacement meter). This difficulty is due to limitations in the measuring range, mechanical interaction, and frequency-response characteristics.

The conventional method of measuring spindle-rotation errors is depicted in Figure 1. Because the reference pieces used in the conventional method, such as the master ball or cylinder, must be large enough to allow the displacement sensors to measure them, they are not appropriate for microspindles. High-speed microspindles can only accommodate small, lightweight reference pieces. Therefore, it is very difficult to measure spindle-rotation errors for microspindles.

To date, many studies have reported measurements of spindle-rotation errors, but these methods are not applicable to high-speed microspindles. In recent years, some optical techniques to measure high-speed microspindles have been reported, but these techniques cannot be applied to a simultaneous measurement of five-degree-of-freedom errors.

This paper presents a method for measuring the five-degrees-of-freedom error motions of micro high-speed spindles using an optical technique. Figure 2 shows an illustration of the system used to measure five-degree-of-freedom error motions for a high-speed microspindle. This measurement system consists of a rod lens, a ball lens, two laser beams, which are each split into two beams (for a total of four laser beams: L1, L2, L3, L4), four condenser lenses (CL1, CL2, CL3, CL4), and multiple divided photodiodes (PD1, PD2, PD3, PD4). The 2-mm-diameter ball lens is fixed at the end of the 2-mm-diameter rod lens, which in turn is mounted to the spindle chuck. The length of the rod lens from fixed end to free end is 5 mm.

The stem of the rod lens is irradiated by a laser beam in the X and Y directions. The dual-element photodiodes, PD1 and PD2, are opposite to the condenser lenses, CL1 and CL2, respectively, and the rod lens is installed orthogonal to the XY plane between the lenses and the photodiodes [Figs. 2(a) and 3(a)]. The laser beams that penetrate the rod lens impinge upon the two dual-element photodiodes, and the intensities detected by the latter are converted into voltages. These signals are defined as IRX1, IRX2, IRY1, and IRY2, as shown in Fig. 2 (a).

Similarly, the ball lens is irradiated by a laser beam in the X and Y directions. The quadrant photodiodes, PD3 and PD4, are placed opposite to the condenser lenses, CL3 and CL4, respectively, and the ball lens is installed between the lenses and the photodiodes with its axis of rotation orthogonal to the XY plane. The laser beams that penetrate the ball lens impinge upon the two quadrant photodiodes, and the intensities detected by the latter are converted into voltages and defined as IBX1, IBX2, IBX3, IBX4, IBY1, IBY2, IBY3, and IBY4, as shown in Fig. 2 (a).

Figure 3 (a) also shows a cross section of the rod lens irradiated by the laser beams in the XY plane. When the spindle rotates without rotation errors, the laser intensities measured by each element of each photodiode are equal (IRX1 = IRX2, IRY1 = IRY2). When the spindle rotates with rotation errors, the rod lens is shifted in the XY plane and the equality of the light intensity measured by each element of each photodiode is no longer assured. For example, if the rod lens is shifted in the +X direction, then IRX1 = IRX2 and IRY1 > IRY2. As a result, the direction and magnitude of spindle runout can be ascertained.

In this research, the measuring system is manufactured for trial and is experimentally evaluated. The results clarify that the measuring system has a resolution of 5 nm and can be used to evaluate micro spindle rotation errors.

8082-97, Poster Session

Algorithms to improve the image process analysis in high-precision alignment techniques

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The proper alignment of the individual elements in an optical system is a crucial point in the final performance of an optical system. A large number of equipments and procedures have been developed and tested along last century [1,2]. Although those procedures are excellent during the assembly of individual parts (lenses or doublets) they lack reliability on the final alignment, so further adjustments must be done on the final stage as fixing correctly the compensation group, a critical optical element.

In previous contributions [3] we have presented a method to determine the misalignments of the individual lenses in the optical system through the analysis of an array of defocused punctual images properly placed in the full field of view. In this previous work the use of an easy procedure of analysis was enough to determine misalignments of 0.1 mm in spherical lenses or 0.2 mrad in cylindrical lens but subsequent work by our group found that the preliminary information of the optical elements was necessary to obtain a quantitative value of the misalignment.

In this contribution we present an algorithm that improves the PSF analysis of the defocused punctual images, the proposed algorithm is capable to overcome the need of preliminary information of the individual lenses. The algorithm is focused in alignment stage of the compensator group and introduces the analyses of the relative shape, energetic distribution, and centroids of each individual PSF. The comparison between the shapes of twins of PSF placed at the same nominal distance from the optical axis was enough for the preliminary strategy. Now we present the improvements on the technique; the preliminary information of the optical elements have been replaced by a selection of known displacements and the weigh of the energy is introduced in the algorithm, finally the individual PSF analysis were replaced by a combined function that all the individual PSF are taken into account.

The final reached accuracy is not better that the previous strategy; 0.1 mm in spherical lenses and 0.2 mrad in cylindrical lens but prediction of the value of the displacement can be obtained and the number of iterations in the alignment process diminishes, with the developed analysis process the algorithm returns the value of the misalignment for the compensator group.

The proposed algorithm has been tested, by simulation, in a Gauss optical system. The behavior of the optical system has been simulated with an array of nine punctual sources. The PSFs have been obtained for different misalignment positions and the second group of the Gauss system is used as compensator group. The set of displacements tested cover a range of 0.5 mm and 5 mrad and the error between the misalignments predicted and introduced was always lower that 5%.

[1] H.H. Karow “Fabrication of optical elements” Wiley 1993

[2] P.R. Yoder “Opto-mechanical System Design” Taylor & Francis 2006

[3] Arasa, J., Oteo, E., Blanco, P., “High-precision alignment technique through quality image analysis,” Proceedings of SPIE Vol. 7389, 73892L (2009).

8082-98, Poster Session

Design and fabrication of white light confocal microscope with tunable resolution and sensitivity

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Lateral and axial resolution and effective depth scanning range in white Light Confocal Microscope are related to the range of longitudinal chromatic aberration of system. In this article simulation and fabrication of white Light Confocal Microscope with tunable longitudinal chromatic aberration is discussed. The simulation has been done by Zemax optical design software. Generation of longitudinal chromatic aberration has been achieved by using two biconvex lenses with focal length of 30 mm and 40 mm and a 40x microscope objective. The effect of variation of distance between lenses on longitudinal chromatic aberration was studied. In addition the optical properties of microscope such as axial and lateral resolution, numerical aperture, effective depth scanning range and total shift of chromatic aberration in optical axis direction were studied. Using this setup with a broadband source of 420nm to 680nm tunable effective depth scanning range covering 23µm to 95µm was achieved. As a result tunable axial resolution of 48nm to 159nm was obtained. Regarding the scale of the sample we could use the optimum resolution.

8082-99, Poster Session

Visual alignment of mechanical structures using a Bessel beam datum: practical implementation

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Non-diffracting or Bessel beams have been demonstrated in the optical laboratory as an alternative to expanded Gaussian beams for alignment tasks. Their main advantages are zero diffraction, which theoretically eliminates lateral beam spread over long projection distances, and self-regeneration, enabling beam recovery and propagation beyond partial beam obstructions. We may also add that the transverse Bessel intensity structure of the beam facilitates accurate visual alignment, and it is this property that will be explored further in this work.

High efficiency visible Bessel beams are easily generated using axicons, however the range of the non-diffracting beam is limited to a few centimeters under practical conditions. We follow the reported technique of using an axicon with a projection lens to obtain near-diffraction-free beams over useful working distances. We also demonstrate quasi-Bessel beams generated with simple lenses having spherical aberration. Compact beam generators for field use can be easily constructed using a commercial laser diode module as a light source.

We were keen to explore the application of Bessel beams as a robust, easy-to-use and low-cost alignment tool in harsh environments. To this end we have coupled our beam generator with home-made crosswire targets, and developed an alignment process that is based solely on visual observation with the aid of simple accessories. Targets are assembled in cylindrical mounts and centered to within 10-40 microns, depending on crosswire diameter, with the aid of a traveling microscope and rotary stage. Crosswire diameter is chosen carefully with respect to the zero order Bessel ring diameter, so as to maximize visual alignment sensitivity. A projected Bessel beam has a ring profile that expands with distance from the source, so this means that our crosswire targets must be designed individually for use at specific projection distances in order to maintain the highest alignment sensitivity.

Our application was the alignment of physically separated large structures having rotating axes, the objective being to set all axes to a common datum. The distance from first to last structure was 19m, and an alignment error for each structure of 0.1mm was specified. The work was to be undertaken within a construction site environment, at an altitude of 4700m above sea-level and mean temperature of 5 degrees celsius. This uncomfortable working environment dictated that ease-of-use and reliability should be the key characteristics of the alignment method and equipment. An appropriate beam generator and set of targets were constructed off-site and characterized in the laboratory using full-scale projection distances. Additional equipment used on-site included a low-cost kinematic support for the beam generator giving a pointing resolution of 3 arcsec and minimum beam displacement of 2.5 microns. Initial beam alignment to two fixed targets required an iterative adjustment process, and this was facilitated with the use of CCTV cameras to relay images of the targets to a single person making beam adjustments.

Whilst visual alignment errors as small as 10 microns were often achieved in the laboratory, degrading factors such as beam turbulence, beam/target mismatch, target centering error and operator fatigue resulted in real-world alignment errors in the range of 50-80 microns at the site. In this work we provide practical details of all aspects of the alignment equipment and method.

8082-100, Poster Session

Choice of the reflector for the autocollimating alignment telescope

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Systems for non-contact control of displacement, linear shift and alignment are widely required in the industry for example autocollimating alignment telescope is the most well-known tool. As usual, measurement accuracy less than 0.05 mm at distances from 5 up to 20 m is required. There are several known schemes for linear control that are similar to alignment telescopes; they consist of an optical part and a reflector which is located at the object under test. As advantage, these schemes do not need any wire or other communication link with the object. In addition, implementation of modern photodetector arrays allows designing of automatic measuring devices based on classical optical schemes (such as autocollimation of parallel or convergent beams, autoreflection). Image processing methods and software could significant improvement of optical systems properties. Detailed problem definition and mentioned trends are presented in the paper.

The research is based on a shift control system built on autoreflection scheme (autoreflection target is located before the objective; the same objective forms the image of the target, that is reflected by reflector). The study is devoted to the choice of reflector for the mentioned system. The features of design, choice and use of tetrahedral reflectors (corner cube prisms) and cat's-eye reflectors are described. Zemax simulations were made to study the influence of beam and image deformation (caused by these reflectors) on the total system error. It is shown that the error value gains with the degree of image defocusing. Theoretical calculations and simulations are supported by experimental tests with autoreflection shift control system. Static characteristics of the system with different reflectors were achieved.

The result of the study is a detail comparison table of tetrahedral and cat's-eye reflectors with recommendations and limitations of their use for alignment control.

8082-103, Poster Session

In-process fault detection for textile fabric production: onloom imaging

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Constant and traceable high fabric quality is of high importance both for technical and for high-quality conventional fabrics. Usually, quality inspection is carried out by trained personal, whose detection rate and maximum period of concentration are limited. Low resolution automated fabric inspection machines using texture analysis were developed. Since 2003, systems for the in-process inspection on weaving machines (“onloom”) are commercially available. With these defects can be detected, but not measured quantitative precisely. Most systems are also prone to inevitable machine vibrations. Feedback loops for fault prevention are not established.

Technology has evolved since 2003: Camera and computer prices dropped, resolutions were enhanced, recording speeds increased. These are the preconditions for real-time processing of high-resolution images. So far, these new technological achievements are not used in textile fabric production. For efficient use, a measurement system must be integrated into the weaving process; new algorithms for defect detection and measurement must be developed.

The goal of the joint project is the development of a modern machine vision system for nondestructive onloom fabric inspection. The system consists of a vibration-resistant machine integration, a high-resolution machine vision system, and new, reliable, and robust algorithms with quality database for defect documentation. The system is meant to detect, measure, and classify at least 80 % of economically relevant defects. Concepts for feedback loops into the weaving process will be pointed out.

8082-104, Poster Session

Three-dimensional optical metrology using multiple-perspective digital holograms of an object

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Digital holography is a technique in which 3D features of an object are encoded into interference fringes. By using suitable image processing and numerical reconstruction algorithms, one can reconstruct the 3D object. The technique also gives quantitative information about the structure of the object. Digital holography is a fast growing field with many applications including Microscopy, Metrology and 3D information processing and display. In digital holography, an interference pattern of coherent light reflected off a 3D object and a plane 'reference' wave is recorded by an image sensor like a CCD or CMOS array. This interference pattern, called the digital hologram (DH), captures the true 3D information of the illuminated part of the object. The image of the object can then be reconstructed from the digital hologram by numerically propagating the wavefield back to the plane of the object using the theory of diffraction.

In this paper, we investigate the use of digital holograms of an object taken from different perspectives for 3D optical metrology. We are involved in a FP7 project (Real3D) which aims to develop 3D capture and display techniques based on digital holography. As a part of this project, digital holograms of a 3D object are recorded using a camera array comprising of 6 cameras. These holograms are numerically processed to remove the out-of-focus twin image noise and enhance the image quality. These processed holograms are then transmitted to a remote location where they are displayed on a 6 SLM setup which is placed in geometry similar to that of the CCD arrangement. In order to maximize the reconstructed image quality, it is important to know the relative shift/tilt between the cameras where the original set of holograms was recorded. We investigate the possibility of registering the 3D camera positions from information obtained from multi-perspective digital holograms of an object. In the general Fresnel geometry of recording digital holograms, one assumes the presence of a plane wave but in practice, there is sphericity and a linear phase tilt as well as non-uniformities in the reference wave. These deviations from the plane wave phase profile causes the relationship between the pixel pitches between the object plane and the reconstructed image plane to change. We derive the relationship between the pixel pitches in the object plane and the reconstructed image plane in the presence of these non-uniformities in the reference beam. These same principles can be applied for camera registration in synthetic aperture holography from non-overlapping holograms and also for creating 3D shape models of small objects. We finally estimate the influence of error on the precision in our calculation and propose methods to reduce the error.

8082-105, Poster Session

Measurement system for hot heavy forgings and its calibration

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Dimensional measurement of hot large forgings is desirable to permit real-time process control, but usually is inconvenient because of the difficulty in working with very hot workpieces. So the on-line dimensional measurement of large-size forgings is a long-term difficult issue. Traditionally, the measurement work of the heavy forgings with high temperature is mostly done by handwork or other very simple length measuring tools. Therefore only very simple parameters can be measured and the measuring efficiency and precision are both totally unacceptable. With the development of optic-electronic measuring techniques, non-contact methods such as industrial computed tomography (CT), charge coupled device (CCD), laser scanner and digital photogrammetry, can be applied to get the geometry parameters with high precision.

This paper presents a novel approach based on Two-dimensional Laser Range Sensor (TLRS). Firstly, the configuration of the measurement system is proposed after the analysis of the traditional online measuring system. The measurement system herein can be obtained by assembling TLRS, an axis of rotation, and a servo motor. The servo motor drives TLRS to rotate, which results in TLRS scanning forgings in different planes. According to software configuration, while motor rotates certain angle every time, laser radar accomplishes one plane scan. The combination among TLRS scanning angle, scanning distance and servo motor's rotate angle will achieve a scanning transform from two-dimensional to three-dimensional with respect to obliquity-probe angle-measuring distance (3D).

Then, the coordinates of points of forging's surface can be obtained in coordinate system set in scanning plane. This coordinate system is called Sensor Coordinate System (SCS), and changes its position and orientation accordingly when TLRS rotates. Secondly, we locate the origin of another coordinate system called Measurement Coordinate System (MCS) at the centre of rotation of TLRS. According to the transformation between SCS and MCS, coordinates of points in different SCS can be transferred into ones in MCS, which is fixed. Then, three-dimensional coordinates of points of forging's surface in MCS can be obtained.

Finally, based on these three-dimensional coordinates in MCS, modeling of forgings can be conducted by implementing Delaulay Triangulation. Then, measurement of different parameters of forgings, such as length and diameter, can be realized. In order to calibrate the measurement system, a pyramid designed by us is scanned. Based on the characteristic of scanning plane and calibration target, the transformation matrix between SCS and MCS of the scanning points is deduced by projective geometry theory. The calibration issue is converted into the solution of the intrinsic matrix and the extrinsic matrix of the system parameters in the globe coordinate.

The validity and accuracy of our method have been verified by experiments in both laboratory and forging workshop. The experiment result indicates that this method is much practical for the real time on-site dimensional measurement of high temperature heavy forgings. The research result lays a good foundation of the further work.

8082-106, Poster Session

3D shape measurement of optical free-form surface based on fringe projection

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1. Introduction

Ultra precision machining technology of complex curved parts such as optical free-form surfaces has become one of the leading research fields in high technology. Ultra precision measurement is the foundation of improving the precision of size, shape and surface roughness of the ultra precision machined parts, and it also helps to realize system integrity control and evaluation of complex free form surfaces. [1] Different noncontact measuring systems have been developed to measure optical free-form surfaces, for example, fringe projection and interferometry technology. [2-3] The former one is mainly used for the measurement of diffusion objects but it is difficult to inspect the specular parts. On the contrary the latter one is mainly used to measure optical surfaces, but for the measurement of aspheric surface a more complex optical system is needed.

A new method for ultra precision measurement of optical free form surfaces is presented in this paper. Sinusoidal fringe patterns and digital phase shift technology are adopted in this method. The fringe patterns are generated on a LCD screen by software programming so that its direction, period and contrast can be conveniently regulated. To avoid designing a real reference surface for regular measurement based on fringe projection method, [4] a virtual reference surface is proposed which can be used to improve the detection efficiency and realize the automation of measuring process. Sinusoidal fringe patterns are projected to the high reflected surface of the measured object. The deflection fringe patterns that modulated by the object surface are captured by the CCD camera. The slope information can be obtained by analyzing the relationship between the phase deflectometry and

the slope of the object surface. Also, a precision calibration method by combining deflectometry with photogrammetry is developed in this method and the wave-front resolution method [5] is used to reconstruct the surface. With the application of fringe projection technology the accuracy of optical free-form surfaces measurement could reach the level of tens of micrometer or even micrometer. Furthermore, combining the white light interfering technology [6-7] under the precision that has been achieved by fringe projection, the measurement accuracy of nanometer scale can be reached.

2. The basic principle

Sinusoidal fringe patterns are projected to the high reflected surface of the measured object through LCD screen. The deflection fringe patterns that modulated by the object surface are captured by the CCD camera. The intensity distribution of a two-dimensional fringe pattern with a spatial carrier is represented by [8]

$I(x,y)=A(x,y)+B(x,y)\cos[(2\pi/p)*x+\phi(x,y)]$ (1)

Where A(x,y) and B(x,y)are background intensity and local contrast, respectively. They are both constant for a given point (pixel); p is the spatial carrier period along the x-direction; $\phi(x,y)$ is the phase deflectometry which is relevant to the slope of the measured object surface. When the surface is a reference surface, the value of $\phi(x,y)$ is zero.

One ray of incident light which is reflected from the screen via the reference surface into the camera. When there is an angle between the measured object and the reference surface, for the same reflected light the incident light will rotate. In each camera pixel the phase of the imaged fringe pattern can be measured by the application of phase shift technology [9-11] and the temporal phase unwrapping algorithm. [12-14] Depending on the local slope of the object surface and the distance between the LCD screen and the corresponding points on the object surface, the phase varies according to the following equation:

$\phi(x,y)= (2\pi d/p)*\tan 2\alpha$ (2)

Projecting horizontal and vertical fringe patterns [15] independently, the slope in horizontal and vertical direction of every point on the measured object surface can be calculated. By using the wave-front resolution method the surface of the measured object can be reconstructed.

In regular 3D shape measurement of optical free-form surface based on fringe projection, two sets of the reflected fringe patterns (one before and the other after deformation) are separately recorded to produce the corresponding fringe phase distribution maps. The difference of these phase distribution is usually related to the slope of the measured object surface as equation (2) illustrated. The 3D height map of the measured object can be reconstructed by integration of the slope values. Thus a real reference surface is needed to calculate the phase distribution before deformation. To avoid designing a real reference surface for measuring process, a virtual reference surface is proposed in this method. With the datum surface which is used to locate the measured object as the virtual reference surface, the phase before deformation can be calculated based on the law of reflection. Then the detection efficiency can be improved and the measuring process can realize automation.

All deflectometry methods are limited by the intrinsic depth of field problem. Since the CCD camera can hardly focus onto the object and the fringes at the same time and the sinusoidal fringes do not change their phase when they are defocused, focusing at the measured object is a better choice. A world coordinate system is built based on the point on the virtual reference surface which is corresponding to the center of the LCD screen in z-axis as its origin. Inside and outside parameters of the CCD camera, the distance between LCD screen and the virtual reference surface and the coordinate of every point on LCD screen in WCS can be obtained by calibration algorithm.

Influenced by factors like the resolution of the LCD screen and the diffuse reflection of the object surface, the precision of fringe projection technology in this measurement system can only achieve micrometer scale. To realize ultra precision measurement for optical free-form surface, with the use of white light interference method in a smaller range (50um-100um) under the accuracy that has been achieved by fringe projection technology, nanometer scale measurement can be performed. Then proper image mosaic technology is used for the processing results to achieve ultra precision measurement.

3.The measurement set and experiments

The whole measuring device is placed in a high precision optical platform. Adjust the LCD screen to parallel the virtual reference surface. For the purpose of achieving high precision detection of optical free-form surface which has large curvature, two 5 mega-pixel cameras produced by Balser were adopted to form an asynchronous measuring system which is different from the traditional binocular vision measuring system. The measured object is placed on a motorized precision rotary stage. The combination of motorized precision rotary stage and motorized high precision goniometer can realize the rotation of the object in incident angles. A motorized high precision positioning stage is place at the bottom of the system. When the object moves into the view scope of one camera along the positioning stage, it will revolve a right angle on the center of the worktable so that the surface of the object can be precisely measured. CCD camera receives the fringe patterns modulated by the measured object surface and the partition of object surface that can be measured by this camera is reconstructed. Then the object moved to the view scope of another camera for measuring. After that, by applying proper image splicing algorithm to the results that the two CCD measured independently large curvature of optical free-form surface can be measured in high precision.

8082-107, Poster Session

Hybrid light source for scanning white light interferometry-based MEMS quality control

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We apply a hybrid light source with adjustable spectrum to Scanning White Light Interferometry (SWLI) for MEMS device characterization. The source combines light from a blue laser, a red LED and a fluorescent material to cover the visible wavelengths. The wide gaussian spectrum of the light source decreases interference ringing and improves surface localization, which is important when imaging diffuse surfaces or layered structures. The new light source is more versatile than earlier light sources used with SWLI. It allows both stroboscopic illumination and spectrum shaping during a measurement. Changing the illumination spectrum allows one to maximize the reflection from the measured surface - compared to reflections from other surfaces - in order to improve signal to noise ratio.

To test the light source we measured MEMS samples featuring known step heights using different spectral settings of the light source. The measured step heights (7.00 ± 0.03 and 7.03 ± 0.11) were close to those measured using a halogen lamp (h = 7.025 ± 0.020 µm) Coherence lengths similar to those obtained with a white LED (1.28 ± 0.13 um) were achieved without the side lobes present with white LEDs.

8082-108, Poster Session

Adaptive holographic illumination in comparative electronic speckle pattern interferometry

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Development of Spatial Light Modulators (SLM) opened a new area in coherent optical metrology. These modulators are capable to optically reconstruct digital holograms; therefore they can be used as active holographic optical elements in Electronic Speckle Pattern Interferometry (ESPI) or in digital holographic interferometry. In our work adaptive comparative ESPI measurement is done, where an optically reconstructed image of a recorded or simulated hologram is used for holographic illumination of another object, with which the difference of the test and master deformations can be calculated. This approach is a straightforward digital implementation of the analogue comparative measuring technique, where regular hologram plates are used to store and reconstruct optical wavefronts. An SLM is also capable to generate computer calculated wave fronts (not belonging to an existing object), and multiple projections can be performed during the measurement time. Using this feature an active measuring system

can be built. These active interferometers can continuously adapt themselves to the change of measuring conditions, because the test displacement profile can be compared with a suitable arbitrary master displacement profile in a relatively simple optical setup.

This technique may find industrial applications if the recorded images are processed in a computer in real time and used for feedback. The computer can generate adequate holograms for the SLM to instantly compensate for the selected displacement component of the test object so the measuring system can adapt to various displacement profiles. For a successful measuring system automated evaluation of fringes is necessary. The evaluation program must separate different deformation components (e.g. rotation, local deformation) after the measurement can be performed using the hologram of the calculated virtual master displacement profile as test object illumination. Measuring the separated deformation components we can extend the measuring range and generate a new output of the measurement, which is the list of the features of deformation components.

In our paper we will demonstrate that a conventional ESPI arrangement with holographic object illumination is applicable for comparative displacement measurement with adaptive features. We will describe the measurement setup in an ESPI arrangement with feedback, which is capable to project the real image of the master object - using its previously recorded or computer simulated digital holograms in the SLM device - onto the test object to calculate the difference deformation directly.

8082-109, Poster Session

Fluorescence errors in integrating sphere measurements of remote phosphor type LED light sources

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No abstract available

8082-110, Poster Session

Optimization of measuring and calibration procedures for gas analyser based on acousto-optical tunable filters

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An optimized algorithm of quantitative gas analysis for spectrometers based on acousto-optical tunable filters (AOTFs) is presented. Efficiency of the algorithm is supported by a unique feature of AOTFs - their ability to random spectral access. This property makes it possible utilization of specialized procedures for on-line processing of spectral information without any significant loss of time. To use this property in the task of trace gas measurements by open-path AOTF-based spectrometric gas analyzer it is necessary to define characteristic spectral points. We have developed a procedure of finding optimal set of spectral points. Besides, criteria for finding this set can be determined by the current situation and procedure may be some kind of adaptive and automated. The opimized algorithm has been tested on gas analytical system GAOS employing movable spectrometer based on double collinear AOTF made of SiO2 (spectral range 0.25-0.45 mcm and spectral resolution 9 cm-1). GAOS allows simultaneous detection of following substances: nitric and sulfur dioxides, formaldehyde, carbon sulfide, benzene, toluene, xylene, ethylbenzene, naphthalene, phenol. GAOS uses DOAS (Differential Optical Absorption Spectroscopy) technique for measuring of gas amounts. Using the optimized algorithm permits either to improve the accuracy of the results or to reduce the measurement time compared to commonly used algorithm. It can be used for such applications as rapid analysis of emissions from emergency, the analysis of large sets of samples in the laboratory or in the production processes, etc.

There was developed specialized software GAOSIS for simulating the operation of the gas analyzer with use of optimized algorithm. GAOSIS uses a database of spectral characteristics of substances and allows simulating the model distributions of gas mixtures with optional adding of white noise to data. The program calculates the concentration of gas mixture components predetermined by user in two modes: (i) by classical algorithm based on least-square method and (ii) by optimized one, which additionally determines operation spectral points and estimates probability of presence of other gas components. GAOSIS also allows estimation of accuracy of both using methods by specially introduced coefficient.

The advantage in accuracy of the optimized algorithm over the commonly used algorithm has been confirmed experimentally for various modeled GAOSIS distributions of gas mixtures. The first group of experiments, which was model ones, were aimed at validation of optimized algorithm and estimation of the limits of the measuring situation in practice. In the second group of experiments, there were used data obtained in laboratory tests, as well as data of typical distributions of gas mixtures emitted by asphalt plants - one of the practical problems solved by GAOS. Inaccuracy decrease in these experiments using an optimized algorithm was 5-9 times as compared with the commonly used algorithm for some gas mixtures.

An optimized calibration procedure for gas analyzers employing AOTF-based spectrometers is presented. It takes into account the possible interference of the calibration coefficients of different substances and is insensitive to possible ill-conditioned calibration matrix. An iterative procedure is used in optimized calibration procedure. It involves a controllable return to the previous steps in case of interference of calibration coefficients and for their corrections. Using the optimized calibration procedure allows to reduce the systematic error. Experimentally achieved decrease of calibration errors was about 2-6 times depending on the substance.

8082-111, Poster Session

Development of traceability methodology for optical coherence tomography (OCT) using depths of calibration grooves as transfer standards

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The standard methods for roughness measurements are based on a stylus which probes the surface of the sample [1,2]. However, depending on the material and characteristics of the sample, some non-contact measurement may be required in order to not impose damage to the sample [3]. OCT measurements are useful in some industrial applications as broad as dermatological and oil pipe repair however they are not reliable. In this paper we present a methodology developed at Inmetro to give traceability to OCT measurements using as transfer standards depths of calibration grooves. The uncertainty components have been estimated and the uncertainty budget will be presented at the conference.

The tomographic measurements presented here are based on optical low-coherence reflectomery (OLCR) [4]. It is based on a broad spectral width optical source with low coherence length. A continuous wave (CW) signal is divided in two arms with equal lengths, reflected back at the end of these arms and combined again at a photodetector. By changing the optical path of one arm relative to the other by a distance greater than the coherence length, an interference pattern can be seen. From the temporal location of the dumped envelope of the interference, which only occurs within the coherence length of the source and with the optical path of both arms matched, distance information can be extracted. Each mirror scan provides axial information (a-scan) and the lateral translation of the sample after each axial scan provides a spatial tomographic image (b-scan).

In this experiment, a superluminescent light-emitting diode (SLED) with 90 nm spectral width centered on 1320 nm was launched on the sample under test from the cleaved tip of a singlemode standard telecom optical fiber. The beam reflected by the sample and the fiber interface was reflected back and sent to a Michelson interferometer with a movable mirror at the end of one arm, whose course is longer

than the coherence length of the optical source. When a scan is performed, the coherence length of the optical source is exceeded and the interferogram shows the surface reflection on the sample face.

We selected a sample from a roughness standard set (Halle KNT 2060/1) consisting of a surface with 6 grooves with different depths, ranging from 0.264 micrometers to 9.457 micrometer, with calibration traced to the German national metrology institute PTB. The measurement procedure was adapted from SIM-Euramet L-K8 surface roughness technical protocol [5].

Preliminary measurements were performed with good agreement to the calibrated depth values 9.5micrometer . Despite the axial two-point resolution (the minimum distance between events which can be resolved) calculated from the spectral content of the low-coherence source being around 8.2 micrometer, the single-point resolution after processing the data converged to 0.52 micrometer. This was assessed by testing the system repeatability with up to 30 single a-scans at the same condition. This stands for the accuracy of localizing the position of occurrence of a single reflection event, referenced to the fiber-air interface. The deeper groove of the sample was characterized with different lateral resolutions, controlling the spotsize with the distance between the fiber tip and the sample, and for different lateral stepsizes.

Here we present the preliminary results of a non-contact roughness measurement based on OCT. The firsts results shown good agreement with certified values for roughness samples. More measurements are being performed and so the uncertainty budget for the measurement system. We are also studying the possibility of increasing the measurement resolution without recurring to a lower coherence time source[6].

[1] International Standard, ISO 5436-1 - Geometrical Product Specifications (GPS) - Surface texture: profile method; method standards - part 1 - material measures, 2000.

[2] International Standard, ISO 4287 - Geometrical Product Specifications (GPS) - Surface texture: profile method- Terms, definitions and surface texture parameters, 1997.

[3] Roughness measurement methodology according to DIN 4768 using optical coherence tomography (OCT)- Marcello M. Amaral et al, Proceedings of SPIE - Optical Metrology: - Optics for Arts, Architecture, and Archaeology II , v. 7391, 73900Z, 2009.

[4] Optical Coherence Tomography - D. Huang et al, Science, v. 254, 1178, 1991.

[5] EURAMET L-K8 Surface roughness comparison- Technical protocol, 2009

[6] Cordes, A.H. ; Xavier, G.B. ; Vilela de Faria, G. ; von der Weid, J.P. . High axial resolution swept source for optical coherence tomography. Electronics Letters, v. 46, p. 27, 2010.

8082-113, Poster Session

Shape and thickness measurements using a reconstruction method for linear sensor microscopy based on improvement of lateral resolution isotropy

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We report the application of a low-cost scanning-stage bench-microscope in bright-field reflection mode for shape and thickness measurements. Firstly we describe overall system architecture emphasizing its effectiveness to easily accommodate different optical setups and versatility of its software for image/data acquisition, processing and visualization. It is based on the following three main components: bench-microscope for bright-field reflection mode; own stand-alone board for sensor readout purposes; MATLAB applications performing object positioning, sensor readout and image processing. The main component of optical layout is LIS1024 (Photon Vision Systems / Panavision) a linear CMOS image sensor of 1024 pixels of 7.8 µm x 125 µm. Two objective lenses are alternatively used: 20x/0.4NA DIN Achromatic and 40x/0.65NA DIN Semi-Plan (both Edmund Optics Ltd). White-light illumination is used from a 35 W Halogen lamp with a DT Green filter of 10 nm band-pass centered in 540 nm. An important feature is its wide range of light intensities starting in very low-light levels in order to enable different illumination modes preventing sensor saturation.

The major drawbacks of this technique for its application in the field of metrology are the limitations on surface slope and height. The objective numerical aperture determines the maximum of each of these surface properties. Higher numerical apertures enable the measurement of higher surface slopes but smaller variations of height owing to its smaller working distance and vice-versa. Nevertheless surface slopes normally also have low values. Measurement fields below square millimeter or above square centimeter are possible depending on objective type.

Previously work already published had shown some results from tests of the application of this optical layout in profilometry. The profile of a Si-frame in a micromachined component was measured using slit-illumination. The low-cost components on the optical setup, particularly the objective, decrease axial and lateral resolution due to objective spherical aberrations and longitudinal chromatic aberration resulting from the use of a white-light source. Actually to reduce spherical aberrations the effective numerical aperture is decreased. In spite of these known limitations the optical arrangement using the linear image sensor and line-illumination had shown optical sectioning ability. Fair accuracy of the height of the profiles from the Si-frame in a micromachined component was accomplished even with the coarse algorithm used in that first approach. Intrinsic optical properties not considered in the algorithm particularly sensitive in surface edges contribute to width enlargement. The flatness of frame surfaces are very reasonable (planar profile) unless a slope due to incorrect mounting.

As this bench-microscope is based on a linear CMOS image sensor it behaves differently for image details parallel and perpendicular to sensor. Lower image acquisition time in comparison to confocal is achieved at expense of resolution degradation for details parallel to sensor. We believe it is possible to address this issue using proper algorithms to improve lateral resolution isotropy. Moreover the versatility of this bench-microscope affords perfect conditions to develop these algorithms in MATLAB and test them on USAF target images using different illumination modes. We aim at accomplishing 2D image resolution simultaneously isotropic and comparable to confocal.

Parallelly slit-illumination configuration is currently being used for acquiring images of 3D structures. Images show depth discrimination ability of overall system. Different axial planes in specimen come forward in image at different depths. Brighter and darker regions in image are changing as axial scanning is made. In spite of anisotropy in lateral resolution relief borders are well defined independently of its particular orientation relative to sensor.

Further results will be presented that show the enhancement of depth discrimination arising from the implementation of a reconstruction method running at this present time that combine developed algorithms to improve lateral resolution isotropy of 2D images and those to build 3D image. This reconstruction provides an excelent mean for shape and thickness measurements. Some results of its application for the measurement of height and thickness of PCB tracks as well as for the representation of the shape of boundaries delimiting the regions on each axial plane on other 3D specimens.

8082-115, Poster Session

Spectral polarimetry-based measurement of the thickness of a thin film

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In this paper, a simple polarimetry configuration [1] is used for measuring the thickness of a nonabsorbing thin film on an absorbing substrate from the ratio between the spectral reflectances of p- and s-polarized components reflected from the thin-film structure. The spectral reflectance ratio measured at a fixed angle of incidence is fitted to the theoretical one to obtain the thin-film thickness provided that the optical constants of the thin-film structure are known. This procedure is used for measuring different thicknesses of a SiO2 thin film grown by thermal oxidation on a Si substrate. Moreover, an approximate linear relation between the thin-film thickness and a wavelength of the maximum of the reflectance ratio for a specific angle of incidence is revealed, provided that the wavelength-dependent refractive index of the thin film is known and the substrate is weakly absorbing. The application of this method is once again demonstrated in determining the thicknesses of the SiO2 thin film. The results of

the techniques are compared with those obtained by a technique of spectral reflectometry [2], and very good agreement is confirmed.

[1] P. Hlubina, J. Lunacek, D. Ciprian, Opt. Las. Eng., 48, 786-791 (2010).

[2] P. Hlubina, J. Lunacek, D. Ciprian, R. Chlebus, Appl. Phys. B 92, 203-207 (2008).

8082-116, Poster Session

Spectrally resolved measurement of small optical losses by cavity enhanced spectroscopy techniques

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No abstract available

8082-117, Poster Session

Dispersion optimized white-light interferometer based on a Schwarzschild objective

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Scanning white-light interferometry (SWLI) provides the capability of fast and high-precision three-dimensional measurement of surface topography. Because of its compact design and high stability the Mirau interferometer is mainly used in industrial applications.

It is well-known that white-light interferometers more than imaging microscopes suffer from chromatic aberrations caused by the influence of dispersion. Chromatic aberrations lead to systematic measuring errors, especially on micro-structures with curved or tilted surface areas. For example, the plane glass plates used in a Mirau-interferometer are a potential source of dispersion. If this influence is not completely corrected for, errors in height measurement occur. In addition, the magnitude of these errors strongly depends on whether the coherence peak's position or the phase of an interference signal is evaluated.

For a sinusoidal structure with an amplitude of 0.1 µm and a wavelength of 8 µm a common SWLI provides the correct height profile if the phase of the signals is evaluated, but the measured amplitude is twice as high if the height information is obtained from the coherence peak position.

Taking these difficulties into account we have build a dispersion optimized white-light interferometer. The design corresponds to a Mirau-interferometer, but in order to reduce dispersion phenomena, we used a reflective Schwarzschild microscope objective.

For beam splitting a so-called pellicle was positioned in-between the objective and the measuring object. This is a 2 µm thick polymer membrane with an optical reflection coating on the front side directed towards the microscope objective. Because there is no antireflection coating, the back side of the pellicle shows a reflectivity of approximately 4 % assuming perpendicular incidence. The reference mirror is located in the blind spot obscuring the center of the pupil of the Schwarzschild objective.

Since the reflective objective is free from dispersion and pellicle beam splitters are generally used in order to minimize dispersion and chromatic aberrations, the interferometer is optimized with respect to dispersion. Although the interferometer works quite well in the micrometer range, significant discrepancies between the results of height measurements obtained from envelope evaluation and those obtained from phase evaluation appear at the nanometer level. Again, for correct amplitude measurement of the sinusoidal surface the phase evaluation is necessary. The effect, which limits the accuracy of the interferometer is supposed to depend on multiple reflections from the front and the back side of the pellicle beam splitter. However, since the angle of incidence varies due to the rather high numerical aperture (0.52) of the objective the resulting disturbances are difficult to quantify. Nevertheless, ghost signals were measured in addition to the typical white-light interference signals. They indicate that multiple reflections influence the results and finally the accuracy of the interference microscope.

8082-118, Poster Session

Comparative analysis of interferometric measurements of PMD on optical fibers

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The polarization-mode dispersion (PMD) is a phenomenon that arises from the random coupling of energy between the polarization modes of light propagating through an optical fiber [1,2]. This effect causes the temporal broadening of optical pulses and can severely impact the transmission rate and maximum achievable distance on modern high-speed telecommunications digital optical links. In this work we compare the measurements performed on a group of fiber spools of different kinds using a PMD analyzer based on the interferometric technique [3]. We analyze the results for three broadband optical sources, covering different wavelength regions. An increasing number of measurements are performed and the convergence of the results is achieved. The measurement results will be assessed by a calibrated PMD artifact traceable to the National Physical Laboratory (NPL-UK). Despise two orthogonally polarized modes are usually coupled into a singlemode fiber optics, the lack of symmetry on the fiber geometry due to environmental action (like fluctuation on temperature) or stress on the fiber deployment (bends and axial strain) causes the fiber birefringence to vary. The time variant random mode coupling gives origin to a differential group delay (DGD) between orthogonal states of polarization propagating through the fiber. The RMS (root-mean-square) DGD over wavelength or over time can be statistically reported as the PMD. This value can be obtained by different methods, usually classified as Stokes parameter analyzer, fixed analyzer and interferometric [4]. The interferometric method is fast and robust for field measurement and commercial devices are widely available.

The PMD analyzer used here is based on a Michelson interferometer with a movable mirror at the end of one arm. The polarized light from a broadband optical source with coherence time lesser than the PMD to be measured is sent through the device under test to the interferometer and splits in its two arms. The movable mirror is scanned and exceeds the coherence length of the optical source. The recombined signals, after passing through a polarizer, give origin to an interferogram from which the PMD parameter can be extracted by fitting a Gaussian curve to the data (after removing the autocorrelation central peak) [3].

Here we perform PMD measurements on a group dispersion shifted and standard fiber spools. Three polarized broadband optical sources are used, covering the O, S, C and L bands. The polarization state of light on the input of the fiber is varied with a polarization controller device. Each set of measurements is performed for some input polarization states covering uniformly the Poincaré sphere. The PMD values are measured and the progressive mean value and standard deviation convergence are monitored. The systematic error of the measurements is corrected after measuring the PMD of a calibration artifact traceable to the NPL, composed by a temperature stabilized quartz waveplate.

Preliminary results indicate that the final PMD values vary for sources centered at different spectral regions. This kind of evidence is not actually clearly covered by the statements of the international measurement procedures [5]. A comparative analysis between the whole results will be presented, assessing the dependence of the PMD value on the wavelength region. The behavior of the results convergence for an increasing number of repeated measurements is also included.

[1] N. Gisin et al, How Accurately Can One Measure a Statistical Quantity Like Polarization-Mode Dispersion?, Photon. Technol. Lett., 1671 (8), 1996.

[2] B. L. Heffner, Influence of optical source characteristics on the measurement of polarization-mode dispersion of highly mode-coupled fibers, Opt. Lett., 113 (21) , 1996.

[3] N. Cyr, Polarization-Mode Dispersion Measurement: Generalization of the Interferometric Method to Any Coupling Regime. J. Lightwave Technol., 794 (22), 2004.

[4] IEC 60793-1-48 Ed 2.0: Optical fibres - Part 1-48: Measurement methods and test procedures - Polarization mode dispersion.

[5] ANSI/TIA/EIA-455-124-A-1999: FOTP-124 - Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers by Interferometry, Telecommunications Industry Association, April 1999.

8082-120, Poster Session

Time-resolved oblique incidence interferometer for vibration analysis of rough surface

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This paper describes a motion-visualization technique for a sample with rough surface by using a stroboscopic oblique-incidence interferometer. Recently, there have been several studies on new driving methods and new usages of a ultrasonic motor in the field of robotic engineering. In these studies, an evaluation of a time-dependent behavior of the ultrasonic motor is desirable. Its characteristic depends markedly on vibration mode of a stator because the ultrasonic motor is driven by a frictional force between a stator and a rotor. However, up till now relatively few studies have been reported on vibration analysis of the stator because it has rough surface and its driving frequency is ultrasonic region with the amplitude of several micrometer. The purpose of this study is to develop a motion-visualization technique for a sample with a rough surface in the ultrasonic region. To observe such a surface, we focused on an oblique-incidence interferometer. The oblique-incidence interferometer is well suited to analysis the rough surface and a displacement of several micrometers because a scattering at a rough surface is reduced. However, by using a continuous light, a visibility of the fringe pattern at a vibrated surface in the ultrasonic region is not good. Therefore, the oblique-incidence interferometer is not suitable for analysis of the ultrasonic vibration. To overcome the problem, a pulsed light synchronized with a vibrated sample was used as a light source by an acousto-optic modulator. To control timing between a reference signal and an input signal of the light source by using a common oscillator, time-resolved behavior of the stator can be measured.

Firstly, we have confirmed to be able to observe an interferogram of a stable sample with a rough surface (Ra=0.23um) of a stator. The stator was a traveling type ultrasonic motor (Shinsei Inc., USR-30-B4) . The interferometer consists of a He-Ne laser, a beam expander, a prism and a COMS camera with an imaging lens. The incident light was induced into the prism and divided a reference light and a measurement light by a bottom of the prism. The interferogram forms reflective beam from the bottom of the prism and the sample surface. An incident angle of the light was 60 degrees. Applied voltages are 310 V in amplitude, and 50 kHz in frequency. We have detected an interferogram on the surface of the stator.

Then, by using the stator of the ultrasonic motor under driving in 50 kHz as a sample, we have compared contrasts of the interferograms with and without a synchronization. A visibility of the interferogram from the synchronized surface is better than the interferogram without a synchronization.

Finally, we have succeeded to detect a periodically movement of a fringe pattern of the vibrated of the stator. Furthermore, installing a piezo-electric transducer in a sample stage, phases of the interferograms have been analyzed by 4-steps phase-shifting technique. Fringe pattern has moved in 50 usec, and from time-resolved interferograms an estimated value of a displacement of the stator is 860 nm.

In this presentation, we will not only show the above results but also demonstration movies of a moving of the interferogram.

8082-121, Poster Session

Testing error simulation in cylindrical object measurement on interferometry

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For non-contact measurement of cylindrical objects by present normal techniques, there are some problems such as randomness, insufficient sampling and the low accuracy. For those problems, some researchers tried to use fringe projecting technique, combined with stitching technique to test cylindrical objects, but the limitation of precision restricts its actual application in industry. The paper puts forward applying interferometry to improve the testing accuracy. The paper first analyzes the basic types of cylindrical errors, including drum, tapered, pillow-shaped error, etc., and combinations of these basic types of errors and local errors get together form composite error. The integrated form of errors is analyzed by basic types of errors. Varieties of errors distribution simulate by computer using the technique interferometry method. We can get the interference pattern about cylindrical object.

8082-122, Poster Session

Monitoring reflection coefficient of polishing surfaces

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A procedure has been developed for recording angular diagrams of reflection and scattering from surfaces of natural nonmetallic materials, and a prototype of an automated setup has been con-structed to implement this procedure.

The setup is shown to offer an angular resolution better than 2, the suppression of light scattered in the angular analyzer and suppression of scattered specularly reflected beam in the case of inclined optical axis of the angular analyzer-at least 400-fold at an inclination angle of 6, which allows re-cording of the scattering indicatrices for polished surfaces against the background of their specular reflection peak.

It has been found out that during the recording of scattering indicatrices for machined surfaces there exists some optimal direction of observation, which can be chosen by varying the inclination of the angular analyzer optical axis with respect to the beam mirror-reflection plane.

A study of the influence of surface roughness on the angular diagrams of reflection and scattering has revealed that the reflection diagrams for granites consist of a narrow peak, a pedestal and some peaks due to speckle clusters. The scattering indicatrices for these materials depend on the surface roughness quite differently; this is attributed to the textured surface of granites, which makes the scattering indicatrix consist of two components: (i) reflection (scattering) from relatively homogene-ous zones of the texture formations and (ii) scattering from the boundaries of these zones.

The present research has enabled us to establish and generalize the pattern of the influence of physic-chemical properties of a workpiece material and a bound polishing powders on the polishing effi-ciency. The dependences of the removal rate and polished surface roughness on the slime particle size, which were derived based on the cluster model of surface wear and the physical-statistical model for the formation and removal of slime particles in OM polishing, have been demonstrated to fit well the experimental data. These relationships permit an optimal choice of powders for a bound-abrasive polishing tools, which will ensure a required polished surface quality for each particular workpiece material.

The dependences of the polished surface microprofile parameters on the coordinate of a zone under study, which were described by periodic functions on the basis of the statistical analysis, do repre-sent the fine effects that occur in the tool-workpiece contact zone in the course of polishing and are associated with the special features of the motion of and interaction between slime and wear parti-cles, directedness or randomness of their mutual movement as well as of their action on the work-piece surface.

We have developed a system and methods for the measurement of reflection coefficients of polished surfaces of OM. This work has demonstrated a theoretical possibility of and created prerequisites for the development of an express method for tentative assessment of polished surface roughness. A suf-ficient body of experimental data have been obtained and a basis has been generated to study the de-pendence of scattering and reflection coefficients of polished OM surfaces on the surface roughness.

Installation and registration technique of the surface reflection factor of details from optic materials are developed. The principled opportunity

to control a surface roughness by intensity of light re-flected from demonstrated. It is shown, that the technique of a surface roughness definition by the light reflection factor in a mirror direction allows to supervise operatively a surface during its ma-chining. It is established, that by the most relevant parameter of a roughness which can be defined by the light reflection factor, is Rz. Dependence of the reflection factor of the optic materials polished surface on parameter Rz is approximated with an error 5-10 % by the formula with the averaged pa-rameters. For samples from concrete materials the error of definition of roughness Rz can make 1 %, that is less on the order than an error of the profilemetric measurements. It is shown, that the method of the surface roughness quality monitoring by factor of the light reflection in a mirror direction is most effective for surfaces, typical for finish diamond-abrasive machining.

A study of the influence of surface roughness on the angular diagrams of reflection and scattering has revealed that the reflection diagrams for structure inhomogeneity materials consist of a narrow peak, a pedestal and some peaks due to speckle clusters. The scattering indicatrices for these materi-als depend on the surface roughness quite differently; this is attributed to the textured surface of structure inhomogeneity materials, which makes the scattering indicatrix consist of two components: reflection (scattering) from relatively homogeneous zones of the texture formations and scattering from the boundaries of these zones.

As the result of researches on index of reflexion of processed material in case of polishing and re-searches on condition of surface of the tool it is determined that their periodical changes are con-nected with process of deposit formation. Dependencies of index of reflexion of the processed mate-rial on time of polishing are obtained experimentally and approximated by periodical functions.

Possibility of active quality assurance of precision surfaces in the course of processing is shown.

8082-123, Poster Session

Novel method for automatic filtering in the Fourier space applied to digital hologram reconstruction

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Spatial filtering techniques are used in the analysis of interferograms and off-axis digital holograms to obtain the phase information from an optical field. The masks applied for the selection of the virtual image order in the frequency space usually have regular shapes and are located by hand. Therefore, they create artifacts that hide some details in the obtained phase, especially when holograms from objects with sharp edges are reconstructed. In this work, a novel algorithm that automatically calculates and locates the mask separating the spectral orders is presented. This new method uses a distance criterion between the maximum values in the amplitude spectrum as a clustering parameter. The values for the distance parameter are changed and the results are analyzed for a simulated image-plane hologram. As an example of the algorithm application, a digital hologram obtained from one USAF-1951 test target is reconstructed and the phase of the test target element is obtained.

8082-124, Poster Session

Mutliresolution analysis of ground surfaces seen in angle-resolved light scattering measurements

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Machined surfaces may be affected by undesirable topography features, e.g., industrially ground surfaces often have a characteristic surface structure named chatter marks. It is known that angle-resolved light scattering techniques are suitable to properly monitor industrial grinding processes, namely that it is possible to reliably determine the topography of ground surfaces. Therefore this optical technique is frequently used in combination with the fast Fourier transform (FFT) to characterize these undesired chatter marks over the entire mapped profile. The FFT, however, introduces unrealistic artifacts, whenever the surface structure is not strictly periodic and/or localized defects occur. To overcome this difficulty of optical data processing, in the present contribution, the multiresolution analysis (MRA) is applied by means of the lifting scheme, i.e., based on second generation wavelets.
It is shown in this manner that chatter marks, for example, can be unambiguously identified by applying the mutliresolution analysis to the angle-resolved light scattering data, even when FFT fails to do this, and hence this procedure opens new opportunities for optical online control of industrial surface finishing processes.

8082-125, Poster Session

Digital holographic microscopy for dynamic imaging of hydrogels

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Hydrogels are formed by crosslinking polymer chains through physical, ionic or covalent interactions and have shown many potential applications in actuators, artificial muscles, sensors and biomedical materials. It is important to study microstructures of hydrogels, for they determine the physical and mechanical properties. However, there are few imaging methods to characterize the microstructure of hydrogels, especially when samples are immerged in liquids.

The microstructures of the samples are conventionally studied by scanning electron microscopy (SEM); this technique requires fully-dried samples because the investigation has to be carried out under high vacuum conditions. The removal of liquid could cause the collapse in the hydrogel, as well as the destruction of the microstructure in the process of ice-dry. A typical image obtained by SEM is presented in Fig. 1. Optical microscopy can be also used in hydrogels measurement, however hydrogels are generally transparent and do not bring obvious change to the amplitude of the light beam passing through them, therefore, it is difficult to image them with conventional microscopy. The phase information of transparent objects can be obtained by using a phase contrast microscope; however it does not work well with thick specimens and limits the numerical aperture of the optical system. Digital holographic microscopy is an effective way for three dimensional imaging and allows to simultaneously retrieve the phase and amplitude of the tested objects with sub-micrometer resolution.

In this paper, a digital holographic microscopic setup is used to record the dynamic process of swells in the presence of alcohol and shrinks in the absence of alcohol. The size of the investigated hydrogel sample is 4mm×4mm×3mm. In the setup, a 40× microscope objective with NA=0.75 is used to magnify the sample. For the experiment, we use a He-Ne laser with wavelength λ=633 nm as the light source. The resolution of the system is 0.77λ/NA= 650 nm. The digital hologram is recorded by a CCD with 2452(H) ×2054(V) pixels; the pixel size 3.45 μm ×3.45 μm and the frame rate 15 fps.

Since the focus depth of the objective is short, it is difficult to get a focused image of a rough surface only through mechanical adjustment. Besides that, floating in the liquid, swelling and shrinking of the hydrogel make it more difficult to obtain focused images during long time recording. In this paper, focus is done numerically by adjusting the distance between the hologram and the focused imaging plane, without mechanical movement.

The intensity distributions of the sample are shown in Fig. 2. From those figures, it can be seen that different sections of the sample are focused at different depth. After a drop of alcohol falls onto the sample, a series of holograms are recorded dynamically. The intensity images included in the marked section of Fig. 2 (b) are reconstructed at different recording time (see Fig.3). It can be seen that the dimensions of the holes expand (compare images recorded at T=0 s and T=153 s), when the sample absorbs the alcohol. With the evaporating of the alcohol, the dimensions of those holes shrink (compare the images record at T=153 s and T=426 s). From the complex amplitude, we can get the phase distribution at T=0 s, T=153 s and T=426 s, denoted as ϕ0, ϕ153 and ϕ426. The phase difference of a part of the sample

(included in the dashed line of Fig.3) between ϕ0 and ϕ153, and between ϕ153 and ϕ426 are shown in the Fig. 4(a) and (c), respectively. The plot along the solid black line in Fig. 4 (a) and (c) are shown in the Fig. 4(b) and (d), respectively, we see a strong phase change in the swell process than in shrink the process.

Numerical focus was used in dynamic imaging of hydrogel sample, by which the different region of the rough object surface can be numerically focused and the phase change in time can be obtained. This method can also be used to study optical properties of hydrogels under different temperature or pressure.

8082-126, Poster Session

Determination of the characteristics of the surface of objects at optical remote sensing by the polarization-holographic imaging stokes spectro-polarimeter

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The information on the state and degree of polarization of light scattered or reflected from the surface of different objects can give the possibility to idetify these objects and to receive additional information about their characteristics. For this reason a polarimetric method seems to be promising because it provides an additional channel of information for identification of an object by finding the distribution of polarization state on its surface. Information on the polarization state of light scattered or reflected by objects plays an increasing role in remote sensing, astropolarimetry, object recognition and others. From this point of view, the development of simple, precision and real-time method of full polarimetry for the determination of polarization state and also the distribution of polarization state on images of different objects, taken into account also a dispersion of this distribution, is rather urgent.

The method of real time complete analysis of polarization state of light (determination of all the four Stokes parameters) by means of polarization-holographic element based on the different type of polarization-holographic gratings was offered. Such an integral polarization-holographic element have many advantages compared to conventional devices of polarization optics: they make it possible to carry out the polarization analysis and transformation of light in real time; they operate in a wide spectral range and do not require making mechanical moving and rotations or tuning of electronic units in working process. Besides, the use of an integral element allows the distortion of the polarization state to be eliminated which inevitably appears when using sequentially several polarization-holographic gratings, and also in polarimeters of other types. Real-time polarization-holographic imaging Stokes spectropolarimeter (PHISSP) was developed in which only one integral polarization-holographic element is used as an analysing detail. The important advantage of PHISSP is its extraordinary simplicity and compactness, which is especially important for its installation on the flying vehicles.

In the suggested work the possibility to recognize the material of different objects is considered by means of PHISSP at a passive optical remote sensing. The theoretical model was developed which allows to establish the correlations between the physical and chemical properties of recognizable object and the distribution of polarization state on its surface. At present the function pBRDF is used to determine the characteristics of the surface material and several measurements is required at different observation angles.The developed theoretical model uses a modified Kirchhoff integral and the matrix of direction cosines both of the illuminating light beam and reflected one. A scheme is suggested for determining the direction cosines in the direction of the reflected beam. This enables to carried out the identification only by one angle of incidence of light on the object and by one angle of observation. In addition, as the surface of the object transforms the incident non-polarized light into polarized, we used the Jones matrix to describe the surface. This matrix includes the refraction and absorption coefficients of the material. The Jones matrix of an anisotropic reflecting surface between two media was obtained. The reflected light beam incident on the analyzing polarization-holographic element of the PHISSP, which decomposes it into an orthogonal basis of circular and linear polarization. In addition, since the element has an angular dispersion, it decomposes each diffraction order in the spectrum. Simultaneous measurement of the intensities of the diffracted beams allows all four Stokes parameters to be determined (and the parameters of the polarization ellipse corresponding to them: ellipticity, azimuth, and the direction of rotation, as well as the degree of polarization) and the dispersion of this state by means of the obtained formulas. A relation between the Stokes parameters of light reflected from an recognizable object with characteristics of the material of the reflecting surface of the object is obtained that allows to define the appropriate correlation relation. A laboratory model was developed for experimental testing of this approach using samples with surfaces from different materials.

8082-127, Poster Session

Particle concentration effect on diffraction efficiency in two views off-axis holograms

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Characterizing tracer micro particles in fluids is of a great challenge for digital holographic techniques [1, 2]. The real locations and the number of these particles are the main parameters in such studies. For the first parameter, holographic techniques are very useful, unfortunately, they suffer from the large depth of focus [3, 4] which increases the location uncertainty of the particles. To minimize this uncertainty, we proposed a two orthogonal views system [5] which, from our point of view, makes the location more precise by crossing the two views data in the reconstruction process. For the second parameter (particle number), off-axis configuration is recognized to be more convenient for large particle numbers than the in line configuration. In order to validate the effectiveness of the off-axis configuration in terms of number of tracer particles, we carry out some experiments. The number of particle was increased continuously after each recording. We have also tried to keep unchanged the experiment conditions during all the recording process. In the present work, we describe the manner in which the experiments were conducted and the obtained results in term of diffraction efficiency of the reconstructed holograms.

[1] K D Hinsch, Meas. Sci. Technol. 13 R61-R72 (2002)

[2] M. Adams, T.M. Kreis ; W.P.O. Jüptner, SPIE Vol 3098

[3] S. Murata; M. Kawamura, Optics and Laser Technology 31 95-102, 1999

[4] S. Kim; S.J. Lee, Exp Fluids 44 : 653-631, 2008

[5] Boucherit S., Bouamama L., Benchikh H., Lenoir J. M. and Simoëns S.; Optics Letters 33 2095-2097, 2008

8082-128, Poster Session

Material tests using the ARAMIS system: a laboratory report

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Since 2009 there is a collaboration between the Civil Engineering and the Geomatic departments at the HafenCity University Hamburg (HCU Hamburg).

The main subject of the cooperation is the application of the industrial measurement technology in materials, building elements and building assembly tests, which are analyzed in the laboratory of Engineering Mechanics at the Department of Civil Engineering.

Optical methods are now often used in the measuring technology. These methods have the great advantage that the inspected objects are measured contactlessly with a high repetition rate. The obtained data can be evaluated in almost real-time or in post-processing. This allows the reckoning of deformations in real-time, as well as the three-dimensional representation and the documentation of the whole process of deformation.

We started the tests with an existing classical photogrammetric system. At that attempt, the employed hydraulic cylinder had to be stopped for the capture of the necessary pictures, which is not the normal application flow in this kind of experiments. The data acquisition must be carried out continuously without interfering with the experiment and the analysis of the data should also be possible in real-time.

The ARAMIS-System by GOM-Braunschweig fulfilled the wanted properties and has been used experimentally for the study of deformations (crack development) on a reinforced concrete beam.

The test was conducted in real-time as a three-dimensional measurement, the detection of deformations and the different ways to represent the results are convincing. Here, small changes (strain measurement accuracy up to 0.01%) are recorded with up to 29 Hz on surfaces up to a few square meters.

Since May 2010 the ARAMIS-System is available at the HafenCity University Hamburg. Since then many material investigations were carried out with the new system parallel to the conventional methods (transducers and strain gauges). The presentation shows an overview of the conducted work up to date, a comparison with the conventional methods and the new knowledge gained through the trials.

8082-129, Poster Session

Calibration routine for in-process roundness measurements of steel rings during heat treatment

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Heat treatment represents one of the last steps in an industrial production process of steel component parts. Workpiece temperatures above 900 °C are usually reached during the heat treatment process. It often leads to workpiece distortion, due to induced distortion potential during the preceding production process. This undesired effect can be minimized by costly finishing treatments like grinding. In case of steel rings, e.g. bearing rings, it mainly appears as roundness deviation.

The Collaborative Research Center 'Distortion Engineering' (SFB570) of the German Research Foundation investigates the origin and the cause of distortion along the entire production chain in order to develop compensation strategies. To achieve this, a furnace and a gas nozzle field are specially designed with the ability to respectively heat and quench a ring symmetrically or asymmetrically. Therefore, both devices are able to induce thermally generated 'counter' deformation to compensate the roundness deviation of a distorted ring.

To avoid overcompensation, an in-process-measuring system based on laser triangulation is applied to the furnace. It employs six evenly distributed displacement sensors along the outer ring surface. Each sensor consists of a fiber coupled green (532 nm) laser and a CCD-camera. The measurement system provides information about roundness deviation up to the second fourier order.

This paper reports on the calibration routine developed for an absolute measurement of the ring mean diameter and the ring ovality. The lack of precise information about the exact position and direction of the sensors and the minimal accessibility to the ring in the furnace is challenging and leads to a complex calibration routine. The calibration includes the application of gauge rings with different diameters. The developed routine is described and calibrated measurement results are compared with coordinate measurement machine data. Concerning the ring radius (~ 72.5 mm), the comparison exhibits a standard deviation in the lower two-digit micrometer range.

8082-130, Poster Session

New type of color-coded light structures for an adapted and rapid determination of point correspondences for 3D reconstruction

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The 3D surface reconstruction in industrial environments requires rapid, accurate and robust methods. Such techniques are based on the determination of the correspondences between the camera and the object. Conventional depth information retrieval approaches use different lighting modalities in order to accurately determine the correspondence between the sensor and the surface. Such particular time consuming operations are therefore not ideally suited in case of reconstruction of moving objects. Reducing the number of necessary recordings, ideally to only one, is the major role of complex coded-light structures. Color plays an important role, as it permits the improvement of spatial localization of reference points. Different methods are proposed in the literature. These are based on the computation of a color coded matrix permitting the unique identification of a certain number of points.

In this paper a new type of spatial- and color-coded light structures, permitting the point correspondence determination with only one recording, is proposed. The novelty of the proposed method consists of defining structures made of spatially independent groups of reference points. This permits to project the necessary group of reference points only on the surface regions to be reconstructed, which offers a higher flexibility than with the conventional coded light matrices. Indeed, with our adapted and optimal point repartition method, all the projected points contribute to the depth information retrieval. As a consequence, in case of preliminary segmentation of free-form regions of interest to be 3D reconstructed, free-form adapted coded light structures can be used. We show that by using the same number of colors, our code permits to identify a similar amount of points as the matrix-based does. The a priori assumption is that the intra-group spatial distance (between each point of a group) is lower, i.e. is easily distinguishable, with the inter-group spatial distance (between each surrounding points of the groups).

The point correspondence algorithm consists of a stepwise approach based on simple and adapted solutions. This permits a fast, robust and general method for real-time industrial inspection processes. The adaptation of the method to complex environments concerns:

- the robust segmentation by adapted 2D functions, such as Gaussian ones, of the colored dots representing each point position. This enables to reach sub-pixel precision even in case of unavoidable optical or object related geometrical image deformations, - the spatial identification of each group by means of distance-based thresholds. This reduced local spatial relation makes the method robust to occlusions or e.g. perturbing glares,

- the use of adaptive color thresholds preceding a normalization in the color space, in order to overcome color distortions induced by the projector or the surface. This allows the threshold-based determination of the real point color value for a specific color transfer function of the systems.

The correspondence is done for each spatially identified group. The points of the group can be ordered or randomly arranged. In the first case, the assumption is that the transformation between projected and observed images preserves the arrangement of the observed points, which can therefore be deduced by simple computations. In this case each point is uniquely identified. In the second case, i.e. if the spatial distortion induced by the surface does not preserve this arrangement, only each group is uniquely identified. This reduces the number of points that can be coded by a factor of p, the number of points for each group. An example based on the overlapping region determination is provided for the first one.

For practical applications, the intrinsic parameters of the method, number of points p and colors c, but also the spatial point repartition can be adapted in accordance to the set-up and surface characteristics. Important factors are the projector size, the degree of surface geometrical complexity, reflectance, color, etc. Our method shows similar results as those depicted in the literature, with the major advantage, that the point repartition can be free-formed and adapted to application specific demands.

8082-133, Poster Session

AFM nanometrology interferometric system with the compensation of angle errors

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The contribution is oriented towards measuring in the nanoscale through local probe microscopy techniques, primarily the AFM microscopy. The need to make the AFM microscope a nanometrology tool not only the positioning of the tip has to be based on precise measurements but the traceability of the measuring technique has to be ensured up to the primary standard. This leads to the engagement of laser interferometric measuring methods. We present a improved design of the six-axes dimensional interferometric measurement tool for local probe microscopy stage nanopositioning with the compensation system of angle errors. The setup is powered with the help of a single-frequency frequency-doubled Nd:YAG laser which is stabilized by thermal frequency control locked to a Doppler-broadened absorption line in iodine. The laser stabilization technique is described together with comparison of frequency stability and angle errors compensation system performance.

8082-134, Poster Session

Noncontact interferometric technique for calibration of coordinate measuring machines

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The aim of our work is to present a new interferometric technique for calibration of the 3D coordinate measuring machines (CMM) using a two-point standard of length, which is formed, for example, by two precisely fabricated spheres or parts of spherical surfaces connected by a bar (ball bar) or by an array of spherical surfaces (ball plate). The distance between these spheres remains constant regardless of the orientation of the bar or plate. An accuracy of such length standards is not dependent on mounting of both spheres to the bar or plate, but it only depends on the precision of coupled spheres. The length that is represented by the length normal is given by a distance of centers of both spheres, i.e. the distance between two points in Euclidean space. This value of length is constant and does not depend on orientation of length standards with respect to the measurement device, which is a large advantage of such length standards. We present a novel calibration technique of the 3D coordinate measuring machines using a standard of length (ball bar, ball plate) which is not being used yet and we propose a design of a new construction of length standards (ball bar, ball plate) for calibration of 3D coordinate measuring machines. The proposed optical technique of determination of the center of the ball bar uses as a sensor a small spherointerferometer and we measure the centre of curvature of the spherical surface. General formulas are derived that make possible to calculate an accuracy of the centre position of the spherical surface, which is used for the length standards. An analysis of the proposed method is described based on the third order aberration theory. The proposed technique can be used as a practical tool for a simple, rapid check of a positioning performance of 3D measuring machines allowing users to benchmark and track the performance of their machines and to quickly diagnose problems that may require maintenance and the error sources that produce them.

8082-135, Poster Session

Submicron displacement measurement by measuring autocorrelation of the transmission function of a grating

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The significance of precise measurement of small displacement is clear and apparent. Many People have measured length and displacement by different mechanical, optical and electronic methods since many years ago. Different optical methods such as optical, electron and scanning microscopes, image processing techniques , interferometeric methods , optical fiber sensors and moiré technique for measuring small displacements are interested due to high precision and minimum effect on measurement result.

Interferometric techniques are very sensitive to environmental noise and require high precise and complicated instruments and set up. Nowadays, the electron and scanning microscopes are commonly used for surface analysis. Considering the high precision of them, on-line study of time variable phenomena by these expensive devices seems difficult. Optical fiber sensors are utilized for different measurements .Their disadvantages are displacement measurement in a small interval and their limited application.

Moiré technique can be applied for measuring small displacement easily without requirement for expensive instruments. By superimposing two gratings and displacing one of them with respect to the other, moiré fringes shift. The relative displacement of the gratings can be evaluated by counting the shifted moiré fringes. Considering limitation in generating a grating by very small pitch, the method of counting moiré fringes is not useful for measuring submicron displacement.

When two parallel gratings are superimposed, the transmission function of them varies with the displacement of one grating with respect to the other. The transmitted light intensity versus displacement is proportional to the autocorrelation of the transmission function of the gratings. In this paper, it is shown by measuring the latter function for gratings of pitches in order of a fraction of millimeter, submicron displacements can be measured.

In experimental set-up, a grating is fixed and the second one is displaced with respect to the other. The moving one can be connected to a system that variation of length occurs in it mechanically.

A uniform beam of light with constant intensity is irradiated the pair of gratings and transmitted light focuses on the detector by the condenser lens. The displacement can be evaluated by measuring the variations in output of the detector. The used gratings are not ideal, so in the neighborhood of maximum and minimum points of the intensity curve, variation of intensity versus displacement is nonlinear. But in the interval between them, the variation is approximately linear. Choosing this region of the curve- about turning point- conduces to easier measuring and no need to calibration of system

We see that a displacement in order of 0.6 micron can be measured by evaluating autocorrelation function of a pair of gratings with d=0.6750 mm. The precision of this technique can be increased easily by decreasing the electronic and environmental noises and increasing the detector gain, light intensity and grating effective area.

This method is not expensive and complicated and it is not sensitive to environmental vibrations. Also, it can be applied to measure time variable phenomena. It is useful for on- line control of phenomena and variations in materials and systems.

8082-136, Poster Session

Optimized dust-proof optical fiber sensing system for real-time monitoring of frequency, phase and vibration of rotating parts

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In industry, the commonly used vibration or rotation sensors are piezoelectric accelerometers, MEMS, inductive, capacitive or optical sensors. Although, in some specific plants such as oil refineries there is no possibility to use these kind of sensors due to some typical disadvantages. Piezoelectric sensors and other sensors with electric elements inside sensing head are sensitive to electromagnetic noise and temperature changes, they may cause risk of fire and are unable to measure low-frequency vibrations. Also most of optical sensors have short connection between head and apparatus, which is also a disadvantage in some cases. For some special applications in industry, there is need to adopt other kind of vibration or rotation sensors.

This paper presents the optimized optical fiber sensor as a device allowing real-time monitoring of rotation of industrial machines parts such as shafts, impellers, compressors, mixers, etc. With proper configuration it continuously monitors the rotation frequency and phase, and thus synchronize the work of separate parts of machinery.

Construction of the sensor head is based on a system of two suitably prepared optical fibers. The main principle or work is similar to standard open-head reflective sensors, but in this case head is shielded by special protective glass and immersive layer. In most other commercial optical sensors, the fiber bundle and the LED light source are commonly used, therefore it strongly limits the distance between photo-detector and measuring head. Proposed sensor uses laser light and only two fibers which allows to place the sensing head far from the measuring equipment. Experimental results show that the sensor works correctly even on distance of hundreds of meters.

One of the fibers is single-mode and acts as a transmitting fiber,

illuminating small area of surface of the tested object. The second fiber is multi-mode and acts as a receiving fiber. In the transmission branch the SM fiber is used to overcome the impact of interference effects between the modes when using light with a high temporal coherence. In the receiving branch MM optical fiber is used to maximize the amount of light returning to the detector. Possibility of using standard telecom fibers significantly reduce the cost of sensor head production. Wavelength of the light source can be adjusted to the specific customer needs. The sensing head is designed to be able to operate in dusty environments or in immersion. Head itself is also not sensitive to electromagnetic noise in contrast to piezoelectric sensors. The low level of optical power transmitted through the fibers and lack of electric elements in the sensing and transmitting part does not cause a risk of fire, which is very important in some specific industry environments like oil refineries.

In our experiment we used rotor with 20 blades as tested object. While testing we measured exact shape of each rotor blade during every turn. It allowed to monitor the state of every blade. It gives precise data about wear of the mechanical parts. The accuracy of measurement was stable in long time of work, which was also proved in long time experiment. Also we measured slow changes of rotation axis caused by misalignment, as well as amplitude of rotor beating dependent terms on its angular velocity.

The sensor, together with dedicated software, can bring out from the signal an information about the precise frequency, phase, and every adverse movements of the element. This allows user to early detect bearings wear, structural defects causing precession of the axis of rotation and beating of shafts or other rotating parts of machines. The presented sensor also allows to measure angular velocity and acceleration of rotating parts during constant work or even during initiation or completion of machines work. Also, presented sensor does not have a bottom-up limitation of the frequency as in the case of piezoelectric sensors. Since the presented head operates without any contact with machine, there are no affects on the operation of the machine, such as in case of attached piezoelectric or inductive sensors. Therefore, the optical fiber sensor can be used to measure the rotation of very small parts, where no piezoelectric or inductive sensors can be attached because of its size. Additional advantages of the sensor are insensitivity to temperature changes and lack of perishable mechanical parts.

8082-137, Poster Session

Optical sensor based on combined GI/DSPI technique for strain monitoring in crucial points of big engineering structures

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The data from a monitored structure/object should be easy acquired, processed and sent to the user, who can asses the health of a structure in short time and schedule necessary maintenance in order to prevent accidences. Systems which provide such information are fundamental for Structural Health Monitoring (SHM).

In the paper novel optical sensor designed for in-plane displacement and strain monitoring in crucial points of a big engineering and civil structures is presented. It combines two techniques: Grating Interferometry (GI) and Digital Speckle Pattern Interferometry (DSPI). GI requires specimen grating attached to the surface of an object under test. It is the unique technique which may provide the information about fatigue process and increased residual stresses. DSPI works with a rough object surface but due to differential measurements cannot be simply used for long time monitoring but to explore the actual behavior of a structure.

The sensor which combines these techniques provides user with wide possibilities concerning functionality, measuring range, object surface and environmental conditions. The crucial issue in implementation of this sensor is the choice of its location(s) at the investigated structure. Therefore it is proposed to be as one of the elements of hierarchical sensors net, which gives complete information about structure state. As the method for supporting the choice of GI/DSPI sensor location we proposed the system based on 3D digital correlation method.

The paper presents detailed mechanical and optical sensor design along with laboratory tests of main component such as sensor heads in form of monolithic (plastic) and cavity waveguides.

Finally the application of proposed sensor in combination with 3D DIC system is presented at an example of an engineering structure investigation.

8082-138, Poster Session

Mueller matrix imaging of plasmonic polarizers on nanopatterned surface

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Standard Spectroscopic Ellipsometry (SE) and recently also spectroscopic Mueller Matrix Ellipsometry (MME) has for a long time been the technique of choice for the inspection of surfaces, thin films and recently also nanostructured surfaces, due to the enhanced phase sensitivity introduced by the measurement of the phase difference between p and s polarized light. Most semiconductor processing factories will perform a large number of ellipsometric measurements during the production. A fundamental problem of SE has been the standard spot size, which traditionally has been on the order of 1-4 mm in diameter. Such a large spot size is often incompatible with research quality samples, and also for in-line monitoring of the homogeneity of a process. Such an issue becomes further important, when the process is a low cost fabrication method which requires stricter attention to homogeneity issues. The standard ellipsometer may partially recover some of its deficits by aiming at a micro-spot, which will typically be of the order of 100 micrometer in diameter, at the cost of much reduced flux due to the lack of commercially available incoherent sources with a high radiance. The use of laser sources could allow a true microspot ellipsometer. However, a complete overview of the sample will require a complete spatial mapping, where the mapping time scales with the spot size. The imaging ellipsometer, and in particular the imaging MME, may be the response to many of these issues, allowing better process control. In this presentation, a fast near infra red Mueller Matrix Imaging Ellipsometer (MMIE) is applied to the characterization of plasmonic polarizers. The MMIE is based on two waveplates and two Ferroelectric Liquid Crystals in the polarisation state generator, and similarly (in reverse order) in the polarisation state analyzer [1-3]. The MMIE is designed to be achromatic for 800-1700 nm, and can thus be adapted to spectroscopic ellipsometery. Evidently, due to its achromaticity, it may be further used for spectroscopic near-infra-red imaging.

We here focus on the interesting subject of imaging plasmonic polarizers prepared by evaporation onto SiO_2 ripples. The nanostructured ripple surface has been produced by ion beam sputtering at a grazing angle of incidence [4,5]. Au has thereafter been evaporated onto the surface at an angle. As a result, thin lines of nearly connected Au nanoparticles form along the illuminated side of the ripples, giving large in-plane anisotropy of the structure. The task of the ellipsometer, is to determine the lateral uniformity of the optical signal in correlation to the real space topography of the sample, and to determine to what degree the nanoparticles tend to form a connected wire, or whether there are well separated Au particles. The success of this method in order to produce polarizers, lies in controlling the process to allow well connected lines of Au particles along the ripples, with a high degree of homogeneity. Mueller Matrix images of the sample recorded at normal incidence are shown, and the information that can be extracted from these images is discussed. For light polarized with an electric field parallel to the wires/ripples, the optical properties of the structure resemble that of a metal. For an in-plane electric field normal to the wires/ripples, the optical properties are drastically different, with a surface plasmon resonance around 600 nm. For longer wavelengths the structure has optical properties resembling an imperfect wire polarizer, with increasing diattenuation with increasing wavelength. The Mueller matrix images contains the complete information of how the sample alters the polarization of light, with a spatial resolution of around 15-30 μm. Large inhomogeneities are observed both in diattenuation and the retardance for different parts of the nanostructured surface, indicating that the structures are highly inhomogeneous. Diattenuation values ranging from -0.4 to -0.6 are observed within the area of a standard spectroscopic ellipsometer spot, which would lead to significant averaging and depolarization effects.

[1] J. Ladstein, M. Kildemo, G.K. Svendsen, I. S. Nerbø, F. Stabo-Eeg, M. Lindgren, 'Characterisation of Liquid Crystal Retarders for

broadband optimal design of Mueller matrix ellipsometers,' Proc. of SPIE 6587 (2007) 65870D1.

[2] L. M. Aas, P. G. Ellingsen, M. Kildemo and M. Lindgren, M. 'Dynamic response of a fast near infra-red Mueller matrix ellipsometer', J. Mod. Opt. 57 (2010) 1362.

[3] L. M. Sandvik Aas, P. G. Ellingsen, M. Kildemo, 'Near infra-red Mueller matrix imaging system and application to strain imaging,' Thin Solid Films (In Press, 2010). http://arxiv.org/abs/1009.5549v1

[4] A. Toma, D. Chiappe, C. Boragno, and F. Buatier de Mongeot, 'Self-organized ion-beam synthesis of nanowires with broadband plasmonic functionality,' Phys. Rev. B 81 (2010) 165436.

[5] A. Toma, D. Chiappe, D. Massabò, C. Boragno, and F. Buatier de Mongeot, "Self-organized metal nanowire arrays with tunable optical anisotropy" Applied Physics Letters 93, 163104 (2008)

8082-139, Poster Session

Measuring the performance of visible, NIR and LWIR optical components: a reliable robust high-accuracy lens measurement system

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The expansion of the world economy has enabled easy access to suppliers of optical components and systems throughout the world. Unfortunately, all manufacturers do not adhere to the same quality standards, so the need for accurate and cost effective inspection has never been greater. To address this growing demand, an economical platform for evaluating the performance of visible, NIR, and LWIR lens assemblies has been developed and will be presented.

Discussion: The measurement system allows the operator to confirm the basic performance of an optical component or system and assess more complicated performance requirements. The system can be configured to automatically measure any variety of an optical system's first order properties (focal length, back focal length), on and off-axis imaging performance (e.g., MTF, resolution, spot size), and third-order aberrations (field curvature, distortion, astigmatism). A broadband light source and multi-position filter wheel enable lens and system testing using the spectral distribution encountered in actual use. It is not restricted to specific wavelengths and enables characterization of the various chromatic effects (longitudinal and lateral color, spherochromatism) that simply are not available with monochromatic interferometric testing. The system incorporates patented video capture technology using state-of-the-art CCDs and uncooled microbolometers to cover the visible, NIR, and LWIR spectral bands. This allows real time determination of the optical system performance enabling faster measurements, higher throughput, and lower cost results than traditional knife-edge scanning systems.

With space at a premium in most manufacturing and testing facilities, the system's table top footprint is less than 4 ft2 (< ½ m2) allowing it to be located on a standard work bench; a floating table is not required. It is portable and can be readily relocated and reconfigured for testing within a few minutes.

Frequently, catalog optical components have tolerances in focal length and centration accuracy that require evaluation of the first order and imaging properties of the lens prior to installation to a system. For example, manufacturers of medical diagnostic equipment frequently incorporate off-the-shelf components including singlets, doublets, microscope objectives, etc. Before mounting and aligning such components into a high value assembly, it is prudent to confirm the characteristics of those components by measuring their first order properties and confirming their general level of performance: effective focal length (EFL), back focal length (BFL), flange focal length (FFL) and on-axis imaging performance (MTF, resolution, and/or spot size) under test conditions simulating their actual use. In order to space components properly to achieve desired magnification and total track between object and image plane, it is essential to know the precise focal length and principle plane locations in a lens relative to mounting surfaces. Thus, an ability to accurately measure parameters such as focal length, back focal length, and flange focal lengths greatly simplify and accelerate the assembly of these systems making the manufacturing process more predictable and deterministic.

Conclusion: An accurate, real time, reliable, robust measurement system has been developed for the visible, NIR, and LWIR spectral regions to enable testing of key optical parameters by technician level personnel. We describe in detail the methodology and accuracy necessary to carry out useful EFL, F/#, on and off axis MTF, BFL, astigmatism, field curvature, distortion, transmission and relative illumination measurements. Specific lens measurements and test results will be presented to illustrate many of these test parameters.

8082-140, Poster Session

Optical fiber macro-bend seismic sensor for real-time vibration monitoring in harsh industrial environment

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In harsh industrial environments such as refineries there is a need to use sensors which are resistant to electromagnetic noise and does not create fire hazard. Electronic devices have limited application in such conditions. Therefore optoelectronic sensors become more proper solution for machines work monitoring in industry.

This paper presents the optoelectronic sensor for vibration monitoring of equipment and machinery in industry. The sensor is based on macro-bend fiber loop with a seismic mass attached to it. The main principle of operation is similar to the widely used piezoelectric accelerometers to measure vibration and displacement without disadvantages like influence of electromagnetic noise and temperature dependence.

The sensor utilizes the phenomenon of bending losses in optical fibers dependent on radius of the bending. This phenomenon is widely known issue in the case of signal transmission in optical telecommunication. In presented device, this effect is used as an advantage. Signal losses are carrying the useful information about the force acting on the seismic mass from which the acceleration of the object is calculated.

The main element of the sensor is a part of fiber bent into the loop. Changes of the loop shape are causing significant loss of optical power and modulate the optical signal on detector. Geometrical deformation is caused by inertial force acting on the mass attached to the optical fiber. Thus, the output electrical signal is proportional to the acceleration of the tested object. Knowing the mass and the type of the optical fiber we calibrated the sensor to measure absolute value of acceleration, and - by using simple integrating algorithms - velocity, displacement and frequency also. In experiment presented sensor was compared with commercial piezoelectric vibrometer.

Construction of seismic fiber loop sensor head is based on single mode optical fiber. As a light source several types of sources can be used, e.g. laser diodes, VCSELs, LEDs, SLEDs. Coherence of the light has no influence on the work of the sensor. Using standard single mode telecommunication fibers and telecommunication light sources makes the possible device production cost effective.

In appropriate configuration several fiber loop seismic sensors can be made on single optical fiber. Every loop has different resonance frequency due to the fact that a different seismic mass is attached to each one. In this case sensor matrix measure and localize source of pulse vibration. Experiment shows that the pulse spectrum has to be wide enough to stimulate all seismic loops and repetition time need to be long enough for loops to relax. After applying Fast Fourier Transform and some further calculations on the signal from photodetector the approximate localization and strength of the pulse is measured.

Unlike piezoelectric sensors the measuring head of presented sensor can be away from the light source and photodetector at a distance of hundreds of meters without the need for signal amplification and reconstruction through using optical fiber connection. Device utilizes low power level optical source and there is no electric parts in the sensing head. Therefore it does not cause fire hazard and does not create a risk of explosion which may be a significant issue in environments such as oil refineries. Also the head is insensitive to electromagnetic noise and the influence of strong magnetic or electric fields. The presented sensor has a chance to compete with commonly used piezoelectric sensors, and in some specific cases it may exceed them with measurement abilities.

8082-141, Poster Session

The Ronchi test using a liquid crystal display as a phase grating

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The Ronchi test with a Liquid Crystal Display (LCD) is used for testing convergent optical systems, where the LCD was employed as a phase Ronchi grating. The rulings are computer-generated (horizontal and vertical ones) and displayed on the LCD. We prove that it is possible to make a variable electronically phase grating by using an LCD. By displaying various phase-shifted rulings and capturing the corresponding ronchigrams, vertical and horizontal wavefront phases are obtained with four steps conventional phase-shifting and unwrapping phase algorithms. Experimental results are shown.

8082-142, Poster Session

High temperature sensing with FBGs using a tunable laser interrogation system

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Within an ESA funded project combustion chambers of Ariane V rockets are investigated for further development. Since temperature gradients of approximately 1300 K/mm occur in the combustion chamber during launch, material damages occur because of the Doghouse effect. To avoid these damages, the combustion chambers have to be redesigned wherefore the occurring temperatures have to be known very precisely. In order to measure the temperature in the small layer between the hot exhaust emissions and the coolant, optical fiber sensing is deployed. Embedding special optical sensor fibers that are high temperature suited within the material allows measuring the wall temperature directly. This is one of the main advantages compared to electrical sensing.

In order to demonstrate fiber optic sensing for high temperature and strain measurement, Thermo Mechanical Fatigue (TMF) panels, constructed as sandwich structure have been developed. TMFs consist of silver alloy and nickel layers with embedded optical fibers that represent the combustion chamber walls. One panel has been subjected to thermal loads up to 1000 K inside a high temperature oven. Online measurements of FBG sensors inscribed in the embedded optical fibers have been carried out. The measurement results of the FBG sensors exactly match the electrical reference.

In order to read-out the FBG sensors during thermal cycling of the TMF panel, our newly developed FBG interrogator system based on a tunable MG-Y (modulated-grating, y-structure) laser diode has been used. The MG-Y laser is controlled by a set of three currents. These currents are provided by a current control unit (CCU) which has been developed in order to improve the accuracy and stability of the interrogator. Because of non-equidistant sampling, a special centroid algorithm is needed to evaluate at high accuracy [1]. Up to eight FBG sensors that are inscribed in one single optical fiber can be read-out by the scanning laser. Three sensor fibers can be connected which allow measurement of up to 24 sensors in parallel. Due to its overall optical bandwidth of more than 40 nm, the interrogator is well suited for high temperature sensing with a measurement rate of up to 1 kHz. Based on the high temperature stability of silica fibers, our sensing system is able to measure temperatures within the range of 200 K to 1100 K. The applied temperature differences of more than 700 K resulted in a wavelength shift of the FBG sensor responses of more than 9 nm. The evaluation of the measurement results revealed a temperature accuracy better than 1 % within the entire measurement range.

Within this paper we present high temperature measurement results of FBG sensors. It is shown how the FBG sensors are calibrated in order to achieve high accuracy. Error estimation is shown that proof the accuracy of the measurement results. Furthermore P-Spice simulation results of the current control unit are shown and compared with measurement results. The CCU significantly improves accuracy and overall sensor measurement rate of our interrogation system.

[1] Müller, M.S.; Hoffmann, L.; Bodendorfer, T.; Hirth, F.; Petit, F.; Plattner, M.P.; Buck, T.C.; Koch, A.W.: Fiber Bragg Grating Interrogation based on monolithic tunable laser diode.

In: IEEE Transactions on Instrumentation and Measurement, accepted for publication, 2009.

8082-144, Poster Session

Interferometric multiwavelength system for long gauge blocks measurements

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This paper describes common efforts of Warsaw University of Technology and Polish Central Office of Measure to build a multiwavelength interferometer with extend measurement range to calibrate long, up to 1 meter, gauge blocks. To achieve this goal modified automatic fringe pattern analysis method based on fringe fraction method is proposed. The opto-mechanical setup of the interferometer together with the system for active control and monitoring of environment parameters as temperature, pressure, humidity and concentration of CO2 is described. Finally the result of interferometer calibration and measurement error analysis is given.

8082-145, Poster Session

Evaluation of thermal expansion coefficient of Fabry-Perot cavity using an optical frequency comb

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In construction of highly mechanical stable measuring devices like AFM microscopes or nano-comparators the low expansion materials are very necessary. We can find Zerodur ceramics or ULE glasses used as a frame or basement of these devices. The expansion coefficient of such low-expansion materials is better than 0.01 x 10-6 m.K-1. For example in case of a frame or basement 20 cm long it leads to a dilatation approximately 4 nm per 1 K. For calculation of the total uncertainty of the mentioned measuring devices the knowledge of the thermal expansion coefficient of the frame or basement is necessary. In this work we present a method, where small distance changes are transformed into rf-frequency signal. The frequency of this signal is detected by a counter which measures the value of the frequency with respect to an ultra-stable time-base.

This method uses an Fabry-Perot cavity as a distance measuring tool. The spacer of the optical resonator is made from the investigated low-expansion material. It is placed into a vacuum chamber where the inside temperature is controlled. A selected mode of the femtosecond frequency comb is locked to a certain mode of the optical resonator. We monitor the changes of the repetition frequency of the femtosecond comb which represent the distance changes of the optical resonator. The frequency is measured by the rf-counter which is synchronized by a time-base signal from an atomic clock. The first results show the resolution of the method in the 0.1 nm order. Therefore the method has a potential in characterisation of materials in the nanoworld.

8082-146, Poster Session

Development of error estimation method for phase detection in phase shift method

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In this report, error estimation method of phase detection in phase shift method is proposed. Phase detection algorithm extracts sine and cosine components of modulated signal from several numbers of interferogram that acquired during phase shifting. After that, phase

distribution is calculated from these components using arctangent function. The fourier domain expression of phase detection algorithms show frequency response for sine and cosine components. And it shows behavior for phase detection in the case that phase shifting error exists. However, these two response functions, those are response function for sine component and that for cosine component, do not directly show frequency response of phase detection itself. On the contrary, new frequency response function is derived from these two frequency response function. That is based on argument of phase detection algorithm. It shows frequency response of phase detection, directly. And it clearly shows the behavior of phase detection algorithm when phase tuning error exists. In other words, if a phase detection algorithm is not robust to phase detuning, the curve of newly developed frequency response function quickly departs from the appropriate phase, actually that is pi over 4. On the other hand, an algorithm is robust to phase detuning, the curve stay around the appropriate phase. The example of former is 4 buckets algorithm, and that of later is 5 buckets algorithm. The newly developed frequency response function is similar to the Bode plot that is often used in the field of automatic control and so on. Then it is easy to assume that magnitude plot also can be defined. It shows sensitivity for frequency components. Therefore the magnitude plot can be used for prediction of the sensitivity to the signal and noise. And the phase plot can be used for error estimation of phase detection in the presence of phase tuning error. After some investigations, it was found that there is good agreement between the developed frequency response function and calculated error value. Therefore, it can be called as an error estimation method for phase detection algorithm. In an error estimation using computer simulation, phase detection error in the presence of phase shift detuning was calculated. Phase shift detuning was created by adding known error value on the phase step. Using this error estimation method, error plot of several numbers of well known phase detection algorithms were calculated. Those are 4 buckets algorithm, 5 buckets algorithm, Fourier transform method with von Hann window, that with modified triangular window and etc. The modified triangular window was created by authors for wavelength scanning interferometry. When the phase step value is 5 percent bigger than intended value, the calculated errors, those are calculated using computer simulation, are 0.0125, 0.0005, 0.00008 and 0.0002 of lambda for 4 buckets algorithm, 5 buckets algorithm, Fourier transform method with von Hann window and that with modified triangular window, respectively. On the other hand, estimated errors, those are estimated using developed estimation method, are 0.0125, 0.0005, 0.00008 and 0.00021 of lambda for foresaid 4 algorithms, respectively. When the phase step value is 70 percent bigger than intended value, the calculated are 0.2097, 0.1225, 0.0261 and 0.0076 of lambda, respectively. And estimated errors are 0.175, 0.1143, 0.0260 and 0.0076 of lambda, respectively. Apparently, estimated error values are very match with calculated error values. Trial for classification of those algorithms using these results is also reported.

8082-147, Poster Session

Optical vibration measurements of coupling effects in capacitive micromachined ultrasonic transducer arrays

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Plaque in coronary arteries is a leading cause of heart attacks. Today different kinds of plaque cannot be distinguished between in-vivo with commercial equipment. A large research project at the Department of Electronics and Telecommunications at the Norwegian University of Science and Technology aims at developing an ultrasonic imaging sensor for this purpose. Some of the main technological challenges are to make the ultrasonic transducer broadband enough to achieve the necessary imaging resolution and to make the device small enough for intravascular use. A 1.2mm2 array with 7500 transducers has been developed and fabricated. The design of this array is a significant part of the project.

The CMUTs work using the same principle as condenser microphones. The top capacitor plate is a membrane suspended over a cavity with the bottom plate at its base. Applying a strong DC bias deflects the top membrane and vibrations are induced by additionally adding an AC voltage. The most recent prototype of this array is made by transferring an LPCVD grown silicon nitride film to a silicon wafer with cavities using wafer bonding. The top electrode is formed after the transfer by applying a metal layer on top of the silicon nitride. At last the surface is insulated by an additional layer of silicon nitride. Before bonding, bottom electrodes of polysilicon and wafer feedthroughs are added.

The necessity to characterize the transducer array in great detail for the development process motivated the construction of an optical system for high frequency vibration measurements. The setup is a heterodyne interferometer, where a frequency shifted reference beam interferes with an object beam to form a beat pattern. The phase modulation of the object beam caused by the vibrating sample, transfers to the beat pattern which is analyzed using lock-in amplifiers and computer software. This allows measurements of vibrations up to 1GHz. A noise floor as low as ~1pm/√Hz has been achieved. A microscope objective is used to focus a diffraction limited spot onto the sample. To characterize the surface, the sample is laterally scanned using a 2D translation stage. The measuring process is automated by LabView software.

Measurements have primarily been performed on transducer samples in air. Recently measurements have revealed adhesion problems in the wafer bonding process used when fabricating the CMUT array. The measurements showed that the membrane was vibrating where it was supposed to be attached to the bottom wafer.

The transducer is intended for use in blood, and because acoustic properties of air and blood differ significantly it is desirable to measure transducers in fluids. The setup has therefore been adapted to measure immersed samples. Measurements have revealed that the transducer bandwidth increases significantly in liquids, which is expected as the radiation loss becomes considerable. Based on analytical calculations, electrical measurements, and finite elements simulations is has been predicted that acoustic coupling between neighboring CMUTs gives rise to a dispersive wave bound to the surface of the transducer. Measurements performed with the optical setup have confirmed the presence of these waves by directly showing their propagation along the array. The setup is also able to characterize the bound waves for example by measuring dispersion relations. The interferometer is also useful for estimating the uniformity across the array, for example by measuring frequency response or sensitivity of individual CMUTs.

The optical measurements can in this way contribute to validate or complement simulations and assumptions they rely on. The heterodyne interferometer is therefore a valuable tool for quality control in the conception, design and manufacturing of new acoustic devices.

8082-148, Poster Session

Singular optics for metrological applications in nanotechnologies

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Based on the newly established relationships between the spatial distribution of optical vortices in the scattered optical fields and the nature of a scattering surface, a novel surface classification scheme was developed. Practical means for characterizing rough surfaces of any kind in terms of both conventional statistical parameters and their fractality were proposed as well. This will constitute a completely new solution to the classical inverse problem of optics and it will substantially impact the surface diagnostic techniques, especially in the case of surfaces with large-scale inhomogeneities. The practical applications of this concept will be of outmost importance for surface processing, etching, crystal and thin film growth in a range of nanotechnologies in microelectronics and optics-related industries. In addition, using approaches of singular optics we anticipate that fundamental knowledge will be developed regarding the specific characteristics of light scattering from random, fractal or fractal-like, and mixed (fractal-to-random) structures. Diffraction- and scattering-induced spectral shifts caused by the phase singularities of different spectral components of polychromatic radiation and interference redistribution of intensity at the resulting field will be an important experimental asset in our diagnostic strategy. We will develop and use novel approaches which complement interference and diffraction techniques to diagnose “white-light vortices” which, in turn, will provide an extended range of capabilities for surface roughness characterization within the range typical for nanotechnologies.

8082-149, Poster Session

Software configurable optical test system for refractive optics

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SCOTS (software configurable optical test system) is a new tool that can provide lens manufacturers with the ability to fully evaluate lens systems, or individual lenses performance without the use of complex metrology systems and setups. This technique is based on measuring the slopes of rays to obtain curvature information using transmission deflectometry, the refractive equivalent of reflection deflectometry. As in the case of previously reported results for SCOTS in the reflection mode1, we are investigating phase shifting methods for data collection and reduction from a Hartmann /Hartmann-Shack perspective as well as investigating slope data calculation and unwrapping with centroiding and line-scanning methods.

The SCOTS technique was developed for rapidly, robustly, and accurately measuring large, highly aspherical shapes. Results on reflective surfaces, such as the primary mirror of the Giant Magellan Telescope (GMT) indicate that, the test can be implemented without complex calibration for many applications by taking advantage of geometry in working near the center curvature of the test part. These results also show that the test has a large dynamic range in which measurement accuracy is comparable with interferometric methods.

Initial wavefront measurements of refractive elements, such as a 1" diameter biconvex N-BK7 lens, show good agreement when comparing them with equivalent ZEMAX wavefront measuring models, which match the measured parameters, where the estimated and measured RMS values agree to within a few percent. The alignment of the setup was done crudely and quickly and the screen used to generate the scanning fringes which had a pixel pitch of 0.1905mm was configured so that only green lines would scan it to have a more precise model that could be generated and used for comparison with ZEMAX. The camera used for the measurements was a simple digital CCD camera. The catalog value of the lens power was compared with two different values, one experimentally measured and estimated using SCOTS and the other one modeled by the optical design software. The difference between these values was small. The technique was shown to be repeatable to within a few percent. We believe that the aperture mask selected, which determines the region of interest to be analyzed with SCOTS played a significant role in determining the wavefront shape and RMS values and could account for the small differences, since sometimes the information on the edge of the lens was difficult to discriminate and we wanted to cover the full lens system. More work on adjusting the experimental setup and the ZEMAX model is being performed to reduce the disagreement between these results and generate more faithful models.

1 Peng, S., et. Al., "Software configurable optical test system: a computerized reverse Hartmann test", Applied Optics, Vol. 49, pp 4404-12.

8082-150, Poster Session

Optic-electronic systems for measuring the angle deformations and line shifts of the reflecting elements at the rotatable radio-telescope

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Nowadays the new radio astronomy instruments are designed at many countries. For example, the Green Bank radio-telescope (RT) with 100 meters diameter mirror is realized in USA, the RT with 30 meters mirror is built on Plato Vilado (Spain).

The Russian Academy of Sciences realizes the project of radio observatory on a mountain Suffa in Uzbekistan. Full rotateable radiotelescope RT-70 for researches in millimeter wave range will be the main observatory tool. The RT 70 Suffa parameters are the following: the main mirror is realized as a 3-D parabola with a 21 meter focal length. The main mirror surface consists the 1200 reflecting boards, the full diameter of the mirror is 70 meters; the diameter of secondary mirror is 3 meters. The surface of the mirror consists 500...2000 section metal boards. It is necessary to realize the small deviation of this section surface relatively a theoretical 3-D parabola.

For working at the millimeter wave range it is necessary the high quality of the main mirror parabolic surface and the stable angular orientation of the secondary mirror relatively main mirror is important too. The necessary accuracy is following: the root mean square of the point deviation on a surface from theoretical parabola is not more than 0,05 mm and the non- stability of a mutual arrangement between main mirror and secondary mirror is not more than 0,08 mm. The researches in the millimeter wave range require the few (no more 2 arc. seconds) deviation of the secondary mirror position relative the theoretic one.

However, the construction weight and the temperature influence are the reason of the radiotelescope component deformations. For example, the linear deformations of the main mirror surface have got value near 30 mm, and the linear displacement of secondary mirror have got the value 60 mm.

The required parameters of reflecting components are realized, if the main mirror surface adaptation system and the means for corrections of the secondary mirror position are used. The commands to flare the adaptation system electric motors are formed after measuring the main mirror surface deformations and the secondary mirror displacements. The optic-electronic systems are effective as the system for the noncontact control.

The mirror RT-70 Suffa is a symmetric complete part of 3-D parabola and the direct sight from the ground to the arm of the secondary mirror is impossible. Therefore systems for measurement the secondary mirror coordinates and for control of the main mirror surface are realised as a "internal" type systems .

The components of the measuring system are placed on a rigid circle base at the top of the main mirror. The diameter of the circle base is B = 8 m, distance to the secondary mirror is 21.350 m and ones to the periphery of main mirror is 39 m.

The measuring system includes two separate systems. One of them measures the coordinates of the points on the main mirror surface and the second system measures the secondary mirror position.

The structure of systems incorporates the non-scanning optic-electronic measuring devices, which measure the coordinates of the radiating targets. These radiating targets are placed on the main mirror surface and on the secondary mirror too.

Every optic-electronic measuring device includes two video-systems; the centers of its objectives are displaced from each other on base distance B . This distance is a diameter of the circle base.

The video-systems measure the view angles of infrared radiating source at a vertical plane and view angles in a horizontal plane. These measurements determine coordinates X, Y, Z of the control point.

The experimental simulation of the optic-electronic measuring channel was made during the researches.

The fluctuation errors of the control point coordinate measurement are not more than necessary value 0.05 mm if the signal/noise rate is more 600 (Fig. 3). This condition is realized for the typical CCD and CMOS receivers.

The simulation of the summary measurement error has shown, what the measurement system for the secondary mirror realizes the necessary accuracy (r.m.s. is not more than 0.08 mm) for three coordinates.

The measuring system for the main mirror surface control, organized by a principle: «one optic-electric channel measures the coordinates of one reflecting board» can not be realized, because main mirror surface concludes the 1200 reflecting boards.

However, the homology feature of main mirror construction helps to design the measuring system. According to the homology principle, after small deformations the 3- parabola main mirror will be also the 3-D parabola surface, but with some another parameters.

Actually, for the control of the main mirror surface position it is enough to measure the coordinates of rather small quantity of control pointes and to calculate the approximation of the 3-D parabola.

The scheme of the main mirror surface deformation measurement system includes 24 measuring units.

The measuring units are located on the circle base. The angle view of these units registers the large part of the main mirror surface.

One measuring unit includes the 5...40 optic-electronic devices.

The experimental value of the measurement errors for line deformations of the main mirror is 0.08 mm (r.m.s) at the work distance 39 m and base B = 8m.

For the angle deformations the experimental research shows, that the error contains the large determination part. This part of error has been approximated. After special compensation the error of measuring is near 1.6 arc. second.

As result the computer and physical modeling of the optic-electronic devices, and also component designing have shown an opportunity of realization of a radiotelescope RT-70 Suffa for researches in the millimeter wave range.

8082-151, Poster Session

Zero-order elimination in digital holography by using of two holograms: one is made by tilting the CCD

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Holography is an important 3D imaging of an object. With development of CCD cameras and high-speed computers, recording and digital reconstruction of holograms became possible. Holography has found many applications in science and industry, like, holographic interferometry, refractive index measurement, and microscopic holography. As increasing of digital holography applications, realization of high-quality images became an essential necessity.

A hologram is made by interference of two waves, object wave and reference wave. The quantity, which we access directly to it, is the recorded intensity forming by interfering of the aforementioned two waves. Thus, in reconstruction of a hologram, in addition to real and virtual images, a zero order component appears too. This component not only has not useful information, but also tends to lowering quality of the reconstructed images. Therefore, elimination of this component results in providing better reconstructed images.

In this paper a process is introduced by which the zero order can be removed. In a suitable set up, a hologram is prepared by interference of the object wave and the reference wave on a CCD camera target, as usual. Then, the camera is rotated by an angle of a few degrees about an axis perpendicular to the plane containing the wave vectors of the object wave and the reference wave. In this configuration, a hologram is prepared. According to some calculations, the two holograms have identical zero order component.

A "hologram" is calculated by subtracting the two original holograms. Therefore, reconstruction of an image by this "hologram" should tend to a pattern that has not a zero-order component.

Based on this idea, some experiments were performed. These experiments verify effectiveness of this method. Experiments shows that the zero order of the images which are reconstructed based on the present procedure, is omitted effectively in the gained patterns.

8082-153, Poster Session

Sub ppm absolute distance measurements using an optical frequency comb generated by a conventional dual-drive Mach-Zehnder modulator

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Optical frequency combs are widely used for applications such as high-accuracy absolute distance measurements. However, these laser sources are usually mode-locked, and it is almost impossible to change the repetition rate, so that in an interferometric set-up, an interferogram can only be measured every multiple of the interpulse distance corresponding to the repetition rate of the mode-locked laser. In these conditions, one needs a tunable mechanical arm in the range of the interpulse distance and in order to get the absolute distance [1]. Moreover, the ambiguity range corresponding to the interpulse distance still remains. In this paper, we propose a simple and low cost technique to generate a tunable optical frequency comb, based on a conventional dual-drive Mach-Zehnder modulator, that overcomes these difficulties and allows absolute distance measurements with a high accuracy. The modulator is driven by a direct-digital synthesizer that is able to deliver a pure ramp in frequency between 13 GHz and 14 GHz, so that in an interferometric set-up, an interferogram may be measured at any optical path difference. This direct digital synthesizer has a reference clock at a frequency of 10 MHz and with a relative accuracy of about 10-8. Under some conditions such as radio-frequency powers and phase difference, it is possible to generate a flat optical frequency comb at the output of the modulator [2]. In our case, the laser source is a standard distributed feedback laser with wavelength 1533 nm and is intensity modulated, thus leading to a frequency modulation. The radio-frequency powers on the two arms of the dual-drive modulator are respectively 32 dBm and 31 dBm. The radio-frequency phase difference is controlled by a mechanical delay line. In such conditions, we obtain about 15 modes, corresponding to a span of more than 200 GHz. The span of this optical frequency comb can be extended with a low Vpi dual-drive modulator and/or with a highly non-linear fibre. The optical signal is then amplified by an erbium doped fibre amplifier and launched in a Michelson interferometric set-up. The absolute distance measurement is realized by continuously sweeping the radio-frequency of the direct digital synthesizer, the optical frequency comb remaining flat during the sweep. The duration of this sweep is 0.1 second, and could be even faster with a dedicated direct digital synthesizer (for example a ramp duration of 1 ms is achievable). Data processing is realized after acquisition of the interferometric signals on a digitizing oscilloscope that is synchronized to the radio-frequency generator. These signals are first low-pass filtered by a recursive and adaptative filter. The interferometric peaks are then detected and a linear regression is realized in order to get the absolute distance. These measurements are compared to a standard, which is a mode-locked femtosecond laser with a repetition rate of 100 MHz, along with a counting interferometer. This standard has an accuracy of about 1 micron. Absolute distance measurements with our new set-up and over a range of 1 to 25 meters give an accuracy of about 5 microns, corresponding to a sub ppm absolute distance measurement.

[1] J. Ye, "Absolute measurement of a long, arbitrary distance to less than an optical fringe", Opt. Lett. 29, 1153 (2004)

[2] Sakamoto, T., Kawanishi, T., and Izutsu, M.: 'Asymptotic formalism for ultraflat optical frequency comb generation using Mach-Zehnder modulator', Opt. Lett., 2007, 32, pp. 1515-1517

8082-154, Poster Session

A novel diffractive encoding principle for absolute optical encoders

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This talk gives details on the operation principle of a novel kind of position-encoder and shows its performance on two exemplary implementations: A compact absolute rotary encoder and a linear encoder which is based on a pseudo-random coding scheme. The implementation as well as results from their experimental characterization are presented.

Rotary and linear position sensors are used in numerous manufacturing and automotive applications, where cost effectiveness is a major goal. To meet the increasing demand for competitive optical rotary encoders, in recent years a novel type of optical encoders have been proposed and demonstrated using a micro grating based encoding scheme. In these encoders, the common but costly glass disc is replaced by a micro-structured plastic disc, manufactured by a conventional and cost-effective DVD-molding process. The microstructures consist of four different binary phase gratings that repeat periodically and are illuminated with a Gaussian readout spot. The grating structure generates a sine- and cosine-signal by detecting the first order spot intensities of its diffraction pattern. With that principle, on a diameter of 27 mm a resolution of 2048 solid measure increments on the circumference can be achieved. The signals of such an encoder allow an interpolated resolution of 15 bit/revolution or more.

For some applications, e.g. in robotics, it is essential to know the absolute angular position. In this contribution we show how the micro grating based encoding scheme described above can be extended to implement compact absolute optical encoders. For this purpose the diffractive code was enhanced by exploiting a residual degree of freedom: By variation of the grating periods and angles the resulting first order spots on the detector plane can be moved arbitrarily. To gain an absolute coding, different positions of a single first order spot are used to encode different states. The spot positions of the first order spots can be determined by detecting their center of gravity on a position-sensitive device. To build the absolute code, the position signals from four varying gratings are cascaded.

Only one single diffractive track is needed, which makes the system both compact and very robust to a radial shift of the encoder disc.

While the position of the first order spots is used to generate the absolute signal the varying intensity of the spots still is used to generate incremental signals. The incremental coding physically corresponds to the absolute code as both are using the same grating structure. Therefore, the incremental signals can be interpolated to enhance the absolute resolution since each period of the incremental code physically relates to an individual angular segment of the absolute code.

In some industry sectors like the semiconductor-, the lighting- or the biomedical-industry, where work is carried out in clean environments, actuators are needed that can move small parts with an acceleration of several hundred m/s2 and a precision in the one-digit micrometer range. Miniature linear motors have the dimensional and dynamic characteristics to optimize these processes. However there has not been a sufficient solution for an absolute position encoder capable of being integrated into such motors until now.

State-of-the-art linear absolute position encoders use pseudo-random coded absolute tracks in combination with a parallel or overlaid incremental track to improve their resolution. The micrometer-sized scale structures have to be resolved by a lens-system which makes the sensor very sensitive to changes in distance between the scale and read-head. The optics gets out of focus quickly as a result. Instead, by coding the position information by diffraction gratings, the small-sized scale structures do not have to be resolved by imaging optics anymore. The depth of focus can be decoupled from the resolution by illuminating the scale by a relatively large spot of light and decoding information on the scale-position by detecting the position of the diffraction-spots on a sensor-matrix.

Here we show for the first time that the highly efficient pseudo-random-sequences can also be implemented by diffraction-gratings. Normally the information about the order of the simultaneously illuminated diffraction-gratings of a code-word is lost if their diffractionpatterns are observed in the far-field. However by cyclically varying the grating-period across the gratings, this information can be retrieved.

These two exemplary implementations show that the novel micro grating based diffractive coding principle is the key to numerous improvements in encoder technology both for rotary and linear position sensors.

8082-156, Poster Session

Positioning of scanned part inside of the predictive laser triangulation system

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The method of laser triangulation (LTM) is for over 30 years successfully applied for distance measurements, scanning 3D objects, as well as in industrial quality control to map the surface topography or even surface quality.

LTM could be possibly used in all modern quality inspection tasks. Unfortunately, as with most optical methods, it is susceptible to many factors affecting the accuracy, sometimes even making it impossible to work. The most important of them are occlusions, multiple reflections, the speckle effect, changing of adjacent surfaces' reflectance, changes of diffuseness resulting from the angle of observation and the surface normal.

A novel method for specular reflections removal has been previously proposed by Reiner and Stankiewicz. It assumes, that for each scanning step (each triangulation image), a theoretical laser profile is calculated, based on the 3DCAD model of scanned part. It is used then to create the confidence interval with the appropriate probability of primary (correct) laser line to be found within this range. The method is applicable for 3D quality inspection, where a'priori knowledge is available. It is not applicable for reverse engineering.

Such solution requires a good method for model registration - that means - aligning the CAD model inside of the virtual triangulation scanning system. The position and orientation of the element being scanned must represent the real situation. Otherwise the theoretical laser profile, estimated by the prediction algorithm will not match the reality, causing the whole algorithm to fail.

The accuracy of registration has a significant influence on the capability of prediction algorithm, and must face the accuracy of scanning process. Because the small changes in the geometry of element being scanned, can cause a big changes in laser profile, the accuracy of positioning system affects the confidence interval near the step geometry changes. The worse the accuracy, the wider the interval, and the more possible specular reflections inside, which can affect the measurement.

To reach the optimum, it was decided to use an additional camera for positioning. Its field of view encompasses the entire space of triangulation measurement system.

The next step in the preparation method of positioning of the scanned object in the system for laser triangulation was to find or develop an algorithm determining the location of the object based on its image. This problem is defined in the literature with the term "3D matching".

To allow easy conversion between multiple coordinate systems used in the description of the position of the laser triangulation, it was decided to use the convention commonly used in robotics, developed by J. Denavit and RS Hartenberg. The same model is used to describe the positions of the laser triangulation, for consistency and ease of description reasons.

For registering of the element being investigated with its model the 3D Matching function from Halcon (MVTec) vision development environment was selected. This procedure has been modified in order to produce more stable measurements results. Based on the fact that during scanning process, the part is translated with constant speed along X-axis, without changing its orientation.

3D matching is an automatic process and if all steps are carried out properly, the model will be found on the image. The result are six values: three translations and three Euler angles. -That is the position and orientation of the coordinate system of the model in the coordinate system of camera. It can be then transformed to the global coordinate system, using appropriate transformations described by the Denavit-Hartenberg notation.

Since the results of positioning base on a CAD model and images that are relatively inaccurate, a Kalman filter implementation has been developed, intended to stabilize the results of the repeated measurement of the uniformly sliding element. Measurements are repeated many times during the scan. Model of such system is known. -The change of position of an element being translated through the scanning system, are constant and known. Based on the described assumptions, a model for Kalman filter has been developed to stabilize the measurements' results in order to reduce the deviation. The states are the coordinates of the element in global coordinate system. The observations are the coordinates of the model in auxiliary camera's system.

Several test has been carried out to check the accuracy and robustness of developed matching algorithm. During the tests, the element was placed on the linear high-accuracy stage. The triangulation profile acquisition was repeated every 0.1mm and 1mm. The translation axis of the stage was perpendicular to the auxiliary camera's X-axis.

To increase accuracy of positioning, it is important to avoid disturbances introduced by the projected laser line. The robustness of the algorithm against the presence of external light pattern inside of the field of view was therefore examined. The measurements were repeated with such disruption. The laser plane was placed with emphasis on the greatest disturbance of the image. The statistical analysis confirmed the absence of any significant impact on the results of positioning interference. The results shows, that using Kalman filter, to stabilize the measurement of a series of 3D matching processes, can decrease the deviation up to about 10 times.

To use the CAD model, to support the segmentation process of laser profile in the predictive triangulation method, a precise synchronization of the part being inspected with its model in virtual scanning system is required. If there is no possibility of precise positioning of the element entering a scanner, it is necessary to calculate its location and orientation by means of additional sensors. The paper describes the use of auxiliary camera for this purpose, and developed algorithm. The accuracy of this method has been evaluated in a specific application for machine vision inspection, and a solution to reduce the deviation of the obtained results has been proposed.

8082-157, Poster Session

Microlens array manufactured by inkjet printing: study of the effects of the solvent and the polymer concentration on the microstructure shape

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Recently, the inkjet printing (IJP) technology is increasingly employed in electronics for the deposition of functional materials and conductive inks as well as for the fabrication of microstructures for several applications, as microlenses. As concerning the last item, refractive microlenses are crucial elements for applications such as laser diode to fiber coupling, beam formation and focusing in free-space optical backplanes and free space to waveguide-fiber array coupling.

In the present work we report on the manufacturing of microlens array by inkjet printing Poly(methyl methacrylate) (PMMA) solutions prepared with different solvent mixtures at different polymer concentrations investigating the effects of these parameters on the shape and geometry of the microstructures in order to determine the main constrains of the fabrication process. The solvents employed to dissolve the PMMA, a polymer with transparency property in the visible range, were N-Methyl-2-pyrrolidone (NMP), toluene (TOL), chlorobenzene (CB) and orto-dichlorobenzene (DCB), all selected for their solubility and chemico-physical (boiling point, surface tension) properties. The solvent mixtures (TOL:NMP, CB:NMP, CB:DCB, DCB:TOL) have been investigated in order to reduce the coffee-stain effect which is typical of the drying process and consists in an higher solute accumulation at the droplet edges where the evaporation is faster [1]. Additionally, the solute distribution also depends on the contribution of the Marangoni flow which is related to the temperature gradient inside the sessile drop, and hence to the different surface tensions at the droplet liquid-air interface [2]. In detail, we studied as the inward Marangoni effect enhances regardless of the coffee-stain effect by modifying the mixing ratios, thus promoting the polymer build-up in the centre of the printed drop. Moreover, we investigated as also the polymer concentration and, hence, the prepared solution viscosity influence the solute flow inside the sessile drop and therefore the final microstructure shape. By varying the polymer concentration, we established that the viscosity parameter is a crucial factor resulting dominant respect to the Marangoni effect for concentration values approaching to 40 mg/mL. Furthermore, we observed that also the printing parameters, in particular, the spacing between contiguous printed microlenses in the array configuration, affect the microstructure geometry. Indeed, the proximity effect influences the evaporation rate, and, hence, also the microlens profile.

The microstructures have been characterized by means of an interferometric technique evaluating the coefficient of Zernike polynomial. In particular, a Mach-Zehnder interferometer in the confocal and cat eye positions of lenses has been employed to measure the focal plain and focal length.

This interferometer uses an illumination microscope objective of high quality to generate a spherical wavefront, which is then collimated by the microlens under test. The interference of this wavefront with a plane reference wavefront allows the determination of the optical quality and the aberration of the manufactured microlens with an accuracy in the range of /20.

Preliminary tests showed the feasibility of the realization of microlenses with diameters ranging from 40 to 200 µm and focal lengths of the order of millimeter. We also observed that the use of a post printing heating treatment for 20 min at T = 250 °C, below the PMMA melting temperature, can strongly improves the morphology of the lenses reducing any disuniformity generated by the drying process of the solvent.

References:

[1] R.D. Deegan, Phys. Rev. E 61 (2000), 475.

[2] H. Hu and R. G. Larson, J. Phys. Chem. B, 110, (2006), 7090.

8082-158, Poster Session

Surface topography and optical performance measurement of microlenses used in high power VCSEL systems

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The recently emerged demand for lasers with specific intensity distributions has lead to the development of high power VCSEL systems. These consist of arrays of high power VCSELs combined with microlenses and field lenses allowing for intensity distributions tailored to the needs of each specific application.

One of the basic conditions for getting ideal intensity distributions is the use of high quality microlenses. Therefore a Shack-Hartmann based instrument has been developed for the measurement of these lenses in reflection as well as in transmission. In addition the form tools used for the microlens production can be measured with this set up. The comparison of measured surface profiles and optical properties with the particular design values then allows for optimization of the manufacturing process.

When measuring the surface topography in reflection the surface is illuminated from top and the reflected light is imaged onto the wavefront sensor. All surface gradients are determined from a single camera image and by performing a numerical integration the surface profile of the lens or the tool can be calculated.

Compared with single shot interferometric methods Shack-Hartmann sensors provide a higher dynamic range. This way aspheric surfaces with deviations from spherical profiles of several hundred lambda can be measured. However, if the dynamic range is exceeded in case of very strong aspheric surfaces, computer generated holograms can be used.

When measuring in transmission a point light source with sufficient numerical aperture is placed in the focal plane of each microlens. The transmitted beam is collimated by the microlens and then imaged onto the wavefront sensor, thus enabling the detection of material inhomogeneities and changes in refractive index.

Besides the aspheric shape of the lenses their very small size poses a considerable challenge. In order to utilize the full area of the Shack-Hartmann sensor a high degree of magnification is required, thus asking for high quality illumination and magnification optics. In addition high positioning accuracy, mechanical stability of the set up and vibration damping are absolutely necessary.

We are going to present the latest results on surface topography and optics performance measurements on microlenses which are used in high power VCSEL systems.

8082-159, Poster Session

Laser self-mixing sensor to monitor in-situ the penetration depth during short pulse laser drilling of metal targets

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A novel system based on laser diode feedback interferometry has been demonstrated to monitor in real-time the laser ablation process. Percussion drilling experiments have been performed on various metallic targets in air atmosphere using a 120-ps microchip laser fiber amplifier. A direct in-situ measurement of the penetration depth was achieved by coaxially aligning the beam probe with the ablating laser. The temporal evolution of the ablation process was revealed by analysing the sawtooth-like induced modulation of the interferometric signal out of the detector laser and the material removal rate estimated with sub-micrometric resolution.

8082-160, Poster Session

Investigation of organic light emitting diodes for interferometric purposes

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Recently the new type of light source based on organic light emitting diode (OLED)on has been introduced to the market. OLED is not only interesting because of the low applying voltage, wide light emitting areas and emission efficiency. It gives the possibility to create a light source of a various shape, various color and in the near future very likely even the one that will change shape (spatial coherence) and spectrum (time coherence) in controlled way.

In the paper authors try to give an answer to the question if the new light source -OLED - is suitable for interferometric purposes, especially for low coherence interferometry (LCI). Theoretical analysis and experimental tests cover the short and long term spectrum stability, spectrum shaping due to the input voltage or the emission area changes and spatial coherence controlling by the emission area selection.

In the paper the results of two OLEDs (red and white) are shown together with the results of their application in low coherence full-field interferometer.

8082-16, Session 4

Recent advances in the field of superresolution

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There are several factors that limit the resolution of an optical imaging system. The first limitation is related to the F number of the optics which expresses the wave nature of the propagated radiation i.e. the diffraction effect of the propagated wave. The smaller the F number of a lens is, the larger is the angular range of optical rays that it may collect and thus the resolvable separation distance between spatial features is reduced. The second is the geometric resolution limit determined by both the pitch of the pixels in the detector (that set the Nyquist sampling limit and therefore the spatial frequency above which aliasing effect is generated) as well as by the non ideal spatial sampling (caused by the spatial averaging performed by each one of the pixels, in contrast to ideal sampling that is done with Dirac delta functions). The third limitation is related to the dynamic range of the detection array and the number of quantization bits allocated per each sample.

Within this contribution, we present a set of new approaches allowing overcoming the above mentioned diffraction and geometric limitations by converting the spatial degrees of freedom to time, polarization, space and wavelength domains. We intend to present techniques suitable for near field imaging as well as for remote sensing applications. We will conclude our talk by showing a new approach capable of monitoring from a distance the heart beats, blood pulse pressure and the glucose level in the blood stream of a patient.

8082-17, Session 4

Advanced 2D die placement inspection system for reliable flip chip interconnections based on 3D information of die and substrate by a phase measuring profilometry

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Demand for flip chip interconnect technology is being driven by package developments with high density and small size from the silicon industry. Advantages of using flip chip interconnect are summarized as follows; 1) Reduced signal inductance for high speed communication and switching devices. 2) Reduced power/ground inductance for the noise reduction of the core power and performance improvement. 3) Higher signal density utilizing the entire surface of the die. 4) Die shrink for pad limited die. 5) Reduced package footprint.

As the flip chip connection is generally formed by using solder bumps, the first manufacturing step for the packages makes the solder bumped die placed to the matched substrate with fine alignment between the die-side and substrate-side bumps. The well aligned matching bumps are physically connected through a solder reflow process. After the die is soldered with the reflow process, underfill is added between them, and the remainder of package construction surrounding the die can take many forms.

Among these processes, the chip-to-substrate alignment is the basic step of reliable flip chip interconnection. According to the miniaturization and high density trend of flip chip packages and dies, the process of die-to-substrate alignment has become more critical and more difficult for reliable formation of interconnections.

In this paper, the advanced die-to-substrate alignment inspection system before the reflow process step is focused. General 2D placement inspection systems used for this purpose should check the shift error between real and target positions of the die on the substrate.

Although the used optical inspection systems do not have highly telecentric optics, the measurement results of relative position errors are based on a big assumption that 3D information of substrates or dies relative to visual inspection systems does not affect seriously to the shift position errors.

However, for highly accurate die position inspection system, the target object, consisting of bumped dies and substrates, should be well placed relative to the optical inspection system before inspections. Conversely, for reliable in-line shift inspections, the posture of the target object should be monitored and measured by using embedded 3D sensors. The main difficulty of inspecting the die-to-substrate alignment is that the substrate is always tilted or off-positioned due to disturbances from in-line process, relative to the sensor coordinate system.

In this paper, to overcome this problem, an embedded 3D phase measuring profilometry (PMP) is proposed and integrated into a conventional 2D inspection system. Therefore, the posture of die-mounted substrate can be directly measured by using the proposed system. Utilizing this 3D information, the numerical compensation algorithm to get accurate positional offset values is suggested. The compensation algorithms are based on the geometrical analysis of the imaging system and the target object.

In addition, as fine 2D position inspection systems need advanced camera calibrations, precise camera calibration algorithms and specially designed calibration targets are proposed for the calibration phase of the proposed system. Finally all 2D and 3D systems are combined with a single optical system, and the whole information is fused to get refined position error values.

The performance of our system is checked by a series of real experiments on commercial flip chip packages, and the obtained experimental results are analyzed in detail.

The obtained results with pose variations of several target objects show the efficiency and the accuracy of the proposed system and algorithms.

8082-18, Session 4

3D interconnect metrology in CMS/ITRI

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3D Interconnect metrology in CMS/ITRI

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ABSTRACT

Semiconductor device packaging technology is rapidly advancing, in response to the demand for thinner and smaller electronic devices. Three-dimensional chip/wafer stacking that uses through-silicon vias (TSV) is a key technical focus area, and the continuous development of this novel technology has created a need for non-contact characterization. Many of these challenges are novel to the industry due to the relatively large variety of via sizes and density, and new processes such as wafer thinning and stacked wafer bonding. This paper summarizes the preliminary trial metrology developing that has been used during via-middle & via-last TSV process development at EOL/ITRI. While there are a variety of metrology and inspection

applications for 3D interconnect processing, the main topics covered here are via CD/depth measurement, thinned wafer inspection and wafer warpage measurement.

A. Via CD/depth measurement: Silicon wafers (with/without oxide hard mask on top of it) with 5-200 um diameter vias and a nominal depth of 30 to 150 um were used for via metrology studies. For via CD 10 um, its CD and depth measurements were evaluated using IR confocal microscopy. For via CD 10 um, spectral reflectometry was used for via depth measurements.

B. Thinned wafer inspection: Wafers thinned down to a nominal thickness of 25-300 um were inspected after grinding and CMP to characterize thickness and TTV (Total Thickness Variation). This was done by IR laser confocal microscopy, and verified with capacitance measurement.

C. Wafer warpage measurement: TSV wafers were filled with Cu by chemical plating process. The wafer warpage vs. varying Cu plating thickness was inspected using both fringe reflection method and capacitance measurements. The main purpose of this application is to optimize process control from minimizing warpage condition.

8082-19, Session 4

Pattern placement metrology using PROVE TM high-precision optics combined with advanced correction algorithms

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Photolithography is the key technology of the chip production in semiconductor industry. Increasing demands on wafer overlay requirements lead to increasing demands on registration accuracy of photomasks. The PROVE TM photomask registration metrology tool has been developed by Carl Zeiss SMS to address the need for high imaging resolution in combination with excellent measurement performance. This paper reports the current status of PROVE TM, highlighting its optical performance and correction algorithms.

The tool is designed for 193nm illumination and imaging optics, which enable at-wavelength metrology for current and future photomask manufacturing requirements. Registration and line width metrology is offered by the optical beam path using transmitted or reflected light. The opportunity of selecting optimized illuminations allows a smart adaption of the tool to the measurement task. The short wavelength together with a numerical aperture of 0.6 allows sufficient resolution down to the 32nm manufacturing technology requirements. The stable hardware platform and the newly developed PROVE TM high precision optics enable a short term repeatability of less than 0.5nm (3sigma). Distortion can be calibrated by using advanced image analysis and self calibration methods. The optical correction of the entire field of view delivers the requested screen linearity of less than 1nm. It is shown, that the calculated optics correction is valid for different structure types and all kind of illuminations.

8082-20, Session 4

Detection of micro-probe displacement using a Shack-Hartmann wavefront sensor

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Micromechanical structures usually include large aspect ratios and steep flanks. For this reason touch probe measurements have been proved to excel optical methods. However, due to the large number of microstructures on a single wafer and the need of multiple measurements for a single feature using a single touch probe is very time consuming. Owing to the alignment of many similar structures on a wafer recent approaches use multiple touch probes composed in an array to measure some of these structures at the same time.

Usually the signal of these touch probes is detected electronically, i.e. by resistors applied to each micro probe. Depending of the design the number of contact pads on a typical 3x3 micro probe array is in the range from 14 (combining the columns and rows in the array in serial connection) to 74 (based on single micro probe setup), increasing with the array size. This leads to a large number of electric contacts and wiring necessary for data acquisition.

For this reason an optical detection of the probes' displacement is investigated. In our approach a Shack-Hartmann sensor is used to observe the mirroring back plane of the micro probe array. Shack-Hartmann wave-front sensors use microlens arrays in conjunction with a CCD array. A planar wave-front that is transmitted through a microlens array and imaged on a CCD sensor will form a regular pattern of bright spots. If, however, the wave-front is distorted, the light imaged on the CCD sensor will consist of some regularly spaced spots mixed with displaced spots and missing spots. This information is used to calculate the shape of the wave-front that was incident on the microlens array. Usually these sensors are used to characterize optical system, e.g. in laser beam diagnosis or real-time monitoring of wave-fronts for adjusting adaptive optics.

In this approach the back plane of the micro probe array is illuminated by a collimated laser beam, i.e. with undistorted wave-fronts. The shape of the reflected wave-front then corresponds to the shape of the back plane of the micro probe array, which in turn is influenced by the displacement of the micro probes.

8082-21, Session 5

Optimal phase retrieval from multiple observations with Gaussian noise: augmented Lagrangian algorithm for phase objects

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No abstract available

8082-22, Session 5

The effect of misalignment in phase retrieval based on a spatial light modulator

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Recently the conception of an innovative experimental scheme for phase retrieval from a set of consecutive intensity measurements had been proposed [1-3]. A schematic setup for that technique is illustrated in Fig.1. The scheme is based on a 4f-optical filter with a reflective phase-only spatial light modulator (SLM) located in the Fourier domain. Thus, the setup allows for dynamic linear filtering operations with the corresponding transfer function defined by the complex transmittance of the SLM. Since the transfer function of free space propagation is a pure phase function, the scheme can be used to generate a sequence of propagated representations of the same wave field across a common output plane. To recover the phase of the investigated wave field within that scheme, the captured set of intensities has been subjected into an iterative process [4] based on the method of generalized projections [5]. The main advantage of this experimental scheme is the greatly reduced measurement time since no mechanical alignment is required throughout the recording process.

Since the employed SLM is a reflective panel, the setup can be described as to be composed of two distinct sections. Each section consists of an optical axis with a Fourier transforming lens on it. Both sections are linked by the common Fourier domain where the SLM is located. The SLM has an optical axis as well, which is defined by its center. Misalignment v between the first optical axis of the setup and the center of SLM causes a shift of the complex amplitude generated across the CCD plane in the transverse directions.

In this work the influence of the effect described above on the performance of the iterative scheme's solution is investigated. It is demonstrated that if misalignments are present, measurement errors will be propagated in the iterative process and thus affects the accuracy and the rate of convergence of the phase retrieval. An alignment procedure is given to compensate for the shift in the

CCD domain by changing electronically the SLM's transmittance by means of the designed transfer function of propagations. The investigation is demonstrated by investigating a wave field diffracted by the U.S Air force resolution target USAF. In the case of an aligned setup, it is shown that only 5 planes and 10 iterations result in a good reconstruction which is closed to the original object.

[1] C. Falldorf, M. Agour, C. von Kopylow, and R. B. Bergmann, ''Phase retrieval by means of a spatial light modulator in the Fourier domain of an imaging system, '' Appl. Opt. 49, 1826-1830 (2010).

[2] M. Agour, C. Falldorf, C. von Kopylow and R. B. Bergmann, ''Shape measurement by means of phase retrieval using a spatial light modulator," AIP Conf. Proc. 1236, 265-270 (2010).

[3] C. Falldorf, M. Agour, C. von Kopylow and R. B. Bergmann, ''Design of an optical system for phase retrieval based on a spatial light modulator," AIP Conf. Proc. 1236, 259-264 (2010).

[4] P. Almoro, G. Pedrini, and W. Osten, "Complete wavefront reconstruction using sequential intensity measurements of a volume speckle field," Appl. Opt. 45, 8596-8605 (2006).

[5] A. Levi and H. Stark, "Image restoration by the method of generalized projections with application to restoration from magnitude," J. Opt. Soc. Am. A 1, 932-943 (1984).

8082-23, Session 5

Quantitative determination of the optical properties of phase objects by using a real-time phase retrieval technique

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The quantitative reconstruction of the amplitude and phase distributions of a complex wave field is a key feature in optics. If a wave field interacts with an object, the incident amplitude distributions is modulated by absorption and also the incoming phase distribution is disturbed by the object. The deviation in the wave front arise from the optical path difference induced by the object, while the path difference is the product of refractive index and geometry. If the amplitude and phase distribution of the wave is known directly behind the object, all information about the complex specimen are available and hence the optical properties and functionality can be determined.

While the amplitude is easy to measure, the phase distribution can not be detected directly. Nevertheless, several techniques exist to measure the phase distribution of a wave field. Well known are interferometric methods but also non-interferometric phase retrieval techniques are applicable. The advantages of these retrieval techniques compared to interferometric methods are - among others - their lower demands on coherence and that no post-processing, like phase unwrapping, is necessary. One of these phase retrieval techniques is the so-called transport-of-intensity equation (TIE). The TIE describes a deterministic relation between the intensity distribution in different focus planes and the corresponding phase distribution. A special Green's function solution of the TIE will be presented to retrieve the phase distribution of an object under investigation. The Green's function solution of the TIE takes into account specific boundary conditions for the observed specimen and thus yields to more precise reconstruction results compared to the common solving algorithm.

The only input data required for the phase retrieval algorithm are a focused intensity distribution of the object and its rate of change along the direction of propagation. The rate of change, respectively the derivative of the intensity distribution with respect to the axis of propagation z is experimentally approximated by a difference quotient.

The intensity distributions out of slightly different planes along the z-axis are gained through the use of a microscope. To capture the necessary intensity distributions at the same time, a multi-camera system was designed whereas up to three cameras can by adapted to the system. The defocus distances of the detectors are adjusted simply and flexible by spacer tubes and rings. The complete multi-camera system is mountable to standard microscopes by replacing the binocular tube with the multi-camera system.

The phase distribution obtained by solving the TIE algorithm corresponds to the optical path difference induced by the object under investigation. Therefore, optical properties of the specimen can be deduced from the retrieved phase data: e.g, if the geometry of the specimen is known, the refractive indices can be calculated.

This method of evaluation can be applied to optical step-index fiber to accurately determine the refractive indices of the core and cladding material. Exact knowledge about the refractive index distribution of fibers is necessary because any change in the index of core or cladding will lead to a variation of the fiber's numerical aperture. The variation arises from varying external influences during the manufacturing process, such as heat, pressure and the drawing speed.

The TIE algorithm for phase reconstruction requires the multiple use of fast Fourier transforms (FFT), which suites well for calculations on parallel computers. Today, the most commonly used parallel computers are graphics processing units (GPU). They can be found in nearly every personal computer. Their major task is the parallel and thus fast computation of matrix operations. Programming environments like NVIDIA CUDA enable the easy use of common graphic processors for the calculations of floating point operations. Using these modern computation techniques it is possible to customize the TIE algorithm to the particular needs of GPUs. Therefore, real-time phase reconstruction can be realized even on consumer computer systems and observation of the amplitude and phase distribution of an object is feasible with a standard microscope.

In our opinion the presented technique is an innovative non-contacting, non-destructive optical measurement system which is able to monitor on-line the manufacturing process of optical fibers despite difficult environmental conditions. The opportunity of calculating the object dependent phase distribution in real-time and the simple optical setup offers new application of phase retrieval for industrial metrology issues.

8082-24, Session 5

Phase extraction in microscopy using tunable defocusing by means of a SLM

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In many practical microscopy applications the use of phase information is crucial. This information can be derived from techniques such as phase contrast imaging or differential interference contrast (DIC). Nevertheless, full phase extraction can provide a wide range of information, such as thickness, refractive index or a combination of both. Moreover the classical phase visualization techniques (phase contrast, DIC, ...) can be derived from the phase distribution, in case that a conventional view is needed.

In this contribution we propose a method for phase extraction in a microscopy system based on analysis of images with varying defocusing. The system has no mobile parts owing to the defocusing by means of a spatial light modulator. The base of the method is the caputre of images in a microscope with varying tube lens focal lengths. This produce a set of intensity images, all of them related, because the can be generated by free space propagation of a complex distribution which is unknown. Fortunately, except for very particular pathological cases there is only a complex spatial distribution which is compatible with a set of intensity misfocused images.

A microscope is prepared in the optical bench, composing a system with the translucent object, the microscope lens, a tube lens and an array sensor in sequence. The illumination is 532 nm wavelength laser (doubled frequency NdYAG solid state laser). The lens is a Mitutoyo M Plan Apo 0.55NA, infinity corrected, the tube lens is a doublet with 300 mm fcl length and the camera is a Basler A312f (582x782 pixel with 12 micrometers size). The microscope is arranged with a spatial light modulator inserted in the imaging arm, between the microscope lens and the tube lens. The system adjustment is such that with the spatial light modulator in the inactive state the image of the object is focused (or nearly focused) in the sensor. The SLM is a Holoeye HEO 1080 P reflective liquid crystal display, which can, with the appropriate calibration, provide a mostly phase only modulation.

The procedure for phase extraction starts by displaying in the spatial light modulator a phase distribution which acts as a spherical lens. This implies using the modulator in a phase only regime and displaying a spherical phase factor onto it. The chirp frequency on the spherical phase factor is varied so that the image in the sensor is defocused. This way a set of intensity images corresponding to different defocusing is obtained. Then the procedure searches for a complex distribution compatible with this images. This is performed by an iterative procedure.

We start by computing the free space propagation of one of the images on the plane of the next misfocused imaged. This gives a phase and an amplitude distribution. The amplitude distribution is replaced by the true amplitude (square root of the image captured by the sensor) while the phase given by propagation is maintained. Next the new complex distribution (propagated phase and sensed amplitude) is propagated to the next misfocused image and the process is repeated until the last misfocused image. The loop ends by propagating the last obtained image into the first one. The full loop is iterated until the images stabilize, this is they do not change significantly between subsequent loops.

After the convergence of the procedure, a complex amplitude is obtained, containing an estimation of the object phase for every plane. Note that in fact the information of a single plane (a misfocused image) is enough, because the other planes can be inferred from a single one just by free space propagation.

The technique produces results comparable analogue to the digital holography microscopy systems but in a much simpler setup. There is no need to arrange a reference arm making the system much more stable. It is also more immune to noise due to the simplicity of the setup and no moving parts are needed.

We have tested the system and procedure for two types of object. First a USAF 1951 test is used. This test is an amplitude one and serves as a calibration step. Then a phase object (a sample of swine sperm) is measured and compared with the results obtained by holographic microscopy.

8082-25, Session 6

Three-dimensional refractive index and thickness distribution of thin film measurements through dynamic multiwavelength interferometry

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A vibration-insensitive white light interferometer, which is composed of an optical polarization interferometer and a pixelated phase mask camera, is employed to measure the curved or patterned samples coated with thin films, as shown in Fig. 1.

The beams reflected from the two arms of the interferometer were linear polarized and their polarization directions are orthogonal to each other. After passing through the quarter wave plate in front of the filter, they then were converted to right and left circular polarizations, respectively. These two beams then had interference with each other after they pass through a linear polarizer. If the polarizer was oriented at an angle α with respect to the polarization direction to the reference beam, it will generate interferograms of phase shift 2α. The detecting element was a micro-polarizer pixelated camera, and the adjacent pixels have different orientated polarizers on them. There were four different polarizers at 0°, 45°, -45°, 90°, respectively, on the camera, and they generate four different phase shifted interferograms at once for phase shifting algorithm. Hence, the phase difference between reference and test beams can be derived without moving reference arm by PZT to avoid the vibration influence. Furthermore, the air turbulence influence can be further removed by averaging data of several frames.

The phase difference coming from the reflection phase difference between test and reference surfaces cannot be distinguished from the phase difference coming from the spatial path difference between reference and test beams, in one single wavelength measurement. Therefore, the conventional interferometer with laser as light source cannot be used for measuring refractive index and thickness of thin film. However, by doing measurements on different wavelengths, they can be separated from each other. It is because that the reflection phase difference and spatial path difference change in different ways when the measuring wavelength changes. The phase of reflection coefficient of the thin films can be thereby obtained. Combining with the reflectance measurement at different wavelengths from the sample, the reflection coefficients of thin films at different wavelength were then obtained. Since they are the functions of the refractive index and thickness, the refractive index and thickness can be calculated. The experimental results show that, after the phase measurements being added into analysis, the results precisions were greatly improved. Especially for multilayer thin films analysis, if only the intensity spectrum is measured, the measurement precision sometimes becomes low. The phase measurements provide more data for calculations.

Collecting the reflection coefficients of thin film under normal incidence of light of each point, the thin film thickness and optical constants distribution in 2 dimensions are calculated. The surface profile can be also known through the spatial path differences between reference and test beams as described above.

This system does not only have all advantages of ellipsometer, but also can measure the uniformity of thin film and the substrate surface profile. The structure is simple, and can be developed as a compact online examination system of the production of any patterned substrate coated with thin films, like LCD displays, semiconductors, etc.

8082-26, Session 6

Comparison of fast Fourier transform and convolution in wavelength scanning interferometry

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The assessment of surface finish has become increasingly important in the field of precision engineering. Optical interferometry has been widely used for surface measurement due to the advantages of non-contact and high accuracy interrogation. In spite of the 2π phase ambiguity that can limit the measurement scale in monochromatic interferometry, other optical interferomtry have succeeded to overcome this problem and to measure both rough and smooth surfaces such as white light interferometry and wavelength scanning interferometry (WSI). The WSI can be used to measure large discontinuous surface profiles by producing phase shifts without any mechanical scanning process. Where the WSI produces the phase shifts by altering the wavelength of a broadband light source and capturing the produced interferograms by a CCD. This paper introduces an optical setup and operation principle of a WSI that used a halogen white light as a broadband illumination source and an acousto-optic tunable filter (AOTF) as a wavelength scanning device. This setup can provide a wide scan range in the visible region. The scanned range is being operated from 682.8 nm to 552.8nm and the number of captured frames is 128. Furthermore, the obtained interferograms from a Linnik interferometer have been analyzed by two methods, Fast Fourier Transform and Convolution. A mathematical description of both methods is presented then a comparison in results accuracy is made between them. The Areal measurement of a standard 4.707μm step height sample shows that FFT and convolution methods could provide a nanometer measurement resolution for the surface finish inspection.

8082-27, Session 6

Absolute surface profilometry of an object with large gaps by means of monochromatic laser interferometry

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Absolute surface profilometry of discrete and discontinuous objects, such as MEMS and complex 3-D electrodes in liquid crystal display panels, is becoming increasingly important in industrial measurements. Despite its height resolution, conventional monochromatic laser interferometry suffers from the height ambiguity by an integer multiple of a half wavelength. It has been a common practice to use white-light interferometry or low coherence interferometry to solve this problem. However, the use of the broadband source causes a dispersion problem when the measurement is made through dispersive media such as glasses, films and liquids.

We propose a technique for monochromatic laser interferometry capable of absolute surface profilometry of an object with large height gaps exceeding a half wavelength. The technique does not use a

broadband source, such as a low-coherence or multi-wavelength source, or a wavelength-tunable device, which causes a dispersion problem. Instead, we make use of the phase change of monochromatic light through the angular shift of illumination introduced by tilting the optical axis of the interferometer. For oblique illumination at angle , the phase difference between the test and reference surfaces separated by distance d is given by , where is a wavenumber. In effect, the change of illumination angle functions as the change of wavelength . Therefore, while using a monochromatic laser light source, we can realize the same effect as a multi-wavelength source. From the relation between the illumination angle and the phase change, the absolute distance d between the test and reference surfaces can be determined without ambiguity of an integer multiple of a half wavelength associated with monochromatic interferometry. The large gap height can be determined also without ambiguity from the change of the absolute distance d across the boundary of the gap. Because the resolution of the absolute distance measurement by means of illumination angle change is not high enough by itself, we enhance the resolution by the following procedure. We first estimate the gap height to an integer multiple of a half wavelength by tilting the optical axis. Then the fractional portion of the phase is measured by setting the optical axis perpendicular to the test surface as in conventional interferometry. By combining the integer and the fractional portion, we can determine the absolute gap height with high accuracy and a large dynamic range exceeding a half wavelength. We present an experimental demonstration with a traditional Twyman-Green interferometer, in which a He-Ne laser was used as a monochromatic light source, and a test surface with a ~0.1 mm height gap was formed by two block gauges attached to a flat surface. The phase shift technique which moves the reference surface with a PZT was used for high accuracy phase measurement. To control the tilt angle of optical axis of the interferometer in high precision, several wedge plates with different wedge angles of known values are inserted into the illumination beam to change the illumination angle. The phases are measured across the gap and the gap height was determined by following the two steps described above. The repeatability for five measurements was found to be as high as 0.1nm (in 1 sigma).

8082-28, Session 6

Structured-illumination microscopy on technical surfaces: 3D metrology with nanometer sensitivity

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Structured-illumination microscopy (SIM) is, principally, a long-time known concept [1,2,3]. Yet, its potential for industrial metrology is not widely exploited. We will discuss this potential and the physical limits.

The principle: A sinusoidal fringe pattern is projected into the focal plane of a microscope. While the object is scanned axially, the contrast evaluation of the observed pattern delivers the 3D topography with a height uncertainty in the nanometer range. By means of high aperture the system can measure steep slopes: +/- 50 degrees on smooth objects (NA=0.8) and +/- 80 degrees on rough surfaces. Furthermore, the axial (z-)range is not limited by the Rayleigh depth of focus. This yields images with SEM-like quality and quantitative height information. Typical samples under test are wafers, micro optical components and micro cutting tools. The sensor is incoherent, robust and based on simple technology.

We present the fundamental physical and information-theoretical chances and limits of the sensor. The dominant noise sources are analyzed. For smooth surfaces the main noise source is photon noise. For optically rough objects the speckle noise is dominating. For the latter, our measurements show that the sensor works on the fundamental limit of distance measurement uncertainty for triangulation sensors. Furthermore, we investigate the physics of the signal formation and link it to the information-theoretical aspects of the signal evaluation. With this knowledge the trade-off between accuracy and efficiency is addressed. It turns out, that the best fringe period for a desired measurement uncertainty can be derived from the modulation transfer function of the optical system. Moreover, it is possible to foresee how far an improvement of the optical setup will lead to a more information-efficient sensor.

In addition, a new method for data acquisition and evaluation is presented. It enables a mechanical scanning of the object without stop-and-go. The existing algorithm required four fringe images with a phase shift of 90 degrees taken at the same z-position. The new algorithm needs only one image per z-position, thus paving the way for an implementation of SIM in an industrial environment.

[1] K. Engelhardt, G. Häusler, “Acquisition of 3-D data by focus sensing”, Appl. Opt. 27, 4684-4689 (1988).

[2] M. A. A. Neil, R. Juskaitis, and T. Wilson, “Method of obtaining optical sectioning by using structured light in a conventional microscope”, Opt. Lett. 22, 1905-1907 (1997).

[3] M. G. L. Gustafsson, “Surpassing the lateral resolution limit by a factor of two using structured illumination microscopy”, J. Microsc. 198, 82-87 (2000).

8082-29, Session 7

Broad spectral range measurement of chromatic dispersion of polarization modes in holey fibers using spectral interferometry

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In this paper, we present two white-light spectral interferometric techniques for measuring the chromatic dispersion of polarization modes in holey fibers with the birefringence induced by two large holes adjacent to the fiber core [1]. First technique is used for measuring the wavelength dependence of the group effective index of the one of the polarization modes supported by the fiber. The method is based on the recording of a series of the spectral interferograms in an unbalanced Mach-Zehnder interferometer with the fiber of known length placed in one of the interferometer arms and the other arm with adjustable path length [2]. We apply a five-term power series fit to the measured data and by its differentiation we obtain the chromatic dispersion over a broad wavelength range (e.g. 500-1600 nm) [2]. Second technique is used for measuring the group modal birefringence in the fiber [3]. The method is based on resolving the spectral interference fringes at the output of a tandem configuration of a Michelson interferometer and the optical fiber under test only in the vicinity of so-called equalization wavelength at which the optical path difference (OPD) in the interferometer is the same as the differential group OPD in the fiber [3]. From these measurements, the chromatic dispersion of the other polarization mode supported by the fiber is retrieved [2]. We measured by these techniques the chromatic dispersion of polarization modes in four different pure-silica holey fibers. We revealed the dependence of zero-dispersion wavelength on the geometry of the holey fiber.

[1] P. Hlubina, et al., Meas. Sci. Technol., 17, 626-630 (2006).

[2] P. Hlubina, D. Ciprian, M. Kadulová, Meas. Sci. Technol., 21, 045302 (2010).

[3] P. Hlubina, D. Ciprian, M. Kadulová, Meas. Sci. Technol., 20, 025301 (2009).

8082-30, Session 7

Inspection of processes during silicon wafer sawing using low coherence interferometry in the near-infrared wavelength region

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Silicon (Si) wafers for photovoltaics (PVs) are today mainly produced by multi-wire sawing, where silicon blocks are cut into wafers about 150-200 µm thick. The sawing process introduces surface defects on the wafers through roughness and micro-cracks, that can lead to breakage further down the production line. This production step is thus one of the most critical processes in the solar cell production.

The wire sawing process depends on a sawing liquid (slurry) consisting

of cutting particles (Silicon Carbide - SiC) and a carrier (Polyethylene Glycol - PEG). Wafer sawing is thus an abrasive cutting process.

Wafer sawing technology is today mainly based on empirical knowledge. The lack of fundamental knowledge and understanding of the microscopic cutting process in the sawing channel are major drawbacks for further developments and optimisations in the PV industry.

Modelling of the sawing process is rather sophisticated due to the necessity of a multi parameter approach. A widely accepted theory is that the SIC particles introduce micro-cracks in the Si material. These cracks propagate and lead to chipping of the Si. For optimisation of the wafer quality a better understanding of this abrasive process is necessary.

Optical inspection can contribute to increase basic knowledge and thus simplify the models of the abrasive process. Since the chipping area generated during indentation of the SiC particles is in the range of 10-20µm, microscopic techniques with high spatial resolution are essential.

High purity Si is nearly transparent for light with wavelengths in the range 1.25µm- ≈10µm. Silion has a high refractive index, and in the near infra red range 1.25µm - 1.7µm nSI= 3.5.

Following the Abbe criteria, the maximum obtainable resolution in an optical microscope with a numerical aperture of NA=0.5 is x= 1.22 in air. This results in a rather low spatial resolution of 1.5µm. In addition, the effective numerical aperture is limited by the refraction of the light beams when exiting the plane surface of the Si material.

Initial attempts to increase the spatial resolution are presented by Gastinger and Johnsen [1, 2]. Here, the fact that the investigated phenomena occur inside the silicon material and by the use of a Si solid-immersion lens, the spatial resolution is increased by a factor of 3.5.

Since the thickness of the Si chips is 150-200 µm, high z-resolution is required,. Low coherence interferomtery is a well known technique for high resolution measurements with accuracy down to the nm range.

In this paper we present a low coherence interferometer for measurement of phenomena occurring during multi wire sawing of Si. The optical setup is based on a Michelson interferometer. A superluminescent diode at 1280nm is used as a light source. In the interferometer arms two identical Si lenses (radius of curvature 8mm) are used as reference and object. The object is imaged by a 20x microscope objective to an InGaAs detector.

Investigations of the spatial resolution and experimental results using an USAF chart are presented. Finally, the first interferometric phase measurements on a sawing channel produced in a lab saw are presented.

8082-31, Session 7

Uncertainty of height information in coherence scanning interferometry

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Coherence scanning interferometry CSI (short known as white light interferometry) is, beside the confocal technique, one of the most popular optical principle to measure surface topography. Compared to coherent interferometry, the advantage of CSI is the calculation of unambiguous phase information. Theoretically, a vertical resolution in the sub nanometer range can be achieved. The horizontal resolution is still given by the rayleigh criteria. In contrast to confocal microscopy the vertical resolution is independent of the numerical aperture of the objective. The carrier of the height information is the so called correlogram which is the correlation function of the two split optical pathes in the interferometer branches. Different methods exist to calculate the height information out of the correlogramm. A coarse information about the height value comprises the envelope function of the correlogramm. Based on this information a precise phase evaluation can be carried out.

We start our paper with a short mathematically survey about the theory of the CSI technique. We will describe the properties in the time domain expressed by the convolution operator and in the frequency domain. The given fundamental equations show the influence of different types of optical aberrations.

Afterwards, we will discuss different methods to find the height information using the envelope function of the correlogramm. Two very popular methods are the hilbert transform and the evaluation in the frequency domain, also known as the FDA-algorithm. Different examples of real measured surfaces are given and we will discuss the robustness of the methods and its properties. We will estimate the cramer rao bounds of the specific methods. The cramer rao bound serves as an objective method to define a lower uncertainty bound.

The second part of our paper deals with the phase evaluation of the correlogramm, which is necessary to achieve a high vertical resolution. The calculated height information of the envelope function serves as a reference for the phase evaluation. Unfortunately, the given envelope function is often distorted and phase jumps lead to ambiguous height informations. In particular, this effect can be observed measuring rough surfaces. This is the reason why complex numerical phase unwrapping methods have to be applied. The necessary phase unwrapping is carried out in the 2D plane of the wrapped phase values. One possible way to unwrap the phase is a simple integration method which often leads to a faulty height map with arbitrary height steps. It will be shown that these virtual height steps are caused by residues in the phase values and depend on the selected integration path. But suitable algorithms can reduce the influence of the residues. We will discuss two well known principles: the “path-following” methods and the “minimum-norm” methods. We will show that the “path-following” methods are not always robust if a high number of residues occur. Finally we will show the properties of the “minimum-norm” methods, which fits a solution function into the gradients of wrapped phase.

All numerical results are calculated using our own software platform and in our presentation, different examples of real measured surfaces are shown.

8082-32, Session 7

Improvement of lateral resolution and reduction of batwings in vertical scanning white-light interferometry

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The precise and fast acquisition of three-dimensional geometrical data of micro-components is a crucial point in industrial production of many high-tech products.

Nowadays, this task is mainly performed by two alternative measuring techniques, either vertical scanning white-light interferometry (SWLI) or confocal microscopy. Both are capable of measuring micro-structured surfaces with a very high precision over a microscopic field of view. In both methods, a matrix camera records image sequences during a so-called depth scan. However, two different physical effects are utilized, which lead to different transfer characteristics of the corresponding instruments. For most applications the axial resolution of these systems is sufficient. Though, in certain applications the lateral resolution of a measurement system is far more critical. The German guideline VDI/VDE 2655-1.1 states that the short cut-off wavelength for SWLI exceeds the diffraction limited optical resolution defined according to the Rayleigh criterion by a factor of two to three. If the full depth of a grating structure shall be determined this factor doubles.

Besides the lateral resolution another consequence of diffraction is the so-called batwing effect, which appears on step height structures and influences the measuring results of SWLI. Especially, if the maximum interference contrast is evaluated systematic errors occur. As a contribution to the EC-funded project “NanoCMM” we developed a special kind of Linnik white-light interferometer, which provides a lateral resolution well below one micrometer even for working distances of more than 5 mm. The resolution enhancement was achieved by wavelength reduction, i.e. LEDs emitting in the blue and near UV range were used for illumination. We compare results obtained from a silicon pitch standard based on different illumination sources. In addition, profiles resulting from the Linnik interferometer are compared with those of a conventional Mirau interferometer providing the same magnification. Furthermore, it is demonstrated that the accuracy of the measuring results depend strongly on whether solely the contrast maximum, i.e. the envelope’s position, is evaluated, or the phase of the interference signal is additionally taken into account. Finally, we show that the batwing effect can be successfully reduced by using a confocal aperture in the illumination path of the interferometer. The combination of these different modifications clearly improves

SWLI measurement results in comparison with those performed by conventional white-light interferometers. The most significant improvement appears, as the lateral dimensions of the measured structure are close to the optical resolution limit.

8082-33, Session 7

Parallel optical coherence tomography (pOCT) for industrial 3D inspection

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Industry rely a lot on vision for in line or off line quality inspection. Whereas most of these applications use 2D vision, an increasing need for 3D vision is required. Optical Coherence Tomography (OCT) is widely used in medical application to obtain 3D images of biological tissues but did not really enter the industrial applications yet. Limiting factors are typically speed, ease of use, price.

We developed a CMOS camera specially designed for parallel OCT (p-OCT). The advantage of this method over other OCT techniques is its high speed and its ability to maintain a high lateral resolution over large measurement depths. Our camera can acquire up to one million 2D images per second. The amplitude and phase of the modulated signal is calculated within every pixel. Up to 10'000 such amplitude and phase results can be return in a second, for every pixel. This allows to obtain multi-million depth scans per second.

We will present our instrument, which includes a rugged and compact interferometer aligned with a robotized assembly technique. This imaging interferometer is scanned during acquisition, allowing to maintain a high lateral resolution (typically 2 micron) over several millimiters. The interferometer is easily interchangeable (snap-in magnets) in order to choose the ideal magnification for the application. This compact and versatile system can be built directly on a robot arm or scanned over large objects.

Several applications of this system will be presented. For most industrial applications the topology of the object is returned. But thanks to the OCT principle, objects with several layers can be measured in order to assert a layer thickness for example.

8082-34, Session 8

High speed fringe projection for fast 3D inspection

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Fringe projection techniques have been widely used for inspection of free form surfaces for quality inspection or reverse engineering purposes. In these applications highest measuring speed is not the highest priority. Typically, image acquisition and processing rates of up to 10'000 frames / sec are state of the art.

In order to exceed this value, we propose a fringe projection concept which uses a high speed CMOS camera with in pixel phase calculation. The camera can record up to 1 Mio frames / sec. An analogue calculation is realized in every pixel to extract the phase of the temporarily modulated light.

In order to determine a phase, the illumination light must be modulated with a quarter of the frame rate of the image acquisition, in our case with up to 250kHz. In fringe projection techniques, the projected fringes must be shifted with respect to the inspected surface. Mechanical phase shifting of the fringes becomes the crucial problem in ultra high speed fringe projection. We have investigated a new way to generate 250kHz phase shifted fringes. In this paper, we will present the new fringe projection technique and discuss results of our high speed 3D measuring device.

8082-35, Session 8

Radial expansion measurements of a high-speed rotor using an interferometric array sensor

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Studies on lightweight construction are of high importance in material science. At the Technische Universität Dresden, a special high-speed rotor test rig exists, where research on the robustness of rotors is accomplished. The rotor under investigation can be accelerated up to 250,000 rpm. Due to centrifugal forces, elastic and plastic deformations result. Their measurement is of huge interest for testing the robustness of components e.g. for aircraft turbo machines. Generally, optical techniques such as triangulation allow non-contact and precise shape measurements. However, the temporal resolution of conventional measurement techniques, such as triangulation sensors, is too low for monitoring high speed rotor deformations. Furthermore, the measurements have to be performed under vacuum condition.

All these requirements are fulfilled by the novel interferometric laser Doppler distance sensor, which enables a non-incremental position and shape measurement of moving and especially rotating objects. Furthermore, its measurement uncertainty of some microns is independent of the rotation frequency. This unique feature allows precise measurements of rotor deformations even at high rotor speed. Furthermore, a compact sensor can be realised by employing diffractive optics. The passive fiber-optic sensor head also allows measurements under vacuum conditions.

In this contribution, we present the application of a novel array sensor system for the investigation of fast rotating solid objects. Using three sensors, the position and the diameter of the rotor as well as its shape can be determined simultaneously. A cylindrical metallic rotor with a diameter of 190 mm was studied. Rotation frequencies up to 14,000 rpm corresponding to surface velocities up to 140 m/s were used preliminarily. Measurement results of the radial expansion of the high speed rotor with only 2 microns uncertainty will be presented.

8082-36, Session 8

High speed, on-line 4D microscopy using continuously scanning white light interference microscopy with a high-speed camera and real-time FPGA image processing

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Achieving real time 3D measurement of microscopic surfaces is difficult, mainly because of the high bandwidths required for the data acquisition by the probe or camera, the transfer to the processor and the processing. In confocal microscopy for example, a typical data acquisition rate using galvanometer scanning mirrors for the laser beam is 20 Mb/s. For an image size of 256x256 pixels (x8 bits depth), this results in an acquisition rate of 38 images slices per second and a 3D image rate of 1 image per second for a 38 slice 3D image. Measuring over large image sizes (greater than 512x512 pixels), high 3D image sampling rates (greater than a few images per second) and high depth resolution (greater than 100 slices per 3D image) therefore requires much higher data rates. In the field of white light interference microscopy, real time measurements can be performed with a high speed camera and continuously scanning fringes. Recording a series of scanned images in RAM or on hard disk, post-processing can be carried out to produce the 3D movie [1]. To achieve real on-line measurements on the other hand, highly parallel processing is required to carry out "on-the-fly" processing. While recent microprocessors could in theory achieve the necessary processing rates, the architectures are not adapted to the input rate from a high speed camera. Using a high speed CCD camera and cabled logic processing (FPGA; Field Programmable Gate Array), we have already demonstrated a data acquisition and processing rate of 65 Mb/s in a first prototype system [1]. An on-line 3D image rate of 5 images/s was

shown for measurements over a depth of 5 µm.

We have spent several years developing a second prototype of the "4D microscopy" system, based on a CMOS camera (500-20,000 i/s) connected via a CameraLink connection to a newer FPGA processing board [2]. In this paper we report on the latest results of this system using two different algorithms for signal processing that are well adapted to implementation in cabled logic. The first one is the Peak Fringe Scanning Microscopy (PFSM) algorithm that detects the maximum signal intensity. It has a variable step size of 20 nm to 100 nm and is very compact to implement. The second one, the FSA (Five Step Adaptive) algorithm uses a fixed step size of around 80 nm (/2) and measures the fringe visibility, resulting in more robust measurements, but slightly lower 3D image rates than with the PFSM algorithm. Data processing rates of 100-160 Mb/s are achieved with this system, resulting in real on-line measurements and recordable results. For example, we achieve a 3D image rate of several images per second for large images sizes (640x1024 pixels) and up to several tens of images per second for reduced images sizes (320x512 pixels) over an axial range of 2 µm to 20 µm. The axial resolution depends on the scanning step, typically between 20 nm and 100 nm (without interpolation).

The high speed, on-line 3D measurement in real time of microscopic surfaces with 4D microscopy opens up new applications which require the absolute measurements of 3D surfaces that are moving or changing in a non-periodic way with time. For example, measurements can be carried out of transients in microsystems, movements in soft materials and liquids and surface modifications due to layer growth or chemical reactions.

References

[1] Montgomery P.C., Draman C., Uhring W. & Tomasini F., Real time measurement of microscopic surface shape using high speed cameras with continuously scanning interference microscopy, Proc. SPIE, Vol. 5458, pp. 101-108, 2004.

[2] Montgomery P., Anstotz F., Johnson G. & Kieffer R., Real time surface morphology analysis of semiconductor materials and devices using 4D interference microscopy, Journal of Materials Science: Materials in Electronics, ISSN: 0957-4522 (print) 1573-482X (online), 19 (Suppl. 1) pp. 194-198, 2008.

8082-37, Session 8

3D high-speed profilometer for micro-manufacturing

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In micro manufacturing (MEMS, polymer hot-embossing, polymer roll-to-roll imprint, etc.) precise micro and nano-structured features are patterned over large areas. Characteristic dimensions span orders of magnitude; micron scale structures are distributed over square meters of area. Micro manufacturing may be improved via statistical process monitoring and feedback control, however, commercial inspection instruments fall short on meeting these challenging demands.

In this paper we detail the design, implementation, and use of an optical system for the real-time inspection of polymer micro devices. We control and vary conditions of the image acquisition (position, illumination, viewing angle, etc.) and acquire a set of raw images. This raw set contains information with which to estimate the three-dimensional map of the observed parts. We create a topographic map and calculate measures related to the fidelity of the manufactured patterns and structures. We analyze the compromises between the system performance specifications of rate, range, and resolution for the system components of mechanical scanning, optical elements and optical sensors, and algorithms. Few commercial inspection instruments simultaneously excel in these areas. White light interferometers provide submicron resolution but have insufficient inspection speed. Structured light profilometers have orders of magnitude faster inspection speed but are limited to 10 micron resolution.

Ours is a novel system with the resolution of a white light interferometer and the potential inspection speed of a structured light profilometer. It is designed to enable in-line inspection and metrology of micro devices and support statistical process control. A microscope objective and high-speed area camera focus and capture light reflected off of or transmitted through the part under inspection. The camera and lens are tilted with respect to the part. We treat each sensor row as an independent line scan camera and can capture over one thousand scans in parallel. Each line is focused at a different height. Depth-from-focus algorithms process the data into a topological height map. From this data we generate an extended depth of focus image with submicron resolution over hundreds of microns vertical range. The submicron lateral resolution is controlled by the magnification of the lens and the pixel size of the camera sensor array.

Many micro-manufactured parts have critical-to-performance depth features with near vertical sidewalls. Such part geometry is not practical or even possible to measure using conventional profiling techniques. The tilted orientation of our camera system provides access to these typically hidden and eclipsed areas. Multiple viewing angles are used to capture the complete surface topology of features with modest aspect ratios. The noise, and therefore resolution limit, in the depth measurement partially depends upon the part. When measuring rough or textured surfaces, such as machined aluminum, this resolution limit was found to be approximately 1 micron. When measuring smooth surfaces such as hot embossed polymer the resolution limit was found to be approximately 2.5 microns. We expect these limits to improve with enhanced processing techniques.

The instrument has been used to collect data on a variety of parts. We conclude the paper with a direct comparison of our instrument's capabilities against commercial instruments. Several exemplar samples were created. The samples were measured with our instrument, a white light interferometer, and a structured light profilometer. The data demonstrates the difference between the instruments' lateral resolution, data acquisition rate, and vertical sidewall measurement capabilities.

8082-38, Session 8

Fringe projection based high speed 3D sensor for real-time measurements

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A sensor based on fringe projection technique was developed at our institute which allows ultrafast measurement with high spatial resolution of measuring objects with a small extension in height like conductor boards. The sensor consists of a fringe projector and two high resolution cameras (5MPixel). The measuring field covers a 50 mm x 40 mm sized area by projection and observation. The measuring objects may be up to 2 mm in height and the spatial resolution in the object space is about 20µm.

The measuring principle of the sensor is triangulation of homologous points using projected fringe patterns. The correspondence between these points is found by phase correlation and use of geometric constraints of the system. In order to achieve a measurement velocity of 35 cm^2/s, strict reduction of the recording time and accelerated computing in opposite to the recently developed systems had to be reached. This was realized by implementation of some new fringe analysis algorithms with reduced fringe code length without loss of measurement accuracy.

For this the concept of epipolar segments was used getting advantage from the small height expansion of the measuring objects. Using the properties of the sensor geometry Gray-Code sequences were omitted leading to further reduction of the number of images per sequence.

Projection and image recording by the high resolution cameras with 5 megapixel are done with 15 Hz image frame rate. The analysis of the extreme huge data amount in the requested velocity is achieved by parallelisation of 16 computing and analysis courses. When 3D data calculation is still performed the system realizes movement and recording of images of the next measuring position.

With the developed sensor a measurement velocity of 8.9 million 3D points per second was realized corresponding to an inspection velocity up to 35 cm^2/s. For measurement of a complete conductor board, for example, the sensor is moved step by step. The cycle time for one measuring position is less than 0.6 s. The measuring uncertainty of the system is < 8 µm. Although the input data are drastically reduced, the accuracy of the sensor is comparable to those of similar systems which full fringe code length. Application examples are given which demonstate the chances as well as the restrictions of the system.

8082-39, Session 9

Alignment methods for ultraprecise deflectometric flatness metrology

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The demand for high-precision topography measurements of nearly flat specimens, such as high quality optical mirrors or synchrotron mirrors, with both smaller uncertainties and larger specimens is constantly increasing. This is why new measuring systems for absolute high-precision topography measurements of plane surfaces were installed at the Physikalisch-Technische Bundesanstalt (PTB) in 2010. The so-called DFR systems (Deflectometric Flatness Reference) are based on deflectometric measurement principles and can measure both circular specimens up to 700 mm and elongated specimens up to 1 m in horizontal as well as in vertical position. With the flatness measuring system, an uncertainty down to 0.1 nm (depending on the specimen and its peak-to-valley) is being aimed at for the 95% confidence interval.

The systems are based on different deflectometric procedures, the so called direct and difference deflectometry. In the direct mode, the deflection angle is measured with a high-precision calibrated autocollimator with accuracy of 0.01 arcsec. In this method, the autocollimator is firmly connected to the granite base, while the specimen is scanned with a pentaprism or double mirror, which deflects the beam by 90°. The subsequent integration of the measured angles yields the topography. In the difference mode, angle differences between positions with fixed distances - the so-called shears- are measured. This method is called the “Extended Shear Angle Difference (ESAD) procedure” and has been invented at the PTB. From these angle difference measurements the slopes and thus the topography can be reconstructed. The principle of both systems will presented.

For estimation of measurement errors, an all-purpose simulation environment was developed at PTB. It is object orientated and modular, so that different machines can easily be implemented. It offers the possibility for realistic 3D-modelling, e.g. 3D optical raytracing, integrating of real optical surfaces and it provides a graphical output.

The DFR-system for the horizontal specimens was realized in this simulation environment and virtual experiments were accomplished. A detailed sensitivity analysis shows for example the necessary specifications for the mechanical stages, the autocollimator or the optical surfaces. Further on, these virtual experiments show that the optical and mechanical components must be aligned in the arcsecond range in order to achieve errors for the topography in the subnanometre range. Different experimental methods were investigated, in order to meet the necessary requirements for the alignment. The alignment can be divided in three steps. First, the optical axis given by the collimated beam of the autocollimator and the scanning axis must be aligned parallel. For this purpose we use a CCD-camera in combination with a sophisticated algorithm, which determines the centre of the autocollimator beam with subpixel accuracy. Second, the double mirror must be aligned to the optical axis to minimize roll, yaw and pitch errors. Finally the specimen must be aligned to the optical axis. We present methods and experimental results for these three alignment steps. The experimental results show, that an alignment with the required accuracies in the arcsec range is possible.

With the well aligned system for horizontal orientated specimens, we present measurements regarding the stability and accuracy of the system. First topography measurements of single sections at horizontal orientated specimens will be shown and discussed.

8082-40, Session 9

Measurement and characterization of cylindrical surfaces by deflectometry applied to ballistic identification

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The inner surface of most firearms barrels contains a set of helical grooves with a dual purpose. The first one is to generate a projectile rotation around the barrel axis, resulting in a more rectilinear, stable and well defined trajectory. The second purpose is to generate a “signature” on the projectile. The shape and the barrel rifling of each firearm are distinct and it generates unique marks on the fired bullets. The comparison between the micro striae (“signatures”) and the set of the spiral grooves impressed by the firearm barrel is the basis of the ballistic identification.

This report describes an optical device that uses a technique known as “Deflectometry” applied to ballistic identification. The main novelty is characterized by the use of a 45° conical mirror to measure the near cylindrical surface of the bullet.

Deflectometry is an optical technique sensitive to variations in topography and unevenness of a surface. This technique allows to identify and to measure the geometry of objects based on the distortions observed in a sequence of images reflected on the surface of interest. The measurement by Deflectometry is very sensitive to the surface local gradients and curvatures.

The optical device, described in this paper, is composed by two low resolution cameras used to align the bullets to the optical axis of the system; two rotation tables to transversal alignment of the bullet; two rotation tables to angular alignment of the bullet; a high resolution camera with objective lenses; a multimedia projector; a beam splitter, a projection screen and a conical mirror.

The conical mirror is used in this optical configuration in order to transform the image of the bullet cylindrical surface into an annular flat image. The conical mirror allows the measurement of cylindrical parts from a single spatial position, simplifies the optical configuration, improves dramatically its performance and reduces the measurement time.

The simplest constructive configuration of an optical device that can be used in Deflectometry is composed by a projection screen or a luminous surface and a video camera. A set of patterns of structured light, typically with sinusoidal profiles, is projected onto the screen. The video camera acquires the surface image with the structured patterns that are reflected by that surface. The camera acquires not only one image, but a sequence of lagged images which are digitally processed. The result is a phase map with the informations that are related to the bullet surface slopes and curvatures.

Comparisons between images of bullets fired as far by the same weapon as by different weapons were made. The results are sorted by numeric indexes calculated from the phase image correlations.

8082-41, Session 9

Endoscopic geometry inspection by modular fiber-optic sensors with increased depth of focus

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A quality inspection of assembly parts and tool surfaces becomes more and more important in times of advanced quality management. The trend leads for many parts to 100% checking methods within the running fabrication process. Suited measurement techniques therefore should be, above all, flexible and fast in order to keep up with the production process. Large area analysis of topographies nowadays can be realised with commercially available fringe projection systems with very high accuracy. However, these systems reach their limits for assemblies of high complexities, because of shading effects in the area of measurement.

Within the scope of the Collaborative Research Centre (CRC) Transregio 73 (SFB/TR73) research project, funded by the German

Research Foundation (DFG), a new kind of micro fringe projection system is being developed. By using flexible imaging fibre bundles, it becomes possible to collect complete data sets of filigree and hardly accessible assembly geometries.

These sets can be used to generate an own geometric model or to complete measurement data sets of large-scale systems. These models can immediately give feedback about the running manufacturing process and can be used for in situ optimization in the fabrication line to avoid high reject rates. Additionally, measured data of functional surfaces can be combined with spot measurements of conventional coordinate measurement systems.

Flexible endoscopes are well known from medical engineering as well as from technical inspection in engines and turbines. Up to now the measuring ability of these endoscopes, especially in the third dimension, is only very limited due to missing information on distance to the object and an integrated scale. Fringe projection systems overcome both problems in one technical approach. However, in contrast to common fringe projection systems micro- optics and fibre couplers have to be used for the adaptation in endoscopy. That also increases the requirements on the light sources to guarantee a high incoupling efficiency and therewith a high contrast micro fringe pattern on the specimen.

For that, principles of despeckled laser light illumination of digital mirror devices (DMD) are shown. Optimized fibre coupling techniques for fringe patterns in 100.000 pixel image fibres with the help of Scheimpflug enhanced gradient index (GRIN) micro optics will be presented. Via adjustable sensorheads the triangulation angle can be fitted to the geometry (Figure 1).

A 7.5 times increase of depth of focus from 0.4 to 3.0 mm on a measuring area of 8 mm^2 will be shown and compared with a system with common light sources and common GRIN micro lenses and sensorheads.

The laser based pattern generation is shown in Figure 1. A common low power consuming 532 nm laser beam is sent through a rotating diffuser disc. The disc changes the generated speckle pattern of the coherent laser light randomly at higher speed than the detector cameras frame rate. This way, several patterns are integrated on the CCD chip to a picture with almost no speckle contrast that normally would develop due to the not optically perfect state of the DMD and the specimen. Further, the laser beam is shaped by a micro lens array from it's Gaussian profile to a flat top with an area of 20 x 20mm to fit to the DMD. (Figure 2)

The beam shaper creates a very homogenous intensity profile with almost no losses on the DMD acting as a pattern generator.

The generated fringe or phase pattern is than coupled to an image fibre by a microscope objective with high numerical aperture (NA). The high resolution pattern by that is reduced to a 100.000 pixel picture, due to the limited number of fibres in the imaging fibre.

However further improvement of picture contrast and depth of focus can be achieved with a new design of GRIN lenses. Using ray tracing simulations ideal micro optical designs and optimized picture planes were determined and adapted.

For the transformation in a 3D model of the specimen it's necessary to transform the reflected picture into coordinates. By the projection of a stack of black and white stripe patterns in order of a Gray-code projector and camera are aligned on the specimen and corresponding pixels of both devices identified. With the information of the triangulation and the beforehand made camera coordinate calibration the exact geometry of the sample can be calculated to compare its shape to the CAD model with the accurate measures. To increase the resolution of the system four phase shift cosine patterns are projected to the specimen's surface. Added to the before taken Gray Code pattern it creates a highly accurate and well defined scatterplot (3) for maximum resolution 3D measurements.

8082-42, Session 9

3D-Measuring in the field of endoscopy

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Industrial optical 3D-measurement techniques are well established to achieve quality targets in production and manufacturing. But measuring inside of objects, especially small ones, is still a challenge as there is no easy access for measurement tools. Inspection tools like endoscopes which provide a 2D-view or a stereoscopic view of inner surfaces are commercially available and widely used. However, there is no technique for precisely measuring the inner surface geometry of a small hollow object. Especially medical applications would greatly benefit from "dimensional" measuring. Thus a novel approach and prototype of a miniaturised endoscopic 3D-scanner is presented. To be suited even for very narrow objects the prototype has a maximum diameter of 3.6mm. Its flexible design allows access to bent tubes or canals. The 3D scanning approach is based on the principle of structured light, which means that a coded light pattern is projected and then viewed under a different angle. It is usually difficult to realise triangulation set-ups within a very confined space. Therefore an optical tandem of a miniaturised pattern projector and a small colour camera with a resolution of 400 x 400 pixel and a frame rate of 30 fps is presented as a practical solution.

There are many approaches to 3D image acquisition using the principle of structured light. Probably the most common one is phase shifting. Most of the approaches require the sequential projection of several patterns onto the scene. Widely used projector chips like a Digital Micromirror Device or a LCOS are well suited to create arbitrary patterns. For phase shifting patterns, it is possible to use an actuator which moves a single slide with a given sinusoidal phase pattern to at least three predefined phase positions. All these set-ups take up comparatively much space and consume power for operation; they also dissipate heat which increases the temperature of the tip in case of an endoscope. In order to overcome the drawbacks associated with a complex projector, a very compact projector is realised. It projects a single static pattern of 15 rings of distinct colours into a cylindrical measurement space where the colour sequence constitutes a code. White light from a LED is coupled into a plastic fibre outside of the sensor head and is guided in the flexible part of the endoscope to the projection unit. A Galilei type telescope serves to adjust the exit diameter of the fibre to the diameter of the circular slide and simultaneously lowers the divergence angle of the effective light emitting area. This helps to reduce stray light and uses the available light in a most efficient manner. Coated dielectric layers on the glass slide create the coloured rings by interference of light. The projection optics itself is in the broadest sense comparable to the design of a telecentric scan lens or an ocular at which the telecentric part is oriented towards the slide. This arrangement complies with the nearly parallel ray paths on the illumination side and helps to avoid a light intensity drop towards the image borders.

The camera uses a catadioptric set-up with a spherical mirror to enhance its field of view. It is axially aligned with the projector and thus constitutes a tandem. Due to this tandem arrangement both the projection space of the projector and the field of view of the camera form an envelope around the endoscopic sensor head.

To generate 3D data, the camera continuously captures images of the scene. The encoding embedded into the sequence of colour rings allows identifying the projected rings within a single colour image reliably even with complex textured scenes. From each image, an algorithm reconstructs the 3D-shape of the part of the scene currently seen unambiguously using ray-cone intersection. As the algorithm computes 3D data from single colour images only, any problems due to motion of the sensor head are effectively eliminated. Exploiting the overlap of typically 90 percent or more between two consecutive images, respectively 3D data sets, the typically hundred or more separate data sets are merged to generate a complete 3D model of the scene.

Experimental 3D-scans of arbitrarily shaped tubes demonstrate good usability and an accuracy of about 0.1mm when measuring an arbitrary shaped tube with a diameter varying from 5 to 15 mm.

The presented approach for endoscopic 3D-measuring has several advantages. Only a static projection pattern is needed which greatly reduces the complexity and size of the projector compared to phase shifting technologies. An "external" LED light source coupled to an optical fibre helps to avoid heating up the 3D sensor head. A tandem like arrangement of projector and camera serves to measure the complete volume around the cylindrical measuring head in one shot.

8082-43, Session 9

3D shape measurement based on color-encoded sinusoidal fringe projection

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Coded structured light is considered one of the most reliable techniques for recovering the surfaces of objects. This technique is based on projecting a color-encoded structured light pattern and recording the image of illuminated scene from a different angle. Since the pattern is coded, correspondence between image points and points of the projected pattern can be easily found, the decoded points can be triangulated and 3D information is obtained. When pattern is coded using different colors, this coded structured light is color-encoded structured light, which is a hot topic in recent years, compared with code with different gray levels or symbols, color is more easily to be identified, and decoding is more accuracy. This pattern is spatially encoded, thus it can be used to inspect dynamic and spatial isolated objects.

If the pattern has a sinusoidal instead of binary distributed intensity, phase information at every pixel can be reached by traditional fringe analysis method. We proposed three color encoding methods in this field, every pattern we designed is encoded with color strips and sinusoidal fringes, while color codification is different from one pattern to another. The sinusoidal fringes have the same pitch with the width of the color stripe, and the fringe orders are corresponding to the color orders. One of these patterns is projected to the tested object's surface by a projector, and the image of the object is captured by a color camera positioned at an angle different from that of the projector. The captured image is processed, in which fringe intensity is used to extract the phase information of the tested object, and the color codification is assisted to recover its corresponding natural phase distribution. In each method, the order of each fringe only depends on its own corresponding color information, has nothing to do with the neighborhood fringes in space, thus, unwrapping error is limited in a small area and won't expand to other pixels. It takes great convenience for 3D measurement of an object with spatially isolated surface. With only one image, 3D shape of the tested object can be exactly reconstructed, thus the speed is limited only by the frame rate of camera, so these methods can also be used in 3D shape measurement for dynamic object.

Principles of this technique and three encoding methods are described in this paper. Some experimental results are also presented. Results of the reconstructed shapes of static, dynamic and spatially isolated objects prove the correctness and feasibility of this approach.

8082-44, Session 10

Structured light measurement and calibration method for 3D documenting of engineering structures

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In the paper a new approach for two step calibration process allowing 3D measurement in large volumes is presented. The maximum assumed volume is equal to 20m x 15m x 6m and the developed system have to be portable and easy to operate by one person. To set-up a traditional 3D structured light system a long enough base distance between projector and detector is required to ensure sufficient measurement sensitivity. In this setup to achieve measurement uncertainty in the range of 20mm the minimum 10m base distance is required. For this base distance it is nearly impossible to set-up a rigid frame for fixing projector-detector configuration and allow to anyone for easy manipulation of such system.

Taking into consideration the above mentioned requirements a new calibration method has been proposed. Its main assumption is that there is no requirement for fixing projector and detector during a calibration phase. The relation between projector and detector is established just before measurement where they are finally positioned to capture 3D shape of investigated surface.

It works in two steps: the first one is based on independent calibration of projector and detector devices to establish relation between their the pixel (i, j) co-ordinates and lines in free space; the second one is based on a set of measurements of a known calibration model and their analysis allowing calculation of a relative transformation between detector and projector co-ordinate spaces. The first step is always done in laboratory and the second one is performed just after any change in a relative position between projector and detector.

During calibration procedure two models are required. The first one is used during separate camera and detector calibration. It is a white diffuse plane with black circular markers. This calibration is based on consecutive measurements of translated and rotated model inside assumed measurement volume. From these measurements a relation between pixel (i, j) and line formula is established. It is done in iterative process on the base of known calibration model dimensions. Additionally, the user should define some initial specification of the distance between two model positions (with precision of 10% in relation to the specified distance) which are required to find initial conditions for the iterative process. The second model is a dark frame with four white diffuse markers. It is used always when a relative position between projector and detector is changed. The relative positions between projector and detector is calculated on the base of measurement of this model.

In the paper an initial assessment of measurement uncertainty will be discussed in relation to calibration model versus measurement volume size. In the laboratory two sets of calibration models with different dimensions will be used for establishing a relation between model size and measurement uncertainty. It will be helpful for practical reasons to minimize the calibration model size as much as possible but still allow to measure with the required uncertainty.

Also some exemplary measurements of real engineering structures will be presented and discussed. As we intend to use the system for civil/engineering structures (bridges, exhibition halls) the structure under investigation will be much bigger than the calibrated measurement volume size. Therefore finally the measurements will be integrated into single 3D data set representation.

8082-45, Session 10

Fast 3D shape measurements using laser speckle projection

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Structured light based 3D-shape measurements achieve very high accuracy and therefore have been applied to many industrial applications.

There are a lot of strategies dealing with the structure of light, and the exact extraction of features from images. The most popular technique often adopted is stripe projection. In the last years more and more effort was put into realizing faster measurements. Mainly driven by the needs of industrial environments, which are facing increasing production rates. Several groups aimed at increasing measurement rate, while maintaining the accuracy level.Usually fast measurements in stereophotogrammetry are addressed by less patterns projected, because current hardware limitations of projectors restrict e.g. the maximum projection rate. Stripeprojection systems with one to three frames or defocused binary stripes have been proposed but unfortunately aren't able to measure spatially separated objects. As the graycode sequence is often omitted for speed's sake an absolute phase cannot be determined for scenes containing height jumps. Using DLP technology binary patterns can be created at the rate of several kHz, but those systems are expensive and in most cases non-binary patterns are preferred. Some groups remove the colour wheel of a projector to project one pattern within one colour channel of the projection unit. Nevertheless the projection rate is increased to merely 180 Hz in this case and the possibility to acquire 3D and colour information at the same time is taken. Hence, there are still hurdles to take and applicants unfortunately normally have to decide whether to measure fast or accurate. For several years now, our workgroup is using bandlimited statistical patterns in combination with temporal correlation to match correspondences to acquire the shape of arbitrary objects. A sequence of statistical grayvalues for each pixel is taken to correlate for homologous points in all views. The number of grayvalues (sequence length) equals the number of necessary projected patterns and mainly defines the possible accuracy, which is comparable for this system to those using state of the art stripe projection and graycode sequences. In particular bandlimited statistical patterns lead to a high measurement accuracy, but in principle any series of statistical patterns can be used with the temporal correlation technique. Based on this previous work the idea was to design a new projection device that is able to create statistical patterns at a very high rate. This new high speed projection device based on statistical laser speckle patterns that is at present able to project 500 statistical patterns per second will be proposed. Using this setup and subsequent temporal correlation techniques we realized 17.25 measurements of independent 3D states per second. In contrast to other fast measuring techniques mentioned above there are no restrictions for the object, like steady surfaces or homogenous reflectivity. The speckle-patterns offer a high contrast within a large volume and could be applied to large measurement volumes if desired. Furthermore, as there is no distinct sequence for statistical patterns, sliding window approaches can be applied, so that every new pattern image can be used to generate a new 3D state. For example, acquiring 13 pattern images for each view 2 reconstructions(1-12,2-13) can be made. With this technique 44 3D states per second could be reconstructed. We are presenting the current setup, and compare the measurement accuracy to conventional DLP projector based systems (i.d. stripe projection as well as statistical patterns). In addition, we show the potential of this system for even faster measurements in the future, aiming at an projection rate of several kHz and combined acquisition of 3D shape and colour.

8082-46, Session 10

Optical measurement and comparison of large free-form surfaces through a regular mesh

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A portable optical measurement system, capable of measuring free form surfaces over large areas and comparing them with reference surfaces was developed within this work. The system merges passive and active stereo vision. Data is acquired in both modes for each partial overlapped position of the system, covering all the area of interest of the free form surface or part being measured.

In passive stereo vision mode, circular targets are used to determine the coarse position of the system (i.e. cameras and projector) referenced to a global coordinate system defined by the targets. In active stereo vision mode, three-dimensional point clouds are locally measured and registered in the global coordinate system. The algorithm performs the calculation of these point clouds into a single intrinsically structured regular mesh, allowing an efficient comparison between different surfaces because the correspondence of points can be pre-defined. Experimental evaluations, using different kinds of geometric patterns and calibrated free form surfaces demonstrate the feasibility and the advantages of the proposed methods.

8082-47, Session 10

Accurate calibration of a fringe projection system by considering telecentricity

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Fringe projection systems are qualified for the measurement of complex work piece geometries due to the short measurement times and the high point density. For an accurate measurement it is necessary to calibrate the sensor. This can be done by the use of black box methods or with a model based approach. Examples for black box methods are a polynomial formulation or neural networks. The model based approach is based on physical backgrounds and tries to describe the real sensor behaviour by regarding the intrinsic and extrinsic parameters.

The main advantage of the use of black box methods is, that there has to be no knowledge about the real sensor behaviour. Usually, this method is applied for systems, whose structure is to complex in order to be described with physics. A major disadvantage is that there is no information, how much the single system parameters (polynomial coefficients, activation function, weighting coefficients) have an effect on the measurement accuracy.

The main advantage of the model based approach is, that there is a completely virtual physical model of the sensor. The physical model of the sensor can be used for comprehensive statistical analysis. For example, the influence of the system parameters concerning the measurement uncertainty can be estimated. Another field of application is the use of the virtual model as part of a virtual multisensor assistance system for the calculation of intelligent and work piece specific measurement strategies with respect to different criteria, like minimal measurement time or measurement uncertainty. This is the main field of research of the subproject B5 "Complete Geometry Inspection" of the collaborative research centre 489 (CRC 489) "Process Chain for the Production of Precision Forged High Performance Components", funded by the German Research Foundation (DFG).

The main task of the subproject is to develop a virtual multisensor assistance system, build up from a shadow projection sensor, composed of with a linear and a rotational axis, and a fringe projection sensor, which is fixed on a 3 DOF (Degree of Freedom) positioning system. The virtual system is applied for the estimation of measurement uncertainties for a certain work piece alignment in the measurement volume. Based on the uncertainty estimation it is intended to calculate the best work piece orientation, so that an optimal measurement is accomplished for the geometric tolerances. Thereby, the optimisation criteria are a minimal measurement time, a measurement with a minimal uncertainty and a holistic measurement. Besides the integration of the named criteria the measurement device of the existing assistance system, which is the most suitable device for the measurement task, should be determined.

The focus of this paper lies on the description of the physical and mathematical model of a fringe projection sensor, shown in the figure, and the model adapted calibration procedure. It is necessary to describe each relevant physical effect in the model and to identify all system parameters with a very high accuracy, if the virtual measurement system should be used for statistical analysis. The camera lens of the used fringe projection system has an object-sided telecentricity. Usually, this is not considered in the physical model and calibration strategies. To get a more precise virtual model, this influence has to be taken account. This means, that existing physical formulations of fringe projection systems and developed calibration strategies cannot be used for this case.

In this paper the physical model of the fringe projection system should be explained in detail. Thereby all intrinsic parameters and extrinsic parameters will be considered. Examples for intrinsic parameters are distortion parameters and the displacement of the image focal point. The relative position and orientation of the optical axis of the camera lens and the projector lens with respect to the inertial world coordinate system (object coordinate system) or the object-sided telecentricity of the camera lens are extrinsic parameters. After the formulation of the virtual system the calibration procedure for the identification of all system parameters will be described and discussed. At the end of the paper a verification of the used model and the calibration strategy will be given. Therefore, the calibration process is repeated and the standard deviation of the system parameters will be calculated. After that, an optical flat and a gouge artefact will be measured in different positions and the planarity of the optical flat and the depth of the gouge artefact will be determined and compared to the calibrated values.

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8082-48, Session 11

Some aspects of error influences in interferometric measurements of optical surface forms

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No abstract available

8082-49, Session 11

Diffractive simultaneous lateral shearing interferometry

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No abstract available

8082-50, Session 11

Aspherical surface measurement using quadri-wave lateral shearing interferometry

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No abstract available

8082-51, Session 11

Advances studies on the measurement of aspheres and freeform surfaces with the tilted-wave interferometer

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No abstract available

8082-52, Session 11

A subaperture stitching algorithm for aspheric surfaces

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This study aims to develop a subaperture stitching algorithm for testing aspheric surfaces that could have more than 1000-wave departure from the best-fit sphere. The considered optical surfaces are circularly symmetric. The proposed measuring scheme is to divide the full aperture into one central circular region plus several partially-overlapping annuli, measure the phase maps at small subapertures in each annulus by interferometry, and stitch all the subapertures together to reconstruct the whole surface. The procedure for data acquisition and processing is described step-by-step as follows.

1. Data acquisition configuration

A modified Fizeau interferometer is adopted to measure the subaperture phase maps. In order to have resolvable interference fringes in each subaperture, a best-fit spherical reference is determined through an optical alignment procedure. Optical null is accomplished by introducing proper amounts of tilt and defocus between the reference and the object wavefronts. The specimen is mounted on a set of multi-direction translational and rotary stages that permits the optical null as well as the subaperture scanning. For each annulus region, the specimen is rotated five rounds to collect five interferograms associated with each subaperture. Phase shifts between the interfering beams are generated by a PZT actuator.

2. Subaperture phase maps by phase-shifting interferometry

To deal with random vibrations from the phase shifter, an iterative phase-shifting algorithm based on the least-squares principle was developed [1]. The algorithm used five phase-shifted interferograms and iteratively calculated the phase distribution and phase shifts to minimize the sum of squared errors in the interferograms. The performance of the algorithm was evaluated via computer simulations. The tested random pistons were up to 90 degrees. The tested tilt amount was up to 0.5 waves in the x and y directions. The achieved rms phase accuracy was 0.0113 radians (0.0018 waves) averaged from 200 sets of random samples.

3. Phase unwrapping

The phase-shifting algorithm transformed the interferograms into subaperture phase maps of modulus 2-pi. The individual phase map is unwrapped by 36-term Zernike polynomial fitting. The higher-order terms are preserved by adding the residue back to the fitted phase map.

4. Phase stitching in an annulus

Once the subaperture phase maps are obtained, the subapertures in one annulus are stitched by applying the least-squares principle to the overlapped regions between subapertures. Adjacent subapertures have an unknown piston and unknown x and y tilts relative to each other. If the number of subapertures is N in one annulus, there will be 3(N-1) unknowns in the least-squares problem. The corresponding cost function is the sum of squared errors in the N overlapped regions. The minimum of the cost function occurs at the location where the partial derivatives with respective to each unknown are zero. This yields a linear problem that can be solved by matrix inversion, while the matrix is sized 3(N-1) x 3(N-1).

For aspheric surfaces with large departure, the interference fringes in an outer annulus are dense and the resolvable region in each subaperture is limited. As a result, the number of subapertures required for an outer annulus is large and the matrix inversion becomes troublesome. Some linear algebraic operations break the matrix inversion into inversions of 3 x 3 matrices. Hence the phase stitching can be accomplished regardless of the number of subapertures in an annulus.

Preliminary evaluations of the phase-stitching algorithm in an annulus region are performed with two data sets: one contains 12 subaperture phase maps directly extracted from the whole aperture with additional random pistons and tilts, and the other has 12 subaperture phase maps obtained through the phase-shifting and phase-unwrapping algorithms. The rms phase residue for the first data set was 10^-5 waves, which confirms the correctness of the algorithm. The rms phase accuracy for the second data set was 0.027 waves; this error is due to the residue in the phase-shifting algorithm. The error-propagation effect can be reduced by having larger overlapped regions between subapertures. By doubling the number of subapertures in one annulus to 24, the rms phase residue was decreased to 0.005 waves, which met the precision requirement of common interferometers.

5. Phase stitching between annuli

The phase stitching between annuli is again a least-squares problem in the overlapped region. Adjacent annuli have an unknown piston and unknown tilts relative to each other. By using the central circular region as the base, the whole aperture can be stitched one by one along the radial direction. The computer implementation of this part is in progress.

A prototype aspheric interferometer is currently under development in the research group. The experimental verification of the proposed algorithm will be carried out in the near future. This algorithm should be applicable to all kinds of stitching interferometers with overlapping subapertures.

Acknowledgement

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References

[1] P. C. Lin, Y. C. Chen, C. M. Lee, and C. W. Liang, “An iterative tilt-immune phase-shifting algorithm,” Optical Fabrication and Testing, OMA6, Jackson Hole, Wyoming, June 13-17, 2010.

8082-53, Session 12

Some challenges in shape measurements of optical freeform surfaces

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No abstract available

8082-54, Session 12

Axicon metrology using high-line density computer-generated holograms

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Axicon surfaces are widely used in nowadays optical system design. This rotationally symmetric, cone shaped element allows concentrating light along a large portion of the optical axis and thus enables systems with a long focal depth. This advantage is exploited in many applications, such as laser machining, optical testing, laser beam shaping and laser resonator design.

In this contribution, we present metrology aspects for high precision testing of this extremely aspheric surface. The testing method is null test interferometry with computer-generated holograms (CGH) used as null optics in the interferometer. This established method provides the advantage of high accuracy, non-contact and fast measurement operation.

With current fabrication technologies such as scanning interference lithography (SBIL), it is possible to efficiently realize large area high resolution CGHs for the use in the characterization of steep axicon surfaces. Increasing line densities in the CGH require a careful consideration of several error sources that receive little attention in every day's shop testing, such as misalignment of the setup, fabrication effects of the CGH, rigorous effects of the high density grating structures and wavelength variations due to environmental effects.

We present a novel testing method for axicons that allows removing systematic errors and thus provides an absolute test. It uses a space shift differencing method that exploits the uniformity of the CGH's line density. With both rotational and axial shifts of the axicon surface, we obtain differential data of the surface figure error in polar coordinates without any other systematical errors. Using a wavefront reconstruction technique for the integration of the differential data, the local error of the surface can be reconstructed.

Nevertheless, as constant error term of axicon surface figure, the cone angle error cannot be determined during the above wavefront reconstruction process. The measurement of this error is obtained from the standard null test measurement. The use of a set of orthonormalized axicon functions and corresponding simulation analysis allows focusing on only the two terms which describe the cone angle error and at the same time calibrating out all the influencing factors. Three influence factors can be identified as the most important parts that need to be taken into account for the calibration. The first two parts, the tilt required for eliminating the zero order backreflection and the substrate figure error are systematic contributions that are determined once. The wavelength as third part needs to be calibrated during the measurement, for its sensitive dependency on environment conditions.

Experimental results of the proposed method are given on the example of 90° cone surfaces.

8082-55, Session 12

3D-profilometry on aspheric and freeform lenses

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No abstract available

8082-56, Session 12

Measurements of aberrations of aspherical lenses using experimental ray tracing

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No abstract available

8082-57, Session 12

Automated alignment of aspheric and freeform surfaces in non-null test interferometry

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No abstract available

8082-58, Session 12

Complete characterization of assembled optics with respect to centering error and lens distances

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The position of optical surfaces and elements in the final assembly of an optical system has a strong influence on the imaging quality of the system itself. Therefore the precise and accurate alignment of lenses and optical elements is becoming more and more crucial. After the assembly of the complete optics is finished it is difficult to check the centration error and the distances of the single optical elements. We will describe a technique to measure the lateral displacement of each centre or curvature with respect to a given reference axis with 0.1 micron accuracy. Additionally it is possible to measure the distances between surfaces of the assembled optics with an accuracy of 1 micron. The measurement is based on the combination of a focusing autocollimator and a short coherence interferometer. The measurement is non destructive and can be applied to optical systems with several optical elements (typically 20 lenses). For both measurements the design data of the optical system are required. It is necessary to enter all radii of curvature, distances and optical materials (refractive index) prior measurement. The design data are required to calculate the image position of the different centres of curvature. This is important for the measurement with the focusing autocollimator. Additionally the design data are crucial to remove the magnifying effect of optical surfaces in front of the surface under test. Because the short coherence interferometer measures the optical distances between surfaces the design data can be used to calculate the correct distances.

Both the focusing autocollimator and the short coherence interferometer are working independently. It will be shown that a combination of these methods improves the feasibility and accuracy of both methods. In general the method can be applied to optical systems based on spherical surfaces. As far as the paraxial area is considered, the use of this method can be also extended to systems with aspherical surfaces. The restriction is that these measurements will only provide the information of the lateral displacements of the paraxial centres of curvature and the distances between the optical surfaces. The tilt of the aspherical axis is not revealed by this technique.

But with the use of an additional optical distance sensor and a special quality control strategy the tilt of each aspherical axis in the assembled optical system can be revealed. The quality strategy requires the preliminary measurement of the tilt of the aspherical axis of the single optical elements before assembly. The tilt of the aspherical axis will be measured with respect to the optical axis of the element (connecting line between the paraxial centres of curvature).

Applications mainly include the measurement of cell phone and digital camera lenses. However, any type of objective lens from endoscope up to very complex objective lenses used in microlithography can be measured with highest accuracy.

Measurement results of different samples will be provided and discussed.

8082-59, Session 12

Interferometric measurement of profile deviations of large precision mirrors

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In numerous interferometric applications of nanopositioning and nanomeasuring technology, plane mirrors are used as flatness or straightness standards for the movement of a positioning device. During this process, the shape deviations of the mirrors used lead to systematic errors of the position measurements, which can be corrected in later applications if known. Most often the effective shape deviations are described sufficiently well by profile deviations along a profile line which is fixed by the movement of the positioning or measuring device.

The novel precision device - a so-called interferometric nanoprofilometer - for measuring the profile deviations of plane mirrors presented in this paper is based on the comparison of the profile line of the mirror to be tested with a straightness standard embodied by a mirror of very high flatness. A specially designed point-based measuring interferometer is moved along the profile line. As the measurement is directly referenced to the straightness standard, the influence of the guide errors was greatly reduced. The uniform movement of the interferometer is ensured through a linear measurement table, which is driven using speed control and pulse-width modulation. Apart from the mechanical and optical design of the interferometric nanoprofilometer, a hardware module was assembled which enables the control of the linear measurement table and the extraction of pulses for the synchronous acquisition of position and profile deviation values. In addition, a software tool was developed for configuring the measurement process and for data recording as well as a program to perform various analyses of the profile deviations.

By subtly considering the functionality of the interferometric nanoprofilometer, the transfer function in relation to the profile deviations was derived theoretically and the system performance was simulated und verified through experimental results. Based on the determination of an inherent cutoff wavelength of the measurement principle of c0=1.12 mm, a FIR filter with a Hanning window was implemented as a robust filter and used successfully. The possibilities and limits of the interferometric nanoprofilometer found were analysed when measuring the discontinuous profile shape as well as the thickness of transparent bodies and layers, which helped to understand and interpret the experimental results.

In measurements performed with the interferometric nanoprofilometer covering the maximum scanning length with lx=250 mm under laboratory conditions, the expanded uncertainty was U(l)=7.9 nm at a confidence level of p=95% (k=2). An expanded error propagation analysis was done to work out the main influencing systematic errors for later improvement of the precision measuring device.

With our state of knowledge we expect to achieve a reduction of the expanded uncertainty below 3 nm for 250 mm profile scans with this machine generation.

8082-60, Session 12

Measuring amplitude and phase of light emerging from microstructures with HRIM

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No abstract available

8082-61, Session 13

Extended range metrology: an age old problem

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No abstract available

8082-62, Session 13

Numerical noise reduction via diffraction for surface profiling interferometry

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Phase shifting interferometry (PSI) can achieve sub-nanometer vertical resolution, and has been used as an essential tool in ultimate precise lens fabrication of the leading edge photolithography systems.

Phase profiles obtained by PSI often include undesirable concentric ripple-noises, like “bull’s eye patterns”. These coherent noises are caused by scattering from defects such as dusts or faint scratches on surfaces of optical elements in interferometers. These coherent noises are regarded as serious obstacles in very precise PSI. A novel scheme that can reduce these coherent noises easily has been required for a long time.

It is well known that these coherent noises can be reduced by using a spatial-incoherence light source. Some types of spatial-incoherence source have been proposed, for example a light source with the shape of a ring concentric to the optical axis. However, these sources mentioned above cannot be applied to some types of interferometer systems such as the point diffraction interferometer.

We propose a numerical method that can reduce these coherent noises. We call this new technique “Numerical Noise Reduction via Diffraction” (NNRD). The NNRD uses numerical diffraction methods that are based on the Fresnel transform or the angular spectrum representation. The NNRD is applicable to phase data obtained from all types of interferometer and furthermore does not use information of modulus or intensity of the optical field.

In the NNRD, we first calculate the optical field at a measurement plane from a phase data including the coherent noises. In this calculation, we assume that all the modulus of the optical field is constant in the plane. Next we reverse-propagate the obtained optical field to the plane where the coherent noise is generated. When the coherent noise is in-focus, the coherent noise becomes a point-like defect. Thereafter we can eliminate it. However, the focused point-like defect is reconstructed by half the amount of the coherent noise, because another conjugate image of a hologram is formed in the out-of-focus plane. So, we can not eliminate half of the noise in this calculation. We propose two practical ways in order to eliminate the whole noise. One way is to double the noise component and subtract it from the original profile data. Another way is to remove the noises from both optical field which are propagated from positions L and -L, where L is the propagation distance from where noises are generated. The NNRD carries out one of these ways iteratively to eliminate the whole coherent noises. Finally, we can make the wavefront data without any coherent noises.

The NNRD can reduce not only the coherent noises originated from point-like defects but also those from defects of the other shapes. For example, the coherent noise from line-like scratches can also be effectively reduced.

Phase profile data obtained from interferometers also have concentric ripple-noises originated from reflections from lens surfaces in the interferometer. These reflective noises usually appear around the center of the profile data and also look like the “bull’s eye pattern”. The reflected wave from lens surface is considered to be a spherical wave from a point. So the NNRD can reduce these reflective noises.

We experimentally demonstrate that NNRD is effective in elimination of coherent noises from interferometer data. This technique is applicable to the data obtained from digital holography as well.

8082-63, Session 13

Dynamic measurements using a Fizeau interferometer

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Single-camera frame instantaneous interferometry is an alternative optical test method where environmental noise prohibits conventional phase shifting methods. For the most demanding applications, the instrument should have high light efficiency and sufficient source power to accommodate short camera shutter times, effectively freezing object motion. Here we report on a newly designed instantaneous Fizeau-type interferometer with fully coherent optics that provide light efficiency and increasing lateral resolution with zoom, and a novel 3mW, stabilized 633-nm laser source for single-shot metrology in less than 100 microseconds. Optimized software enables continuous live display of surface profiles and Zernike fits, and dynamic data acquisition for recording varying surface profiles at a rate of 82 Hz.

8082-64, Session 13

Fringe pattern characterization by OPD analysis in a lateral shearing interferometric profilometer

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Lateral shearing interferometry has been successfully tested under rough environmental conditions to measure opaque scattering objects. Its common-path nature makes the setup ideal for on-line industrial applications due to its simplicity, low cost, and immunity against vibrations and unstable atmospheres.

A good example of such a technology is Conoscopic Holography [1], which provides depth resolution in the order of the micron when measuring in the phase signal if triangulation is included [2]. Haüsler et al. [3] also proposed a similar system using a Savart plate as lateral shearer. Point-wise configuration is the simplest approach for both technologies, but they can be improved projecting a thin laser line instead of a point, so the distance information of a whole profile of the object's surface can be obtained in a single shot. Based on this last approach, our system is a common-path interferometric profilometer that uses a Savart plate as a lateral shearer.

Although these systems have been successfully used for surface inspection and defect detection (many examples of the applicability are reported in [4]), we have experimented behaviors which cannot be explained by the simple model for fringe formation we have been using, which amongst other things, considers normal incidence of the incoming rays into the Savart plate. These deviations from the ideal case are more noticeable when dealing with high precisions from short distances, and include variations in the density of the fringes which do not relate to profile depth changes and variations in the frequency and phase signals for small defects which are either outside the system's theoretical precision or with a magnitude that does not correspond to the defect size.

In order to characterize the fringe pattern, which is crucial for understanding the behavior of the system and proper calibration, an exhaustive analysis of all the real parameters that determine the total optical path difference (OPD) has been developed. The no-ideal working conditions of the Savart plate described by Wu et al. [5] have been considered, like the influence of the rotation of the Savart plate respect to the optical axis of the system, or the angles of incidence of the incoming light.

In this paper, it has been proved that slight changes in the orientation of the Savart plate imply a change of the shear along the profile and result in variations over the obtained fringe pattern. Therefore, the interferogram frequency is modified, which is translated into the measurement. In our system, angles of incidence in the order of 0.1° may result in variations in the frequency which are in the same order than a change in height of one micron.

If the phase signal is used, the measurements are only affected by changes in the internally generated OPD because these imply an extra contribution to the initial phase. Slopes of the surface in the orthogonal direction to the line projection would introduce the maximum shift of the fringe pattern, while slopes in the profile direction would not affect the initial phase value.

The influence of the working distance, the triangulation angle, the rotation of the Savart plate and errors in the alignment of the setups will be analyzed and its repercussion will be under discussion. The possibility that changes in the slope of the surface may alter the fringe pattern, adding information about the derivative of the profile's height will be also expounded. This study is an important step forward to improve the usability of the system and proper scaling when high precisions are aimed.

References

[1] Gabriel Sirat, Jacob Vecht, and Yann Malet. Linear conoscopic holography. US patent 5953137, October 1999.

[2] José María Enguita, Ignacio Álvarez, María Frade, and Jorge Marina. Common-path two-wavelength interferometer with submicron precision for profile measurements in on-line applications. Optical Engineering, 49(2):023602, 2010.

[3] Gerd Häusler, J. Huffless, Manfred Maul, and Hans Weissmann. Range sensing based on shearing interferometry. Appl. Opt., 27(22):4638-4644, 1988.

[4] Ignacio Álvarez, José M. Enguita, María Frade, Jorge Marina, and Guillermo Ojea. On-line metrology with conoscopic holography: Beyond triangulation. Sensors, 9(9):7021-7037, 2009.

[5] Lei Wu, Chunmin Zhang, and Baochang Zhao. Analysis of the lateral displacement and optical path difference in wide-field-of-view polarization interference imaging spectrometer. Optics Communications, 273(1):67-73, 2007.

8082-65, Session 13

State of polarization mapping using a calibrated interferometric polarimeter

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In conventional polarimetry, a polarization analysis optics comprising of polarizers and retarders are used along a with a CCD camera to record the intensity. The state of polarization (SOP) defined by the Stokes vectors are measured by processing a set of images each of which are acquired by different geometries or alignments of the polarization optics. Since these methods need mechanical rotation of optical elements, they suffer from vibration noise. Moreover these techniques due to their relatively long time of measurement find less application in the situation where SOP may be slowly evolving with time. The interferometric polarimeter invented by Ohtsuka and Oka, capable of mapping SOP with only single CCD image using Fourier transform method of fringe analysis solved this problem. Even though spatial resolution of the mapped SOP is limited by the spatial carrier frequency introduced in the recorded, hologram, this technique allowed mapping of rapid spatiotemporal changes in SOP. The sample beam is interfered with two reference beams with orthogonal polarizations whose tilt can be controlled suitably to introduce a linear phase that generates spatial carrier frequency in the interferogram. Recently Oka and Kaneko demonstrated single shot imaging polarimeter using birefringent wedge prisms in which no separate use of reference beams is required. In this case the spatial carrier frequency in the interferograms was introduced by proper choice of the wedge angles of the prisms. To reduce the beam-splitting and beam deviation effects mainly due to inclined incidence of the imaging rays at the interfaces of the prism, an imaging polarimeter using Savart plates has also been proposed and demonstrated. The fact that no separate use of reference beams is required lead to miniature polarimeters that is easy to be incorporated into imaging cameras.

In single shot polarimeters mentioned above that use Fourier transform method of fringe analysis, a spatial carrier frequency is introduced in the fringes of recorded interferogram either by introducing the relative tilt between the sample beam under test and a reference beam or by passing the sample beam through birefringent optical components such as Wollaston prisms or Savart plates. In this technique, the amount of spatial carrier frequency that enabled to filter different terms in the Fourier spectrum of the recorded interferogram had to be calibrated with the use of light with a known SOP. Even in this case, the spatial carrier frequency introduced in the recorded interferogram is influenced by the relative tilt of the beam used for calibration. To eliminate the linear phase introduced by spatial carrier frequency, usually the spectrum around the carrier frequency location in the Fourier transform is shifted and brought to the centre. During this process an error of a fraction of a pixel in the shifting of the spectrum after filtering to remove the linear phase introduced by spatial carrier frequency will drastically change the measured SOP of the light. For accurate SOP mapping, it is important that we eliminate the artifacts and errors due to the spatial carrier frequency in the single shot polarimeters those are otherwise very promising.

In the present work, we propose a Mach-Zehnder interferometric polarimeter that uses a common path Sagnac interferometer to generate reference beams with orthogonal state of polarization. The common path geometry ensures that the two reference beams with orthogonal SOP does not relatively get phase shifted due to surrounding vibrations. By taking advantage of this, we propose a simple calibration scheme using a light of known state of polarization. To demonstrate this technique, in our experiment, we used a 45-degree linearly polarized light for calibration purpose. This calibration beam interferes with the reference beam to generate an interferogram. Again the sample beam also interferes with the reference beam to generate another interferogram. From these two interferograms, the spatial distribution of SOP can be mapped with better accuracy, considering the stability aspect of the Sagnac interferometer. We do not determine the amount of spatial carrier frequency, as it gets eliminated in the process leaving behind only the information on the state of polarization of the sample beam.

8082-66, Session 13

High resolution speckle interferometry by replacing temporal information with spatial information

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Speckle interferometry is a useful measurement method for measuring the deformation of an object with rough surfaces. This measurement method has been improved to ESPI (electric speckle pattern interferometry) by using a TV camera. Furthermore, it has been also improved to a high resolution measurement method by introducing fringe scanning methods. Now, temporal carrier technology is also used for deformation measurement.

Generally, there are a lot of unsolved speckles in the speckle pattern under the measurement process using speckle interferometry. These unsolved speckles usually obstruct a fringe analysis in speckle interferometry. However, when there are some unsolved speckles in the analyzed image for deformation measurement with a large deformation, the measurement method based on a virtual speckle pattern is effective. Because the method based on virtual speckle pattern is a two dimensional fringe analysis method, a high resolution analysis can be performed even if there are unsolved speckles in the speckle pattern. On the other hand, because one dimensional processing in each pixel is performed in the fringe analysis method based on temporal carrier, the method cannot generally deal with the speckle pattern which includes unsolved speckles in the deformation measurement with a large deformation. However, because the fringe analysis by using virtual speckle patterns can handle such speckle patterns as two dimensional processing, fringe analysis in high resolution can be performed by using spatial two-dimensional information of fringe image. Furthermore, virtual speckle patterns can be produced at arbitrary points on the deformation process. Under this situation, a large deformation which cannot be generally analyzed is divided to some small deformation calculating parts and small deformation in each small deformation process is sequentially analyzed by using virtual speckle patterns at each divided area. As the results, the deformation measurement with a large deformation can be performed by accumulating such a fringe analyzed result in each small deformation process. In the measurement by the method using virtual speckle patterns, Fourier transform operation at the datum of each pixel of CCD was required in the measurement method based on a virtual speckle pattern. Therefore, it took a long operating time to produce a virtual speckle pattern in this measurement process. In order to solve this problem concerning operating time, the method by Carre algorithm was also proposed. The method by Carre algorithm can produce a virtual speckle pattern faster than the method by Hilbert (Fourier) transform. This feature is usefully employed in the case of deformation measurement with a large deformation.

In this paper, the producing process of virtual speckle patterns is improved from the method based on Carre algorithm by using the feature of speckle pattern under sampling process by CCD camera. When the speckle patterns are grabbed in the deformation process of the object, the temporal and spatial information is constructed as a three dimensional information. That is, speckle patterns as two-dimensional information are sampled every sampling time of CCD. And, such speckle patterns are also grabbed sequentially every sampling time of CCD. As the results, one group of the three-dimensional information is given by continuous sampling of CCD.

In this paper, virtual speckle patterns are produced from this three-dimensional information by the effect of temporal and spatial sampling. As the results, the fast and high resolution fringe analysis is proposed by using the new producing method of the virtual speckle pattern. In new fringe analysis method, virtual speckle patterns are easily produced by replacing temporal information with spatial information on CCD without any processing by Fourier transform or Carre algorithm.

The processing time for producing a virtual speckle pattern is about 1/26 as against the ordinary method based on Carre algorithm in the simulation and experimental results. It is also confirmed that the new method can analyze not only the measured object with a mono-tone phase distribution but also a complicated phase distribution in high resolution. Then, it is also confirmed that the measuring accuracy of the new method is almost equal to ordinary method based on Carre algorithm.

As shown above, it is confirmed that the new method is useful deformation measurement method and that the new fringe analysis method will expand the use of speckle interferometry in the industries.

8082-67, Session 14

SLM-based multipoint vibrometry

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Heterodyne interferometry is a very accurate and robust technique for measuring vibrations under industrial conditions. Typically, instruments based on this principle are used with single detectors and scanning. For the simultaneous measurement of vibrations (e.g. to detect transients) it is possible to use a fixed arrangement of measurement beams. Dynamic steering of multiple beams, however, is not easy to achieve.

In this contribution we present a solution for multipoint vibrometry using a high resolution (HDTV) programmable spatial light modulator as the core element.

By using an LCD for displaying a dynamic hologram it is possible to independently control multiple measurement spots in three dimensions with high repeatability and accuracy and without any mechanical movement that might introduce unwanted vibrations and therefore measurement errors.

The main challenge in designing such an LCD-based multipoint vibrometer is to avoid problems due to the unwanted spurious diffraction orders that will be present when using commercially available spatial light modulators for reconstructing holograms.

We present a system in which the illuminating as well as the detection is programmable. One half of the HDTV LCD is used for illumination and the other half is responsible for the detection.

Different possible methods to avoid spurious diffraction orders are shortly discussed. Emphasis will be laid on a method based on complex multiplexing (using hologram optimization) and a spatial multiplexing method based on Golay arrays. The two methods have different properties and lead to different optical implementations. We show the optical design and first experimental results for the system based on complex superposition which works with 15 channels at a wavelength of 532 nm and a heterodyne frequency of 5 MHz. Hologram computation is based on a joint optimization of the detection and the illumination hologram using a modified Gerchberg-Saxton algorithm together with a combinatorial optimization of the spot/detector mapping.

8082-68, Session 14

Adaptive optical head for industrial vibrometry applications

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A self-mixing laser diode interferometer combined with a compact and robust optical system including an adaptive optical element in the form of a voltage controllable liquid lens (LL) is presented, forming a compact optical head suitable for general industrial vibrometry applications.

The system is based on self-mixing interferometry (SMI). The self-mixing phenomenon occurs when the laser beam getting out of a laser diode is back-reflected on a target so it partly re-enters into the active laser cavity. This beam interferes (becomes self-mixed) with the standing waves inside the cavity. Self-mixed interference affects the spectral properties of the laser beam as well as the optical output power (OOP) out of the laser. This OOP emitted by the laser, related to the intensity of the self-mixed signal (SMS), is monitored using a photodiode integrated in the laser package is processed to measure the target displacements. The system is thus cheap, self-aligned, compact in size and very robust.

Conventional SMI setups typically use a single lens which is mechanically adjustable to properly focus the beam on the target, so the system has the proper amount of feedback at a given distance. In the optical head we propose, the LL configuration enables the interferometer to adjust the optical focus position and the beam spot diameter on the target surface easily by just applying a certain voltage corresponding to the desired focal length. This adaptive optical system has been designed to focus the beam at distances going from a few centimetres from the front facet of the laser diode to infinity.

This way, we can modify and control the intensity of the back reflected laser beam from the target surface into the laser cavity by changing the focus position and the beam spot diameter on the target surface, controlling in practice the optical feedback level (feedback regime). The final effect obtained is full active control of the feedback level of the self-mixing effect taking place. This has allowed keeping the feedback level of the interferometer in the desired regime for measurements along very long distances, or for different levels of backscattering in the targets, with the same setup.

The results which will be presented will demonstrate that at different focus positions of the laser beam for a fixed-distance target which is vibrating, the corresponding coupling factor values are changing, proving the feasibility of feedback level control by the proposed configuration. In fact, the most important benefit of the system is to keep the feedback level in a regime which is suitable for measurement purposes, as some of the possible feedback levels include highly nonlinear behaviours of the system, which may even become chaotic, so the existing SMS processing is not able to reconstruct the displacement properly, due to hysteresis, fringe losses or directional ambiguities.

The presented system presents also precise metrology capabilities, with signal reconstruction of the target vibration amplitude containing a maximum error of $\lambda/16$ when compared with a commercial capacitive sensor in the whole focusable range for displacement measurements. As an example of the measurement enhancement, the system will be applied to the extension of the measurement working range of the sensor, which has been taken from a few centimetres in a classical fixed-focus sensor to a range of over 2.5m. The system has great potential in application where automated optical feedback control of a laser beam is required, and in operator-free industrial applications.

8082-69, Session 14

Vibration amplitude recovery from the time averaged interferograms using the directional spatial carrier phase shifting method

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Vibration measurement plays an important role in the microelectromechanical (MEMS) object characterization especially during reliability testing, objects functionality and material property examinations. Rapid development of the technology, mainly in the field of product quantity, quality and complexity, forces the development of suitable measurement methods characterized by high accuracy and speed. Optical characterization methods suit very well these requirements. Among different optical measurement methods the interferometric techniques are of main interest due to their noncontact and noninvasive character as well as high measurement precision. Laser Doppler Vibrometry (LDV) is considered to be the most accurate one. As it is a pointwise method it requires additional scanning to obtain amplitude distribution over the object under test. This elongates measurement time considerably. For short measurement times the full field methods are preferable. The most widely used ones are time-averaging interferometry and stroboscopic interferometry. Unlike the latter, the former one is not limited to the vibration frequency, hence it may be used for investigations of high frequency systems. Unfortunately, time averaging interferometry encodes the information on the vibration amplitude in the fringe pattern contrast distribution described by the zeroth order Bessel function (Jo). To decode the amplitude information either very complicated optical systems realizing heterodyned time averaging interferometry or advanced algorithmic solutions, allowing for regional function inversion, need to be used.

The authors of the paper propose alternative approach to the Bessel function analysis. The directional spatial carrier phase shifting technique (one of the automatic fringe patter analysis methods) is proposed to decode the information encoded in the function argument. With additional correction process (the analyzed Jo function differs from the cosinusoidal one) the investigated object vibration amplitude may be evaluated. An unquestionable merit of the proposed technique is its processing simplicity and single pattern analysis scheme. The paper presents abilities of proposed approach, as well as its resistance to possible measurement errors, via extensive numerical simulations. Performed experiments corroborate the theoretical findings.

8082-70, Session 14

Application of wavelet transform and image morphology in processing vibration speckle interferogram for automatic analysis

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Digital speckle pattern interferometric (DSPI) technique has emerged as powerful tool for online full-field monitoring of deformation in components. Obtaining speckle interferogram with high signal to noise ratio (SNR) requires a good quality of optics and its fine tuning, selection of proper grade of surface of the test object suited for the experiment etc. In general, the SNR of speckle interferogram is poor. The speckle noise in DSPI fringes limits its use for automatic analysis of speckle interferogrms. Many filtering techniques have been proposed to improve SNR in the speckle interferograms and have been effective as well to a large extend. It has been established that a combination of filters and its repetition 2-3 times improves the SNR in the speckle interferograms. In vibration fringes the great challenge is to get the intensity variations among the fringes and smoothness in the line profile so as it approaches closer to the governing Bessel function/ diagram. To achieve this target a new filtering scheme is investigated and applied to the image of speckle interferograms.

The speckle interferogram is recorded with proper threshold. The average filter of matrix 3x3 is applied for limited smoothening. Linear phase wavelet denoising is applied to preserve the border effect and discontinuity. Further smoothing filtering and gray morphological operations are performed. Structuring element for the purpose is designed so as to remove isolated pixels in the dark and bright region of the fringes and make continuity in the fringes if some of the segment in fringe got affected due the previous filtering action. The morphological open operation using 7x7 unit matrix followed by gray morphological operation erode the image using 3x3 unit matrix are implemented twice for the purpose. Thinning of the fringes to some extent is also achieved without altering its mean position/line so as the line profile on the filtered image can be closer to the Bessel function plot with proper intensity variation and contrast in the image. The developed scheme is implemented on recorded fringe patterns of a vibrating cantilever plate. The performance and effectiveness of the proposed scheme in reducing speckle noise is evaluated and compared in terms of reduction in speckle index and the improvement of the signal-to-noise ratio (SNR) of speckle interferograms. The new scheme has the ability to improve the speckle index and SNR significantly. It can enhance the SNR on a fringe by about 50 times which is much more than the earlier reported work.

8082-71, Session 15

High-sensitivity low-coherence dynamic light scattering and particle sizing for nanoparticles

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Dynamic light scattering (DLS) is a powerful tool for measuring particle sizes, molecular mass distributions, and diffusion constants. The scattered light from particles or molecules suspended in water temporally fluctuates due to their diffusion, rotation, and vibration. DLS measures a temporal autocorrelation function or power spectrum of the scattered light, from which the diffusion constant of the particles can be obtained. For a dilute suspension, in which singly-scattered

light is dominant, the temporal autocorrelation function and the diffusion constant have a simple, exact relationship, and the diffusion constant can be determined from DLS measurements. However, at higher concentrations of particles or molecules, the influence of multiple scattering is no longer negligible. Recently, dynamic light scattering combined with the use of a low-coherence interferometer was proposed, and then confirmed to effectively suppress multiple scattering effects. By excluding the influence of multiple scattering, conventional DLS analysis can be used, even with dense media. We proposed the measurement of particle size distribution using low-coherence DLS, and demonstrated the successful application of the method. However, the system had poor sensitivity to scattered light intensity, and its use was limited to particles with a diameter larger than 100 nm. (K. Ishii, R. Yoshida, and T. Iwai, Opt. Lett., 30, 555-557 (2005))

In this report, we develop a high-sensitivity, low-coherence DLS system, which can be applied to particles with a diameter of only a few tens of nanometers. In order to improve the sensitivity of the method, a Mach-Zehnder interferometer was adopted, and the incident light was focused on the sample. We demonstrated the use of the measurement system to determine the size distribution of particles with an average diameter of a few tens of nanometers. The measured particle size distributions agreed quite well with those obtained by transmission electron microscopy (TEM).

The developed low-coherence DLS system is as follows. The light from a super-luminescent diode, with a central wavelength of 833.6 nm and a spectral width of 16.2 nm, was divided by a fiber coupler into 99% probe light and 1% reference light. The probe light went through a circulator and a 10x objective lens, and was incident upon the sample. The back- scattered light was coupled again into the optical fiber, and sent to the other coupler with a coupling ratio of 50:50. The reference light underwent sinusoidal phase modulation by an electro-optic modulator, and was detected by a balanced detector after combining with the scattered light at the coupler. The modulation frequency varied from a few kHz to a few hundreds of kHz, depending on the bandwidth of the scattered light. The power spectrum of the detected signal had several peaks. One peak was located around 0 Hz, and was related to both the homodyne and the heterodyne spectrums of the scattered light, and was therefore influenced by multiple scattering. Other peaks, located around the modulation frequency (8 kHz in this case) or its harmonics, contained only the heterodyne spectrum, from which the particle size distribution could be estimated, even for extremely dense media.

We carried out some measurements for 10 vol.% suspension of polystyrene particles using the developed system. As a result, the developed system has a sensitivity 3000 times that of the previous system, and successfully measured the particle size distribution of particles about 10 nm in diameter. The measured particle size distribution was in good agreement with a TEM measurement, with respect to not only the median particle size but also the width and the deflection of the distribution. The developed system was effective for particles ranging from about 10 nm to 10 m in size. The range is comparable with conventional DLS and the accuracy of the developed system in particle sizing is equivalent to conventional DLS. Moreover, the developed system can be applied to suspensions denser than 10 vol.%.

8082-72, Session 15

Novel non-contact optical characterisation methods of polymeric nanocomposite structures based on their particle loading and dispersion profile

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Current methods to characterise specific properties of polymeric nanocomposites (PNCs), such as particle loading and dispersion profile, rely on a number of techniques that require special sample preparation and treatment, are very expensive, require long measurement times, and quite often produce ambiguous results that are difficult to evaluate and interpret. In addition, given their complexity, they are not entirely suited for in-situ industrial environments. This paper presents alternative techniques based on optical diffraction and diffusion mechanisms combined with signal processing that can successfully discriminate between different particle loadings and levels of dispersion. Most importantly, they are non-invasive, require no sample preparation, are compact, fast and efficient and therefore suited for a wide variety of research and industrial situations.

The first technique introduced was termed Fraunhofer wavefront correlation (FWC). A beam from a He:Ne source (633 nm) was diffracted by a suitable grating producing a two-dimensional (2-D) spatial pattern. This pattern was then spatially modulated (diffused) by nanocomposites of different loading and dispersion profiles. The resulting modulated patterns were then captured in the far-field by a suitable charge couple device (CCD) camera. Post signal processing based on multiple stage spatial filtering and cross-correlation between these patterns versus the unmodulated one by the reference material (i.e. no embedded particles) discriminated the materials in terms of their particle loading and dispersion profiles.

Measurements were also attempted by a second technique termed oscillatory photon correlation spectroscopy (Os-PCS). PCS is applied in a vast variety of fields and applications, one of them being in the field of acoustics, to measure particle velocities due to airborne sound waves. In this case, a dual beam PCS system (532 nm wavelength) produced a three-dimensional (3-D) ellipsoid interference volume with fringes. As particles oscillate due to sound, they traverse the fringes and photons are scattered that are captured by a photo-multiplier tube and then forwarded to a correlator board where the auto-correlation function (ACF) is obtained. The theoretical form of the ACF includes numerous parameters, two of which relate to the number of particles per unit volume and their scattering cross-section. For solids, this process became dynamic by mechanically oscillating PNC samples with a piston tranducer at specific frequencies within the aforementioned ellipsoid such that experimental ACS can be produced. It was found that the dynamic range of these ACFs in conjunction with the captured photon counts can be used to discriminate between different classes of materials.

In order to validate the results for these two novel techniques, Fourier-domain optical coherence tomographic (FD-OCT) measurements were also conducted. In this case, the optical source was set in a swept frequency mode (1305 nm centre wavelength, 150 nm bandwidth). The interferometer selectively detected and measured non-scattered light resulting from features below the surface and for various depths, such that 2-D representations (slices) were obtained for penetration depths up to approximately 1 mm. By analysing the resulting information from all the investigated nanocomposite materials, the discrimination between different classes depending on particle loading and dispersion was achieved in agreement with the results obtained from the two previous newly introduced techniques.

8082-73, Session 15

Mueller matrix imaging of nematic textures in colloidal dispersions of Na-fluorohectorite synthetic clay in solution

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Mueller matrix imaging is a new and interesting technique that has become largely simplified in recent years, due to the appearance of a simplified formalism for the design and calibration of such an optical imaging system [1-4]. In order to perform high resolution Mueller matrix imaging, it is largely advantageous to use non-rotating or non-moving active polarization components, such as e.g. liquid crystals. For many applications, it is further interesting to enable reasonably fast imaging. We have developed a Ferro electric liquid crystal based Mueller matrix imager, designed to operate achromatically in the range 800-1700 nm. Such a system can also be denoted a Mueller Matrix Imaging Ellipsometer, and it differs from the imaging polarimeter, in that additionally the illumination must consist of four optimally selected polarization states.

Mueller matrix imaging is highly interesting due to the fact that many polarization modifying phenomena are spatially variables across a sample, and can thus supply enhanced spatial information about the sample. Typical examples of polarization altering phenomena are birefringence which induces retardance, dichroism that induces the so-called diattenuation, and light scattering that induces depolarisation. All of these are spatially varying functions across a given sample, and are linked to the locally intrinsic properties of the material. The Mueller matrix effectively probes all these phenomena, although separation of each phenomena may in certain cases be a challenging task. However, in many cases, the polar decomposition technique can be used, and allows thereby the retardance, depolarization and diattenuation to be effectively separated. Furthermore, organic materials, strained solid state materials and nanostructured materials, colloids/liquid crystals often show anisotropic optical properties as a function of e.g. Anisotropic shaped particles (form birefringence), anisotropically induced strain, Inherent optical anisotropy due to reduced symmetry (both birefringence and dichroisme). These effects are in addition to standard effects described by Fresnel reflection coefficients from surfaces and thin films.

In this work, we exemplify the Mueller matrix imaging technique, using the single wavelength of 980 nm, to study nematic textures in colloidal dispersions of Na-Fluorohectorite synthetic clay in aqueous saline solution. These synthetic clay particles are polydisperse disc- shaped nano particles with thickness around 20-100 nm, and lateral dimensions on the order of 1 µm. The Mueller matrix imaging technique is able to determine the corresponding retardation matrix, even in the presence of other effects such as light scattering and diattenuation. From the retardation matrix one determines the orientation of the particles, the local order, and to what degree the particles are ordered. We have here studied samples similar to those that have been previously thoroughly studied by imaging between crossed polarizers, and by x-ray small angle scattering [5]. As a result we show that the Mueller matrix imaging technique can directly supply high quality images, with information that would require the combined effort of both x-ray small angle scattering (using synchrotron radiation), and crossed polarizer spectroscopy. In particular, the orientation of ordered domains of particles, and the density of such particles are spatially determined , with a resolution superior to standard x-ray scattering techniques, which is limited by the size of the x-ray beam (typically hundreds of microns). The sample studied are prepared by adding synthetic clay particles into a aqueous saline solution contained in a thin rectangular glass container. Upon letting gravitation act on the sample, different phases appears after a few weeks. One phase contains nematic textures and we are able to determine the ordering and also estimate the density of the domains/texture within the phase, in addition to estimating the local order within a domain. Similarly, we are able to separate this phase from isotropic sol, isotropic gel, and observe the so-called floccolated sol at the bottom of the container. Future studies on related samples are envisaged in the near future.

[1] E. Compain, S. Poirier, and B. Drevillon, “General and self-consistent method for the calibration of polarization modulators, polarimeters, and Mueller-matrix ellipsometers,” Appl. Opt. 38 (1999) 3490.

[2] A. De Martino et al.,”Optimized Mueller polarimeter with liquid crystals,” Opt. Lett. 28 (2003) 616.

[3] L. M. Aas, P. G. Ellingsen, M. Kildemo and M. Lindgren, M. ‘Dynamic response of a fast near infra-red Mueller matrix ellipsometer’, J. Mod. Opt. 57 (2010) 1362.

[4] L. M. Sandvik Aas, P. G. Ellingsen, M. Kildemo, ‘Near infra-red Mueller matrix imaging system and application to strain imaging,’ Thin Solid Films (In Press 2010). http://arxiv.org/abs/1009.5549v1

[5] N. I. Ringdal, D. M. Fonseca, E. L. Hansen, H. Hemmen, and J. O. Fossum, “Nematic textures in colloidal dispersions of Na-fluorohectorite synthetic clay,” Phys. Rev. E 81 (2010) 041702.

8082-74, Session 16

3D optical measuring and laser technologies for scientific and industrial applications

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No abstract available

8082-75, Session 16

Lockin-interferometric imaging of thermal waves for non-destructive testing

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Phase shifting speckle-interferometric methods like ESPI and shearography monitor the mechanical behaviour of an object under load, which makes them valuable tools for non-destructive testing. They usually apply a short, static loading to the test object, and monitor the displacement field of the object or its gradient, respectively. Though lots of fringe images can be recorded, only the one with the best contrast is used for further evaluation. So, time-dependent effects cannot be measured. This is one reason why these techniques suffer from some limitations: the depth of defects cannot be determined, and in some cases, the displacement of the object itself is so large that the small deviations caused by flaws can be hidden. To overcome these drawbacks, we apply the Lockin-principle to speckle-interferometry. This technique is based on a combination of speckle-interferometric imaging of thermal waves and a data evaluation via Fourier transformation. By intensity modulation of halogen lamps, the object surface is heated periodically, thereby launching a thermal wave into the object. At thermal boundaries, the wave is reflected back to the surface where it is superposed to the initial thermal wave. Thereby, both local phase angle and amplitude of the modulated temperature field are modified. We use both electronic speckle pattern interferometry and shearography setups to record stacks of fringe images during the periodical excitation. The number of fringe images can be up to 1000, depending on the image size. After a temporal phase unwrapping of the stack of fringe images, a discrete Fourier transformation at the excitation frequency is applied to the signal of each pixel along the time axis of the image stack. The discrete Fourier transformation extracts the phase and the amplitude of the sinusoidally modulated object displacement, therefore eliminating the dc level and condensing the image stack to only two images: the lockin amplitude image (showing the local height of the modulation effect) and the lockin phase image, displaying the local temporal delay between excitation and object response. Though this is very much like Lockin-thermography, the image generating mechanism is substantially different: the thermal wave generates periodical thermal expansion correlated with an overall deformation where the depth integral of the thermal wave is involved. So, the depth range of this method is larger than the one of lockin-thermography, but it is less robust against inhomogeneous illumination by the excitation lamps. The displacement of the test object itself is mathematically reduced since only the sine-coded object response is extracted by the Fourier transformation, and this response (the phase angle) is constant for constant object thickness. The depth range of this method can be adjusted since the thermal diffusion length of the thermal waves depends on their frequency. Since a whole sequence of fringe images is used for evaluation (and not only one fringe image like in conventional speckle-interferometry), the signal-to-noise ratio is substantially increased (by up to one order of magnitude). This paper discusses the performance of this technique on model samples and demonstrates the advantages of this approach on modern automotive and aerospace structures.

8082-76, Session 16

Laser ultrasonics evaluation and testing of coated HTR nuclear fuel

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The quality control of manufactured components in nuclear industry is of paramount importance for the security of nuclear plants. The total integrity of the components which are designed to confine nuclear products must be thoroughly assessed, since these components are designed to avoid the leakage of fission products in the environment when the reactor is operating. In the 60’s - 70’s, a generation of nuclear reactors was designed in order to reduce the quantity and the radiotoxicity of waste in nuclear plants. In this generation-the High Temperature Reactors (HTR)-the nuclear fuel is conditioned as spherical beads of about 0.5 mm in diameter that are coated by several layers of materials to ensure the perfect confinement of fission products. The fuel kernel is surrounded by four spherical layers: (i) a porous pyrocarbon layer (PPyC), (ii) a dense internal pyrocarbon layer (IPyC), (iii) a silicon carbide layer (SiC) and (iv) an outer shell of dense pyrocarbon (OPyC). A composite HTR coated particle is designed to have a diameter of about 1 mm. The security of operation of a HTR plant requires the quality assessment of 100% of the manufactured

HTR particles, i.e. for about one billion particles that are comprised in a reactor. Laser ultrasonics proved to be an efficient method of control and was applied to the quality control of manufactured HTR particles. We applied laser ultrasonics to assess the absence of a crack in the SiC shell, to evaluate the Young modulus of the SiC shell and to characterize the anisotropy of the IPyC shell.

A homodyne interferometer was used both to permit measurements in the 1-10 MHz range and to detect nanosecond acoustic pulses. The sensitivity of the interferometer could reach 10mV/nm with a probe beam focused on the diffusive outer pyrocarbon shell (OPyC). Vibrations of dummy HTR particles with a ZrO2 core were excited by a pulsed laser in the thermoelastic regime and eigenfrequencies was measured in the 1-10 MHz range. The measurement of eigenfrequencies, i.e. the resonant ultrasound spectroscopy (RUS), of an HTR particle by laser ultrasonics is thus non-destructive. We applied the laser ultrasonics RUS method to the quality control of the manufactured HTR particles. In particular, we performed tests to control the quality of the SiC shell, which is of paramount importance, since this layer guarantees the solidity of the confinement shells. Moreover, the SiC shell has the major role of being an impenetrable barrier for fission products.

Resonant ultrasound spectroscopy was applied to detect a possible crack in the SiC shell. Artificial cracks of 10-50 μm wide and 500 μm long were created in the SiC shell. The presence of a crack is detected without doubt by the inspection of the vibration spectrum of the cracked HTR particle, which appears significantly different compared to the reference vibration spectrum of a defect-free HTR particle.

The Young modulus is an important parameter that must be measured to assess the quality of the SiC shell. From the measurement of the vibration spectrum of a defect-free particle, the Young modulus of the SiC material was determined. The measurement of the Young modulus of the SiC shell was also obtained by another ultrasonics method. In this latter method, we measured the period of echoes of nanosecond longitudinal acoustic pulses that propagate back and forth over the thickness of the SiC shell. These two methods of measurement are in good agreement but the non-destructive RUS method has an advantage compared to the echoes method, since the outer pyrocarbon shell must be suppressed prior to the excitation and the detection of acoustic pulses directly on the surface of the SiC shell.

Laser ultrasonics was applied to characterize the anisotropy of the internal pyrocarbon shell (IPyC). This latter characteristic must be controlled, since the anisotropy of the IPyC shell is required to ensure an optimum operation of HTR reactors. A polished cross section of the coated particle was prepared. Using a subnanosecond pulsed laser, short Rayleigh acoustic pulses of about one nanosecond in duration could be generated on the surface of the pyrocarbon material. The pump laser beam was shaped to form a line at the focus. The focused beam of the interferometer was positioned at a distance around 30μm from the pump line in order to detect the arrival of Rayleigh waves. By measuring the time of flight of Rayleigh pulses over the distance from the pump to the probe beam, the Rayleigh wave velocity was measured. Measurements were done in both the radial and the orthoradial directions of the IPyC shell. We observed that acoustic velocities were significantly different in the two directions, thus assessing a mechanical anisotropy of the internal pyrocarbon shell.

8082-77, Session 16

Laser-induced deflection (LID) method for absolute absorption measurements of optical materials and coatings

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Absorption is one of the key parameters in high power or high end laser applications since the absorption not only reduces the laser power transmitted through an optical system but, even more critical, yields e.g. focus shift, wave front deformation and depolarization due to the induced thermal lens. Since these effects nowadays need to be considered in the optic design, characterizing optical coatings and bulk materials regarding their absorption is one central task for the manufacturers e.g. to ensure stability in the production process, to verify functionalities and to understand possible performance changes and limitations during their use in high power laser applications.

At IPHT the laser induced deflection (LID) method, one amongst many photo-thermal deflection techniques, is applied to measure small absorption values in optical materials and coatings directly. In contrast to many photo-thermal measurement techniques the LID method allows an independent absolute calibration by using electrical heaters. Thus, absolute absorption data are obtained without the actual knowledge of the material properties responsible for the thermal lens generation.

Optimized concepts with the focus on high measurement accuracy are presented for measuring bulk or high reflecting mirrors and transparent coatings, respectively. Various experimental results are presented for optical materials and coatings covering a wide range of applications from optics for deep UV laser lithography at 193 nm, nonlinear crystals for frequency conversion, materials and coatings for high power material processing in the NIR to the pre-characterization of doped raw materials for high power fiber lasers at 1550 nm.

For industrial application, an advanced LID prototype is realized and presented combining high sensitivity and improved handling. Moreover, the modular setup allows the use of both optimized measurement strategies to ensure high accuracy combined with high a sample throughput.

8082-78, Session 16

Reflectometry for TSV etching depth inspection

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TSV (Through Silicon Via) is a vertical via that passes through a silicon wafer or chip. This technology is a major enabler for three-dimensional integrated circuits (3D ICs) of stacking different functional chips. Vertical stacking chips of 3D ICs allows gates to be placed closer and thereby provides more computing process in a compact space. As TSV technique with unique processing steps that are not used in standard 2D ICs, a number of new parameters need to be measured and controlled. TSV etching depth is a critical parameter for ensuring the performance of 3D ICs, thus metrology and inspection of the TSV etching depth are very profitability of the overall manufacturing process. Spectroscopic reflectometry (SR) is currently being used in industry to measure the internal reflectance of thin films, from which the thickness and other properties can be obtained. It is a non-contact and non-destructive in-line metrology tool. In this study, we demonstrate the use of SR by employing the fast Fourier transform (FFT) algorithm for measuring the etching via depth and the thickness of oxide layer in one shot measurement. First, the specifications of reflectometer system, such as spectral range and resolution of spectrometer for depth analysis are discussed. The longer spectral range improves the depth resolution which can distinguish smaller difference on TSVs' depth. The spectrometer with high resolution can collect the authentic spectrum from higher etching depth. We verified our system through a mutual measurement comparison with the national standard traceable step height system. Our system is capable of measuring step height up to 100 um and measurement precision is in the range of 0.6 um. In this report, TSV arrays with nominal CD 5~25 m, and aspect ratio up to 7 are measured. The measurement precision is better than 0.01 μm. Metrology results from actual 3D interconnect processing wafers indicate our system provides excellent correlation to cross-section scanning electron microscope (SEM) measurement results. The maximum discrepancy between each other is smaller than 1 um.

8082-80, Session 16

Development of a frequency domain optical coherence tomography system (FD-OCT) for the inline process metrology in laser structuring systems

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Laser structuring is a rapidly developing manufacturing technique with long-term technological impact on future economics and ecological challenges. Due to its high process flexibility, the laser structuring system permits the structuring of different work pieces (different forms and structure complexity) with the same machine configuration. A crucial fact is the process knowledge and its control. In a broad spectrum of industrial branches, laser structuring is applied to minimize air resistance, reduce operating noise, optimize manufacturing tools [1] and minimize friction losses of innovative products [2].

The state of the art in laser structuring has however a crucial deficit. Present structuring systems contain no metrology setup to detect the shape geometry (depth and length) and contour accuracy during the structuring process. Instead, a test object is structured with sample structures, unmounted and analyzed with an external measurement setup, e.g. white-light interferometer. Additionally, the object needs to be aligned in the lasing plane before the structuring process is initiated. This increases the manufacturing time of precise microstructures significantly, limiting the throughput and increasing costs in a large scale. Consequently, an automation and acceleration of this complex and manual procedure is in general not available.

In order to close this technology gap and assure an automated and robust manufacture process, a feedback control needs to be executed. By means of a machine integrated measurement system a robust process feedback can be guaranteed. For solving this task with a high level of compatibility and integration, an optical metrology technique based on the frequency domain optical coherence tomography (FD-OCT) is proposed.

With the FD-OCT technique, it is possible to share the complete optical body of the structuring machine, including the optical systems for the light deflection and focusing, which provides a high degree of integration. Due to the high wavelength optimization of the lens system for the used laser wavelength range (1064 nm +- 10 nm), and the consequently large aberrations for other wavelength ranges, a customized and in the laser wavelength adapted and optimized measuring system needs to be developed.

The large application variety of the technology leads also to a broad band of laser structured surfaces with different macro and micro forms. Fact, which complicates the overall light coupling. Therefore a high numerical aperture as well as a high performance light source are required for an enhanced light efficiency. Another important characteristic of the proposed technique, which increases the robustness of the measurement itself, is the possibility of a large measurement range. In order to implement it, a light source with a large frequency bandwidth and a camera detector with a large resolution need to be applied.

In this work the concept and the development of an adjustable FD-OCT measuring system with sub-micrometer accuracy for the in process measurement in a laser structuring process is described. Goal of the research presented here is the development of the measuring system, with special focus on the spectrometer development (optical and software) and machine integration (optical and mechanical), as well as the development of an innovative wideband source based on amplified spontaneous emission (ASE) in ytterbium-doped double-clad fibre.

[1] Klocke, F. et al., "Reproduzierbare Designoberflächen im Werkzeugbau: Laserstrahlstrukturieren als alternatives Fertigungsverfahren zur Oberflächenstrukturierung ", Werkstatttechnik, Issues 11/12, Pages 844-850, 2009.

[2] Schreck, S. and Zum Gahr, K., "Laser-assisted structuring of ceramic and steel surfaces for improving tribological properties", Proceedings of the European Materials Research Society 2004, Applied Surface Science, Volume 247, Issues 1-4, Pages 616-622, 2005.

8082-81, Session 16

Turning process monitoring using a robust and miniaturized non-incremental interferometric distance sensor

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In-process measurement of the diameter and the 3D-shape of fast rotating objects is an important task in production engineering, e.g. for monitoring and controlling turning or grinding processes, respectively. However, this is very challenging for metrology, since compact and robust sensors with concurrently micrometer precision and high measuring rate (> 10 kHz) are required.

Optical sensors operate contactless and offer high accuracy inherent to the small laser wavelength. However, incremental sensors such as Michelson interferometers fail if radius jumps of more than half the laser wavelength occur that cause ambiguous measurement results. Furthermore, the measuring rate of most optical techniques is fundamentally limited either by the speed of mechanical scanning (time domain OCT, focus sensing) or by the detector frame rate and minimum exposure time required (triangulation, chromatic confocal techniques, frequency domain OCT). Therefore, precise and highly dynamic measurements are not possible with these sensors.

To solve this problem, we developed an interferometric laser Doppler distance sensor, which is able to measure concurrently the tangential velocity and the radial position of rotating objects non-incrementally. Thus, the object diameter and its shape can be determined with micron precision. In addition, a high temporal resolution in the microsecond range can be achieved simultaneously since the measurement uncertainty of this sensor is generally independent of the object speed. This outstanding feature enables precise in-process measurements at fast rotating bodies.

One area of application of this new sensor is the in-situ shape measurement at metalworking lathes e.g. to monitor the turning process or for zero-error production. In order to integrate the sensor into the lathe, a small-sized and robust sensor was necessary. For this reason, a miniaturized fiber-optic sensor head with an overall size of only 30x40x90 mm³ was developed, which is about 10 times smaller than previous sensor setups. Due to this small size, the passive sensor head could be directly integrated into the lathe adjacent to the turning tool bit. Hence, measurements at the turning workpiece are possible during the turning process.

We will present the results of in-situ shape measurements during the turning process at a metalworking lathe. Influences of present vibrations and turning swarfs flying around are discussed. Due to the feed motion during the turning process, the measuring points follow a helix along the circumference of the workpiece. Via a specific evaluation process, the three-dimensional shape of the workpiece could be determined. In order to obtain a reference value, the processed workpieces are measured by a coordinate measuring machine subsequently. The measured object shapes were in good agreement with the tactile reference data. Hence, an in-situ monitoring of the turning process is possible with this novel sensor.

8082-132, Session 16

New method for evaluation of the high-quality fog protective coatings

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Water micro-droplets condensing on optical surfaces below the dew point produce clouded appearance (fogging) due to light scattering, which creates problems with visibility through windshields, windows, cold cabinets, visors, goggles, spectacles, and protective eyewear making the observed image blurred and hazy. To protect from fogging, the lenses are typically modified by so-called Anti-Fog (AF) coatings, which make their surface strongly hydrophilic thus inducing water vapor condensation as a smooth, thin and invisible film that uniformly flows down on the lens as the condensation progresses.

Various AF coatings differ in quality, stability, susceptibility to contamination etc. Some of them perform acceptably only in limited environmental conditions, beyond which the condensing water film becomes unstable or nonuniform, which is detrimental to visibility through the lenses in spite of the absence of typical fogging. Nonuniformities in water film scatter the light or show refractory distortions both affecting the acuity of vision through the lens. They include partly coalesced droplets, nonuniform islands of water film on otherwise fogged lens, nonuniform islands of fog besides uniform water film, nonuniform condensed film (e.g. wavy, smudgy or having pinpoint menisci), and their combination.

Comparing the performance of good, very good and excellent AF-coated lenses is difficult: they do not show classical fogging and the existing testing methods, which are based on fog detection, are therefore inapplicable. The proposed method of evaluating and quantifying AF properties is based on light scattering on the lenses exposed to controlled humidity and temperature conditions. The AF quality of lenses is assessed by measuring the intensity of the laser light scattered on the lens surface at four pre-selected angles namely 1, 2, 4 and 8 degrees from the direction of the incident beam. Simultaneously, the development of the scattering pattern is followed on a translucent screen and a vision test chart is observed through a lens.

The system can be used for analysis of fogging/defogging phenomena, and for studies of water condensation on hydrophilic, hydrophobic and ultrahydrophobic surfaces. It is especially useful in the development of temporary and permanent AF coatings for eyewear, automotive and medical applications as well as in testing their compatibility with cleaning solutions, where the pass/fail results of existing tests are insufficient.

8083-01, Session 1

The promise of metamaterials for new applications in optics

H. C. Schweizer, L. Fu, P. Schau, K. Frenner, W. Osten, H. W. Giessen, Univ. Stuttgart (Germany)

Metallo-dielectric structured materials, or in other words metamaterials, are in principle a well established composite to improve efficiency, functionality, and weight of micro-wave components. In recent times, it has been demonstrated that the functionalities of metamaterials can be scaled down to optical frequencies by nano structuring techniques. Examples include negative index materials in the near infrared and visible frequency range, cloaking structures, filters, and structures for improved sensing of environmental gases.

The physical processes in plasmonic metamaterials depend strongly on the excitation of surface plasmons and the interaction between them. We have learned how to control the plasmon-photon and the plasmon-plasmon interaction through which the electromagnetic response in a metamaterial can be well manipulated for wavelengths well below the vacuum wavelength. Many interesting and novel optical applications and devices are expected. For instance subwavelength imaging, compact polarisation splitters, slow light media structures, compact colour filters and resonators.

It is also the basis of ultra-dense photonic integration by all-plasmonic circuits not achievable by conventional optical integration.

In the talk we give a brief overview on metamaterials and related nanofabrication techniques. With examples of several metamaterial structures we try to illustrate their application potential and comment on their fabrication feasibility to show whether metamaterials can hold their promise. Their investigation is in any case a rewarding adventure.

8083-02, Session 1

Rigorous modeling of meander-type metamaterials for sub-lambda imaging

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Many effects associated with negative index materials (NIMs) are due to the resonant coupling of surface plasmon polaritons (SPPs) propagating on the metal/dielectric interfaces. It has been shown that the near field imaging effect of Pendry's perfect lens [1] for instance can be mimicked by two resonant surfaces such as arrays of metallic nanospheres as long as they allow for SPP propagation [2-5]. We show that metal films, which are corrugated on both surfaces - so-called meander structures - can be employed as such resonant surfaces enabling near field imaging. Due to the design flexibility of meander structures (thickness, corrugation depth, duty cycle and periodicity) the short (SRSPP) and long range surface plasmon polariton (LRSPP) frequency can be influenced to a large degree. More interestingly, for certain geometries, a Fano-type pass band region of direct resonant transmission occurs between these two plasmon frequencies. When stacking two meander sheets onto each other, the pass band of the whole structure still shows single meander characteristics. Additionally, the pass band region becomes almost independent of the distance between the sheets due to the interaction between Fabry-Perot modes and SPPs. When building up stacks with different periodicities the pass band shifts in frequency for each sheet in a different way. This can be compensated by changing the remaining geometrical parameters of each single sheet. We present a basic idea how high-transmittive stacks with different periodicities can be created to provide energy transfer at low loss over practically arbitrary distances inside such a stack. The possibility to stack meander sheets of varying periodicity might be the key to far field superlenses since a controlled transformation of evanescent modes to traveling wave modes of higher diffraction order could be enabled.

References:

[1] J.B. Pendry, "Negative refraction makes a perfect lens" Physical review letters, vol. 85, 2000, pp. 3966-9.

[2] S. Maslovski and S. Tretyakov, "Phase conjugation and perfect lensing," Journal of Applied Physics, vol. 94, 2003, p. 4241.

[3] S. Maslovski, S.A. Tretyakov, and P. Alitalo, "Near-field enhancement and imaging in double planar polariton-resonant structures," Journal of Applied Physics, vol. 96, 2004, p. 1293.

[4] C.R. Simovski, A. Viitanen, and S.A. Tretyakov, "Resonator mode in chains of silver spheres and its possible application," Physical Review E, vol. 72, 2005, pp. 1-10.

[5] P. Alitalo, C.R. Simovski, A. Viitanen, and S.A. Tretyakov, "Near-field enhancement and subwavelength imaging in the optical region using a pair of two-dimensional arrays of metal nanospheres," Physical Review B, vol. 74, 2006, p. 235425.

8083-03, Session 1

Simulating photonic structures in layered geometries by Multiple Multipoles Program

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Lately, the improvements in the fabrication process in the nano scale made it possible to fabricate resonating structures with sizes comparable with the wavelength of the visible spectrum. In the literature, a vast number of applications are analyzed in the optics range by tailoring the shape and material properties of the resonant structures including photonic crystals [1]- [3], chemical and bio-sensors [4], [5], optical antennas and waveguides [6]-[8] and so on. Usually, these devices are fabricated on a substrate or, in the more general case, in a multilayered structure. In the literature, the substrate is often ignored for reasons of simplicity. This may lead to substantial inaccuracies and it may even suppress strong effects such as field singularities in the triple points on the substrate. Furthermore, the layered geometry may support guided waves that are highly important. In order to understand the related physical phenomena and to improve the efficiency of the devices, it is crucial to analyze nano structures within layered geometries numerically.

One of the most reliable and efficient simulation tools for the analysis of photonic structures is OpenMaX, which is an open-source program containing the semi-analytic method of multiple multipoles (MMP) solver [9], [10]. MMP uses arbitrary superpositions of analytic solutions of the Maxwell equations or so called expansions (e.g. plane waves, cylindrical waves, spherical waves, etc.) in order to mimic scatterers. The boundary conditions are fulfilled on the boundaries of the scatterers by using the fields generated by the expansions and the incident field. As the result of this boundary matching process, the scattered field generated by the scatterer is obtained as a superposition of the expansions those are used to fulfill the boundary conditions. In the case structures involving layered media, the boundary conditions must be satisfied simultaneously on the boundaries of the layered media by using extra expansions positioned near these boundaries. As a result of this approach, several difficulties may be faced by the user including: 1) A truncation of the layered geometry is needed, 2) The locations of the expansions responsible for the layered geometries must be carefully tailored, which needs some experience of the user and 3) The possible guided wave modes (guided waves in dielectric slabs and Surface Plasmon Polaritons (SPP) on the metallic layers) cannot be simulated. In order to tackle these problems and make OpenMaX a more user friendly and robust simulation tool when dealing with layered geometries, a new expansion set, layered geometry Green's functions, is introduced. In this talk, it will be shown that, with the new expansions, since the necessity of matching the boundary conditions in the layered geometry is eliminated, the complexity of the problems including layered geometries is decreased. Some hints for the derivation of the layered geometry Green's functions and for using them in the OpenMaX package will also be provided. The robustness and the efficiency of the new expansions will be illustrated by various numerical examples in both 2D and 3D, including layered geometries that support guided waves and SPPs.

References:

[1] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, "Photonic

crystals," Solid State Communications, vol. 102, no. 2-3, pp. 165 - 173, 1997.

[2] S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, "Guided modes in photonic crystal slabs," Phys. Rev. B, vol. 60, no. 8, pp. 5751-5758, Aug 1999.

[3] J. Smajic, C. Hafner, and D. Erni, "Design and optimization of an achromatic photonic crystal bend," Opt. Express, vol. 11, no. 12, pp. 1378-1384, 2003.

[4] T. Sannomiya, C. Hafner, and J. Voros, "Shape-dependent sensitivity of single plasmonic nanoparticles for biosensing," Journal of Biomedical Optics, vol. 14, no. 6, p. 064027, 2009.

[5] S. M. Borisov and O. S. Wolfbeis, "Optical biosensors," Chemical Reviews, vol. 106, no. 2, pp. 423- 461, 2008.

[6] P. Muhlschlegel, H. Eisler, O. J. F. Martin, B. Hecht, and D. W. Pohl, "Resonant Optical Antennas," Science, vol. 308, pp. 1607-1609, Jun. 2005.

[7] L. Novotny, "Effective wavelength scaling for optical antennas," Phys. Rev. Lett., vol. 98, no. 26, p. 266802, Jun 2007.

[8] P. Bharadwaj, B. Deutsch, and L. Novotny, "Optical antennas," Adv. Opt. Photon., vol. 1, no. 3, pp. 438-483, 2009.

[9] C. Hafner and N. Kuster, "Computations of electromagnetic fields by the multiple multipole method (generalized multipole technique)," Radio Science, vol. 26, no. 1, pp. 291-297, Jan. - Feb. 1991.

[10] OpenMaX. [Online]. Available: http://openmax.ethz.ch/

8083-04, Session 1

Near-field introscopy of two-dimensional nonhomogeneous left-handed material slab

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We propose a new approach of near field introscopy of a left-handed material (LHM) layer (Veselago's lens) without using any waveguides: the near field image of an inhomogeneity in a tested homogeneous LHM layer appears on the wave receiver (e.g. screen) placed near a wave source provided that this layer is illuminated by source in a way that inside Veselago's lens focus appears near inhomogeneity considered.

The central point of our approach is a transformed integral equation for the Green function of inhomogeneous LHM slab written in terms of the Green function for homogeneous LHM slab and a volume scattering potential accounting the dielectric inhomogeneity inside the slab. A solution to this transformed integral equation is presented with the aid of a scattering operator, which satisfies a Lippman - Schwinger equation. Solution to the Green function for inhomogeneous LHM slab is expressed by a scattering amplitude in the case of a thin linelike scatterer as compared with the free space wavelength. We consider singular wave scattering by weak and thin dielectric inhomogeneity placed near inside focus of Veselago's lens. In this case the linelike scatterer is radiated by singular quasistatic field near the inner focus of lens that enhanced the effect of scattering. Besides, the outgoing from the LHM slab scattered radiation is enhanced by similar singular manner near outside focus of Veselago's lens. In result the effect of wave scattering by linelike scatter near inside Veselago's lens focus is proportional to product of singular quasistatic parts of two empty space Green functions that means — multiplicative quasistatic singularity of the Green function for inhomogeneous LHM slab.

Modelling the linelike scatterer by non-local separable scattering potential reveals a resonance property of the scattering amplitude related to singular behaviour of the Green function for waves propagated inside perfect LHM slab.

8083-05, Session 2

Advanced data evaluation and determination of measurement uncertainties for scatterometry on a MoSi photo mask

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Previous work has shown that the reconstruction of geometric parameters describing the profile of an attenuated phase shift (MoSi) photomask can be carried out using a conventional inverse method based on rigorous FEM-based solutions of the Helmholtz-equation as model for the scattering process and a least-square minimisation of the difference between measurement data and simulations results. Modelling work on other related systems, in particular EUV scatterometry at EUV masks, has revealed that it is difficult to assign correct uncertainties to the input measurement data. This may introduce a systematic bias into the reconstruction of geometric mask parameters and prevents a realistic uncertainty evaluation for the obtained geometric quantities like top- and bottom CDs and side-wall angles. Here we employ a recently developed method for scatterometric evaluation, that uses a maximum likelihood estimation to obtain geometric mask parameters as well as realistic uncertainties for the input data simultaneously. As input data we use a set of goniometric scatterometry measurements at a wavelength of 193nm on a state-ofthe-art MoSi mask. As a result, we can provide accurate values for the CDs and sidewall angles as well as realistic estimates of the associated measurement uncertainties. This is an important step towards absolute and traceable CD metrology using scatterometry. In addition, the roughness of the profiles is determined and provided as an additional property of the investigated mask.

8083-06, Session 2

A Bayesian Statistical Model for Hybrid Metrology to Improve Measurement Accuracy

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There is significant interest in new methods to combine measurement techniques to reduce uncertainties and optimize measurement throughput. This approach has immediate utility to improve model-based optical critical dimension measurements. Model-based optical measurements use a library of curves that simulate a multi-dimensional parameter space. Measurement uncertainty is introduced into the fitting process due to parametric correlation, measurement noise, and model inaccuracy. In this paper we will provide a strategy to decouple parametric correlation and reduce measurement uncertainties. We develop the rigorous underlying Bayesian statistical model to apply embedded measurements into OCD metrology. We will present statistical methods that rigorously use a priori information to reduce measure uncertainty and develop improved reference metrology.

New methods to reduce uncertainties and improve measurement throughput attempt to combine measurements from different tool configurations or different platforms potentially improving throughput and measurement accuracy. Parametric correlation, measurement noise, and model inaccuracy all lead to error and measurement uncertainty in the fitting process. The cross-correlations among parameters can lead to very large uncertainties even when a measurement technique demonstrates good sensitivity to a single parameter. The hybrid metrology method described here can directly improve measurement uncertainty by reducing parametric correlation and has further utility in selecting the correct minima among multiple nearby local minima in the fitting space.

In this presentation we will develop the rigorous underlying statistical model to apply this methodology and present applications of the approach to scatterometry and scatterfield measurements. We apply Bayesian statistical methods that rigorously use a priori information in the optical fitting process. This presentation will demonstrate embedded metrology methods applied to different optical metrology tool combinations. In this application we will explore the importance of an expanded uncertainty for each measurement or measurement

method. We will also directly apply the hybrid metrology approach to embedded AFM reference measurements to improve the resulting uncertainty from the library fitting process. We will present both simulation results and experimental data demonstrating this methodology.

8083-07, Session 2

Reduced basis method for real-time inverse scatterometry

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Optical metrology of lithographic structures usually bases on the comparison of experimental and modeled light field data. The measurement error budget and the complexity and feature size of a given pattern, thereby, govern the level of accuracy needed for the model.

With shrinking feature sizes and increasing need for highly accurate metrology methods, approximate light field computations like the Kirchhoff approach can not be used any longer. This problem arises for example, when 3D mask effects become important or EUV mask patterns are surveyed.

Then rigorous near field computations have to be used to obtain realistic model data, which can be used for pattern reconstruction and parameter estimation. However, long computational times usually forbid real-time and many-query simulations, wherefore the common approach is the usage of libraries. The geometrically parametrized lithographic structure under consideration is simulated in an offline phase for values lying on a dense parameter grid. In the online step, i.e., the actual measurement, a library search is performed to obtain best fitting parameter values. This brute force method has several drawbacks. First, with increasing number of parameters, the number of points in the interpolating parameter grid increases exponentially, which is referred to as the curse of dimensionality. If for example 4 parameters are variable and 10 interpolation points in each parameter dimension are used, a total number of 10000 rigorous solutions have to be computed to fill the library. Even with moderate computational times for a single solution, the total costs are huge. A second major drawback of the library approach is the fact that it is a priori not clear, how fine the parameter space has to be sampled. Maybe one parameter has only little influence on the near field and output data. Then a lot of computational time is wasted with a fine sampling of this parameter. The opposite case is undersampling of a given parameter, which finally leads to inaccurate measurements. Finding the appropriate interpolation space for a database, usually involves consumption of valuable working hours of the responsible person and can cost a lot of time - wasted time!

A clever, self-adaptive algorithm should build an accurate model, which can be used for model based metrology. Requirements are reliability and low offline and online computational costs to construct and evaluate the model. The reduced basis method meets exactly these demands. Given a parametrized model and parameter space, it determines self adaptively, where exact, so-called snapshot solutions of the full problem are taken. These snapshot solutions form the reduced basis and are used to construct a reduced model in the offline phase. The reduced model is obtained by Galerkin projection, which could be characterized as physical interpolation: the solution for a given point in the parameter space is not obtained by data interpolation, but by solution of an electromagnetic scattering problem on the reduced basis space.

The reduced basis method is closely related to the finite element method (FEM). The snapshots included in the reduced basis are FEM solutions and the reduced model is a projection of the high dimensional finite element discretization onto the low dimensional reduced basis. Therefore, the reduced basis method inherits all of its unique features: exact modeling of complicated geometries with unstructured meshes, high-order ansatz functions, and low computational times for highly accurate solutions. Furthermore, methods from the well-developed area of a-posteriori error estimation of finite element solutions can be applied to the reduced basis setup. They are the key for self-adaptive algorithms which construct the reduced basis approximation and guarantee reliability of the reduced basis results.

In this contribution we will introduce the reduced basis method and demonstrate its performance for relevant, real-world metrology applications.

8083-08, Session 2

Fast online inverse scattering with reduced basis method (RBM) for a 3D phase grating with specific line roughness

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Library or data based scatterometry as a non-destructive measuring tool for parameter identification of known lithographic structures is meanwhile an established method and becomes more important with shrinking feature sizes along the lithography road map. Finite element methods (FEM) for the rigorous electromagnetic solution of Maxwell's equations are known to be very accurate and possess a high convergence rate for the determination of near field and far field quantities of scattering and diffraction processes of light with structures having feature sizes in the range of the light wavelength. However, FEM are actually still rarely used as numerical method for the solution of Maxwell's equations in scatterometric applications. This may be due to the fact that 3d FEM is supposed to be too slow for that purpose.

In our paper we show that this assumption is totally wrong as only FEM allow the application of a brilliant and extremely fast solution method: the so-called reduced basis method (RBM) preserving all good properties of FEM like excellent accuracy and high convergence rate. Since the popularization to a broader audience by Anthony Patera from MIT the reduced basis method allows the FEM solution of large physical problems originally intended for supercomputers, on a simple smartphone /1/.

One dimensional scattering and diffraction methods such as RCWA, C-method, Differential-, Boundary Integral-, Rayleigh-Fourier-method, and others can be used for grating like structures. Really 3d structures and 2d-periodic structures often need adequate 3d methods such as FDTD or FEM leading to significantly increased computation times with FDTD having a too weak accuracy and a too slow convergence. The Reduced Basis Method with a posteriori error estimation and together with FEM provides a fast and accurate direct and inverse scattering parameter identification method fully based on Maxwell's equations.

The considered diffractive structure looks like a one-dimensional phase grating. Due to the specific line roughnesses at both sides of the grating lines, it necessarily must be treated fully three-dimensional. The discretized FEM area of the 2d elementary cell is large and takes 20 times 10 wavelengths. The structure is parametrized and the three parameters to be reconstructed from diffraction efficiency "measurement" are height h, filling factor f and amplitude s of the line roughness. Calculated efficiencies with added statistical errors are used instead of measured efficiencies.

The reduced basis method is based on the full decoupling of the "truth" solutions of Maxwell's equations by FEM and the RB results through Offline-Online procedures: the complexity of the Offline stage depends on the huge dimension of the "truth" FE solution; but the complexity of the Online stage - in which RBM responds to new values of the input parameter set - depends only on the small dimension of the reduced basis space and our three dimensional parameter space /2/. In essence, one is guaranteed the accuracy of a high-fidelity finite element Maxwell solver but at the very low cost of a reduced-order model.

Maxwell solver software firm JCMwave is the first one developing a RBM for commercial applications in 3d electromagnetic scattering and diffraction. Using this FEM Software for 3d scatterometric diffraction calculations together with fast RBM /3/ we achieve an efficiency accuracy of about 10-4 for the direct problem with only 35 snapshots being the reduced basis dimension, guided by the unique error estimator. This speeds up the calculation of diffraction amplitudes by a factor of about 1000 compared to the conventional solution of

Maxwell's equations by FEM. Having this in mind we are now able to solve the inverse problem to reconstruct the three parameters of our phase grating from "measured" scattering data in a 3d manifold online in a minute having the full FEM accuracy available. Additionally, also a sensitivity analysis or the choice of robust measuring strategies, for example, which usually needs dozens or hundreds of very time consuming FEM runs, can now be done online in a few minutes. Clearly, similar investigations would also be possible by library or data based methods with precalculated results for samples of the whole parameter space. This procedure would have at least two significant drawbacks compared to the RBM approach: (1) the computational amount would be tremendous as the whole parameter space has to be sampled which is not the case for RBM, and (2) the accuracy of results for parameters between the sampling points is very weak because of the interpolation of data points while RBM uses a real basis having inherently the full Maxwell equations incorporated.

We show the way for achieving the fast and reliable RBM for our 3d diffractive structure and we discuss the results and the potential of the method.

1. Anthony T. Patera, MIT Ford Professor of Engineering, Smartphone as Supercomputer Surrogate: In-Situ Scientific Simulation, Lecture at the University of Ulm, Germany, 07 December 2010.

2. A.T. Patera and G. Rozza, Reduced Basis Approximation and A Posteriori Error Estimation for Parametrized Partial Differential Equations, Version 1.0, Copyright MIT 2006, to appear in (tentative rubric) MIT Pappalardo Graduate Monographs in Mechanical Engineering.

3. Jan Pomplun, Frank Schmidt, Accelerated a posteriori error estimation for the Reduced Basis Method with application to 3D electromagnetic scattering problems, SIAM J. Scientific Computing 32(2), 498-520 (2010).

8083-09, Session 2

Full-scale simulation of angle-resolved focused-beam scatterometry applied to aperiodic isolated features: model validity analysis and numerical results

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Scatterometry is commonly referred to as a high-resolving method of characterizing pattern features being much smaller than a light wavelength. Surprisingly, the state-of-the-art scatterometry tools which are based on ellipsometry hardware use test structures and light beam probes with overall dimensions being up to thousand times greater than the wavelength. Having a large measurement spot may seem advantageous as quite many periods of a test grating structure is illuminated providing high sensitivity of the method. Also, such experimental reality is more or less adequately described by a simulation model which imposes periodic boundary conditions on a computational domain assuming infinity and regularity of test structures. On the other hand, standard scatterometry may not be considered to be a locally-resolving method. Upon a measurement one obtains a feature parameter, like critical dimension or side-wall angle, averaged over the large area. It becomes inconsistent with demands of the microelectronics industry, a major consumer of the technique, which prefers to shrink the dimension of test structures for the reason of costs and intention to control the performance of lithography tools on a smaller scale better matched to the writing resolution of steppers.

By having a scatterometer with improved lateral resolution one potentially may resolve single defects in a grating or characterize truly three dimensional features. Making use of asymmetry of test structures one may remove correlations between different profile parameters. In general, for application to in-situ metrology much wealthier description on various kinds of imperfections of imprinted pattern may be obtained thus improving understanding of what goes wrong during lithographic or etching processes.

Characterizing aperiodic isolated structures still remains a challenging problem for modern scatterometry and requires advance both in development of new hardware and sophisticated modeling. Recently focused-beam scatterometry has fallen under focus of intensive research. Several optical setups and measurement strategies has been proposed, in particular, different variations of microellipsometry, including spectral and angular resolved [Opsal et all (1994-2006), Qwen Zahn (2006)], oblique incidence scatterometry [Germer (2006)], back focal plane imaging [Osten, 2009] and focus-depth scanning microscopy [Silver, 2006, 2009]. These techniques have been found promising for certain applications, however none of detailed analysis of the sensitivity to profile characteristics and applicability to different types of structures has been provided. Concerning modeling there are few works related to full-scale simulation of a measuring tool and its performance. Full-scale should mean a synthesis of methods of physical optics to describe focused illumination, imaging, and detection; and some of near-field solvers, like RCWA, FEM, FDTD or integral methods. In addition appropriate imaging and/or measurement model has to be formulated. Among few existing works devoted to the problem one has to reference [Torok et all, 2010] who proposed a rigorous model based on Straton-Chu formulas applied for near-to-far field transformation.

In this paper we have extended the ideas mentioned to develop a full-scale modeling approach which can be applied to focused-beam scatterometry. The calculation of incident field is based on Richards-Wolf theory which represents a beam focused by a lens as a set of plane waves. The complex amplitudes of plane waves describe a result of light refraction in focusing optics and include polarization and phase aberration factors. Near-field diffraction simulation is based on a finite difference time domain method (FDTD), which is argued to be the most effective, however is more universal and easy extendable for simulation of dispersive materials, smooth surfaces representation, and near to far field transform. The field distribution in far zone is calculated according to Stratton-Chu theory using Green functions representation with Richards-Wolf formulas.

This paper consists of two parts. First, it presents a model validity analysis related to focused-beam scatterometry. We have evaluated convergence and accuracy of Stratton-Chu and more common vector Raylegh- Sommerfeld far field calculations dependent on such parameters as number of plane waves in incident field expansion and FDTD mesh size. Also, we have studied how accurate a focused beam could be modeled and what a term 'isolated object' should mean, i.e. what is the influence of neighboring objects and boundaries of a test zone on a measurement signal could be. These issues are quite general and have to be related to scatterometry itself rather than to numerical issues which depend on the selected near-field solver (FDTD in our case). Some FDTD-related performance characteristics have been studied which overlaps partially or can be compared to the results of other groups obtained in the field.

In the second part our method was applied to calculate the sensitivity of the far field signal to small variations of structure profile. A group of rectangular trenches in quartz layer on top of silicon substrate has been used as a test structure. The sensitivity has been estimated by a deviation of a far field intensity distribution from a reference calculated for different values of the sidewall angle of trenches. The influence of polarization and asymmetry of the input beam on detection sensitivity has been uncovered. Numerical simulation has been carried out for linear, radial and tangential polarization of the beam incident on the focusing objective. Images in the back focal plane of the objective have been simulated. It has been demonstrated that asymmetry of the scattered field distribution allows one to separate measurements results obtained from the top, bottom width, height and spacing between test trenches, their orientation and position relative to polarization direction and focus position. Finally, we present a comparison for oblique incident scatterometry and normal-incidence reflectometry in terms of sensitivity to CD and side-wall values.

8083-10, Session 3

Physical optics light propagation through components with measured refractive, diffractive and hybrid surface profiles

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The optical function generated by a real optical system differs typically from the simulation result. Differences are caused for example by light source radiation tolerances, by alignment tolerances or deviations of the fabricated surfaces from ideal surfaces. In order to simulate the influence of surface deviations of a real system on the optical function it is required to import surface measurement data into optics software. Measurement processes return often the height profile at discrete data points. This allows the recording of surface deviations with low as well as with high spatial frequencies. In order use these measurements in optical simulation software it is required to construct a continuous height profile with the help of an interpolation method. That means that an interpolation is used to return on any (not measured) surface position a reasonable height value.

Surfaces deviations can have high spatial frequencies. This requires often a simulation of light propagation including diffraction, interference and vectorial effects. In general different models of light propagation are needed depending on the required physical simulation accuracy and on the surface deviation. The light propagation through a lens with surface errors in the range of several tens of micrometers can be often done by geometrical optics while in the free spaces after the lens a propagation algorithm including interference effects is required. In case of the simulation of light propagation through a diffraction grating with surface deviations of hundreds of nanometers typically rigorous electromagnetic approaches are required.

The authors show the modeling of refractive, diffractive and hybrid surfaces from discrete data sets. It turns out that for the description of these different surface types different interpolation methods are required to allow an efficient construction of a continuous surface from measurement data. In addition the authors introduce the Field Tracing concept that allows using different light propagation models from geometrical optics to rigorous on a single software platform. In several practical examples it is not useful to apply just one propagation model for a full system. Instead it is helpful to select in every region another model depending on the required physical simulation accuracy. A system region can be identified by optical engineers and can be a group of components, a single component or just one surface.

The simulation of the effects of measured surface deviations will be demonstrated on two examples. The first example is a refractive beam shaping system. The system uses an aspherical surface to generate in the target plane a circular Top Hat intensity distribution. Surface deviations will lead to uniformity errors. These deviations were measured by an interferometer and included in the system simulation. The simulated intensity distribution will be compared with measurements. The second example, the simulation of a diffraction grating, shows the splitting of laser light in several diffraction orders. Surface deviations will affect the amount of power diffracted in the different orders. The authors will demonstrate the import of surface measurement data with deviations in nanometer scale and the simulation by rigorous Fourier Modal Method. Both examples show the importance of including diffraction, interference and vectorial effects in the simulation of optical systems with surface deviations.

8083-11, Session 3

Modeling of profilometry with laser focus sensors

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Submicron and nanometer patterning is one of the key technologies for high-tech products such as microelectronic integrated circuits. In order to ensure a stable production process the generated patterns have to be measured very accurately in order to determine the linewidth and profile information. Appropriated methods are scanning electron microscopy and optical scatterometry. The latter is non-invasive, highly accurate and enables to do optical cross sections of layer stacks but it requires periodic measuring samples. To this end, extra reference gratings have to be patterned on the scribe lane in between the chip areas resulting in an increase of dissimilarities to the real chip structures with shrinking feature size. Laser focus sensors are a viable alternative. Here, the sample is scanned with a diffraction limited spot and thus aperiodic patterns can directly be measured. A severe limitation is imposed by the diffraction limit resulting for instance in substantial errors related to the edge location. This issue can be overcome by an accurate modeling. Here, the basic idea is to match the simulated signal to the measured signal and retrieve the edge location after a sufficient goodness of fit is achieved. This can be done quite similarly as known from optical scatterometry by means of optimization techniques or libraries. In this way, the edge location accuracy can be improved by about two orders of magnitude from submicrons to nanometers (and beyond).

The paper presents an efficient approach for the modeling of two-dimensional patterns such as line-space profiles probed by a three-dimensional beam. It is based on a conical RCWA (Rigorous Coupled Wave Approach) in combination with the plane wave spectrum decomposition of the incident focussed beam. The basic idea of the approach is as follows. First, the feature to be simulated is embedded in a super-period p, i.e., a periodic continuation is assumed. In contrast to a pure 2D approach, it is necessary to sample the beam in the whole pupil plane instead of sampling it in the tangential plane only. The directions of the plane waves of the incident beam in the pupil plane are described by two parameters - a radius r which corresponds to the sine of the polar angle of incidence i after focussing and the azimuthal angle i. The pupil is sampled by means of equidistant lines running parallel to the grating vector. The advantage of this sampling is that a separate conical solving can be assigned to each sampling line where i = 90° and i = mλ/p (λ is the wavelength and m an integer between -N and +N = int (NA p/λ), NA is the numerical aperture of the incident beam). In this way, the 3D diffraction problem can be decoupled into 2N+1 2D conical problems and the convolution with the incident field can be done separately for each. A diffraction matrix is computed for each line by means of a conical RCWA algorithm. It contains both the polarization coupling as well as the coupling of directions defined by the /p ratio. Then, the discretized incident beam is convolved line by line with the associated diffraction matrix which simplifies to a multiplication in the modal domain. Then, individual solutions for each sampling line are assembled to form the diffracted beam. It can be multiplied with a vector that describes a filter in the detection optics for instance a pin hole. Finally, the intensity on the detector is computed by superposing all the resulting plane waves. Due to the 3D character of the probing light, the superposition has to be performed vectorial, i.e. by a separate treatment of each spatial component. To this end, the components of the diffracted rays given in local (θ, φ, r)-coordinates are transformed into space invariant (x,y,z) components by means of a rotation matrix. A lateral and/or vertical scan can be simulated by multiplying the diffracted plane wave spectrum by additional phase terms. A particular advantage of our approach is the separation of diffraction and beam shape/ scanning modeling. Since the diffraction computation and the illumination/detection paths are completely decoupled only one time-consuming RCWA solving is required for a certain profile. It can be stored for example in a library and reused for different detection and scanning schemas.

Particular autofocus principles such as Foucault's knife, astigmatic lens and pin holes can be easily simulated by means of complex valued filter functions in the entrance and exit pupil of the system. The whole model is fully vectorial and thus polarization is implicitly taken into account. Likewise, the intensity on the detector can be computed from the outgoing spectrum and evaluated for example with a quadrant diode. Comparisons between measurement and modeling are presented that show a good agreement resulting in substantial improvement of the measurement accuracy. This will be discussed with a few examples.

8083-12, Session 3

Study of the convergence behavior of the vectorial modal method for metallic lamellar gratings

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Periodic structures find numerous applications in the telecommunications, microelectronics and optical metrology industry. The importance of these structures is further enhanced due to their use in the recent and exciting fields of photonic crystals, metamaterials and plasmonics.

Due to their increasing importance considerable research effort has been devoted to develop rigorous and efficient numerical models for propagation of electromagnetic waves in periodic structures. In the field of optical metrology one of the most commonly used methods to analyze diffraction from periodic surfaces is the Fourier modal method (FMM) also known as the coupled wave method [1]. Recently Boria et. al [2] has analyzed the diffraction from a waveguide gratings using a new approach called as the vectorial modal method (VMM). In this method the Maxwell's equations for the electric and magnetic fields in the grating region are written as linear differential operators satisfying eigenvalue equations. These operators are nonself-adjoint hence an arbitrary electromagnetic field cannot be represented in terms of the

eigenvectors of these operators. An auxiliary problem is defined which uses the Fourier basis to expand the electromagnetic fields in the grating region and allow the matrix representation of these differential operators using the standard method of moments. In their paper the authors check the results of this numerical model with the FMM for sub wavelength gratings and dielectric gratings with low loss.

This paper compares the convergence behavior of the VMM with the FMM for highly metallic gratings. The study is carried out for the cases of both the TE and TM polarization. First the results presented in reference [2] are verified to confirm the accuracy of the developed numerical code.

The case of the TE polarization is studied next as it results in a simpler eigenvalue problem for the FMM hence only a small number of space harmonics and a smaller size of the eigenvalue matrix are required to achieve convergence of the diffraction efficiencies. This also appears to be case for the VMM as demonstrated by the numerical results for a metallic lamellar grating.

As is well known the FMM converges slowly in TM polarization, this convergence behavior has been extensively studied [3-5] and the matter appears to be practically resolved by applying the correct rules of Fourier factorization [4-5]. An example of highly metallic gratings taken from reference [3] is used to study the convergence of the diffraction efficiencies for the FMM and VMM. It is observed that the convergence behavior of the VMM is quite poor as compared to the FMM. The problem appears to be in the formulation of the eigenvalue equation which involves differentiation of the discontinuous relative permittivity function.

An alternate formulation of the eigenvalue equation for VMM for TM polarization is suggested which circumvents this problem and provides it with the same convergence behavior as that of the FMM. Numerical results are presented to demonstrate the validity of this formulation.

[1] M. G. Moharam, E. B. Grann and D. A. Pommet, “Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings”, Journal of the Optical Society of America, vol. 12, pp. 1068-1076, 1995.

[2] A. Coves, B. Gimeno, J. Gil, M. V. Andrés, A. A. San Blas and V. E. Boria, “Full-Wave Analysis of Dielectric Frequency-Selective Surfaces Using a Vectorial Modal Method”, IEEE Transactions on Antennas and Propagation, vol. 52, no. 8, pp 2091-98, 2004.

[3] L. Li, “Convergence of the coupled-wave method for metallic lamellar diffraction gratings”, Journal of the Optical Society of America A, vol. 10, pp. 1184-1189, 1993.

[4] P. Lalanne and G. M. Morris, “Highly improved convergence of the coupled-wave method for TM polarization”, Journal of the Optical Society of America A, vol. 13, pp. 779-784, 1996.

[5] L. Li, “Use of Fourier series in the analysis of discontinuous periodic structures”, Journal of the Optical Society of America A, vol. 1

8083-34, Poster Session

Method of adjusting an optical axis of receiving module of laser rangefinder to the main axis of space vehicle

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A new method of adjusting an optical axe of the lens of receiving module (RM) of laser rangefinder (LRF) to the main axe of space vehicle is described. The testing unit for LRF was designed and described. The unit allows to measure the focal plane position of main lens, RM detectivity, level of nonaxis source of light, transmittance of optical system and dynamic range of RM. The uncertainty of adjusting four laser beams to the main axe of space vehicle consists of uncertainty of adjusting the optical axe of RM to the main axe of space vehicle, uncertainty of adjusting central fiber of fiber-optic coupler (FOC) RM to the optical axe and uncertainty of adjusting laser beams of laser transmitter module (LTM) to all of four fibers of FOC RM. The uncertainty of adjusting an optical axe of RM to main axes of space vehicle is determined as ±45 arcsec and is described in this paper. The main axe of space vehicle is determined as a line between two points 1 and 2 of intersections of axes of gauged cylinders with a base plane of a main body of LRF.Finding of these two points was done mathematically by the coordinate measuring machine 6-axis KIM750. As the points 1 and 2 are on plane XY and they are out of view of autocollimator it is necessary to lift them up. The line 3-4 is parallel to the line 1-2. The points 3 and 4 and the optical axe are in the same horizontal plane parallel to the plane XY. The optical axe is determined as a collective line of collimating points of lens of RM. These points were found by the autocollimator with the function of refocusing (AFR). The displacement of the optical axe and the axe 1-2 is about 130 mm. It is more convenient to work with the line 3-4 because the displacement in this case is about 80 mm. A gauged plane of four faced prism was a base plane for the moving of AFR in the direction of the axe X. Misalignment of axes was observed by AFR. The alignment was done by the changing the thickness of the washers used for fastening of lens body.The analysis of uncertainties of this method and many gauged procedures are described.

8083-35, Poster Session

Specification of optical surface accuracy using the structure function

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Irregularity of an optical surface is commonly characterized by peak-to-valley or root mean square error after subtraction of low order aberrations. It is sufficient if the surface is fabricated with the help of conventional techniques. Modern manufacturing methods employ undersized polishing tools generating irregularities on sub-aperture scales or mid-spatial frequencies. This is particularly important for the fabrication of aspheric or free-form surfaces. The smoothness of local polishing depends on how uniformly the influence function is distributed and how well the dwell time is controlled over a part. Diamond turning is known for the variety of shapes, however, a single point tool tends to form surface features on the scale determined by the uniformity of feed rate. A deterministic way to quantify and specify mid-spatial irregularity is important for all areas of optical production.

Optical surface can be represented by infinite number of Zernike polynomials. Due to the intrinsic symmetry of terms in this expansion, local features are difficult to model, let alone abrupt discontinuities such as triangular grooves etc. Interferometric map of an optical surface is usually obtained from original data by subtraction of the fit of 9 Zernike Fringe polynomials corresponding to piston, tilt, focus and third order astigmatism, coma and spherical aberrations. This paper describes how to characterize the spectral content of residual surface height error, which depends on multiple factors during the fabrication. To quantify small scale irregularities, the residual error is regarded as a random process. The method of structure function (SF) is applied to the surface errors at different spatial scales yielding RMS height difference vs. physically measurable separation on an optical surface.

The detailed mathematics of SF method is discussed. SF turns out to be a convenient quantity enabling simultaneous specification of RMS height and RMS slope or gradient of a surface. The correlation between SF behavior and surface irregularity is demonstrated on interferometric data. The method is applied to analytically generated surfaces and compared with the approach of power spectral density.

8083-36, Poster Session

Analysis of the spectral-shadowing crosstalk in a quasi-distributed fibre sensor interrogated by an optical frequency-domain reflectometer

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Optical frequency domain reflectometer (OFDR) is a technique for high-resolution metrology that can find applications in both telecommunication networks [1] and optical fiber sensors. In its basic form, the optical frequency of the tunable laser source (TLS) is swept linearly in time without mode-hops. Then, the frequency-modulated continuous-wave signal (probe signal) is split into two paths, one of which probes the device under test (DUT) whereas the other is used as reference signal (or local oscillator). The reference signal returning from the reference mirror and test signal returning from the reflection sites in the test arm coherently interferes on the detector. This interference

signal has the beat frequencies which appear as peaks at the spectrum analyzer display after the Fourier transform of the time-sampled photocurrent. Using a linear frequency sweep, the measured beat frequencies can be mapped into a distance scale (the proportionality factor between beat frequency and the corresponding distance is determined by the rate of change of the optical frequency), while the squared magnitude of the signal at each beat frequency reveals the reflectivity of each reflection site.

OFDR providing millimetre resolution over medium measurement ranges (up to a few hundreds of meters) has been attracting great attention as an interrogating tool for several sensor applications. Utilisation of Fiber Bragg Grating (FBG) arrays interrogated by OFDR for strain sensors were studied and experimentally demonstrated [2, 3]. In these demonstrations however, the distortions inherent to the concatenated FBG array were included, neither in the calculations nor for the analysis of the experimental results. Therefore limitations of the technique due to these distortions were not evaluated.

In this paper, we describe a fiber sensor system for temperature measurement applications using as sensing points a set of uniform, identical, low-reflective fiber Bragg gratings inscribed on a single fiber and an OFDR as the interrogator tool. Indeed, reflection spectrum of each FBG modulates a sinusoidal function with a unique beat frequency. Therefore, reflection spectrum of each FBG can be obtained by band-pass filtering the signal in the frequency domain around each beat frequency with a sufficient bandwidth. Then, inverse Fast Fourier transform (IFFT) on this selected portion, can be used to recover the complex reflection spectrum of each grating independently from each other. Finally, from the estimation of their Bragg wavelength and from their temperature characteristic individually established in advance in a calibration process, the temperature is deduced for each FBG in the array.

The measurement time of our sensor is much shorter (a few seconds) than OTDR (Optical Time Domain Reflectometer)-based solutions. Moreover the measurement time is independent on the number of interrogated gratings and temperature measurement range. The distance between concatenated gratings can be at the order of a few cm. Repeatability measurements highlighted a standard deviation on the demodulated temperature of smaller than 1.5°C.

In addition to experimental work, spectral-shadowing crosstalk effects were analyzed by the way of simulations. Spectral-shadowing crosstalk occurs when a concatenation of gratings sharing the same spectral characteristics are addressed simultaneously. Obviously, the signal entered into the concatenation gets modified during its (round-trip) propagation along the fiber. Indeed, the spectrum of the light in front of each grating depends on the previous ones as their transmission spectra are superimposed. Therefore, one can already predict that the further the FBG under test, the more distorted the measured reflection spectrum.

Simulations were undertaken to estimate the error due to spectral-shadowing effect on the demodulated wavelength. In these simulations, there was a concatenation of N FBGs (N = [10 30 50 70 100]). N-1 FBGs were subject to 1000 random temperature profiles and the last FBG (Nth FBG) was at fixed temperature. In this analysis, all downstream FBGs are assumed to be at room temperature and to have about identical spectral characteristics (Bragg wavelength around 1583.7 nm at room temperature and small reflectivity below 10%) with small fluctuations in the central (Bragg) wavelength. These inevitable fluctuations due to fabrication process correspond to the specifications of the real gratings written in our clean room facilities and can be modelled by a Gaussian distribution of the Bragg wavelengths with a standard deviation of 50 pm.

Simulations show that, the mean error value depends not only on the number of gratings but also on the following factor: the temperature deviation between the mean value of all downstream FBGs and the temperature to be measured on the FBG under test. The error values up to 5°C are observed for N=100.

We proposed an enhanced algorithm together with small modification in the set-up (measurements from two inputs of the sensor by using an optical switch) which is easy to implement in practice, to obtain smaller errors on the measured temperature. By using our enhanced algorithm, the error on the measured temperature due to spectral-shadowing crosstalk has been considerably reduced (up to 3.5°C of enhancement).

To the best of our knowledge, this is the first time that the theoretical model takes into account the spectral-shadowing crosstalk to obtain more realistic values of the design parameters (i.e. maximum number of sensing points on a single fiber, reflectivity of the gratings...).

Solutions based on new system configuration and enhanced algorithms were also proved to increase the maximum number of sensing points still keeping an error on the measured temperature smaller than 1.5 °C (repeatability of our experimental set-up).

[1] K. Yüksel, M. Wuilpart, V. Moeyaert, and P. Mégret, J. Opt. Commun. Netw. 2, pp. 463-468 (2010)

[2] Y. Shinoda et.al, in Proceedings of Int. joint conference of SICE-ICASE, 4332, pp. 1672-1675 (2006).

[3] A.M. Abdi et al., Aplied Optics, vol.46, No.14, pp.2563-2574, (2007).

8083-38, Poster Session

The off-axis alignment of an asphere by a Fizeau interferometer

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The mechanical alignment of an aspherical surface grows difficult when the aspherical departure of the surface is high. An obscured aspherical surface is even more difficult to be aligned due to the missing obscured paraxial spherical vertex surface area for implementation of the auto-collimating technique. This research paper aims to develop a method to align an obscured aspherical surface with respect to the mechanical axis of a precision rotational stage by analyzing the multiple off-axis interferograms measured from a phase shifting Fizeau interferometer. The optical null of the aligned aspherical surface is achieved by geometrical defocus, tilt and decenter of the aspherical surface. Neither computer generated holograms nor null optics are utilized in the alignment process. By analyzing the acquired multiple interferograms and fitting the unwrapped phase with the Zernike polynomials, we are able to find the varying off-axis aberrations and the associated alignment errors including decenters and tip-tilt errors. Past researches and experiences tell that the coma and astigmatism is especially useful for the alignment purpose. The alignment induced varying coma and astigmatism are successfully shown in the ray tracing results. Even without knowing the full prescription of the aligned aspherical surface, the method can detect the vector direction of mis-alignment errors by least square fitting. An iterative process is possible to be implemented to bring the already misaligned aspherical surface back to aligned status.

To successfully align the aspherical surface mounted on a rotational stage by the Fizeau interferometer, one has to know that there are three axes involved in the alignment process. These three axes are the rotational stage axis, Fizeau interferometer optical axis, and the aligned asphere optical axis. Each two axis has 4 degree of freedoms for the alignment , including x y de-center, bore sight errors. Thus, the whole alignment procedure involves 8 potential alignment errors to be corrected. The geometrical null of the aspherical surface tends to cause a large amount of off-axis aberrations while the misalignment between the rotational stage and aspherical surface cause directional varying off-axis aberration. The aligned asphere is first put on the rotational stage and rotates to certain angles for off-axis interferogram acquisition. One also has to choose a proper off-axis section of the aspherical surface to have enough sensitivity. After phase shifting the interferometer, the interference phase is unwrapped and analyzed by the Zernike polynomials fitting. Pupil coordinate re-mapping is also required to have accurate coordinate mapping under large aberrations if exist. The alignment error mostly comes from two parts : One is the misalignment between the optical axis of the Fizeau interferometer and the rotational axis the rotation stage, the other is the misalignment between the optical axis of the aspherical surface and the rotational axis the rotation stage. By properly set the rotational angle of aspherical surface, we are able to find the all the 8 misalignment errors given proper prescription data. Even without the prescription data, an iterative process is possible to reduce the alignment errors in a few steps.

8083-39, Poster Session

Direct modeling of external quantum efficiency of silicon trap detectors

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Silicon detectors mounted in a light trap configuration are used as transfer standards in radiometry. The applied configuration is usually obtained using three Hamamatsu S1337 photodiodes. The external quantum efficiency (EQE) of these trap detectors is traceable to electrical standards through comparison with electrically calibrated cryogenic radiometer. This calibration is time consuming and usually done at some discrete laser wavelengths. A continuous spectral responsivity scale is only obtained by interpolation of detector response to fill the gap between these wavelengths.

Two main approaches have been applied to interpolate trap detector responsivities.

The first one uses the measurement of detector reflectance at the same laser wavelengths such that its internal quantum efficiency (IQE) is determined. This parameter has frequently been modeled by a five parameter phenomenological equation when the aim is to extend the responsivity beyond 900 nm up to 1050 nm [1,2]. Recently, it was also shown the possibility of using a simplified three parameter model when the range of interest is between 400 nm and 900 nm [3]. Once the spectral IQE is obtained, it is necessary to get the spectral reflectance of the detector in order to recover the EQE. This task is based on the well-know Fresnel relations for the reflection of light of a thin film over an absorbing substrate. Input parameters for these relations are the refractive index and thickness of silicon dioxide (SiO_2) film and the complex refractive index of silicon (Si). The optical constants can be obtained from literature, while the oxide thickness is left as a free fitting parameter to the experimental reflectance data. By using these adjusted parameters, the spectral reflectance of the photodiode is obtained and, together with the spectral IQE, it enables to recover the EQE and consequently the spectral responsivity.

A second straightforward approach is based on directly fitting EQE by means of phenomenological functions. B-spline, high order polynoms and others mathematical functions have been used [2,3]. The advantage of this approach is related to the absence of reflectance data analysis, but the main drawback is the lack of physical meaning for the adjusted parameters.

The aim of this work is to show the feasibility of direct fitting of external quantum efficiency (EQE) for silicon trap detectors which are applied as radiometric transfer standards at National Metrology Institutes (NMIs).

In order to fit EQE data of trap detectors, an objective function which considers both detector reflectance and collection efficiency is numerically constructed. This function depends on the physical parameters of IQE modeling previously discussed and on the thickness of SiO_2 layer, which are left to vary, as well as on the refractive index of Si and SiO_2, obtained from literature. A numerical optimization algorithm in association with initial guess values is applied to extract the best fitting parameters.

The big advantage of the suggested approach is the possibility of pursuing interpolation of spectral responsivity without loss of physical meaning of the fitted parameters. Furthermore, there is no need of measuring light losses by reflection in the detector, which could be cumbersome for three element trap detectors.

[1] Gentile, T.R.; Houston, J.M.; Cromer, C.L. Applied Optics, v. 35, 22, p. 4392-4403 (1996).

[2] Werner, L.; Hartmann, J. Sensors and Actuators A: Physical, v. 156, p. 185-190 (2009).

[3] Gentile, T.R.; Brown, S.W.; Lykke, K.R.; Shaw, P.S.; Woodward, J;T. Applied Optics, v. 49, 10, p. 1859-1864 (2010).

8083-40, Poster Session

Inverse calculation of position and tilt errors of optical components from wavefront data

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High performance optical systems are capable of diffraction limited imaging over large areas. To maintain this performance the tolerances for perturbations in such systems are extremely low. Identification and suppression of static and dynamic errors in high performance optical systems, like alignment errors due to drift or structural vibrations, can lead to superior imaging quality. A method is presented that allows for intra process monitoring of deviations of a lens from its ideal position. It can track the movement of a lens by illumination through the rim such that the light gets reflected of the optical surfaces of the lens by total internal reflection before exiting the lens on the opposite side, where a Shack-Hartmann wavefront sensor is used to detect the wavefront. It is referenced to a standard wavefront for the case with no deviations in the system. The wavefront-error caused by decenter or tilt of the lens is used for the reconstruction of the geometrical perturbations. The identification of the geometrical perturbations of the lenses from optical forward simulation data is an inverse problem. Different approaches for the reconstruction of the geometrical properties from forward calculation data (model-based and regularization methods) are compared. Different light sources and geometrical setups can have an effect on the wavefront properties. A comparison is made to investigate their influence on the reconstruction quality. As the measurement principle does not interfere with the imaging process of the system, the method can be used to monitor the system while in use. This could enable a real time tracking of errors up to the sampling rate of the detector making the method suitable for measurements of system dynamics. The method can potentially be enhanced to detect some lens deformations in combination with mechanical finite element simulation, as well as dynamic perturbations of the optical system.

8083-41, Poster Session

Deconvolution of non-zero solid angles effect in bidirectional scattering distribution function measurements

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The Bidirectional Scattering Distribution Function (BSDF) represents how a specific surface scatters optical radiation. It is in consequence a key function to explain visual appearance of objects. It depends on the radiation wavelength, on the incidence direction (polar and azimuth spherical coordinates, θi and i, respect to the sample reference system) and on observation direction (θs and s), therefore it is denoted as fs(θi, i; θs, s; λ). BSDF is defined as the ratio between the radiance at the observation direction and the irradiance on the surface, for every incidence angle. It is expressed as an infinitesimal value, a derivative that represents the radiance scattered by an infinitesimal element to a given direction dLs per the irradiance on an infinitesimal surface element dEi:

fs(θi, i; θs, s; λ)=dLs(θi, i; θs, s; λ)/dEi(θi; λ) (str-1) [1]

This function cannot be directly measured, because it would require the existence of infinitesimal surfaces. It has to be calculated from measurements on finite intervals, both as surfaces and as solid angles. Therefore, the measurement equation is written as:

fs(θi, i; θs, s; λ)=Ls(θi, i; θs, s; λ)/Ei(θi; λ) (str-1) [2]

When the sample is illuminated with a specific solid angle ωs (an incident ray cone), the radiation scattered in a given direction is the sum of the radiation scattered in that direction coming from every ray within the cone. Thus, the proportion of radiation scattered in a direction (or, in other terms, the measured fs) is the average of the proportions of radiation scattered for every ray (the average fs). On the other hand, when the sample is observed with a solid angle ωi, the measurement system receives all the radiation within the cone and returns an average value. The mathematical treatments of the effects of ωi and ωs are indistinguishable. The magnitude measured under real non-zero solid angles conditions can be denoted as Biconical Scattering Distribution Function (BCSDF), fcs:

fcs(θi, i; θs, s; λ)=(1/ i s)∫ ωi ∫ ωs fs(θi', i'; θs', s'; λ)d i d s [3]

where i y s are the incidence and observation projected solid angles, respectively.

The effect of real non-zero solid angles conditions on BSDF measurements with different scattering directionality degrees is studied in this work. The scattering directionality is a quality of both the surface and the angular configuration. A surface is more directional as higher is the ratio of the maximum to the minimum BRDF values. A configuration is more directional than another simply because its BSDF value is higher.

A matrix formalism is presented that allow this effect to be compensated from the own BSDF measurements (BCSDF) and from the previous knowledge about the solid angles in the system. Using this formalism, it is possible to recover the shape of directional peaks.

The problem to solve is to obtain fs(θi, i; θs, s; λ) from equation [3] by deconvolution. For that, we can rewrite equation [3] as the following approximation:

fcs,l=(1/ l)Σm=1Nfs,mΞs,mlsin(θs,m) cos(θs,m) Ξi,mlsin(θi,m) cos(θi,m) [4]

where the subindexes s and i are referred to observation and illumination, respectively, l is the index that identifies every configuration, N is the total number of configurations of fs, l is the similar approximation of the product i s, and Ξml a rectangular function, that is 1 within the solid angle of integration.

It can be easily expressed in a matrix-based formalism as:

fcs=Wfs [5]

Thus, fs can nbe calculated using the inverse of W:

fs=W-1fccs [6]

Recent psychophysical experiments, conducted to characterize the visual perception of gloss, have shown that the amount of flux reflected in the specular direction correlates only at a first order with the sensation of gloss and is too weak to fully describe the sensation. We have today good reasons to believe that the visual system extracts the gloss not only from this level of flux but also from the shape of the specular peak itself.

8083-42, Poster Session

Analysis and application of refractive variable-focus lenses in optical microscopy

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We present an approach to an analysis of the third order monochromatic and chromatic aberrations of refractive fluid lenses with a variable focal length. A detailed theoretical analysis is performed for a simple variable-focus lens and formulas are derived for an optical design of such lenses. The advantage of these active lenses is their capability to change continuously the focal length within a certain range. These lenses give a possibility to design non-conventional optical systems which change their parameters (focal length, magnification, etc.) in a continuous way without a need for mechanical movements of lenses. Such lenses with a variable focal length make possible to design optical systems with functions that are difficult or even impossible to combine using conventional approaches. We perform an analysis of optical design of such lenses. The experimental analysis and calculations are provided for Varioptic lens Arctic-416. Potential applications of variable-focus liquid lenses in optical microscopy are analyzed and simulated. We also investigate a possibility of increasing the depth of focus using such lenses and the influence of a variable-focus lens on the image quality.

8083-43, Poster Session

Modeling the ultrafast optical response of a multilayered sample subject to transient distributed perturbations

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Studies of ultrafast phenomena in multilayered samples (superlattice, stack of thin films, ...) using femtosecond pump-probe time-resolved spectroscopy requires models to simulate the sample transient optical response. A short pump optical pulse is used to generate some phenomenon in the sample. Then the evolution of the phenomenon is probed on a picosecond time scale by using a delayed pulse that is reflected on the sample. The sample optical response is determined by measuring the variations on the optical field of the reflected probe beam. If the optical field is described by its complex amplitude a, then the relative variation of the modulus of the amplitude and the phase variations can be measured by transient reflectometry and transient interferometry, respectively. The sample alternatively be characterized by its reflectivity r=a/a0, where a0 is the constant amplitude of the incident field. The relative variation of r represents the transient optical response of the sample. But the latter quantity is not adequate in general. For example, in magnetooptics experiments, the Kerr rotation is measured instead of the transient sample reflectivity. Another example can be given in the field of picosecond acoustics, where the propagation of transverse waves induces complex rotations of polarization, which are analogous to Kerr rotations. A general formalism is needed to handle both the transients of amplitude and polarization state. This can be achieved by describing the transient phenomenon by a 2x2 transient reflection matrix. This 2x2 transient reflection matrix contains all the variables that can be measured on a coherent optical field: amplitude, phase and polarization.

The transients of complex amplitude and complex rotation of polarization can be readily obtained from the components of the transient reflection matrix.

We present a method to calculate the transient reflection matrix. This method is based both on the formalism of Berreman and the formalism of Yeh which was used to calculate the reflection matrix of multilayered anisotropic inhomogeneous planar structures. Here, the sample is not considered as static but the sample is perturbed by transient phenomena which modulate the optical response. The magnitude of the transient reflection matrix is in the range 10-6-10-4 in most ultrafast experiments. A first order perturbation approach is then valid in that case.

The formalism can be used to simulate the transient optical response of anisotropic multilayered samples submitted to any transient inhomogeneous field (strain, electric, magnetic, thermal, ... fields). Moreover, the formalism can be used to calculate the effect of the interface displacements within the multilayer. These displacements may be caused by acoustic strain pulses which propagate back and forth within the layers.

We illustrate the method in the field of picosecond acoustics by calculating the optical response of a piezoelectric semiconductor with short acoustic pulses (longitudinal or transverse) propagating within the sample submitted to an electric field.

8083-44, Poster Session

Analysis of servomechanisms for high-density optical disks with the vectorial and scalar diffraction theory

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Currently, next generation optical disks with high capacity and data transfer rates are being developed. These optical disks include holographic data storage (HDS), microholographic data storage and near-field optical disks. In these disks, some sort of structures on the disk is used for a servomechanism. The size of these structures is almost the same as the wavelength. We analyzed these servomechanisms based on the vectorial and scalar diffraction theory, and present a structure on the disk for a servomechanism of high density optical disks.

Heretofore, land/groove structures are widely used for a servomechanism of optical disks. In optical disks with the land/groove structure, digital data is recorded on the groove, and readout beam sweeps along the groove. The width of the land/groove is almost the same as the spot size of the beam. For the analysis of these structures of the wavelength order, the finite-difference time-domain (FDTD) method is popularly used. The FDTD method is a numerical algorithm for solving Maxwell's equations, and it is easy to implement the algorithm. In the FDTD method, Ampère's law and Faraday's law in Maxwell's equations are discretized using a staggered grid called the Yee cell. The FDTD method can handle subwavelength structures, and polarization. However, in order to suppress numerical dispersion, the grid size should be maintained at less than 1/10 of the wavelength, so the FDTD method needs high computational costs. In general, it is hard to handle a domain more than 1,000 times of the wavelength. In contrast, the scalar diffraction theory does not have these phenomena, but it can handle large domain compared with the FDTD method. Therefore, we present a combined method that is the combination of vectorial and scalar diffraction theory. In this method, we use the FDTD method in the domain include structures of the wavelength or subwavelength order, and the scalar diffraction theory is used in other area. By using this method, they can analyze servomechanisms of optical disks include subwavelength structures

such as the land/groove. In this study, we analyzed servomechanisms for high density optical disks as a practical matter. In this analysis, we assumed following optical system as an analysis model. An analysis object is multilayer optical disk that mainly consists of protecting layer, recording layer, and reflection layer. It is assumed that the reflection layer has a groove and its depth and width is tens - hundreds of nm. The material of protection layer is polycarbonate (PC), and it behaves as a dielectric in the electromagnetic field. The reflection layer is constructed from aluminum. Since aluminum has large conductivity, electromagnetic waves are reflected on the reflection layer. We assumed that the material of the recording layer is a photopolymer. Photopolymers are suitable for recording thick phase holograms and stable media with high diffraction efficiency; therefore, they are widely used as holographic recording media. We calculated diffraction of the wave, and obtained the distribution of the energy density of reflected beam in the far field. We show that the declination of the disk can be detected by measuring the bias of the energy density distribution. We believe this study will be useful for design of high density optical disks.

8083-45, Poster Session

Optimization of scanning and command functions of galvanometer-based scanners

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Galvanometer scanners (GS) have imposed themselves as one of the best type of scanning systems, as their duty cycle (the scan efficiency, i.e. the ratio of scan or active time vs. the total time) is better than for the rotating plane mirror (monogon) scanners, high scan frequencies and velocities are achieved in compact constructive solutions, with good precision positioning. GSs also do not have the drawback of the various sources of errors that characterize the polygon scanners, their principal competitor when fast scan rates are required.

Different possible profiles of the scanning functions of the galvoscanners, such as sawtooth, sinusoidal and triangular are discussed in the paper, highlighting their advantages and drawbacks.

As a result of this discussion, we focus on the optimal profile the scanning functions of a galvanometer-based scanner should have for the user: with symmetrical, linear on their active portions and with as fast as possible stop-and-turn parts. The scope is to obtain the function that provides the highest theoretical limit of the duty cycle of the device. From the classical equation of the oscillatory mirror the active torque is obtained with regard to the scanning function. Several equations for the stop-and-turn parts have been considered in our study: polynomials of different orders and sinusoidal. However, we demonstrate that the comparison is finally reduced to the two most advantageous scanning functions: linear + parabolic and linear + sinusoidal. The relationships between the characteristic parameters of the GS are deduced and compared for these two functions, i.e. stop-and-turn time interval, scan frequency and velocity, duty cycle and maximum inertia torque. While in literature the most appropriate function is considered the linear + sinusoidal, we demonstrate that actually the best one, which is the function that provides the highest duty cycle (and in order to obtain that, the lowest inertia torque, for minimum stop-and-turn time), is the linear + parabolic.

The expressions of the active torque that drives the mobile element of the galvoscanner are deduced for the linear + parabolic scanning function, and the command function of the device is thus obtained, on its characteristic time intervals. A study of this command function is performed, with regard to the constructive parameters of the device (moment of inertia, damping coefficient and elastic coefficient of the torsion springs), and to the imposed parameters of the scanning regime (scan frequency, amplitude, velocity and duty cycle). Especially the trade-off that can be done between the various - and contradictory - requirements one has for the device is of interest. The main one that is studied is between the duty cycle and maximum value of the command voltage,. We work on mimimizing this maximum electrical signal for the device with a minimum loss in what concerns the scan efficiency. Thus, this modeling of the command function shows the practical limits of the duty cycle, after the first part of the study, concerning the scanning function has shown its theoretical limitations.

Selected Reference: Duma V. F., Optimal Scanning Function of a Galvanometer Scanner for an Increased Duty Cycle, Optical Engineering 49(10), 103001 (2010); doi.org/10.1117/1.3497570.

8083-46, Poster Session

Full vectorial finite element method for acoustic mode calculation of suspended core fiber

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Brillouin scattering in optical fibers is explained by interaction between the acoustic mode and two optical modes. Acoustic modes cause to coupling between two optical modes when phase matching condition is satisfied. They are affected by external parameters such as temperature and strain. This characteristic is used for distributed optical fiber sensors based on Brillouin scattering. So, knowledge about acoustic modes of fibers with various structures is so important.

In this article, acoustic modes of suspended core fiber that is fabricated by IPHT (Institute of Photonic Technology, Jena, Germany) are calculated. Real picture of suspended core fiber's cross section is converted to matrix by Labview program for calculation. Full vectorial finite element method is used. We used Matlab 7 program for calculation. The first two modes are presented. Each mode has longitudinal and transverse components of density displacement.

Acoustic modes of suspended core fiber have large transverse density displacement on the boundary of air holes when the effective acoustic velocity of modes is larger than the longitudinal acoustic velocity. So, sensitivity of these acoustic modes to viscosity of material in holes is expected. We proposed the usage of this fiber for distributed viscosity sensor.

Since air holes of fiber are so large, core of fiber is supposed as a bare silica rod in air. So, acoustic modes of the bar silica rod is calculated analytically and numerically. Then the result is compared to acoustic modes of suspended core fiber. It was seen that acoustic modes of two structures are not same due to the silica connector between air holes in suspended core fiber's structure.

8083-48, Poster Session

Rigorous simulations of 3D patterns on extreme ultraviolet lithography masks

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Extreme ultraviolet (EUV) lithography at a wavelength of about 13 nm is expected to replace DUV photolithography for manufacturing features on integrated circuits with critical dimensions as small as 22 nm or beyond. Computational lithography allows to enhance attainable resolution and has allowed to push the limits of DUV lithography to a small fraction of the optical wavelength of about 193 nm. Rigorous simulations of light propagation through photomasks are also an essential component in optical metrology of such structures.

In DUV lithography and metrology simulations a main challenge consists in accurate resolution of light fields in the presence of complex 3D absorbing structures of high refractive index-contrasts. In the EUV regime available materials exhibit far lower refractive index-contrasts. This leads to additional challenges for rigorous simulations: Computational domain sizes increase due to the fact that absorber structures need higher volumes. Deviations from ideal geometries like sidewall-angles have a larger effect on the diffraction spectra. EUV Masks are tyically mounted on multi-layer mirrors with a high number of single layers. This again increases 3D computational domain size and complexity.

We develop a time-harmonic finite-element (FEM) solver which also allows to address 3D EUV simulation tasks. The solver incorporates higher-order edge-elements, domain-decomposition methods and fast solution algorithms. In this contribution we report on simulations of EUV lithography of periodic arrays of contact holes. In a convergence study we show that accurate results can be attained also in the presence of sidewall-angles and corner-roundings.

8083-49, Poster Session

Opto-mechanical modelling and experimental approach to the measurement of aerospace materials using shearography and thermal loading

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The aerospace industry is in the progress of moving from classical materials, such as steel and aluminium, to lightweight composite and hybrid materials, such as carbon fibre and GLARE. These lightweight materials require advanced measurement techniques that are preferentially fast, non-destructive, non-contact and full-field. Optical methods supply all these requirements and appear as a suitable solution for non-destructive inspection both in the production environment and for maintenance. In particular interferometric and holographic techniques offer a high sensitivity to displacements, allowing components to be assessed non-destructively using small loading levels. Unfortunately many interferometric and holographic techniques are sensitive to disturbances from the measurement environment. Shearography overcomes this as its common-path interferometer configuration makes it insensitive to small amplitude displacements, such as vibrations. To perform a measurement in shearography the object is illuminated by a laser and an interferogram is recorded by a camera viewing the object through a shearing interferometer. A reference interferogram is recorded before object loading and this is correlated, in the computer, with reference interferograms recorded after loading. Processing using techniques such as phase-shifting allows maps of displacement gradient to be determined. By selecting different shearography configurations in-plane and out-of-plane displacement gradient maps may be determined. Meanwhile a detailed knowledge of the measurement environment is necessary to detect the defects. Less well known is the relationship between measurement technique, loading method and the material under test. Very often selection of parameters is made by intuition, experience or trial and error.

This paper is concerned with modelling the complete opto-mechanical measurement system, including shearography instrument, loading technique and the response of the object under test. The aim of the research programme is integrate these components in a combined opto-mechanical model, eventually covering a wide range of aerospace materials. Various static and dynamic loading techniques may be used with shearography, for example mechanical, pressure, vacuum, thermal or vibrational excitation. In this paper the authors study in detail the measurement of an aerospace sample using shearography and thermal loading. First a finite-element mechanical model is developed to obtain the dynamic mechanical response of the sample under thermal loading. The numerical model is generated using experimental temperature and strain data, measured using thermocouples and strain gauges, together with reference material parameters. An opto-mechanical model of the complete measurement system, including the shearography instrument, is then developed where simulated shearography phase maps will be generated using the data from the finite-element simulation. These phase maps are compared with experimental results to assess the quality of the model. To analyse the accuracy of the system as a quantitative measurement tool, a shearography instrument using one laser and four camera heads has been developed and is used to measure the in-plane and out-of-plane strain components. The data recorded by the instrument will support the transfer function of the system, where the analysis of the input heat, the phase map and the strain will be combined. As the model develops it will be used for more complex aerospace materials and those containing defects. The development of the opto-mechanical model, the experimental shearography instrument and the loading techniques will be presented. Data from the simulation and experiment will be compared and the suitability of the technique will be assessed.

8083-50, Poster Session

Modeling of photoluminescence intensity of ultrathin layer with silicon nanocrystals

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Most of prospective applications of silicon nanocrystals (Si-NCs), such as active media for optical waveguides, amplifiers and lasers, or basis for light-emitting diodes, or absorbing ultrathin layer for the third generation photovoltaic devices, imply utilization of thin films containing Si-NCs. Therefore, the control of optical properties (including theoretical calculations) of such films is of current importance. However, small optical thicknesses of the films (which are often much less than characteristic wavelengths) and complicated multilayered structure make certain difficulties for the ordinary estimations using standard formulas.

We present a model, which enables one to calculate the photoluminescence (PL) and Raman intensities of multilayered structures. In this work we consider the sample containing emitting layer with Si-NCs. Using theoretical predictions we experimentally observed PL intensity enhancement of ultrathin (4 nm thick) film with Si-NCs for optimally chosen silicon dioxide (SiO_2) buffer layer thickness (Fig. 1a). Moreover, our model enables one to explain nonmonotonic dependence of PL intensity from Si-NCs layer on its thickness (Fig. 1b).

PL intensities were calculated using the method developed by Benisty et. al. [1]. The PL process is approximated by radiation of chaotically oriented oscillating electrical dipoles. The amplitude of oscillation is proportional to the electric field of excitation light at the position of dipole. Calculations were made by 2x2 transfer matrix method.

Alternating layers of stoichiometric SiO_2 and silicon rich silicon oxynitride (SRON) were deposited on Si substrates using PECVD system. Subsequently, all samples were annealed for 1 h in high purity N_2 atmosphere at 1100oC in order to form Si-NCs in SRON layers. Triple-layered structures consisting of buffer SiO_2 layer, emitting SRON layer and capping SiO_2 layer were fabricated. For the first set of samples the thickness of buffer layer was varied from 0 to 125 nm, while the thicknesses of emitting and capping layers were fixed. On the contrary, the second set of samples is characterized by variable thickness of emitting SRON layer, while the thicknesses of other layers were constant.

References

1) H. Benisty, R. Stanley and M. Mayer, J. Opt. Soc. Am. A 15, 1192 (1998).

8083-13, Session 4

Image simulation of projection systems in photolithography

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The well-established Abbe formulation is one of today's most common approaches for the accurate image simulation of partial coherent projection systems used in semiconductor lithography. The development and application of lithographic imaging systems close to the theoretical resolution limits and the desire for the simulation of larger mask areas with high accuracy require several extensions of the classical Abbe approach.

This paper presents the basics of the Abbe approach including the so-called Hopkins assumption. For the accurate simulation of today's lithography systems important physical effects like strong off-axis illumination, small feature sizes, ultra-high NAs, a polarization dependent behavior, imaging demagnification, aberrations, apodizations, Jones pupils, flare, scanner and illumination band width effects have to be described and taken into account. The corresponding models and the resulting extensions of the Abbe approach will be presented. The accuracy improvement, flexibility and computational performance of the new approach are demonstrated by several application examples.

8083-14, Session 4

Combining rigorous diffraction calculation and GPU accelerated nonsequential raytracing for high precision simulation of a linear grating spectrometer

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In many illumination applications multiple white light LEDs have to be grouped together to give sufficient luminescence levels. To provide homogeneous colour perception, spectrally matched LEDs have to be chosen even from one production batch.

Therefore there exists a substantial demand for fast high accuracy measurement of emission spectra of LEDs. Grating based array spectrometers offer the possibility for one-shot measurement of spectral properties. However their signal to noise ratio is not sufficient to satisfy increasing requirements for color accuracy. In order to quantify the noise sources to enable a consequent system optimization, we present an effort towards a high precision simulation of such spectrometers.

Simulating grating spectrometers offers two main challenges. The grating inside the spectrometer is a nanostructured surface whose interaction with an incident lightfield can only be modelled adequately via rigorous electrodynamic theory. The other components of the spectrometer however constitute a macroscopic system that is most efficiently modelled with geometric optics. The second challenge comes with the fact that simulating high signal to noise ratios within a straylight dominated system calls for a large number of rays to be traced nonsequentially. Additionally the broad spectrum of white light LEDs has to be simulated as a superposition of many monochromatic raysets. This results in an even larger overall raynumber rendering this simulation vastly ineffective for conventional raytracers.

Therefore we present a double precision raytracer that utilizes the massively parallel computing architecture of modern graphics cards to speed up scientific raytracing. Furthermore we use a rigorous coupled wave analysis (RCWA) algorithm to compute the spectral efficiency of the grating orders from an AFM scan of the grating surface. We use this data to represent the grating in the raytracer and compare the results of this simulation to measurements with a real array spectrometer.

8083-15, Session 4

Fast virtual shadow projection system as part of a virtual multisensor assistance system

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The quality inspection is one of the most important parts of the production process due to the continuous increasing requirements of manufacturing and construction techniques. The main task of the quality inspection is to ensure that all significant geometry parts can be detected with a measurement uncertainty which is less than the pre-defined work piece tolerances, e.g. the planarity or the cylindricity. A cost and time expensive measurement analysis using an appropriate reference work piece has to be done to estimate the reachable accuracy. The measurement analysis has to be accomplished for each metrological individual case, which enhances the money and time effort, too. Using virtual measurement techniques and Monte-Carlo methods it is possible to estimate the reachable measurement accuracy and therewith to reduce the costs, whereas the virtual system is implemented in the computer as a software. The whole calculation is done in the computer and needs only the CAD-model of the work piece. This is a big advantage compared to the usual procedure because the software can give some feedback and some useful information to the constructer without the use of a real work piece. For example, the software can tell the constructer, if the available measurement system can achieve the claimed tolerances.

Another field of application for the virtual measurement systems are the virtual multisensor assistance systems. The measurement systems can be integrated in a virtual multisensor assistance system which is used for the automatic (intelligent) calculation of optimised measurement strategies concerning different criteria. For example the criteria can be the minimisation of the measurement time, the holistic measurement or the minimization of the measurement uncertainty. This is the main field of research of the subproject B5 "Complete Geometry Inspection" of the collaborative research centre 489 (CRC 489) "Process Chain for the Production of Precision Forged High Performance Components", funded by the German Research Foundation (DFG). The main task of the project is the development of a virtual multisensor assistance system, which is build from a fringe projection sensor, a shadow projection sensor, a system of linear axes, another linear axis and a rotation axis. Thereby the shadow projection system is combined with the rotation axis and a linear axis and the fringe projection sensor is fixed at a system of linear axes. The concept of the system is shown in the figure. The assistance system should be used for the calculation of intelligent and work piece specific measurement strategies in respect of the measurement of geometric dimensioning and tolerancing. Beside the integration of the named criteria it is foreseen to determine the best measurement system for the measurement task.

Previous research works dealt with the development and the identification of the fringe projection system. This work should be focussed on the numerical simulation of the shadow projection system. Shadow projection systems are applied for contour measurements. Therefore the measurement object is lighted from one side with parallel monochromatic laser light. The light is interrupted from the edge of the object and the projected shadow is detected from a CCD row sensor, which is equipped with telecentric projection optics. To calculate the expansion of the projected shadow the shadow boundaries have to be extracted. Therefore the gray scale values from bright and dark crossings were evaluated using sub pixel methods and interpolated using polynomial functions. The shadow border can be found at the pixel-position, where the interpolated gray scale trend deceeds a predefined digitalisation barrier.

To get a precise simulation model and to have the possibility to simulate the real measurement effects the theory of wave optics has to be used. The solution of the diffraction integral results in the diffraction images. The modelling of diffraction brings along a high simulation time, especially in the case that the lenses and the apertures have large dimensions. For the statistical analysis multi-measurements must be executed, which is usually not practical in the case that one single simulation lasts a few hours. Using the virtual shadow projection system for the estimation of measurement uncertainties the simulation time has to be reduced. In this work the numerical efficient simulation of a shadow projection system should be presented. Special algorithms have been developed and the simulation time can be reduced with nearly the factor 2700 to a few seconds for a single simulation. The algorithms and a comparison between simulated and real measurement results will be discussed. Furthermore the procedure for the estimation of the measurement uncertainties will be explained and an example will be given.

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8083-16, Session 4

Speckle pattern simulations for encoding applications

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Optical encoding using speckle pattern has been reported in the literature [1,2]. In summary, a displacement of a rough surface is measured by measuring the displacement of the roughness induced speckle pattern in the image plane of an imaging system. The cross-correlation function between e.g. successive images is often used to estimate the displacement [1]. Recent work [3] has shown that sub-micron resolution can be obtained using high-resolution picture and high magnification imaging optics. Several parameters can affect the accuracy: magnification, number of pixels, signal processing, defocus, etc...

The application of this technique to encoding technologies is of a great interest for many applications, since it enables two-dimensional measurement of displacement, without the need for expensive optical glass rules. However, the cross-correlation processing of successive high-resolution images may limit the measurement rate, because of the computing time. Therefore, we must limit the number of pixels. The impact of the number of pixels on the measurement accuracy is therefore critical.

We present a simulation tool, which allows simulating speckle pattern in an imaging system, and its measurement with a limited number of pixels. The simulation tool is based on the Fourier Optics theory [4]. The speckle pattern is simulated by considering the two-dimensional Fourier Transform of a plane object with a given roughness O(fx,fy), and the imaging optics transfer function H(fx,fy). The transfer function will depend on the focal length, numerical aperture, and also defocusing errors. Spherical aberrations can also be included in the optical transfer function. The speckle pattern is then determined from the inverse Fourier transform of the product O(fx,fy).H(fx,fy). The uncertainty on the displacement measurement is then estimated using the Monte-Carlo method.

In parallel, a CMOS-based camera prototype has been developed. The imaging optics has been designed in order to reach diffraction-limited performance with a magnification factor of 10. Figure 1 shows a comparison between two images. The one on the left has been simulated by our software, and the other one is the measured one. This prototype has been used for preliminary experimental verifications of the Monte-Carlo speckle simulator. The displacement of a scattering metallic plane surface has been measured using the speckle patterns observed by means of this prototype. At the same time, we measured the displacement with an industrial Agilent interferometer, whose resolution is typically 10 nm, and whose relative accuracy is around 2 ppm (limited by the ambient temperature and pressure). The interferometer is used as reference in this experiment.

Comparison between simulation and experimental results are shown in Fig. 2. These theoretical and experimental analyses show that an accuracy of 0.2 micron can be reached over a displacement of 40 microns between two speckle images, with only 32x32 pixels and a magnification of 10.

References

[1] I. Yamaguchi, and T. Fujita, “Linear and rotary encoders using electronic speckle correlation” Opt. Eng. 30, 1862-1868 (1991).

[2] U. Schnell, J. Piot, and R. Dändliker, “Detection of movement with laser speckle patterns: statistical properties,” J. Opt. Soc. Am. A 15, 207-216 (1998).

[3] R. Filter, T. Scharf and H.-P. Herzig, “High resolution displacement detection by speckle pattern analysis : accuracy limits in linear displacement speckle metrology”, J. of the European Optical Society - Rapid publications, Vol 5 (2010).

[4] J.W. Goodman, Introduction to Fourier Optics, McGraw-Hill Book Co.,New York, N.Y., 2nd edition, 1996.

8083-17, Session 4

Modeling of modulation functions of different configurations of optical chopper wheels

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Choppers, one of the most used optical devices for the modulation of light, have a large area of applications: attenuation of light, as in photometers and colorimeters; obstruction of undesired wavelengths or of ambient light, and/or selection of desired wavelengths, as in radiometers and telescopes, generation of a controlled train of light impulses or of a certain light flux profile, as in spectral systems or biomedical applications.

However, despite their myriad of applications, there is not yet a systematic theory regarding an optimum designing calculus that would allow for developing the best solution for certain requirements (i.e. for a required modulation function of the light flux). We shall present in this paper our results regarding this direction of research, for choppers working with top-hat light beam distributions. Two configurations of chopper wheels will be considered: with windows with straight and with circular edges. A rigorous analytical modeling will be performed for each type of device.

For the first configuration, all the four possible relationships between the diameter of the beam in the plane of the wheel and the dimensions of the window of the chopper are presented and discussed: (i) large wing and focused beam in the plane of the wheel; (ii) large wing and beam of finite diameter in the plane of the wheel, but with a wing large enough to cover the section of the beam; (iii) narrow wing, finite diameter beam and large windows, so there is only one wing at a time in front of the beam section; (iv) narrow wings and windows, so there are more wings at a time in front of the beam section.

The second and more general wheel configuration that we have proposed in a previous study, with windows with circular edges (for which choppers with circular windows are a particular case) is also discussed in this paper. Both outwards and inwards circular edges are considered. The modulation functions of this type of devices are derived and studied. The results will be discussed in comparison to those for the first, classical types of wheels (with windows with straight edges), which are a particular case of the wheels with circular edges. The real functions of the transmitted flux, with transition portions are derived, in contrast to approximate approaches, of flux functions considered as series of rectangular impulses. The configuration of the new device allows for more degrees of freedom in the designing process. From this discussion, the various profiles of the function of the transmitted flux are obtained: rectangular, approximate trapezoidal, approximate triangular, sinusoidal, and with non-null values. The possible geometries of chopper wheels that may generate a required function of the transmitted flux are discussed.

An insight in the experimental part we are currently working on, with the stall we have developed to study the different configurations of chopper wheels is also provided in the paper.

Selected References:

Duma V. F., Optical choppers with circular-shaped windows: Modulation functions, Communications in Nonlinear Science and Numerical Simulation (Elsevier) - CNSNS 16(5), 2218-2224 (2011); doi.org/10.1016/j.cnsns.2010.04.043;

Duma V. F., Theoretical approach on optical choppers for top-hat light beam distributions, Journal of Optics A: Pure and Applied Optics, 10(6), 064008 (2008); http://iopscience.iop.org/1464-4258/10/6/064008/.

8083-18, Session 5

Alternative robust statistical methods to reduce parameters uncertainty: application to scatterometry

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The determination of interesting parameters is very often performed through curves fitting, like in scatterometry for example. Classically, the problem is solved by means of least-squares. It is well known that least squares are statistically optimal (ie give the lowest parameters variance) when the difference between parameterized theoretical model and experimental curves are gaussian. In real life systems, this assumption is not valid mainly because of modelling and calibration errors, thus inducing some uncontrolled biases. In this paper, we propose radically different principles of fitting techniques, based on entropy criterion instead of the Maximum Likelihood Principle. Combining simple implementation and high performance, we show that this technique is optimal for pure gaussian noise and dramatically reduces bias on parameters for corrupted data. We provide also test on real scatterometry samples.

As an introduction, we recall the basic principles of Maximum Likelihood Estimation principle (MLE), generally used, and the link with least-squares in the case of gaussian noise. After a brief description of the pros and cons of the technique, we introduce the Minimum Entropy principle (ME), often used image processing and speach recognition, and we explicit the link to MLE.

Fisrt of all, ME relies on the determination of the Probability Density Function (PDF) of the residual error (difference between theory and experimental curve). It is characterized through the use of a Kernel Density Estimation technique, providing finally the statistical properties of the errors. The ME estimator finally performs the minimisation of the entropy of the PDF, reducing utlimately the spread (and not the variance) of the PDF while optimizing fitting parameters. In this context, we show numerically that this estimator leads to the same asymptotical properties of MLE if errors are gaussian.

In a second part, we show that ME is far more robust to outliers and modelling errors in the simple case of linear models, providing a fundament for further experiments in scatterometry.

Third, we develop an extention of this principle to take into account the non-homogeneity of the corrupted data. Concretely, this occurs when the modelling errors are bigger for some groups of wavelenght. By a smoothing process, the PDF is determined for each wavelength, providing an improved determination of the entropy. The performances are shown to be far superior to conventional techniques for simple linear cases.

Finally, ME estimation is used for scatterometry. The test samples are nearly 60 nm resist lines scatterometry gratings provided and measured by ST Microelectronics on a focus-exposure matrix. We show that a very good agreement with CDSEM is obtained compared with standard MLE techniques.

We believe the Minimum Estimation technique to be very generic. It could be applied to other parametric inverse problems occuring in optical metrology.

8083-19, Session 5

The effect of line roughness on the diffraction intensities in angular resolved scatterometry

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Scatterometry is a common technique for the characterization of nano-structured surfaces. It is an indirect measuring method, where a chosen set of parameters describing the scattering object is fitted numerically to the data obtained from a scattering experiment. In order to detect several diffraction orders with an angular resolved measurement, it is necessary to choose the wavelength of the light to be of the same order or smaller than the size of the scattering structure. At PTB, detailed scatterometric investigations of an EUV photomask with periodic absorber line gratings on an EUV multilayer mirror have been performed using EUV and DUV radiation. Multiple propagating diffraction orders could be observed and it was possible to derive information about the line profile by means of rigorous numerical modeling. A comparison with microscopic measurements yields consistent results. The sidewall angle of the line profile, however, was determined in the scatterometry measurements performed in EUV spectral range as well as in DUV, to be distinctly lower than the angle provided by AFM. Analyzing different sources of uncertainty, it could be shown that structure disturbances such as line edge or line width roughness cause significant impact on the angular distribution of the diffraction intensity. This effect can be formulated analytically. On the one hand, this can be used to investigate the consequences of roughness for the structure reconstruction algorithm. For instance, a considerable variation of the reconstructed sidewall angle can be observed as a function of roughness. On the other hand, it would be possible to estimate the roughness parameter within a scatterometric experiment and to compensate its influence on the numeric data evaluation. In this paper we will sum up the sources of uncertainties involved in scatterometry and focus on the line roughness and on how it affects the profile reconstruction.

8083-20, Session 5

Inverse scattering problem solving for low-dimensional periodically-arranged nanocrystals

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Carrier confinement in low-dimensional periodically-arranged nanocrystals (LDPAN) leads to the dependence of the operating wavelength in LDPAN-based optoelectronic devices on the average size and shape of heterostructures. Scatterometry as a non diffraction-limited optical method is applied to LDPAN (i.e. quantum dots, quantum moleculars, nanowires, etc) which are arranged on periodical masks. We propose numerical algorithms for the determination of periodic relief nanostructures from light diffraction patterns measured in UV-IR wavelength ranges. The solution of the direct 3D diffraction problem is reduced to the solution of boundary integral equations [1] for the 2D Helmholtz equation. The ratio wavelength-to-period is very small for typical inverse scattering problems and so the modified boundary integral equation method [2](MIM) has to be applied to obtain accurate results at a fast convergence rate [3]. The inverse problem is formulated as a non-linear operator equation in the Euclidean space with an assumed set of unknown structural parameters of nanocrystals (height, width, slope angles, and refractive indices) and a given set of determined efficiency or phase shift values. The operator maps the sought structural parameters to the amplitudes of diffraction orders. The present approach employs the gradient Levenberg-Marquardt method to solve the operator equation. This type of iterations is close to the Gauss-Newton method, but more efficient and stable for poor or improper input data [4] due to an additional regularization parameter. The inverse problem, mathematically, severely is ill-posed [5] and regularization techniques have to be used to improve the solution. Unfortunately, such a regularization is not enough even for simplest geometry considerations and serious restrictions to the number and values of reconstructed parameters must be applied. Here we consider problems with a few polygonal-type boundary profiles having several edge points only. The method can be applied to LDPAN grown in different material systems (group III-V, IV, II-VI, their combinations, etc) by various techniques (MBE, MOCVD, MOVPE, etc).

[1] L.I. Goray, G. Schmidt, J. Opt. Soc. Am. A 27, 585 (2010).

[2] L.I. Goray, Waves Random Media, 20, 569 (2010).

[3] L.I. Goray, J. Appl. Phys. 108, 033516 (2010).

[4] P.E. Gill, W. Murray, and M.H.Wright. Practical Optimization, Academic Press, London, 1981.

[5] H. Gross and A. Rathsfeld, Waves Random Media 18, 129 (2008).

8083-21, Session 5

Fourier scatterometry with white light for characterization of sub-100 nm periodic two-photon polymerization structures

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In recent time Fourier-Scatterometry has become of increasing interest for quantitative wafer metrology. But also in other fields the fast and precise optical characterization of periodical gratings of sub 100 nm size is of great interest.

We present the application of Fourier-Scatterometry, extended by the use of white light for the characterization of sub-wavelength periodic gratings of photosensitive material structured by two-photon polymerization.

First a simulation-based sensitivity comparison of Fourier-Scatterometry at one fixed wavelength, Fourier-Scatterometry using a white light light source and also additionally using a reference-branch for white-light-interference has been carried out. The investigated structures include gratings produced by two-photon polymerization of photosensitive material and typical semiconductor test gratings. The simulations were performed using the rigorous-coupled-wave-analysis included in our software package MICROSIM.

The sample is illuminated with white light through a high-NA microscope objective (NA: 0.95) allowing an incoming illumination with wide illumination (0°-72°) and azimuthal angle ranges (0°-360°). Using the full pupil illumination, Fourier-Scatterometry gives access to the complete information for every incident direction in one shot compared to fixed incident angle scatterometry equipment which has to scan over these angle ranges.

Using white light instead of a fixed wavelength illumination gives a new dimension of freedom and finally using scanning white-light-interference allows increasing sensitivity towards structure height and shape.

Based on the results of the sensitivity simulations the expected gain of information using Fourier-Scatterometry in combination with white-light-interferometry is verified.

We also show our experimental implementation of the measurement setup using a white-light-laser with an almost flat intensity distribution in the used spectral range (400 - 700 nm) and a modified microscope with a high-NA (NA: 0.95) objective as well as a Linnik-type reference branch for the interferometry measurements. First measurements for the investigation of the performance of this measurement setup are presented for comparison with the simulation results.

8083-22, Session 5

Improved geometry reconstruction and uncertainty evaluation for EUV scatterometry based on maximum likelyhood estimation

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Scatterometry is used in wafer metrology to determine the critical dimensions (CD) of lithography masks: Profile parameters such as line width, line height, and side-wall angle (SWA), have to be reconstructed from the measured diffracted light pattern and the associated uncertainties of the evaluated profile parameters need to be estimated. The choice of the statistical error model for the measured input data is crucial to the reconstructed profile parameters and its impact is demonstrated for EUV masks, where light with wavelengths of about 13.5 nm is applied.

A wrong estimate of the variances of the input data, i.e., the measured light defraction pattern, can lead to an unsatisfying solution of the inverse problem. To overcome this problem we apply the maximum likelihood estimation (MLE). In addition to the geometrical parameters of the mask the parameters of the statistical error model are treated as variables to be determined simultaneously. This approach leads to a higher consistency between the measurement data and the calculated diffraction pattern of the optimized solution. The MLE approach is applied to EUV measurement data and the results are compared to those obtained with a predefined error model.

8083-23, Session 5

Perturbation method for scattering matrix interpolation: application to feature shape control by scatterometry

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Evolution of electronic components miniaturization requires very precise and preferably non-destructive control. Conventional techniques such as the Atomic Force Microscopy (AFM) or the Scanning Electron Microscopy (SEM) commonly used in industry are not adapted to a real-time monitoring or are destructive to the analyzed structure. Techniques based on optical control such as scatterometry provide a very convenient alternative in terms of reliability and numerical integration. Scatterometry is an electromagnetic characterization based on the analysis of the electromagnetic signal diffracted by an object. This characterization can be divided into two steps:

The first step conventionally called direct problem consists in managing a database of scatterometric signatures of periodic structures, similar to the characterized object. A scatterometric signature is a dispersion curve (representation with respect to the wavelength) of diffracted field complex amplitudes for both polarizations (TE and TM). The generation of such a database is done through a numerical electromagnetic simulation and the most commonly used is the Rigorous Coupled Wave Analysis

The second step which seems to a reverse method consists in finding the geometrical parameters of the patterns from experimental measurements. One of the most commonly used methods is to establish a library,i.e. a set of electromagnetic signatures obtained through a direct electromagnetic simulation for different values of the pattern's geometrical parameters: height, critical dimension (CD), angle of the slope, curves radii, etc. The establishment of this library can quickly become a huge task penalizing the technique.

The direct electromagnetic simulation therefore appears to be one of the most important step in scatterometry. The electromagnetic simulation is based on the RCWA method which is coupled with the staircase approximation. This technique which consists in regarding the grating as a stack of lamellar gratings was first suggested by Peng & al. and was later used in the very popular Rigorous RCWA . In all the methods employing this technique, the electromagnetic field is written as a modal expansion in each layer and the tangential components of the field in the different slices are connected by boundary conditions. Several connecting algorithms exist to solve boundary equations but the most robust and stable is probably the algorithm of scattering matrix . We present in this paper an interpolation method of the . For a given pattern, the S matrix is a function of the geometric parameters of the grating (height, CD, slope, etc) but also in terms of physical parameters of the problem including the wavelength. The calculation method is based on evaluation by a perturbation method, local variations of the eigenvalues and eigenvectors of the scattering matrix. The technique is applied to a canonical structure commonly found in scatterometry. It is a trapezoidal grating with rounded edges.

8083-24, Session 6

Gradient reconstruction for the phase recovery from a single interferogram with closed fringes

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The need to analyze a single interferogram may appear when experimental conditions do not permit the implementation of phase shifting techniques. A single interferogram may be easily demodulated if a carrier function is introduced with well-known open fringe analysis methods. However, if the dynamic range of the phase to be measured is such that the introduction of a carrier function would lead to obtain an undersampled interferogram. The phase recovery from a single interferogram with closed fringes is known to be a difficult task. The problem is that exist infinity solutions for the inverse problem of finding the phase from a single interferogram. However, the desired phase can be found if appropriated assumptions are implemented and priory knowledge is used. The most basic assumption may be that the phase is continuous and a smooth function. Other assumption is that the phase behaves almost linearly in a small region. The above priory knowledge and assumptions are used by regularized phase tracking (RPT) techniques. Although, these techniques are robust, they require identifying correctly the maxima, minima and saddle regions of the phase to work properly. This is because in such regions the initial assumption of a linear behaviour of the phase do not holds. In this work we propose a method, based on RPT techniques, that do not require identifying specific regions of the phase. The method is based on the gradient reconstruction of the phase from the derivatives, in orthogonal directions, of the interferogram being analyzed. A differential equation containing the gradient information is solved numerically by means of a minimization process as done with RPT techniques. The phase gradient is assumed to vary almost linearly in a small window. Solving for the phase gradient, instead of the phase itself, have the advantage of that during the minimization process results a set of linear equation and with RPT methods results a set of non-linear equations. In this way, the gradient reconstruction is faster as compared with RPT methods. Additionally, the need of identifying the maxima, minima and saddle points of the phase is eliminated since the phase gradient is assume to behaves linearly which means that the phase is a quadratic function and no a linear function as considered with RPT techniques. A regularized term is aggregated to the differential equation which enables us to find the solution for the phase derivatives. Both phase derivatives terms are obtained simultaneously from a set of linear equations that results from the minimization process. The algorithm requires a small initial region with the phase derivatives already estimated. The calculated values of the phase gradient from the initial region are used as a regularized term to solve the differential equation. The phase derivatives solution is then propagated from the initial region until the whole interferogram field is processed. Each value of the phase gradient found is aggregated in the

regularized term which makes the solution stable. The initial region may be easily found applying a band pass filter in the frequency domain as done with the Fourier method. The phase of the interferogram is calculated with a least square method using the information of the phase derivatives found with the proposed technique. The feasibility of the described approach for phase gradient reconstruction is tested in simulated and experimental data.

8083-25, Session 6

Physical marker based stitching process of circular and non-circular interferograms

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In this paper a stitching concept to combine a multiple set of interferometric data is presented. Interferometry is probably the most popular measuring method in optical metrology for high end optical components, such as microscope lenses. Unfortunately the measurement area of this measurement technique is limited by the aperture size. If the diameter of the lens under test exceeds the maximum patch size it is impossible to measure the lens interferometrically without using stitching technologies. There exist already a few products providing stitching technologies, e.g. the well known Sub-Aperture Stitching Interferometer SSI-A [1] from QED. This metrology machine first ac-quires a certain number of sub-measurements and aligns them relative to each other. After the alignment these measurements are combined to the surface error profile of the whole test object. However these available systems are limited to common diameters and not suitable to measure large mirrors with a diameter of more than one meter. In order to realize a large mirror project the University of Applied Sciences Deggendorf develops their own stitching software to combine circular and also non-circular interferometric data.

Introduction

Due to the increasing demand for large mirrors for aerospace and military applications the University of Applied Sciences Deggendorf initiated a project to design a production machine with integrated metrology for large telescope mirrors with a diameter of more than one meter. These large parabolic mirrors may be tested with the aid of a Computer Generated Hologram (CGH). A CGH transforms in the majority of cases a spherical wave front of the interferometer in order that it matches exactly with the mirror to be tested [2]. To avoid the costs for a CGH the surface may also be tested using stitching interferometry. When using stitching technologies it is not necessary to test the entire surface with one single measurement. The surface is separated in a certain number of sub-areas which are measured step by step. After the data acquisition these sub-measurements are combined to the error profile of whole test object. One of the metrology systems providing stitching technologies is the Sub-Aperture Stitching Interferometer SSI-A [1] from QED Technologies. Since measurement platforms like the SSI-A are not suitable to measure mirrors with a diameter of more than one meter the University of Applied Sciences Deggendorf develops their own stitching routine to combine a certain number of sub-measurements. Until the design of the large production and measurement setup is finished the developed algorithms are tested on common lenses with a diameter of 70 to 100 mm. The raw data is obtained by the SSI-A, which is already distortion corrected.

Measurement setup

At a chosen measurement example a flat lens with a diameter of 71 mm was measured. The first four measurements were taken around the center of the lens at different rotation angles phi. Then the test object is moved out of the center for the sub-measurements five till eight. Thereby the lens is rotated about 90 degree clockwise after each measuring step. After the acquisition of the eight distortion-free measurements the raw data is transferred to our stitching software. The phase data are represented with a set of orthonormal polyno-mials calculated according to [3] [4]. Due to this orthonormalization process the algorithm is not limited to circular sub-measurements. The first four measurements are aligned in the three dimensional space in order that they match as good as possible. After this adjustment the arithmetic mean value of the sub-measurements one until four is calculated, which serves as reference for the addition of the other four measurements [5]. In order to fit the interferograms five until eight to the reference the alignment coefficients (coefficient one to three) of the orthonormal polynomial sets are adjusted to each other at a first step [6]. The fine adjustment of the surfaces is an optimization problem in the least squares sense which is solved with the aid of a single value decomposition [5]. After the alignment of all sub-measurements to the reference the complete error profile is calculated.

Compared with actually available stitching metrology systems the large measurement machine to be designed will show a significantly lower positioning accuracy of the measuring patches. As a consequence a cross-correlation based detection tool to find the necessary translation of the sub-measurements in x- and y-direction with respect to the reference interferogram is implemented. To ensure a correct detection of the lateral shift physical markers are brought up onto the test surface.

Results and discussion

In order to evaluate the quality of the developed stitching routine the stitched results are compared with the outcomes of the well known QED metrology system SSI-A and with the single full aperture measurement in each case. Concerning the test of the flat lens with a diameter of 71 mm our stitched result reached a pv-value of 660.0 nm and a rms-value of 170.2 nm. For comparison the stitched result of the SSI-A showed a pv-value of 657.4 nm and a rms-value of 170.5 nm. In the case of sufficient stable measurement conditions the stitched results are quite similar to the outcomes of the SSI-A. Too high measurement uncertainties caused by temperature drift or vibrations of the system in combination with the translation detection tool may lead to a corrupt stitching result because of an incorrect identification of the necessary shift in x- and y-direction. To stabilize the measurement physical markers on the test surface are used, e.g. six small dots. The resulting “holes” in the interferogram may be easily detected with the cross correlation method. After the calculation of all necessary translations a median filter is applied to eliminate the holes.

Conclusion

According to the results the developed stitching algorithm provides good results, which are comparable with the stitched results of the QED metrology system. The problem of a corrupt translation-detection may be easily solved with the aid of markers on the test surface. With some further improvements, like an own distortion correction for instance, the software routine should be applicable in the planned metrology machine.

References

[1]. Marc Tricard, QED Technologies. Subapertur-Stitching-Interferometrie: Messtechnik für die Asphären-Präzisionsfertigung. Photonik 6/2008, pp 38-41

[2]. James H. Burge, James C. Wyant. Use of Computer Generated Holograms for Testing Aspheric Optics. Optical Sciences Center, University of Arizona, Tucson, AZ 85721

[3]. Daniel Malacara. Optical Shop Testing - Third Edition.Wiley-VCH, (2007). ISBN: 978-0-471-48404-2. pp 530-544

[4]. Guang-ming Dai, Virendra N. Mahajan. Nonrecursive determination of orthonormal polynomials with matrixformulation. Optics letters. Vol. 32. January 2007. ISBN/ISSN: 0146-9592. pp 74-76

[5]. Mikael Sjödahl, Bozenko F. Oreb. Stitching interferometric measurement data for inspection of large optical components. Optical engineering. Vol. 41. February 2002. pp 403-408

[6]. Peng Su. Absolute measurement of large mirrors. The University of Arizona. 2008. Chap. 2-3

8083-26, Session 6

Ronchigram analysis based on effective wavelength techniques and wavefront slope

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The Ronchi test has been consolidated as one of the most successful and powerful techniques applied to determine the quality of optical surfaces. Its physical interpretation fully connected with a lateral sheared interferometer, this kind of interference pattern could be associated with the idea of interference with effective wavelength. This proposal has been applied in the evaluation of optical surfaces. This testing technique measures the wavefront slope instead of contour of the wavefront like conventional interferometry. In order to reconstruct

the surface under test, two orthogonal slope Interferograms are required. Williams and Phillips [1] show the procedure to change a Ronchigram into a slope interferogram.

In this work we present the combination of two methods of analysis, for evaluate the quality of optical surfaces using the Ronchi test. First, we described a procedure to evaluate surfaces employing separately, two distinct wavelengths [2]. Position of the source of light and frequency of the grating remain in the same position when we capture at each different wavelength such that we obtain two Ronchigrams with distinct frequency. In order to generate an effective Ronchigram we compute a Moiré pattern of both Ronchigrams and apply some image processing algorithms to increase the visibility of the results. In this work, our results were computationally processed in order to reconstruct the wavefront of a particular mirror with effective wavelength.

After that, we use the technique of analysis is based on the change of a Ronchigram to a slope interferogram by proper scaling of the shearing interferogram via the equivalent wavelength [1]. This transformation can be done due to the fact that the irradiance in an interferogram depends on the measurement wavelength and the OPD (Optical Path Difference). In the lateral sheared interferometer the OPD is directly given by the difference between two adjacent diffracted orders. By replacing the OPD of the lateral sheared interferometer into the interferometric equations it is obtained the scaling factor or equivalent wavelength, which depends on two factors; frequency of the grating and the f# number of the system. It is careful to observe that the effective wavelength and equivalent wavelength are distinct concepts and are independent of the wavelengths used in the image registering process.

We developed an algorithm in order to transform, applying the scaling factor, our Ronchigrams into interferograms. This afforded us to employ some commercial software for interferogram analysis. For instance, we used the Apex software in order to generate the wavefront slope. In the other hand, for the effective wavelength, we decided to reconstruct the wavefront with our computational algorithms. Comparisons of the Zernike Polynomials of the wavefront of each method presented here were done against with that of a reference wavefront obtained with a commercial Fizeau interferometer of the Zygo Company. From the differences found in the last step, we determine quantitatively the aberrations of the system. The use of commercial software enhances the versatility of analysis making the polynomial adjusting easy to carry out.

Finally, we present some advantages and disadvantages of our proposal, and mention an improvement in the illumination system with a polishing process of high luminescence commercial light emission diodes (LEDs) and some colour filters, which are low cost devices. With this process, the noise in the captured images was reduced (commonly noise increases when using longer wavelengths), and we have obtained results with different effective wavelengths.

8083-28, Session 6

Diffraction limit and possible solution of white light interferometry

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Batwing error which is due to the diffraction of light is recognized since the invention of White Light Interferometry. The diffraction limit of light is well known as Rayleigh criterion since the 1873. The resolution of White Light Interferometry is limited by the diffraction limit of light which caused by the loss of evanescent waves in the far field and additional wave mode generation that carry high spatial frequency information. This paper studies the diffraction phenomena of several typical micro structures (size from several hundred nanometers to sub hundred micrometers) while White Light Interferometer (WLI) is applied to measure them. Siemens Stars, grating with rectangular profile, Atomic Force Microscopy (AFM) cantilevers which are fabricated by using different materials are measured under WLI.

To compare with the measurement results, the propagation behavior of white light reflective on structured surfaces is simulated which is based on Maxwell's Equation and finite difference time domain (FDTD) approaches. The Rayleigh criterion limits the lateral resolution of the SWLI, while the modulation precision influence more on the vertical resolution. However, the interaction of the measurement resolution is unclear up to now in either experimental or theoretical view. The difficulty is that it is not permissible to invoke the assumptions of the classical diffraction and reflection theory, which simplify the light propagation procedure and allow to approximate solutions, when measurements research on the surfaces with micro or nano structures. For such cases, the solving of Maxwell's equations offers an alternative way to solve the interactions between the light field and the micro structures. By working on the FDTD method which involves a central difference operator of both time and space variables into Maxwell's equations offers an alternative way to solve the interaction between the light field and the micro structures.

A diffraction which is contrived by the steep edges of the surface structures is recognized. This diffraction plays a key role with the Surface Plasmon (SP) when the reflective light does not follow the law of reflection in the area close to the structure edges. The above phenomenon could lead to the measuring error, decreasing of lateral resolution, inducing vertical measuring uncertainty, or even origin the non-measured signal when using the WLI.

Several measuring phenomena described above are specified into detail. The batwing effect which occurs at the position on or close to the edge of the lower part of the step height is concerned as WLI measurement error, due to the algorithms do not provide correct height value of surface. To observe the batwing effect, lateral edge detection at height profiles is investigated. Periodic gratings and micro-Siemens-Star structures are applied as step height artifacts to examine the performance of WLI at the discontinue area, while the structures has step height close to the coherence length of the light source. Batwing effect is observed as expectation. Numerical simulations are applied to analyze the wave propagation and the surface when white light is used in the measurements. The analyze results prove the batwing effect is due to the Surface Plasmon (SP) and interference fringes coursed by the SP. Several possible solutions are given to compensate the diffraction during the measurement.

8083-37, Session 6

Ronchi test for refractive optics off-axis using a nodal bench

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When evaluate the quality of the optical systems using the Ronchi test, the source and Ronchi ruling should be placed on the axis systems. However, usually the systems are working off-axis too, for this reason it is necessary to know the values of the aberrations on these positions. In order to know the quality of the system in off-axis, we propose to use the nodal optical bench. In particularly we use the principal property of this instrument, consists in its, when we mounted the refractive system in a rotating mount and his mechanical axis coincide with nodal point of the refractive system, we can rotated about the nodal point, then the focal point of systems does not have any movement in a plane located in this focal point. So, now we can put a Ronchi ruling in the exit pupil and observe the pattern of fringes, without movement of the source and the ruling. We are in the possibility of measuring the aberration off axis. For this, we placed the CCD camera located in the focal point of the refractive system and focused in the exit pupil. The principal advantage of this proposal is test the system without auxiliary optics, and provided a new option for one classical instrument, commonly used in an optical shop.
For implemented this options we use a simple optical system, one positive singlet lens. In particularly the lens are rotated 5, 10, 15 and 20 degrees. In the optical setup we use a Ronchi ruling of 50 l/inch, 150 l/inch in each case. Finally, we compared our experimental results with a simulation made with ZEMAX, a commercial optical design program.

8083-29, Session 7

Ab initio intensity distribution of diffusely scattered light from rough metallic surfaces

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Quantitative monitoring of roughness in case of machined surfaces is frequently performed via optical systems, e.g., by analyzing the diffusely scattered light. By using confocal microscopy to analyze a rough surface, for example, a height profile is extracted from the measured intensity distribution of the scattered light. In the present contribution, a recently developed two-scale approach to the diffuse light scattering from rough surfaces is applied to calculate the corresponding theoretical intensity distribution. Within this two-scale approach, the Maxwell equations are solved by means of a 2 x 2 matrix technique for ab initio layer-resolved permittivities and the visible light propagating in form of a harmonic plane wave. Applied to semi-infinite bcc Fe/Fe(100), beyond the comparison between measured and calculated intensity distributions, their angle of incidence dependence is also discussed in case of variously machined surfaces.

8083-30, Session 7

Modeling of the surface color controlled by Ag nanograin structure

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In this paper, we propose an optical model of the surface color controlled by Ag nanograin structure.

A localized surface plasmon resonance at a metal nanoparticle is well known as a color phenomenon found in metals. A forming method of Ag nanograin structure on the surface of a silver mirror by chemical conversion treatment was discovered. The surface has not only unique colors but also properties of a bulk metal. The color of the surface, initially shinny white, is changed into shinny yellow, red, and blue by controlling treatment time. A color phenomenon of Ag nanoparticles dispersion liquid, such as yellow transmittance color or blue reflectance color, is well described by the effective permittivity based on the Maxwell Garnett theory. However the colors of the Ag surface with the nanograin structure cannot be described only by the proposed theoretical concept, from the measured reflectance spectrum analysis of the colored surface. To overcome the problem, the permittivity model based on the Drude Lorentz model is adopted.

In a first step, we present the method of forming Ag nanograin structure on a surface. The Ag surface with nanograin structure was made by silver mirror reaction and the nanograin structure was grown by dipping into a solution of a sulfide. The change of color occurred on a second time scale. A silver mirror reaction itself has been used as an established method of metallized paint in industrial field. The advantages of this method are short fabrication time, flexible to general surface and low cost. In the next step, properties of the nanograion structure were analyzed by SEM (scanning electron microscopy) and XPS (X-ray photoelectron spectroscopy). The result of SEM observation of the Ag surface showed nanograin structure and varying in the grain size depending on the color. The size of the grains was from 20nm to 100nm. The grain shape almost had no change on the other hand the density of the grain decreased on the colored surface. In addition, the element analysis using XPS confirmed that the nanograin structure was composed of only Ag. These results proved that the colors of the Ag surface were mainly attributed to the grain size. Therefore, we focused on microscopic behavior of electrons in the Ag grain and the permittivity model was formulated based on Drude Lorentz theory. The model was designed on the assumption that the individual grain behaved like a metallic atom with bound electron unlike Ag. The analytical values from this proposed model were compared with the measurement values in a reflectance spectrum and a chromatic variation. The chromatic variation was calculated according to the interaction between reflectance spectrum and daylight spectrum. These results were summarized in a chromaticity diagram. As the result, the analytical values corresponded to the measurement values and the validity of the model was demonstrated.

8083-31, Session 8

New high compression method for digital hologram recorded in microscope configuration

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For an efficient storage and/or transmission of digital holograms, it is necessary to find a good representation of digital holograms using a compression technique. In order to compress holograms, several techniques, usually used for image compression, can be applied. For example, the wavelet analysis can be applied to the compression of complex-valued digital holograms of three dimensional real world objects. Moreover, lossless data compression of a three dimensional object reconstruction can be obtained by phase shift digital holography; alternatively a method of information reduction using digital composite holography in lensless Fourier transform configuration can be used. Another effective procedure exploited to compress digital holograms is numerical multiplexing, based on the combination of an high number of holograms in a single synthetic hologram. We propose a new method to compress digital holograms using a sparse matrix representation. Using digital holography to numerically manage complex wavefields, we are able to apply an adaptive mask, based on a threshold filter, to the object wavefield. From there, we store the result of this filtering by sparse representation.

We use a sequence made of about 500 digital holograms with the aim to test the proposed compression technique. It is applied on digital holograms acquired in microscope configuration.

Firstly, we reconstruct each hologram in the back focal plane of the microscope objective obtaining a complex wavefield proportional to the Fourier transform of the object beam. The object spectrum is centered around a carrier frequency whose position depends on some geometrical parameters of the experimental setup such as the angle between the reference and the object beams. Then, to compress this signal, we store only spatial frequencies that contain the largest quantity of information, and discarding the remaining ones, by means of the sparse representation method. The proposed method show that the use of the sparse representation allows for a high compression factor with minimal loss in the quality of the reconstructed image even when the compression factor is 200.

Finally, we compare the reconstructed original holograms with that processed by the compression procedure. In order to quantify the advantages of this technique, we analyze the quality of the reconstruction of the hologram varying the threshold value and we consider also the correlation coefficient between the amplitude reconstruction of the original hologram and the processed one.

The results show that this technique is a powerful means to compress a large amount of holograms. We can achieve a compression factor of about 300 times preserving a high quality reconstructed image. In fact, in this case, the correlation coefficient between the original and processed image is equal to 0.95.

8083-32, Session 8

Multi SLMs holographic display with inclined plane wave illumination

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Holography can store full wide angle information about a registered object, since during registration process information about amplitude and phase of an optical wave scattered from an object is captured. Because of this unique feature people put hope in holography as the method which can be utilized in a 3D imaging display. In the paper we present the design of a wide viewing angle display system utilizing multiple Spatial Light Modulators (SLMs). The system is capable to display objects from both virtual and real worlds. In our system we utilizing phase only reflective SLMs based on liquid crystal on silicon (LCoS). There are designed to work with normal illumination. In order

to simplify an optomechanical system of the display the SLMs are used with an inclined plane wave illumination. Therefore in the paper at first we focus on determination of a tilt depended SLM calibration, so that SLM even with highly off axis inclined illumination is capable of an accurate wave reproduction. Then we focus on obtaining high quality reconstruction of objects from virtual world. We introduce an algorithm for hologram generation, so that they can be reconstructed in multi SLM display system. The introduced algorithm is based on Gerchberg-Saxton scheme and diffraction computing between tilted and parallel planes. All of the paper discussions are accompanied with experimental results obtained in the multi SLMs display.

8083-33, Session 8

An autometed method for increasing the numerical aperture of a IR digital holography recording system

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In the last decades, also in holography traditional films were replaced by digital imaging cameras. The object wave field is then reconstructed numerically, by means of Digital Holography (DH).

In DH the film recording material of analog holography is replaced by an electronic matrix detector. Together with the many advantages typical of any digital camera, like to developing time etc, or specific for the holographic technique, like plane of focus adjustment, amplitude and phase images computation from a single hologram, aberrations correction, and more, the change in the recording device implies some drawbacks as well. The size of matrix detectors' pixels, compared to what achievable with films, restricts the field of view, and the limited number of pixels in sensor's matrixes bounds the resolution in the reconstructed holographic image.

Holograms in the visible range are mainly acquired with charged coupled devices (CCD) or complementary metal-oxide semiconductor (CMOS) cameras. Their dimension is generally no larger of some MByte. In the IR range this limit is much higher since the sensor size in generally less than 1 MByte.

In the study reported in this paper we managed to increase the synthetic aperture of our system by scanning the larger aerial hologram (the interference light field of the object and reference waves in the hologram plane) with a small matrix detector and stitching together the single holograms acquired. The stitching is performed in an automatic way, based on registration of the adjacent portions of neighboring holograms. In this paper the application of an automatic registration technique based on the computation of the mutual information is proposed. We applied it to the challenging case of speckle holograms. The speckle effect is a result of the interference of many waves, having different phases, which add together to give a resultant wave whose amplitude, and therefore intensity in holograms varies in an apparently random way. Speckle holograms have therefore a very fine pattern which is very complex.

Standard stitching algorithms have severe difficulties dealing with such images.

In this paper we present some of the experimental results obtained by applying the implemented MMI-based registration algorithm to a real case. Moreover, the optoelectronic display of the stitched holograms, by means of a phase only spatial light modulator, will be presented and the discussion on its quality in comparison with a single capture will be discussed.

8084-01, Session KS

A nuclear-free land For Kennewick Man

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In 1964 a human skeleton was discovered in the sediments of the Columbia River near Kennewick, Washington (the extreme northwest portion of the United States). Subsequently, these bones were analyzed in several scientific laboratories and dated at more than 6000 years BP. Now known as "Kennewick Man", the remains are associated with the "Clovis Period" and, indeed, a Clovis spear point was discovered imbedded in the bone of the pelvis. Equally significant were DNA results indicating the individual was of Caucasian racial origin. Consequently, this sensational archaeological discovery stimulated widespread debates concerning the populating of the Western Hemisphere: the migration routes, the eras of the waves of migration, and the peoples involved. In spite of the enormous historical and cultural significance of the Kennewick find, contemporary Native American Indian Tribes (Nez Pierce, Umatilla, Yakima, Wannapum, Colville) prevailed in the courts and were awarded the bones for a "dignified" and "sacred" reburial on the Columbia River bank at the discovery location. Whereas this reburial may have been culturally sensitive, it was both dangerous and imprudent. The internment site is only a short distance downriver from one of the most contaminated nuclear repositories in the world. The Hanford Nuclear Reservation has twelve shutdown atomic reactors that were constructed almost seventy years ago and built for the production of plutonium. The facility also encompasses five chemical-processing complexes for the extraction and refining of plutonium. During the past few decades many of the reactors, as well as their single-wall waste storage tanks and ponds, have deteriorated and have been leaking radioactive and toxic-chemical waste into the local aquifer. This contaminated ground water has been seeping ever closer to the banks of the Columbia River and the resting place of Kenewick Man and other associated (yet to be found) artifacts. Without remediative steps the toxic flow will continue past Kennewick to threaten cities such as Portland with a Chernoble-like tragedy. Consequently, a remediation program was initiated to drain the leaking tanks and ponds so that the toxic wastes could be buried elsewhere and/or transferred to more secure double-shell reservoirs. Unfortunately, hazardous substances adhere to pores and corrosion on the vessel walls after draining. This poses problems when disposing of refuse materials and hardware from the site. It has been experimentally determined that this hazardous surface contamination may be ejected by means of radiation ablation. It was concluded that this is most effectively accomplished with underwater flashlamp irradiation. In this manner the dislodged surface contamination is freed to float in the water and is then captured and concentrated by the filters of the fluid circulation systems. The final phase of the project was assistance in designing a Stonehenge-like monument to celebrate the cleanup of the Hanford Reservation and the removal of the radioactive threat to the final resting place of Kennewick Man ("The Ancient One").

8084-02, Session 1

New portable instrument for combined reflectance, time-resolved and steady-state luminescence measurements on works of art

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UV-Visible reflectance and luminescence measurements have been largely used in cultural heritage diagnostics.[1-5] In particular, over recent years, fibre optics and electronic miniaturizations have permitted to design and set-up compact portable equipments to be used in-situ as powerful non invasive investigation tools.[6] Measurements of both absorption and emission spectral features can provide basic information for the identification of organic dyes and some inorganic pigments. Sometimes, the identification is possible even when colorants are mixed, as was found, for example in purple-violet areas of the Domus Aurea's frescoes, where a mixture of Egyptian blue and a hydroxy-anthraquinone red lake was found. [3]

In in-situ UV-Visible luminescence measurements, relevant additional information for diagnostic purposes, can be provided by kinetic analysis of the luminescence decay-time, as it was demonstrated very recently using a new portable instrumentation both on painting mock-ups and on real artworks. [7] In this case, two organic dyes, indigo and orcein, were identified as colouring materials used in The Book of Kells, one of the most renowned illuminated manuscript in the world.

Starting from this evidence, within the EU-funded CHARISMA Project (Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/Restoration, FP7 Capacities - Specific Programme Integrating Activities for Research Infrastructures, n. 228330) a compact and easy-manageable combined reflectance spectrophotometer, capable to carry out time-resolved and steady-state fluorimetry measurements, has been designed and set-up. The instrument is composed of three diode lasers for steady state luminescence excitation, emitting at 375, 445 and 640 nm which are, at the moment, the smallest diode lasers available in commerce. They have dimensions of 100x40x40 mm and weigh just 250 g each. White light from a very compact deuterium-halogen lamp (175 x 110 x 44 mm) is exploited for reflectance measurements. Three pulsed diode lasers and/or LED emitting at 375, 458 and 635 nm are used as excitation sources for luminescence decay-time measurements in a scale from hundreds picosecond to few ten nanoseconds. A dedicated fibre optic system is able to transfer the three different excitations (the pulsed laser flash, the continuous laser beam, and the white light from the deuterium-halogen lamp) to the same point on a surface. Within the same system, three optical fibres for each excitation, collect the emitted/reflected light to three different detectors: a high sensitivity photocathode for decay-time, a 2048 pixel CCD for luminescence, and a 2048 pixel CCD for reflectance. The entire instrumental set-up is of very reduced dimensions and suitable for in-situ material characterization of artworks not only in museums, but also in uncomfortable conditions as for example scaffoldings for restorations and others.

The most relevant application of this new instrumental device concerns organic dye and pigment identification. Indeed, at the present state-of-the-art, the best way to achieve this goal through completely non-destructive techniques is to exploit the photophysical behaviour of coloured molecules, investigating them by both absorption and emission spectroscopic techniques. However, databases on this behaviour are necessary. Therefore, the construction of an ample database of reflectance/luminescence/lifetime features of materials used in artworks, in the past and in contemporary times, is ongoing in the lab, using standards and pictorial replicas obtained from several partners of the CHARISMA project, such as the National Gallery of London, the British Museum, and the KIK- IRPA in Bruxelles.

The integrated instrumentation and the databases will provide a significant new tool for the non-destructive and non-invasive in-situ diagnostics on cultural heritage. The system will be added for the first experimentations to the portable facilities already available within the MOLAB transnational access (Mobile Laboratory) to European researchers. MOLAB is part of the CHARISMA programme (http://www.charismaproject.eu).

References:

[1] M. Picollo, M. Bacci, A. Casini, F. Lotti, S. Porcinai, B. Radicati, L. Stefani, Fiber optics reflectance spectroscopy: a non-destructive technique for the analysis of works of art, in: Martellucci et al. (Eds.), Optical Sensors and Microsystems: New Concept, Materials, Technologies, Kluwer Academic / Plenum Publishers, New York, 2000.

[2] M. J. Melo, A. Claro, Bright Light: Microspectrofluorimetry for the Characterization of Lake Pigments and Dyes in Works of Art, Account Chem. Res. 43 (2010) 857-866.

[3] A. Romani, C. Clementi, C. Miliani, G. Favaro, Fluorescence Spectroscopy: a powerful technique for the non-invasive characterization of artworks, Account Chem. Res. 43 (2010) 837-846.

[4 A. Nevin, D. Comelli, G. Valentini, D. Anglos, A. Burnstock, S. Cather , R. Cubeddu, Time-resolved fluorescence spectroscopy and imaging of proteinaceous binders used in paintings, Anal. Bioanal. Chem. 388 (2007) 1897-1905.

[5] M. Thoury, M. Elias, J. M. Frigerio, C. Barthou, Nondestructive

Varnish Identification by Ultraviolet Fluorescence Spectroscopy, Appl. Spectr. 61 (2007) 1275-1282.

[6] C. Clementi, C. Miliani, A. Romani, U. Santamaria, F. Morresi, K. Mlynarskad and G. Favaro, In-situ fluorimetry: a powerful non-invasive diagnostic technique for natural dyes used in artefacts. Part II: Identification of orcein and indigo in Renaissance tapestries", Spectrochimica Acta A, 71 (2009) 2057-2062.

[7] A. Romani, C. Clementi, C. Miliani, B.G. Brunetti, A. Sgamellotti, G. Favaro, Portable equipment for luminescence lifetime measurements on surfaces, Applied Spectroscopy, 2008, 62, 1395

8084-03, Session 1

Visible to infrared reflectance and luminescence imaging spectroscopy of works of art

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Imaging spectroscopy, the collection of images in narrow spectral bands, has been developed for the remote sensing field. This paper presents new findings on its use to identify and map artist materials as well as to improve the visualization of preparatory sketches and paint changes. Two sets of portable hyperspectral cameras operating from the visible to the infrared have been used to collect reflectance image cubes of paintings and an illuminated manuscript. The first set operates from 417 to 973 nm (240 bands) and in the SWIR from 970 to 1650 nm (85 bands), and has been used to map and identify the primary pigments used in Picasso's Harlequin Musician (1924) (1) as well as to provide improved visibility of the extensive paint changes in Picasso's The Tragedy (1903) (2). The same cameras and processing algorithms have been used to help in the identification of the primary materials used in Giorgione's The Holy Family (1500) and Carlo Crivelli's Madonna and Child Enthroned with Donor (1470). The infrared region of the spectral data is found to not only provide useful 'spectral infrared reflectograms' but also help in identifying the artist materials that are responsible for the contrast seen in the infrared reflectrograms, thus providing a deeper understanding. The second set of cameras operating with higher sensitivity from 380 to 1000 nm (124 bands), and with an expanded range from 1000 to 2300 nm (260 bands), has been used to study Madonna and Child (1470), a painting by a follower of Filippo Lippi and Pesellino. The extended range provides improved spectral reflectograms by penetrating the malachite paint and revealing the edges of gold leaf. The high sensitivity of the visible to near infrared camera allowed acquisition of image-cubes of illuminated manuscripts at high spatial resolution with low light levels (250 lux). For example the primary pigments have been mapped in Lorenzo Monaco's Praying Prophet (1410/1413). Moreover the same instrument has been used to acquire luminescence image cubes (500 to 900 nm, 5 nm sampling) from Gustave Caillebotte's The Skiffs (1877), after exciting at 420 nm, in order to map the use of red lake pigments, These results show that portable hyperspectral cameras and analysis methods can be of great use for the study of paintings.

1) John K. Delaney, Jason G. Zeibel, Mathieu Thoury, Roy Littleton, Michael Palmer, Kathryn M. Morales, E. René de la Rie, and Ann Hoenigswald, "Visible and Infrared Imaging Spectroscopy of Picasso's Harlequin Musician: Mapping and Identification of Artist Materials in situ", Applied Spectroscopy 64, 6, 584 (2010).

2) John K. Delaney; Jason G. Zeibel; Mathieu Thoury; Roy Littleton; Kathryn M. Morales; Michael Palmer; E. René de la Rie. "Visible and infrared reflectance imaging spectroscopy of paintings: pigment mapping and improved infrared reflectography". Optics for Arts, Architecture, and Archaeology II. Proceedings of the SPIE, Volume 7391, pp. 739103-739103-8 (2009).

8084-04, Session 1

Autofocus laser system for multi-NIR scanning imaging of painting surfaces

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Multispectral imaging in the near infrared (NIR) has demonstrated to have a big potential in the analysis of paintings because the simultaneous acquisition of spectral data and high resolution images allows the nondestructive and in situ discrimination of many painting features, as well as the study of their spatial distribution in the entire artwork surface. The multispectral image dataset can be processed to extract information related to artists' materials opening the way to a more quantitative approach in the use of IR reflectography. To this aim, it is essential to have a high-quality dataset.

We present a new autofocus system for multi-NIR scanning acquisition of paintings. The scanner device is essentially made of a catoptric optics mounted on XY stages for raster imaging of the painting surface. The optics has a fixed focal length thus an autofocus system is necessary for the acquisition of curved paintings. The developed autofocus is based on a high-speed triangulation laser sensor for real-time measurement of the working distance, and on a fast precision motorized stage to adjust the position of the optics respect to the painting surface.

8084-05, Session 2

Wide-band IR imaging in the NIR-MIR-FIR regions for in-situ analysis of frescoes

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IR imaging is one of the most suitable optical techniques in the investigation of painted surfaces. Traditionally, IR reflectography, i.e. IR imaging in the NIR (Near InfraRed) band 0.8-2.5 μm, is particularly useful to detect the features of the paintings underneath the visible surface, thanks to the partial transparency of pigments in this band [1-3]. Recently, the investigation in the NIR was coupled with thermography, which works in the FIR (Far InfraRed) band 8-12 μm, in a successful integration, giving much more information [4-6]. FIR thermography was found capable to detect several structural defects in the deep structure of panel paintings and fresco models, as well as on genuine panel paintings [5-7].

Wall paintings are extremely complex artworks since they are an integral part of buildings and their conservation is strictly linked to the monument and to the complex interaction between outdoor and indoor conditions; therefore, fresco diagnostics needs to be performed in situ. Moreover, wall paintings are very heterogeneous and cover large surfaces. All the above remarks make the investigation of real frescoes very different from working on models.

In this paper we present the recent results of a joint project among the two research institutes DIMEG and CNR-INO, and the restoration facility Opificio delle Pietre Dure, concerning the wide-band integration of IR imaging techniques, in the reflection and thermal bands, for in situ analysis of artworks. First applied to the analysis of panel paintings, the integrated IR approach is now extended to the crucial investigation of frescoes. If the NIR reflection band was tipically regarded as less effective on wall paintings because of their specific technique, recently, it has become increasingly clear that even in the early Italian Renaissance painters quite frequently employed a secco techniques so as to allow the use of a broader range of pigments. The role of these investigations also on wall paintings is warmly welcome, allowing the detection of more features underneath the surface and the localization of the areas of different materials.

Previous knowledge about the joint use of NIR and FIR bands was extended to include MIR (Middle InfraRed) band 3-5 μm, so that the present work involves:

1. A complete wide-band IR imaging in the reflection and thermal bands, in a multi-modal acquisition, including dual band MIR-FIR thermography and multispectral NIR imaging;

2. Use of ad hoc software tool for easy integration of collected data, a graphical user interface with options such as image adjustment, overlaying and transparency variation.

3. Full field in situ diagnostics. Here, we report the results of the investigation of some Italian masterpieces, such as the wall painting "The Resurrection" by Piero della Francesca in Sansepolcro, and the Theodelinda Chapel by the Zavattari Family in Monza.

High resolution IR reflectography and, to a greater extent, IR imaging in the 3-5 μm band, are effectively used to characterize the superficial layer of the fresco and to analyze the stratigraphy of different pictorial layers. IR thermography in the 8-12 μm band is used to characterize the support deep structure. Data integration provides a multi-layered and multi-spectral representation of the fresco that yields a comprehensive analysis. On the whole, the use of wide-band IR imaging is a very promising tool for the nondestructive inspection of frescoes in situ and, while maintaining the traditional visual analysis, could be usefully integrated with different diagnostic techniques.

References

[1] Van Asperen de Boer, J.R.J., "Infrared Reflectography: a Method for the Examination of Paintings", Appl. Opt. 7, 1711-1714 (1968).

[2] Bertani, D., Cetica, M., Buzzegoli, E., Cecchi, S., Kunzelman, D., Poggi, P. and Piccioni, G.P., "A scanning device for infrared reflectography", Studies in Conservation 35, 113-115 (1990).

[3] Fontana, R., Bencini, D., Carcagnì, P., Greco, M., Materazzi, M., Pampaloni, E. and Pezzati, L., " Multi-spectral IR reflectography", Proc. SPIE 6618, (2007).

[4] C. Daffara, D. Ambrosini, R. Di Biase, R. Fontana, D. Paoletti, L. Pezzati, S. Rossi "Imaging data integration for painting diagnostics", Proc. SPIE 7391, 17-18 June 2009, Munich (Germany).

[5] D. Ambrosini, C. Daffara, R. Di Biase, D. Paoletti, L. Pezzati, R. Bellucci, F. Bettini "Integrated reflectography and thermography for wooden paintings diagnostics" Journal of Cultural Heritage 11, 196-204 (2010).

[6] C. Ibarra-Castanedo, S. Sfarra, D. Ambrosini, D. Paoletti, A. Bendada, X. Maldague "Infrared vision for the non-destructive assessment of panel paintings", Canadian Institute for NDE (CINDE) Journal 31, September/October 2010.

[7] C.Ibarra-Castanedo, S. Sfarra, D. Ambrosini, D. Paoletti, A.Bendada, X.Maldague "Subsurface defect characterization in artworks by quantitative pulsed phase thermography and holographic interferometry", Quantitative InfraRed Thermography Journal 5, 131-149 (2008)

8084-06, Session 2

New trends in imaging spectroscopy: application for the non-invasive study of stained glass windows

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Imaging spectroscopy (IS) extends the measurement of one-dimensional UV-Vis-NIR spectroscopy to two-dimensional domain providing material characterization and localization. The technique is gaining importance for the study of cultural heritage but its application is mainly focused on the analysis of pigments in paintings.

An IS device has been developed and then applied to the study of chromophores in glassy objects. It consists of a visible imaging spectrograph, mounted on a rotation stage, which captures monochromatic images of the sample within a wavelength range from 420 nm to 850 nm. Firstly, several tests have been conducted with laboratory samples, comparing the results acquired with the IS device with those obtained by a spectrophotometer in order to verify the validity of the measurement methodology. Then, the system has been used for the characterization and mapping of chromophores of hundreds of coloured glass tesserae of the stained glass windows from the Scrovegni Chapel of Padua, Italy. These vitreous objects are composed by different panels of approximately 75cm x 110cm (the smaller ones). Each of them is constituted by hundreds of triangular and intense coloured glass tesserae and circular and fairly coloured glass tesserae assembled with lead cames. There are also some rhombus colourless tesserae, but in most cases the glass shows some kind of coloration. The aim of the analysis was to characterize the chromophores used in order to study the technical production of these objects. When dealing with a so elevate number of glass tesserae, spot techniques are feasible but time consuming. Visible imaging technique represent a solution to map chromophores in relatively short times. Two measurement methodologies have been performed: transmission and double-transmission modes. In the first case, lamps used to illuminate the sample and the spectrograph are placed on the opposite side of the window, to acquire directly the signal transmitted from the glass. In the latter case, the lamps and the spectrograph are placed on the same side of the window, that is laid on a white scattering screen. The acquired signal comes from the light of the lamps that has been transmitted through the glass, then diffused back by the opaque white screen and finally transmitted again through the glass.

Results will be discussed comparing both modalities in terms of signal-to-noise ratio and spectral contrast. It has been observed that when measuring glass tesserae fair coloured, the double-transmission mode generally give better results considering the signal-to-noise ratio. This seem to be produced by an enhancement of fair absorptions in this modality. On the other hand, when studying glass with a stronger coloration the transmission mode appear most adequate. The IS device has captured numerous spectra in relatively short times and in a non-invasive way. The visible spectra acquired allow the clear identification of several chromophores present inside the glass matrix, e.g. Co(II), Cr(III) or Mn(III). If this technique is integrated with other non-invasive elemental technique as X-ray fluorescence (XRF) it could represent a really interesting approach. In fact, visible imaging technique can integrate the XRF elemental information: the technique is a powerful tool to identify Co(II) or to give evidence about the oxidation state of some elements as instance. According to the authors knowledge, this is the first time in which visible imaging spectroscopy technique has been applied for the study of stained glass windows. As the results show, it could represent a powerful and innovative tool for chromophores mapping of this kind of artefact, particularly when integrated with other non-invasive techniques such as X-ray fluiorescence.

8084-07, Session 2

Open issues in hyperspectral imaging for diagnostics on paintings: when high-spectral and spatial resolution turns into data redundancy

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Hyper-Spectral Imaging (HSI) has emerged in the last decade as one of the most promising technologies for diagnostics and documentation of polychrome surfaces, and it is still recognized as the latest frontier for non-invasive investigation of paintings [1,2]. As is known, this approach, that simultaneously provides spatial and spectral information of the imaged scene, is based on the sequential acquisition of quasi-monochromatic reflectographic images over an extended spectral range. The obtained data-set (the so-called file-cube) may be processed to obtain high-quality color or grey scale, at different wavelengths, images. At the same time, it is possible to extract the spectral information necessary for the identification and characterization of pictorial materials. Although presently HSI is a well-established tool applied in the cultural heritage field, a number of technological issues still require further investigation and are topics for of on-going studies. In particular, it is known that high spatial resolution is a crucial parameter for obtaining high quality images, whereas the possibility to identify pictorial materials strictly depends on the spectral sampling rate (spectral resolution) and on the extent of the spectral region investigated. At the same time, by increasing the sampling rates in both the spatial and spectral dimensions, the size of the data-set will be enlarged and the typical acquisition times will be lengthened. As a consequence, non-trivial problems of data handling, processing, and visualization will be encountered. In many cases the file-cubes acquired by imaging large surfaces need to be reduced in order to make the use of these data easier and faster. Moreover, suitable software interfaces that could respond to the requirements of the end-users still have to be developed. A good compromise between acquiring high-quality data and their actual use should always be reached taking into account the specific purposes of the HSI application. The above questions have been carefully considered in the last updated version of the hyperspectral scanner designed at IFAC-CNR for artworks digitization. The prototype, initially assembled in 2005 [3], has recently been upgraded, with new visualization software and mechanical and optical improvements.

This high performance system, based on a prism-grating-prism line-spectrograph connected to a silicon CCD camera, operates in the 400-1000nm spectral range [4]. It can provide a high spectral resolution (about 2-3 nm) with a spatial sampling of 0.1 mm over areas of about 1 m2.

In the present work, two case-studies are discussed, which highlight the importance of high spatial and high spectral sampling rate, respectively, in hyperspectral imaging. The first case focuses on a set of small-dimension (about 10cm x 12cm) paintings, dated at the beginning of the eighteenth century, which belong to the Uffizi Gallery, Florence. These paintings by Gaspare Lopez represent still-life and landscape subjects and are so finely depicted that they could be considered miniatures. In this case, HSI was applied in order to provide a faithful digital documentation, which could be used to reconstruct the whole palette of the artist. Given the finesse of details, only a very high spatially resolved image could provide such information for every point of the surface. The results obtained using the IFAC-CNR hyperspectral scanner will be shown with indication of the importance of using the full spatial data. Conversely, high-quality RGB calibrated images can be obtained even using a sub-sampling together with the spectral dimension.

The second case-study, instead, will address the exploitation of high spectral resolution properties of the imaging system. The investigated painting is the Ritratto di Maffeo Barberini, an oil-painting on canvas recently restored for the exposition Caravaggio e i caravaggeschi a Firenze (Florence, May 2009 - Jan. 2011). The painting, dated around 1596-1604, has been object of controversial attributions and only recently, after a careful examination of art-historians and conservators, has been attributed to Caravaggio. Among the different scientific techniques applied to examine the painting was also HSI, which provided results concerning the pigments used and the artistic technique. In this case, the high spectral resolution of the HSI system made it possible to identify, by a very weak signal, the presence of a red lake, which was applied by the artist with the glazing technique.

References

[1] C. Fischer, I. Kakoulli, Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications, Reviews in Conservation, n. 7, (2006), p.3-16.

[2] J. K. Delaney, J. G. Zeibel, M. Thoury, R. Littleton, M. Palmer, K. M. Morales, E. R. De La Rie, A. Hoenigswald, Visible and Infrared Imaging Spectroscopy of Picasso's Harlequin Musician: Mapping and Identification of Artist Materials in Situ - Applied Spectroscopy, Vol. 64, n. (6), (2010), p.584-594.

[3] A. Casini, M. Bacci, C. Cucci, F. Lotti, S. Porcinai, M. Picollo, B. Radicati, M. Poggesi, L. Stefani, "Fiber optic reflectance spectroscopy and hyper-spectral image spectroscopy: two integrated techniques for the study of the "Madonna dei Fusi", SPIE Conf. 5857 "Optical Methods for Arts and Archaeology", Munich 13-14 June 2005.

[4] M. Aikio, Hyperspectral prism-grating-prism imaging spectrograph, VTT Pubblications 435 - VTT Electronics ESPOO - 2001

8084-08, Session 3

Terahertz pulse imaging of stratified architectural materials for cultural heritage studies

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In recent years, Terahertz pulse imaging (TPI) has become a novel nondestructive technique for the examination of cultural heritage artifacts. It has the advantage of broadband spectral range, time-of-flight depth resolution, and penetration through optically opaque materials. Fiber-coupled portable systems have also enabled the technique to be taken out of the laboratory and into the field. At many architectural heritage sites, it has been found that decorative renovations for pragmatic, stylistic or religious purposes have resulted in the stratification of generations of architectural artwork. Each layer can provide insight into the history and culture of the people who created it. Thus, by exploiting the "optical" inhomogeneity of these structures, we can analyze terahertz pulse reflections from each interface and reconstruct multi-dimensional images of the sub-surface layers.

This work concentrates on the TPI of laboratory models of multilayer mosaics and fresco paintings, specimens extracted from a neolithic excavation site in Çatalhöyük, Turkey, and specimens measured at the medieval Église de Saint Jean Baptiste in Vif, France. Furthermore, terahertz spectroscopic studies were made of the various composite materials-including ochre pigments and lime, gypsum and clay plasters-with the intent to aid future computer simulations of the TPI of similar subjects.

Our time-domain terahertz systems consisted of an ultrafast, optically-excited, photoconductive antenna emitter and receiver pair, oriented in a reflection geometry. The terahertz beam was focused on the first surface plane-for thinly stratified objects-or, on the layer with the next largest interface reflection-for thickly stratified objects. The cross-sectional information was obtained using a scanning optical delay line which enabled the sampling of the terahertz pulse signal in time, and thus the measurement of the time-of-flight of the terahertz pulse in the Z-direction. The structures were then physically scanned en face using a motorized X-Y translation stage.

The mosaic model was produced using a variety of colored Smalti glass tiles secured to a wooden support with a grout composed of gypsum powder and animal glue. The mosaic was then divided into four sections; three of which were covered with 5-6 mm of semi-hydrated gypsum plaster, fresh lime plaster, or aged lime plaster, while the fourth remained exposed. The reflected terahertz pulses were analyzed using several imaging modes which revealed the tile pattern. However, with the exception of the gold tiles, no particular color could be determined from the data.

The fresco models were produced secco-style using white lime, black carbon and yellow ochre pigments dispersed in a lime milk binder, and painted on a dry semi-hydrated gypsum plaster support. Two nearly identical pictures were painted; one was covered by 5 mm of semi-hydrated gypsum filled with fine sand at a 1:1 ratio, while the other remained uncovered. The hidden painting was reconstructed through the analysis of the reflected pulse, while the image details were enhanced by additional spectroscopic analysis.

Çatalhöyük, Turkey is considered to be possibly the oldest excavated city in the world. The buildings on this site are believed to date as far back as 7400 BC and were used by several generations over the course of one to two centuries, thus requiring regular maintenance resulting in the accumulation of hundreds of stratigraphic layers. The compositions of the layers vary with the purpose of the applications and available materials, but are primarily composed of clay, lime and gypsum plasters, with iron oxides (ochres) used as pigments. The thicknesses of the layers vary from tens of microns to a few millimeters. We had the privilege of examining three small wall samples and more than a dozen pigment samples that had been extracted from the site.

The Église Saint Jean Baptiste in Vif, France began construction near the end of the 8th century. There were three significant and distinct decorative campaigns, occurring during the 13th, 14th and 19th centuries, respectively. During restoration activities, incidental désassemblage revealed figures from the second campaign which had been obscured by several paint and preparation layers from the 3rd campaign and beyond. Three partially exposed sections were investigated with visible indication of continuance of the paintings through the covering stratified layers. Scattering in the inhomogeneous prep layers, as well as surface nonuniformity, demand complex signal analysis for ideal extraction of images.

In conclusion, we have used terahertz pulse imaging to extract information from individual layers of stratified architecture. We have investigated four common building materials used for surfaces in historical sites, as well as decorative pigments. Our preliminary results are promising and will contribute to the computer simulation of stratified archaeological materials.

8084-09, Session 3

New methodological analytical approach of wall painting studies using LIBS

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The field of Cultural Heritage has many analytical and treatment needs, both in the field of conservation than in restoration. For these reasons optical techniques, non-destructive or microdestructive and for historical monuments characterisation are present for many years. The maturity of new optical metrology instrumentation allow now to modify the analytical approach of material studies.

For 6 years the research laboratory of historical monuments (France) works on developing LIBS (Laser Induced Breakdown Spectroscopy) portable system for in situ identification of pigments, salts, metals or other materials. This laser technique has many advantages: portability, analysis of light elements, stratigraphic analysis capability makes it an essential technique for this application. The LRMH was the first laboratory depending from the french ministry of culture to get and develop the technology and to apply it systematically in situ (Notre Dame Cathedral, Saint Savin sur Gartempe abbey...)

The first step was to design an optical set-up able to work on site. Then, a dedicated user-friendly software was built in order identify pigments [1-2]. We focus on the painting techniques identification [3] and we try now, to exploit the polymer identification capabilities by LIBS in order to reach the analysis of older restoration products. [4]

In this works, we present the new methodological approach for wall painting studies. We worked on the old rood screen of the cathedral of Nevers. Cathedral Saint-Cyr-et-Saint-Julitte of Nevers is a French Roman Catholic cathedral dedicated to Saint Cyr (Cyricus), martyr at the age of three years, in 304, and his holy mother Julitte (Julitta). She is also a French national monument, located in the city of Nevers. 19 stones that make up it's rood screen have recently been found and it became important to study the material and style It appears on the stones two sets corresponding to two periods of painting the last of which represents in particular the Virgin and his tomb. Considering the amount of stone and sets, the number of samples to be taken might be massive. Also, the analytical strategy consisted in a campaign as complete as possible by LIBS identifying the pigments of the different periods and then limiting the sample to confirm and supplement the gathered information. Then, we performed classical analytical approach on the ten samples, making cross section using classical optical and electronic microscopy with edx for element identification and using FTIR for organic determination. This study demonstrates the superior capability of using this technical approach in terms of efficiency, allowing to answer quickly to the end-user: conservator, restorer, architect...

We present in this work the results obtained and the new strategy adopted by the analytical laboratory for the study of monumental works. We show how LIBS techniques can be used as a part of global analytical methodology in order to reduce the sampling given a general overview of a monumental artwork.

[1] Bruder R, L'Hermite D, Semerok A, Salmon L, Detalle V. " Near-crater discoloration of white lead in wall paintings during laser induced breakdown spectroscopy analysis". Spectrochim. Acta Part B 62:1590-1596, (2007)

[2] Bruder R., Detalle V., Coupry C. "An example of the complementarity of laser-induced breakdown spectroscopy and Raman microscopy for wall painting pigments analysis", Journal of Raman Spectroscopy volume 38, issue 7, pp. 909 - 915, (2007)

[3] Duchêne S, Detalle V, Bruder R, Sirven JB. "Chemometrics and laser induced breakdown spectroscopy (LIBS) analyses for identication of wall paintings pigments". Curr. Anal. Chem. 6:60-65, (2010)

[4] Gregoire S, Boudinet M, Pelascini F, Surma F, Detalle V, Holl Y. "LIBS (Laser Induced Breakdown Spectroscopy) for polymer identication" submitted to the Analytical and bioanalytical Chemistry

8084-10, Session 4

Virtual restoration: detection and removal of craquelure in digitized image of old paintings

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Every day, digital image processing techniques are used in all science fields. In digital image analysis, crack-like pattern detection, better known as ridge-valley structure extraction in some literature, has been a matter of high concern among researchers, mostly for its potentially useful contribution to a variety of applications. Many old painting suffer from breaks in substrate, the paint, or varnish. These patterns are usually called craquelure and can be caused by aging, drying, and mechanical factors. Many other images contain similar patterns, such as fatigue crack in MEMS/NEMS, crack in epoxies used for underfill and encapsulation microelectronics components,etc. All these examples are current areas of research in the modeling and classification fields for which the results in this dissertation can find an application.

Image processing techniques used to detect and remove crack can be employed to inspection and/or diagnosis. Besides it can be useful for, improve her perceptiveness (legibility) of the digital images. In particularly this is true for the digital images used for didactic or multimedia applications.

An integrated methodology for the detection and removal of cracks on digitized paintings is presented in this paper. Here we focus the attention on the possibility of classification and virtual cancellation of cracks on digitized old paintings. In this way, a "virtual" restoration is performed. It can provide clues to art historians, museum curators and the general public on how the painting would look like in its initial state, i.e., without the cracks. Furthermore, it can be used as a nondestructive tool for the planning of the actual restorationA methodology to identify and to restore the present cracks on digital images is introduced in this paper. The technique consists of the following stages:

- Detection of the cracks.

- Separation of the brush strokes, which have been misidentified as cracks.

- Implementation of the crack filling procedure.

Craquelure is the pattern of cracks that develop across a painting with age. It is apparent in all older pictures and influences their appearance to greater or lesser extent. Craquelure can be a very important element in judging authenticity, use of material or environmental and physical impact because these can lead to different craquelure patterns. Although most conservation of fine artwork relies on manual inspection of deterioration signs, the ability to screen the whole collection semi-automatically is believed to be a useful contribution to preservation. It is hoped that the mass screening of craquelure patterns will help to establish a better platform for conservators to identify the cause of damage. Crack-like pattern detection, also known in some literature as ridge-valley structure extraction, has been a matter of high concern among researchers mostly for its useful contribution to a variety of applications. Cracks can be detected with the implementation of a very useful morphological filter known as the top-hat transformation. In some paintings, thin dark brush strokes exist (e.g. in hair), which have almost the same features (thickness, luminance) as cracks. Therefore, it is possible that the top-hat transform misclassifies these brush strokes as cracks. Thus, in order to avoid any undesirable alterations to original image, it is very important to separate these brush strokes from actual cracks, before the implementation of the crack filling procedure is necessary to prevent undesirable alterations to the image. Such a separation can be done on the basis of the hue and saturation values of the corresponding pixels.After identifying cracks, the next task is to restore the image using local image information to fill (interpolate) the cracks.

The correction of defective pixels can be viewed as an image reconstruction task. Within it, the pixel being repaired, as well as much of its neighboring pixels, may be defective, i.e., their values are only loosely related to the respective original values. The values at these pixels should thus be ignored by the reconstruction algorithm.

At this stage of the solution, we assume that the defects are already detected. Two approaches to image restoration of missing regions, in literature, are image inpainting and texture synthesis.

Image inpainting attempts to fill in, a defective image region, in a natural way. The pixels in the defective image are treated as missing. The algorithm iteratively solves some partial differential equations that smoothly propagate the information to the surrounding missing region preserving the gradients apparent in the boundary.

Texture synthesis algorithms are concerned with producing a large texture image from a small sample of a texture. The resulting texture image should appear to arise from the same texture to a human observer.

8084-11, Session 4

Development of a UV to IR extension to the standard colorimetry, based on a seven band modified DSLR camera to better characterize surfaces, tissues and fabrics

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In many application and industries it is enough to obtain a colorimetric measure of a surface, bounding the analysis to the visible spectrum and representing the surface reflectance through three standard colorimetric coordinates.

Until the human vision is the final target of the applications, this is all we need, due to the way the human eye weights any visible colour through the sensitivity functions of the three kinds of cone in the retina tuned around the blue, the green and the red.

At the opposite extreme we find the spectroradiometric analysis, that, giving the reflectance as a function of the wavelength, is a key technological investigation in several application where a surface has to be thoroughly characterized.

There are specialized application fields where the characterization of a surface needs to extend the analysis outside the visible spectrum. This includes, for example, all the surfaces that appear of black color to a visual inspection but reveals significant differences when “seen” in the UV or IR.

Generally speaking, leading an UV to IR analysis we expect to find at least two kind of results. The first one, as already mentioned, is the possibility to reveal differences among surfaces, materials and textures, otherwise indistinguishable to the human eye. The second one is the possibility to reveal inner structures usually hidden by the external surface. This is the case, for example, of some ancient painting where external pigments become more transparent to the infrared light, unveiling antecedent paintings or, more often, early drawings to guide the completion of the final one. As another example, in dermatology UV reflectance is more related to the very surface of the skin while IR are able to explore structures more in deep.

Furthermore, using selectively the illumination band and the acquisition band it is possible to explore florescence in the UV and IR.

The use of spectroradiometric measures is without doubt the most precise method to characterize a sample and it is, where practically and economically viable, the procedure to prefer. However, the high spectral precision given by this analysis could conflict with some technical and practical issue that makes its use limited, complex or expensive.

For instance, to acquire reflectance data with a high degree of spatial resolution of a flat surface (for example a painting), requires a linear scan (scanning of the area line by line), then a long time, the use of expensive equipment and the management of high volume of data. On the other hand, if the sample to analyze is not flat, the technology and therefore the cost, increases even more.

Another way to proceed is to use an optical fiber based probe, part of them connected to the light source and part bringing the reflectance signal to the spectroradiometer. This is a cheaper solution, provided that the required spatial resolution is quite coarse.

Last consideration is that in both of the above cases the acquisition of the data is not instantaneous: separate pieces of the sample are measured at different time. This could be a problem, especially when the sample under analysis is of organic nature that changes (or moves) in the time.

Moving from Nature and the way natural selection has shaped and optimized a way to distinguish colors without recording detailed spectra, we propose a similar approach to deal with broaden UV to IR range of wavelengths. The standard Colorimetry (developed by CIE organization) is based on the human physiology and weights every spectra with three standard sensitivity functions, the so called Color Matching Functions (CMF). The shape of these functions is derived from the shape of the human eye cones sensitivity, after a mathematical transformation based on practical considerations.

We found that most of the color digital cameras make use of a so called Color Filter Array (CFA) and each single pixel is specialized by a red, green or blue filter to become sensitive to a specific portion of the visible light. The sensitivity function of a digital CFA based camera show a shape that remember the CMF functions.

In this way the light spectrum captured by a color camera is already transformed into a three component array (Red, Green and Blue level) that could be easily converted to the XYZ standard colorimetric coordinates through a 3x3 conversion matrix or a look up table (according to the International Color Consortium format).

In taking into account a wider spectrum, UV to IR, we propose a sort of Hypercolorimetry based on 7 Hypercolor Matching Functions (HMF) suitable to weight every spectra in the range of 300 to 1000nm, that will be characterized by 7 hypercolor coordinates.

In absence of a physiological (natural) reference, we identified the shapes of the HMF optimized to give the best identification and discrimination of single near-monochromatic (narrow-band) components. As a results every spectra in the range of 300-1000nm will be evenly weighted and characterized by 7 values.

One of our concerns has been to preserve a bidirectional conversion between standard Colorimetry and the proposed Hypercolorimetry, to let them to be comparable in the range of visible light (400-700nm). So we developed the mathematics needed to change the XYZ colorimetric coordinates into H2, H3, H4 (out of H1 to H7) and vice-versa.

The proposed approach to characterize a wide (300-1000nm) spectrum gives the advantage to be able to characterize the spectral response of a sample (a surface or a 3D object) at the full resolution of the DSLR camera, just in a few shots. The total number of shots to obtain a 7 band image is 5: one in the UV range (300-400nm), one in the visible range (400-700nm) that is segmented by the CFA respectively in the Blue, Green and Red ranges, and three in the IR range (700-800nm, 800-900nm and 900-1000nm). Each shot requires either a bandpass filter or a narrow-band illumination.

This approach doesn’t require special equipment and devices, and allow a quite good characterization of a surface at the cost of a modified camera, a bank of bandpass filters and some software to decode the RAW data coming from the digital camera and transform the data into Hypercolorimetric coordinates.

At the same cost it is possible to easily conduct fluorescence analysis.

8084-12, Session 4

Determination of the complex optical index of red pigments, vermillon and minium

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The non destructive analysis of works of art and more specificaly the paintings with the aim of a non ambiguous identification of their components and the understanding of the techniques of the artists still remains a challenge. The aim of our research is to elaborate a purely optical way for this identification, based on the exlusive use of the intrinsic characteristic optical parameters (spectral complex optical index) of the components, instead the derived parameters presently commonly used, depending on several other parameters (morphology, environment...).

The identification of pigments is usually made by comparison with a reference database of reflectance spectra or at least by K/S, ratio of the absorption coefficient, K, to the diffusion coefficient, S. This model is widely used in industry and is penetrating the domain of the analysis of works of art and cultural heritage. K/S is calculated by using the Radiative Transfer Equation, RTE, solved within the 2-flux approximation (Kunbelka-Munk theory). Its domain of validity is limited (strongly scattering media, hemespherical lightning and detection...). Moreover, K/S depends on the size and shape of the pigments in addition to the optical index of the matrix and pigments. This method is therefore unsuitable for an unambiguous analysis of the paintings and has been often criticized.

The alternative approach we propose is based on the resolution of the RTE using the 4-Flux approximation, combined with the Mie theory, allowing the identification of the pigments via the spectrum of their complex optical index entered in the model via a data bank. The key point of this approach is the index data bank. We report in this communication on this crucial step of the method : the determination of the intrinsic optical index of pigments under the form of grains of micrometric size. This step is non trivial and presents a lot of difficulties which are not completely solved. It is one of the reasons why a more rigourous analysis of the paintings has not been up to now developed.

We illustrate this problem with two red pigments: vermillion and minium randomly dispersed at low concentration in a transparent polymer. The morphology of the sample is well characterized (thickness, concentration, size and dispersion of the pigments, surface roughness) as well as the index of the matrix. We use the same approach and model as presented above, applied this time to the calculation of the complex index of the pigments. The model is supposed to account for the diffuse and the specular flux measured on our samples by spectrophotometry with an integrating sphere in the visible spectral range 400-800 nm. This resolution allows to determine independently the coefficients of scattering and absorption of the pigment which are finally related to the complex index of refraction via the Mie Theory.

8084-13, Session 4

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No abstract available

8084-23, Poster Session

A small-dimension portable instrument for in-situ multispectral imaging

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Both conservation and reproduction of artworks take advantage of the spectral imaging technology, based on the spatial measurement of their spectral reflectance factor. This non-invasive method gives fundamental information on paintings and written documents. The measurement is usually made by illuminating the observed object with a proper light source and detecting the reflected light by spectrometric cameras or scanners. Different instruments are presently in use in which either the light reflected by the observed area passes through different filtering elements, or the light reflected by a stripe of the object is dispersed in wavelength through a proper optical device. In the first case either a tunable filter or a rotating wheel for filter changing is used with the risk of mechanical vibrations and low tuning speed. In the second case the instrument is moved, with respect to the artwork, for analyzing different stripes of the observed object which prevents real-time imaging and besides the whole apparatus is not very compact and really portable.

This work proposes the design of a miniaturized spectrophotometric scanner. A transport lens is inserted between the objective lens and the image sensor. This lens is shifted in the direction orthogonal to its optical axis and this movement shifts the image transported on the image-sensor plane. In such a way the image is scanned. A spatial filtering of the light is obtained through a spatially variable narrow-band transmission filter, positioned on the image plane in front of the image sensor (e.g. a CCD detector). The collection of the filtered images corresponding to different shifts of the transport lens, subdivided in monochromatic strips, after a wavelength ordering, allows to measure the spectral reflectance factor and/or the spectral radiance of the objects of a scene. A reflex system, inserted between the objective lens and the transport lens allows a visual view of the scene and an accurate image framing.

The spatially variable narrow-band transmission filter, developed for remote sensing in space, shows a transmission band which central wavelength is continuously displaced over the filter surface on a distance of few millimeters. To fabricate such device, an optical coating is deposited on a glass substrate to be combined with the CCD. The coating thickness is wedged along one direction of the filter surface, by positioning a moving mask inside the deposition system. The use of such filter allows the reduction of the instrument dimension that is useful for in-situ artwork analysis.

8084-24, Poster Session

Colour measurements of surfaces to evaluate the restoration materials

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In this paper two case studies on the application of colour measurements for the evaluation of some restoration materials are discussed. The materials related to the research are: water colours employed in restoration of wall paintings and preservative/consolidants for wood artefacts. The choice of these products has been due to their wide use in cultural heritage but at the same time to the poor knowledge of their behaviour concerning relative humidity (RH) variations and sunlight exposure. Moreover, especially as it regards wood artefacts, there is a wide requirement from restorers for new and more stable consolidants with low toxicity and harmless for the environment.

Water colours are widely used during the final retouching of wall paintings due to their water solubility. But wall paintings are often located inside buildings with high and fluctuating RH levels that can cause water colour solubilisation and - as a consequence - the “staining” of the restored surfaces. As water colour binder is soluble in water and aqueous media, RH values could be decisive for their use or not in wall paintings retouching.

For these reasons, commercial water colours, supplied by Maimeri, Windsor&Newton and Talens have been tested. Colour measurements have been performed by means of a reflectance spectrophotometer (RS) before and after accelerated ageing of water colours in a 92% RH environment. Moreover, colour measurements have been carried out also on water colour samples aged in a SolarBox chamber.

Before the ageing tests, water colours have been analysed by means of FTIR and EDXRFS.

The experimental results show that water colours based on natural earths and artificial ultramarine undergo the main colour changes, expressed as L*, a* and b* variations and total colour difference (ΔE^*). In the other cases colour differences depend on both water colour typology and suppliers.

The other example of colour monitoring concerns the evaluation of colour change due to surface treatment of wooden samples. In fact, as demonstrated in many literature papers, colour change method is the most sensitive to determine the extent of photodegradation of consolidated wood exposed to ultraviolet and visible radiation, although other indicators such as strength loss and weight changes can also be used.

Poplar (Populus spp.) and Chestnut (Castanea sativa L.) have been selected due to their widespread use in Italy for the realization of statues, furniture, doors and painted panels. The wooden samples have been treated with a novel organic preservative/consolidant product that has been tested also in a real case as comparison. The treated samples have been artificially aged in SolarBox chamber equipped with a 280 nm UV filter. Colour has been measured before and after the artificial ageing by means of a RS.

Colour has been monitored also in wood samples without preservative/consolidant treatment, during the artificial ageing in SolarBox, in order to evaluate the photodegradation of wood constituents. In fact total colour change of the treated samples depends on both wood and consolidant colour changes.

Colour changes have been determined also in the case study referred to the main door of an historical mansion in Viterbo, made of chestnut wood. At present time it is exposed to outdoor conditions. The door has been recently restored with the same product used for the experimental aged samples.

8084-25, Poster Session

Quantitative chromatic analysis of the Turin Shroud for features recognition

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The TS (Turin Shroud) is a 4.4 m x 1.1 m linen cloth that shows the image of a scourged, crowned with thorns and crucified man who many believe is Jesus Christ. This image, very particular also at a microscopic point of view, is not yet explainable by science and then not reproducible1.

Many studies on the TS have been performed2 and many results have been obtained, but the only quantitative photograph of the whole TS was presented in 20103 starting from the photograph of G. Durante made in 2002.

The TS body image is very faint1 (the measured CIE chromaticity coordinates are in the range of 0.480-0.515 for x and 0.410-0.417 for y) and the TS bloodstains show slight color differences depending on both the type and conditions of the blood soaked with the linen.

This quantitative photograph now allows color measurements with an uncertainty of about 4% and therefore permits to detect the different kinds of features represented on the TS.

This paper presents a chromatic analysis, made in reference to the ratios x/y versus x/z of the x, y, z CIE color values, in order to highlight some TS features.

In particular the area corresponding to the body image is distinguished from the different colors of the background in the relative x/y versus x/z plot even if in some areas the background has been darkened due to various ambient factors. In addition it seems that some areas of the background, around the body image, have chromatic characteristics similar to the body image; if verified, this fact will be in favor of the hypothesis that the radiation responsible of the body image formation was also reflected in areas outside the body.

The scourge marks are evidenced from other bloodstains and burnings in similar plots and the water stains with other signs are also characterized in terms of x, y, z CIE color values. For example the couple of stains in correspondence of the buttocks of the body image, that can seem similar to bloodstains (and someone interpreted as a sign of a particular torture instrument) resulted not chromatically coherent with the typical bloodstains, leading to think that these stains can be due to a different ambient factor.

This analysis confirms the hypothesized characteristics of some features of the TS and explains some other stains that up to now were of doubtful origin. In conclusion, the results obtained are in agreement with the enveloping in a linen cloth of a man tortured up to death.

References

1. G. Fanti, J.A. Botella, P. Di Lazzaro, T. Heimburger, R. Schneider, N. Svensson, “Microscopic and macroscopic characteristics of the Shroud image superficiality”, J. of Imaging Sci. Technol., 54 (4), 040201-1/8, (2010).

2. G. Fanti, R. Basso, “The Turin Shroud, Optical Research in the Past Present and Future”, Publisher Nova Science Pub Inc., 2008.

3. G. Fanti, C. Privitera, “Construction of a quantitative image of Turin Shroud for details recognition”, IWSAI Proceedings, ENEA, Frascati Italy 2010.

8084-26, Poster Session

Nanosecond and femtosecond UV lasers for varnish removal on tempera paints

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During recent years, laser radiation has been widely used to remove unwanted layers from artwork surfaces and analyse cultural heritage artifacts and materials [1,2]. In the case of painting conservation ongoing research is devoted to the use of lasers for thinning down oxidised varnish layers and over-paintings with minimal light penetration and thermal effects to the underlying paint [3-7]. Due to the sensitivity to light of the components of pictorial artworks, pigments, binders and varnishes, detailed studies have been carried out to characterize the effects of laser irradiation on those materials in order to provide a safe and efficient procedure that could improve and complement traditional conservation and restoration practices.

Most investigations on the laser removal of degraded varnish or contamination layers from paintings and polychromes have been carried out using pulses of nanosecond (ns) duration delivered by UV excimers, Q-switched Nd:YAG and Er:YAG lasers [3,4]. With these systems, non-contact etching of the unwanted superficial layers can be performed with in-depth resolution as high as 0.1 µm per pulse and lateral resolution of the order of 50 µm, allowing accurate control of the amount of removed material. The use of shorter laser pulses of picosecond (ps) and femtosecond (fs) duration has been recently introduced in this field, and investigation of the advantages offered with respect to ns pulses is underway [5-7]. Ultra-short pulses allow the minimisation of photo-thermal and photo-mechanical effects, the possibility of processing even nominally transparent substrates and the optimization of morphological aspects (to avoid melting, bubbling, crack formation, etc.). Although, ultra-short lasers overcome several of the limitations of the existing laser cleaning methodologies based on ns or longer pulses, more research is necessary to assess their potentialities in painting conservation. More specifically, initial studies on tempera paints using pulses of 120 fs at 795 nm [5], have shown that a high degree of control may be achieved in comparison to using ns pulses at 248 nm [3]. Complementary investigations on tempera paints using ps and ns pulses in the UV and IR have revealed the importance of laser wavelength during laser-paintings interaction [4,7].

In this study, model shellac varnished egg-yolk paints uncoloured and coloured with vermillion, lead chromate, lead white and azurite were investigated by using two laser cleaning approaches for varnish removal based in ablation by UV laser pulses of fs and ns duration. Physical and chemical effects induced by laser irradiation on the varnish layer and on the underlying temperas were examined following a spectroanalytical approach based in the use of optical microscopy, colorimetry and laser induced fluorescence. In a multipulse approach with pulses of fs duration at 398 and 265 nm it was found that the varnish layer either is removed at fluences that exceed the damage threshold of the underlying paint (at 398 nm) or experiences irreversible modifications of the initially smooth superficial texture in the form of a laser generated foam that reduces its transparency (at 265 nm). Together with this unacceptable varnish degradation, the underlying paint layers undergo colour changes, in various extents depending on the nature of the pigment, that are interpreted as due to chemical degradation caused by exposure to the transmitted laser light. On the contrary, irradiation with pulses of 15 ns at the highly absorbed wavelength of 213 nm, allows the controlled pulse-by-pulse micrometric layer removal of the varnish and preserves the colorimetric and spectral properties of the underlying paints. Similar outcome is foreseen for painting varnishes based on dammar and mastic resins, due to the similarity of their absorption spectra to that of shellac. These results and the increasing availability and compactness of Q-switched Nd:YAG lasers providing frequency multiplied output, envisages good prospects for this laser cleaning approach in the field of painting conservation.

References:

[1] M. Castillejo, P. Moreno, M. Oujja, R. Radvan, J. Ruiz (Eds.), Proceedings of the 7th International Conference of Lasers in the Conservation of Artworks, CRC Press, London, 2008.

[2] P. Pouli, A. Selimis, S. Georgiou, C. Fotakis, Accounts of Chemical Research, 43, 771 (2010).

[3] M. Castillejo, M. Martin, M. Oujja, D. Silva, R. Torres, A. Manousaki, V. Zafiropulos, O. F. Van den Brink, R. M. A. Heeren, R. Teule, A. Silva, H. Gouveia, Anal. Chem. 74, 4662 (2002).

[4] M. Castillejo, M. Martín, M. Oujja, E. Rebollar, C. Domingo, J. V. García-Ramos, S. Sánchez-Cortés, J. Cult. Herit., 4, 243 (2003).

[5] S. Gaspard, M. Oujja, P. Moreno, C. Méndez, A. García, C. Domingo, M. Castillejo, Appl. Surf. Sci. 255, 2675 (2008).

[6] P. Pouli, I. A. Paun, G. Bounos, S. Georgiou, C. Fotakis, Appl. Surf. Sci. 254, 6875 (2008).

[7] M. Oujja, P. Pouli, C. Fotakis, C. Domingo, M. Castillejo, Appl. Spectrosc. 64, 528 (2010).

8084-27, Poster Session

Importance of integrated results of different non-destructive techniques in order to evaluate defects in panel paintings: the contribution of infrared, optical and ultrasonic techniques

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In recent decades, there has been a world-wide growth of interest in cultural heritage protection. The increasing deterioration of panel paintings can be due to physical processes that take place during exhibition or transit, or as a result of temperature and humidity fluctuations within a building, church or museum. In response to environmental alterations (temperature and humidity), a panel painting can expand or contract and a new equilibrium state is eventually reached. These adjustments though, are usually accompanied by a change in shape in order to accommodate to the new conditions. Hence, the dynamical equilibrium of the painting structure may be continually changing as the panel adapts to environmental changes. Painted wooden artworks can be considered as a class of composite structures of multiple layers; consequently, they react structurally as composite objects. A holographic method for detecting detached regions between the priming layers and the underlying wood support in panel paintings is described. In this work, Holographic Interferometry (HI) has been applied in the Double Exposure (DE) configuration. In DE HI, two holograms of the object waves occurring sequentially in time are recorded on a single photographic plate. The interference between these images produces interference fringes overlaid on the image of the object. This method was found extremely useful in the detection of surface and subsurface cracks (besides defects inherent the wooden support), some of which are confirmed by Thermographic Signal Reconstruction (TSR) technique. In fact, two of the surface cracks can be observed by extracting the first time and second time derivative images from the raw thermographic data. In this case, the specimen was investigated working on the maximum camera's frame rate (30 Hz). Lower frame rates were also investigated in order to confirm the existence of internal hidden defects in deeper layers of the painting, although no defect was detected. Furthermore some testing was performed in the rear side of the sample with similar results. In addition, Pulsed Phase Thermography (PPT) identified with greater contrast two artificial defects in Mylar, simulating detached regions, confirming the results obtained by HI. PPT is a practical way to analyse data obtained from a Pulsed Thermography (PT) experiment. A short pulse of energy is applied to the surface of the specimen to be analyzed using lamps or powerful photographic flashes. The temperature evolution of the surface is recorded using an infrared camera (IR). Phasegrams at f = 56 mHz provided a good experimental results. Traditional contact ultrasounds applications, have been widely used in the evaluation of the wood quality in several characterization procedures. In our case, inspecting the specimen from the front side, i.e. with the waves propagating perpendicularly to the fiber direction, was used for the identification of the Mylar inserts. Experimental results derived by the application of the integrated methods on an Italian panel painting reproduction, called The Angel specimen, are presented. The Angel, consists of a 20 x 25 x 2 cm panel of poplar wood. The great advantages that these techniques can offer to the conservation and restoration of artworks are emphasized.

8084-28, Poster Session

A new method to certificate the lithography authenticity: hylemetry versus biometry

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The main problem when we buy an artwork object consists in getting a certificate of authenticity, in particular for the artwork bought through a seller and not at first hand from artist. There is a tremendous abuse in the "certificate of authenticity" business, because unless a certificate of authenticity originates from and is signed by either the artist, the publisher of the art (in the case of limited editions), a confirmed dealer or agent of the artist (not a third party or reseller), or an acknowledged expert on the artist, that certificate is pretty much meaningless. A legitimate one must contain specific details about the artwork such as when and how it was produced, the names of people or companies involved in its production, dimensions, and the names of reference books or similar resources that contain either specific or related information about either that work of art and/or the artist. It should also state the qualifications and full contact information of the individual or entity that authored the certificate, and include his or her complete and current contact information.

Unfortunately, often these certificates are exchanges between similar artworks: the same document is supplied by the seller to certificate the originality. In this way the buyer will have a copy of an original certificate to attest that the "not original artwork" is an original one.

Certificates of authenticity are often problematic; many are just worthless. Unfortunately, most people believe that art with a certificate is automatically genuine, but that's not even close to truth. It happens because no law govern who is or is not qualified to write certificates of authenticity, or what types of statement, information or documentation a certificate of authenticity must include. In other words, anyone can write a certificate whether they are qualified or not. As if that is not bad enough, unscrupulous sellers forge official looking certificates of authenticity and use them to either sell outright fakes or to misrepresent existing works of art as being more important or valuable than they actually are. A possible fraud can be put the following way into effect. An art merchant, starting from an original lithography and its certificate of authenticity, duplicates both the lithography and the certificate of originality.

A solution for this problem would be to insert a system that links together the certificate and a specific artwork. In this way the exchange will not be possible and the buyer will be able to verify the originality by himself. To do this it is necessary, for a single artwork, to find unique, unrepeatable, and unchangeable characteristics. If these characteristics are present, we have the possibility to identify the artwork and to distinguish it from the other.

Currently, this procedure is used by biometrics authentication systems. Biometric identification relies on physical characteristics that are unique to each person to ascertain the identification of an individual. The most commonly known method of biometric identification is fingerprint, DNA iris scans, hand geometry, facial feature, and voice.

The term Biometrics derives from two Greek words: βιος that means "life" and μετρον "measurement"; so it is possible to literally translate the word as "life measurement".

Since the biometric identification has given excellent results, it comes spontaneous to apply similar criterions for unique identification of "nonliving matters", as for instance the artworks.

Obviously the identification will be possible if, for a specific work of art, we can choose, as for the biometrics systems, unique characteristics, unrepeatable and unchangeable ones. In other words, if for an object we are skilled to find unique characteristics and not repeatable ones we have the possibility to implement a system of recognition similar to the biometric one. As for biometric authentication, it is possible to coin a new word to identify this new method of authentication of nonliving matters. As for Aristotle the term λη (hyle) means nonliving matters, the hylemetrics authentication may identify the procedure for the identification of an inanimate object.

In theory, every casual and non-reproducible characteristic could be used in hylemetrics identification.

The proposed solution, based on lithography certification, uses the color spots distribution, which compose the lithography itself, as hylemetric characteristic. This distribution, even if referred to a very small part of a lithography, differs from a copy to another one, because the lithographic technique transfers on the paper the roughness of the stone used as matrix. Due to the necessity of changing colors on the matrix stone at any impression, the color spots distribution varies from a copy to another one randomly.

It is possible digitally acquiring at high resolution, an image of a portion of this distribution. This acquired distribution image is enciphered using an asymmetric algorithm, after have been opportunely segmented using digital image processing. The encoded solution is based on

asymmetric encryption, with a private key given with the certificate and a public one, known only to the certificate originator.

Due to the high resolution acquisition media available today, it is possible using analysis method typical of speckle metrology. In particular, in verification phase it is only necessary acquiring the same portion of lithography, extracting the verification information, using the private key to obtain the same information from the certificate and confronting the two information using a comparison threshold. Due to the possible rotation and translation it is applied image correlation solutions, used in speckle metrology, to determine translation and rotation error and correct allow to verifying extracted and acquired images in the best situation, for granting correct originality verification. In this article are reported the motivation for selecting color spots as hylemetric characteristic, and the selected encipher solution applied at the color spots distribution image. Than the verification phase is detailed, showing the possibility to identifying original lithography also in case of verification area acquisition errors, such as translation and/or rotation. An example based on an original lithography is also reported.

8084-30, Poster Session

Laser cleaning investigation to remove biological crust on stone

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Lasers have been shown to be a promising alternative to more conventional cleaning techniques for certain applications. In fact laser cleaning of stone is a well established technique in the field of cultural heritage because it provides a fine and selective removal of superficial deposits and encrustations. Architectural stones exposed to environmental pollutants and an array of past conservation treatments, including the application of consolidants, often exhibit a condition where a hard crust of dirt and contamination is well adhered to the fragile stone and protecting patina. In certain critical cases, traditional techniques of microsand blasting, chemical poultices and water washing have all failed to protect the fragile surface. In a number of laboratory and on-site conservation projects, the laser based cleaning procedure has yielded very satisfactory results overcoming some of the disadvantages of traditional techniques. In particular it has been shown that irradiation at 1064 nm using nanosecond (ns) pulses efficiently removes black encrustation but unpleasing yellowing effects often accompanies the cleaning process. To correct and/or prevent such undesired coloration, several alternatives have been proposed including the use of IR and UV radiation, both in sequential and synchronous mode [1], and the use of laser pulses of different duration,in the range of ns-μs [2].

When biodeterioration films are present in the stone crust to be cleaned, the laser approach has different peculiarities, and in fact removal of biological crust on stone using lasers has received less attention [3]. A physical parametrization, associated with a detailed petrographic and mineralogic diagnosis of the induced effects, allows deriving the irradiation thresholds for damage phenomena and understating the nature of these effects.

In this work, stone samples from Redueña quarry front, Madrid (Spain) and from Segovia Cathedral (Spain) presenting different types of biological crusts were investigated in order to find the conditions for efficient laser treatment ensuring preservation of the lithic substrate. The samples presented superficial areas colonized by lichens, epilithic thalli and crustose lichen, such as Diploicia canescens, and Verrucaria sp., fungi and cyanobacteria which were selected for laser treatment. Lichens are a symbiotic association of a fungus with a photosynthetic partner, usually a green alga or a cyanobacterium. In many lichens, the fungus presents thick polysaccharide cell walls and may produce secondary compounds not found in other organisms. Also melanized slow growing fungi are common colonizers of these types of stone. Particularly, in one of the Redueña samples, part of the external surface was removed to allow the endolithic colonization by cyanobacteria to be exposed for laser irradiation tests.

A comparative study was carried out on the mentioned samples with infrared and ultraviolet nanosecond laser pulses using the fundamental (1064 nm) and 3rd harmonic (355 nm) output of a Q-switched Nd:YAG laser system (pulse duration 5 ns, repetition rate 1-10 Hz).

A number of surface analytical techniques were employed to detect chemical and morphological changes on the irradiated surfaces. Stereomicroscopy, light and fluorescence microscopy were applied to detect morphological and metabolic changes using specific fluorescence stains, such as DAPI (4’,6-diamidino-2-phenylindole). Scanning electron microscopy (SEM) in secondary electron mode (SE) served to analyze the stone samples with biological surface colonization, while the cross sample sections were observed by SEM with backscattered electron imaging (BSE). Microprobe analysis was carried out using energy dispersive spectroscopy (EDS) during SEM observation. Micro-Raman spectroscopy was employed to detect possible structural and chemical changes on the irradiated areas.

For the Segovia stone samples, the optimal cleaning conditions of the mixed colonization composed by lichen and fungi were obtained for irradiation at 355 nm. However, UV irradiation resulted in an inhomogeneous removal of the crustose lichen (D. canescens and Verrucaria sp.). On the other hand, the fundamental wavelength of 1064 nm appeared more efficient to partially remove the upper thallus cortex of lichens and in this case the algae partner becomes exposed. For Redueña stone samples, the exposed endolithic cyanobacteria could also be better removed using 355 nm. However, for removal of Verrucaria sp. crusts (the most important crustose lichen observed in these samples), the IR wavelength was found more adequate.

References

[1] Pouli, P.; Fotakis, C.; Hermosin, B.; Saiz-Jimenez, C.; Domingo, C.; Oujja, M.; Castillejo, M. “The laser-induced discoloration of stonework; a comparative study on its origins and remedies”, Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy 71 (2008) 932-945.

[2] Siano, S.; Salimbeni, R. “Advances in laser cleaning of artwork and objects of historical interest: the optimized pulse duration approach”, Accounts of Chemical Research 43 (2010) 739-750.

[3] De Cruz, A.; Wolbarsht, M.L.; Andreotti, A.; Colombini, M. P.; Pinna, D.; Culberson, C. F. “Investigation of the Er:YAG laser at 2.94 μm to remove lichens growing on stone”, Studies in Conservation 54 (2009) 268-277.

8084-31, Poster Session

Hand-held 3D sensor for documentation of archaeological excavations

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The preservation of archaeological traces concerning the history of earth is a sophisticated procedure. High qualification of the researchers and adequate equipment are necessary, and long duration of the preservation procedure must to be approved. With support of 3D digitization of archaeological finds a complete reconstruction of the dig may be produced and the working time at the sites may be considerably reduced. The typical partial destruction of the site by the archaeological works themselves and subsequent weather influences do not destroy the information of the dig anymore.

Additionally, more information can be obtained in contrast to documentation only by photographs which are taken naturally, too.

A hand held sensor based on fringe projection technique was developed at our institute in order to support the work at archaeological excavations. The sensor is a mobile hand held battery powered device with a laptop as control unit.

The sensor consists of a fringe projector and two measuring cameras. The measuring field covers a field of 175 mm x 240 mm in lateral direction and about 160 mm in depth. The measuring distance is approximately 400 mm. The core time for data acquisition is 0.2s and the measuring result of a 3D point cloud is obtained after a few seconds. Errors due to movements of the sensor are detected.

The sensor was used at archaeological excavations of rock layers from Triassic near Jena. Impressions in the rock consisting of sandstone and clay were captured by the sensor and stored in a database. The 3D property of the data allows a further matching of the single datasets. So an area of some square meters could be inspected and digitally preserved. The digitized traces were analyzed concerning shape and depth. Especially the depth of the traces which cannot be recognized using only photographs could be measured accurately.

8084-32, Poster Session

Assessment of the underlying structures in paintings with LCI and multispectral imaging techniques

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Scientific 3D surface reconstruction techniques are important to study the state of artworks and useful in their conservation process. Amongst others, two of the most innovative and non-invasive methods for evaluating the texture and the 3D structure of paintings are Multispectral Imaging and Low Coherence Interferometry (LCI) techniques, the combination of which is here proposed for diagnostic analysis on paintings.

Studies for a painting's material identification and analysis of the state of conservation are mainly based upon techniques that examine paintings as two dimensional objects, neglecting the depth information. 3D surface methods on the other hand are currently mainly intended to give quantitative information about the discontinuities on the surface layer. A painting, however, is generally a multilayer structure, where several materials (i.e. ground, paints, varnishes) are placed one on top of the other. Combining LCI and Multispectral Imaging we aimed at assessing also the underlying layers of a painting, analyses that are relevant for a correct planning and evaluation of the restoration process. Multispectral image analysis and in depth 3D surveying with LCI techniques can be used for pigment identification, precise color measurement, characterization and rendering, and also for the measurement of the paint-layers roughness.

Multispectral Imaging technique focuses on a system that acquires and processes images in the UV, visible and IR parts of the electromagnetic spectrum. It is a non-invasive methodology which exploits the fact that each material reflects and absorbs, reemitting radiation according to its molecular composition and shape. Multispectral images are acquired with frame cameras or scanning devices mounting on single or linear array sensors that are generally coupled with interferential filters or diffraction gratings. A series of multispectral images are generally acquired, one for each transmission bandwidth of the employed filters, in this way it allows to recover specific information on the painting for each wavelength used.

LCI is the optical technique on which the Optical Coherence Tomography (OCT) works on. OCT has been initially used for medical imaging analysis and subsequently entered the artworks diagnostic field to monitor, with non-invasive examinations, the conservation state of artworks. The principle on which it works is that light passes through the first layer of varnish, penetrates to some extent the underlying layers and is than reflected towards the detector. LCI acquires and processes optical signals determining the distances from the scattering surface of an object that moderately absorbs or reflects light and hence recovers high quality 3D images. With this technique it is then possible to measure the distance that light travels from the source to the reflecting surfaces and the 3D structure of the painting layers may be recovered. Basically, it is a Michelson's interferometer with superluminescent diode (SLED) in the near IR as light source that, because of its characteristic high spatial and low temporal coherence, resolves phase ambiguity, thus making it possible to measure surface topography up to the millimetric range, with depth resolution reaching 1 μm. Surface reconstruction made by LCI provides high resolution 3D data of an object: the accuracy required by restorers for the conservation treatment is of the order of tens of microns and the LCI technique fulfills this requirement.

The combination of 3D data recovered with the LCI working in the near IR region with the IR part of the multispectral images helps to quantify the extension of retouches and their cohesion, which is an information of crucial importance for conservation. The IR radiation may also allow to inspect and reveal the hidden drawings laying underneath the first paint layers. We present and compare results obtained by painting's analysis for pigment identification of paint layers and stratigraphy of oil paintings.

8084-33, Poster Session

"IRIS": a novel spectral imaging system for the analysis of cultural heritage objects

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A new portable spectral imaging system has been developed capable of acquiring images, of high resolution (2MPixels), ranging from 380 nm up to 950 nm. The system consists of a digital color CCD camera, 15 interference filters covering all the sensitivity range of the detector and a robust filter changing system. The acquisition software has been completely developed in "LabView" programming language allowing easy understanding and modification by non-programming scientists. The system has been tested and evaluated on a series of objects of Cultural Heritage value including paintings, encrusted stonework, ceramics etc. This paper aims to present the system as well as its application and advantages in the analysis of artworks with emphasis on the detailed compositional and structural information of layered surfaces based on reflection & fluorescence spectroscopy. Specific examples will be presented and discussed on the basis of system improvements.

8084-34, Poster Session

3D reconstruction of monumental surfaces by LCI and micro-photogrammetry

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Two 3D modeling techniques for the reconstruction of monumental surfaces for documentation, preservation and conservation of Cultural Heritage assets are presented: Low Coherence Inteferometry (LCI) and micro-photogrammetry. Both the proposed techniques are non-invasive, portable and they may represent a new tool for the monitoring of the conservation state and the effects of the restoration's work

LCI is the base of several widely used techniques: the Optical Coherence Tomography (OCT), which works on this principle, was basically used for medical applications and subsequently was applied to different fields where it is used to produce high quality 3D images by acquiring and processing optical signals, nowadays has entered the artworks field. In fact, the use of partially coherent light interferometry, as LCI is also known, for contactless 3D measurements of artworks is becoming of interest in the art diagnostics community, alongside to the micro- photogrammetry technique because of their non-invasive characteristic.

The principle of the LCI scanning system consists in processing the information carried by the light back scattered from the discontinuities of the structure of the studied object to achieve the three-dimensional image, i.e. the spatial construction of the object. LCI studies the light wave's properties, in this way we determine the distance of the scattered light from an object that partly absorbs light or reflects it completely. The interferometer's configuration is a Michelson's type, in which the light beam probes the object perpendicularly to its surface thus scattering and allowing for the position to be recovered from the interference-fringes. The system uses a superluminescent diode (SLED) as light source, a near infra-red (IR) broadband light source working at λ=830 nm, free of the phase-ambiguity, thus making it possible to measure the surface topography up to a millimetric scale range.

Our team realized an optical set-up of the interferometer, now a laboratory prototype, which features 1 μm in depth resolution at a central wavelength of λ=830 nm. The results are imaged on a bi-dimensional CMOS sensor and the spatial resolution depends on the different objectives used for different resolution needs and are of the order of tens of μm/pixel. Image analysis is carried out with a real-time processing software and because of the portability of the device, it is appropriate for use beyond the laboratory for in situ measurements.

Digital photogrammetry is a modern image-based and 3D rendering

technology obtaining metric information of objects from their photographic images. The principal application of photogrammetry is the production of topographic maps, but now is currently in use in the field of Cultural Heritage, for the conservation and documentation of monumental buildings, historical objects, and architectural surfaces. To investigate small size of surfaces with high accuracy a new tool based on principle of photogrammetry has been developed and it has been called micro-photogrammetry.

Micro-photogrammetry technique can generate a 3D model of a surface acquiring a sequence of three images by a common digital camera appropriately calibrated and positioned in reference of the area of interest. The system consists of a 260 mm long motorized bar and of a Canon EOS 400D digital camera (10M pixel) equipped with Canon EFS 60mm and 28mm macro lens. The camera is positioned on a motorized bar and a specific software allows to control the camera position during the process of acquisition: three single shots are sufficient to generate the 3D model of the area of interest using a specific elaboration software. The software can perform a quantitative evaluation of the pattern surface, as roughness and profile reconstruction. The system is able to reconstruct the surface pattern by a single acquisition with an accuracy of 50 m on the height and 20 m on horizontal plane.

A performance comparison between LCI and micro-photogrammetry techniques has been made on several reference sample with certified sizes, in order to define the accuracy, reproducibility, sensibility, and reliability. Several samples of stone, plaster, and wood are made in order to simulate common alteration phenomena and the 3D surface reconstruction is done. The acquired profile of the surface of the samples by the two methods is compared with a results obtained with an electronic profilometer, some results will be presented.

LCI and micro-photogrammetry represent two interesting methods for the analysis of pattern surfaces. Their application in the conservation field allows to investigate and evaluate cracks on monumental surfaces, to estimate and monitor the loss or deposit of material, and more in general surface pattern alterations due to pollution, ageing, and treatments for diagnostic and conservation.

8084-35, Poster Session

Optical techniques for the charactetrization of surface-subsurface defects in painted layers

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In the field of Cultural Heritage, 3D optical techniques are proven to be useful for the study of the artwork's surface morphology because they allow non-contact and non-invasive measurements. In particular, a detailed topographic analysis of the surface including a quantitative evaluation of defects related to the painting layers can be performed by means of holographic conoscopy on a micron scale. Moreover, artwork surfaces can be examined with suitable 2D optical techniques, such as infrared imaging, for mapping the defects at a subsurface level. In particular, thermography in the MWIR band 3-5 micron allows the detection and the spatial mapping at a suitable resolution of the delamination of the painted layers. An integrated model of the surface-subsurface defect distribution can be obtained by superimposing the results of the two above techniques for a complete analysis and monitoring of the delamination decay typology according to the specific case study, i.e. target and purpose of investigation.

The delamination of organic paint layers from inorganic support is a decay that affects many contemporary wall paintings based on both traditional (oil and tempera) and synthetic media (acrylic and vinyl copolymers). Defining the factors that cause the delaminations, finding out strategies to restore the adhesion between paint layers and support, and monitoring the restoration intervention is a fundamental conservation objective for wall paintings.

This work investigates the feasibility of a joint use of holographic conoscopy and infrared thermography for exploring the delamination decay typology of ad hoc laboratory samples. They were cast by brushing commercial waterborne emulsion paints on cement lime mortar supports and then exposed to different conditions in order to simulate the delamination of the paint layers. Set-up includes a microprofilometer based on a laser distance probe moved by a precision scanning system, and a thermal PtSi camera with a controlled IR source to provide heating and pulse heat stimulation.

8084-36, Poster Session

Remote multispectral imaging with PRISMS and XRF analysis of Tang Tomb Paintings

H. Liang, Nottingham Trent Univ. (United Kingdom); Q. Zhang, Shaanxi History Museum (China)

The Shaanxi History Museum has in its collection over 1,000 square meters of wall painting from the Tang dynasty (7th to 9th century), which are mostly from excavated tombs of Tang aristocrats.

PRISMS (Portable Remote Imaging System for Multispectral Scanning) is a multispectral/hyperspectral imaging system designed for flexible in situ imaging of wall paintings at a high resolution (sub-mm to tens of microns) over a large range of distances (less than a metre to over ten metres). It consists of modular components: 1) for imaging remotely at distances >3.5m, a telescope is used; 2) for close range imaging at distances <3.5m, lenses are used; 3) for imaging in the range 400nm-880nm, interference filters are used with CCD detectors; 4) for imaging in the short wave infrared range of 900nm-1700nm, an AOTF (Acousto-Optic Tunable Filter) is used with InGaAs detectors.

PRISMS is potentially useful as an instrument for recording the initial state of the wall paintings as they are being excavated. Initial mock field tests of PRISMS were carried out on wall paintings from tombs of the Tang dynasty paintings in the collection of the Shaanxi History Museum. Spectral reflectance data obtained from PRISMS were verified with spot measurements using a portable fibre optic spectrometer.

Non-invasive identification of pigments using spectra obtained from PRISMS were carried out and verified with non-invasive in situ XRF analysis of elemental compositions of the pigments. PRISMS spectra of pigments from different tombs were compared with each other. Ultimately, a reference database for 'real' Tang pigments can be constructed with the help of multispectral imaging.

8084-14, Session 5

Non-invasive investigations of a wall painting using optical coherence tomography and hyperspectral imaging

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Routine examination of wall paintings is carried out by taking a tiny sample to examine under a microscope. To identify pigments in various layers, the sample is prepared and polished to examine the cross-section. An experienced microscopist can visually identify the pigments according to their colour and shape. For detailed analysis of the material composition, routine analytical chemistry techniques such as SEM, FTIR, XRD etc. are used. The disadvantage of the methods is that it is invasive and conservation ethics restricts sampling to regions of damage or edges of the art work, hence it is difficult to obtain a global view of the material composition of the whole piece.

The advantage of non-invasive and non-contact investigations over invasive techniques is that it is possible to examine any region on an object giving a global rather than a restricted view of the composition of an object. With non-invasive methods, the entire object can be examined, which is impossible with invasive techniques without destroying the objects.

The most effective method of investigation is by combining non-invasive techniques with in-depth analysis of selected samples. The non-invasive techniques can be used for global investigations to identify strategic areas for sampling. The invasive chemical analysis methods have the advantage of being able to give more specific and detailed information about the material composition.

Optical Coherence Tomography (OCT) applications to heritage science is currently an active research area. Direct comparisons between OCT cross-section images and real cross-sections of paint samples showed the effectiveness of OCT cross-section imaging. Apart from the non-invasive examination of the stratigraphy of paint and varnish layers, OCT has also been shown to be the most sensitive technique for revealing preparatory sketches or underdrawings beneath paint layers owing to its high dynamic range, depth selection capabilities and resolution.

In this paper, we demonstrate the effectiveness of OCT imaging of wall paintings through a case study of a recent in situ OCT examination of a 14th C English wall painting in the Byward tower of the Tower of London. Unlike cross-sections of paint samples viewed under a microscope, OCT cross-section images do not have colour information. However, a combination of OCT images of paint cross-sections and multispectral/hyperspectral imaging of the same area can yield structural and spectral (hence colour) information non-invasively.

The wall painting was also imaged with a hyperspectral/multispectral imaging system, PRISMS (Portable Remote Imaging System for Multispectral Scanning). PRISMS was designed specifically for the in situ imaging of wall paintings. High resolution multispectral/hyperspectral images (sub-mm resolution) spanning the wavelength range of 400nm to 1700nm can be obtained in situ from a distance of a few metres to over ten metres.

The paper shows how the combined information from OCT and PRISMS can be used to assist the understanding of the painting scheme and technique, the identification of the material and layer structures.

8084-15, Session 5

Application of optical coherence tomography (OCT) for real time monitoring of consolidation of the paint layer in Hinterglasmalerei objects

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Hinterglasmalerei (reverse painting on glass) is a painting technique involving applying colours directly to the sheet of glass, which thus becomes not only the support, but also the front protective layer of the picture. As a result, the paint layers closest to the viewer (e.g. contour and glazes) are applied first, followed by opaque colours. Therefore, due to reversing of the whole painting process, the layers of a painting decisive to its aesthetics are directly adjacent to glass support, which makes them hardly accessible both for physical inspection and conservation treatment.

Inherently to the technique, the condition of Hinterglasmalerei artefacts is usually poor. Typical conservation issues include vast detachments of paint layer due to its low adhesion to the glass support and discolouration of dyes and pigments.

Optical Coherence Tomography (OCT) is a fast and non-invasive technique of imaging of the internal structure of objects consisting of transparent or semi-transparent layers. It utilizes near infrared light and a phenomenon of interference. Among its many applications concerning examination of artworks, the OCT technique has been already successfully used for imaging of results of both deterioration processes and past conservation treatments, occurring in an exemplary nineteenth century reverse painting on glass (Iwanicka et al., Lasers in the Conservation of Artworks Lacona VIII, CRC Press 2011).

The most important conservation process in case of such artefacts is consolidation. Fundamental for this kind of treatment is to apply the adhesive between the paint layer and supporting glass in such a way that the repair will not be visible. Apart from factors like matching refractive index, the speed of penetration and ability of filling in the blisters without air bubble residuals are essential. These depend on physical properties of the bonding agent like viscosity and size of the particle. However, the behaviour of the consolidant in contact with particular object is difficult to be predicted. Therefore, the technique of real time monitoring of the process is very desirable. OCT is well suited for this task since it provides cross-sectional views of the structure, obtained by examination through the supporting glass.

The aim of this contribution is to present preliminary results of monitoring of the consolidation process in a real time with the OCT technique. We will show the differences in the interaction between various adhesives and model Hinterglasmalerei paintings. In conclusion, the Optical Coherence Tomography technique will be presented as an asset to solving practical conservation issues.

8084-16, Session 5

OCT and NMR for non-invasive in-situ monitoring of the vulnerability of rock art monuments

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This paper will introduce a new application of Optical Coherence Tomography (OCT) to the monitoring of vulnerability of rock art monuments in-situ.

The porosity of host rock is an important factor affecting the susceptibility of rock art monuments to decay. Pore characteristics of rocks are one of the main factors that control the intensity of physical deterioration. The porosity is also an important factor in rock strength, in that the voids reduce the integrity of the material.

Weathering processes can cause important changes in rock porosity. Besides porosity, distribution of pore sizes is significant for the identification of changes due to rock weathering. The exposed surface and subsurface areas are the most vulnerable to decay. Surface recession due to weathering presents a serious threat to decorated rock surfaces in situ.

Standard methods for investigating porosity are dependent on sampling and as such are not suitable for continuous monitoring or culturally important materials. Current methods such as mercury intrusion and water vapour adsorption are also limited as to the range of pore size distribution they are effective over. The demand for thorough characterisation of material used in cultural heritage requires development of advanced diagnostic methods.

OCT has been successfully applied to paintings and archaeological objects, including geological materials, to produce cross-sectional images non-invasively. This method uses a ThorLabs SROCT operating at a wavelength of 930nm, an axial resolution of 6μm and transverse resolution of 9μm. The instrument is small and portable and has been used previously for in-situ studies.

The stack of cross-sectional images produced can be rendered as a volume to visualise the structure in depth over an extended area. Preliminary studies show that it can directly image the pores and subsurface structure of rocks to within 300 microns of the surface depending on the lithology. This will enable study of the progression of porosity changes and weathering rind development in the surface and subsurface of rock art panels in-situ.

The results obtained from OCT porosity measurements from weathered and fresh samples will be compared to those from Nuclear Magnetic Resonance (NMR) and from conventional methods.

Nuclear Magnetic Resonance (NMR) is a non-invasive imaging technique which relies on the detection of the spatially resolved NMR signal from a hydrogen containing fluid and can be used to investigate the presence of water in porous media. Our method uses a portable MRI device, the Mobile Universal Surface Explorer (NMR-MOUSE®) which allows scanning of samples placed outside the instrument. The NMR can provide depth profiles of up to 10mm into the surface and measure the porosity and pore size distribution in fluid saturated samples. Such devices are used extensively in the oil industry for well logging but have recently also been shown to be suitable for cultural heritage applications. However, unlike OCT which provides direct images of the pores and so provides information about the pore shape and structure, NMR is unable to image the pores.

If changes in the surface and subsurface structure can be monitored on a microscopic scale, decay may be detected at an early stage informing conservation decisions.

8084-17, Session 5

X-Ray “shape from silhouette” for three-dimensional reconstruction of ancient handworks

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X-ray tomography is a very powerful method to reconstruct the 3D structure of an object in non-invasive way, that has been successfully applied to the analysis of ancient handworks. In some cases, such as objects completely hidden by clay, ground or products of oxidation, the reconstruction of the 3D appearance of the object is required before restoring it. Since the object is not visible, X-ray tomography is one of the available techniques to analyse it. However, in some cases, such as small objects fully realized with hard metals, the tomography, although necessary to obtain the 3D profile of the object otherwise not visible, does not give any additional information on its internal monolithic structure.

We present the application of the “shape from silhouette” technique on X-ray images to reconstruct the 3D profile of handworks. The acquisition technique is similar to tomography, since several X-ray images are taken while the object is rotated. Some nails acting as reference points are placed on a light structure co-rotating with the object and are acquired on the images for calibration and co-registration. The “shape from silhouette” algorithm applied to the acquired images gives finally the 3D profile of the handwork.

There are two main differences with classical X-ray tomography: 1) the angular steps between consecutive images are typically 5 to 20 deg on the full 360 deg angle, so very few images (i.e. some to several tens) are taken compared to what is required for tomography (i.e. some to several hundreds); 2) low-energy X-ray are used, since it is not required that the radiation is transmitted through the object, but only its X-ray “shadow” is needed. Therefore, the acquisition process is very fast compared to tomography. In addition, low-energy and low-power X-ray sources are used.

We discuss the technique and describe the algorithm. We present the validation tests made on a known pewter object. Finally, we present the analysis of a tin pendant of VI century b.C. (Venetian area) completely hidden by solid ground. The 3D reconstruction shows surprisingly that the pendant is a very elaborated piece, with two embraced figures that were completely invisible before the restoration.

8084-18, Session 6

Preliminary investigation on monitoring transportation effects by full field methods: a digital holographic speckle pattern interferometry study on canvas paintings

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Safety on transportation and handling of artworks has been studied through the last decades. Sensors proving the event of a mishandling or the application of a critical frequency have been developed. In the same direction, there are also sensors monitoring the characteristics of the applied vibrations during transportation, but not the impact of the vibrations or the reaction of the artwork itself to these events. Digital Holographic Speckle Pattern Interferometry (DHSPI) is a tool which retrieves the artworks mechanical reaction after a shock, vibration or mishandling, providing a method for the valid assessment of the transportation impact and a reliable risk analysis, but also defining limits of tolerance in order to develop new preventive strategies

In this context, a preliminary investigation has taken place at the Hochschule der Kuenste Bern / TI-Burgdorf Berner Fachhochschule employing DHSPI in order to assess the effect of handling and transportation on canvas paintings. Dummies of canvas were used on a series of measurements simulating the transportation vibrations. The transport simulator, developed through a research project, allows reproducible simulation of any transport logs on sample paintings in the laboratory. The simulator applied frequencies and accelerations previously documented in bibliography, during canvas transportation. The measurements took place in lab environment, with stable conditions, to ensure that the recorded differences of the reaction of the dummies would only be due to the vibrations. A number of cycles of controlled vibrations were applied on the samples and after each cycle a measurement with DHSPI was taken to monitor the behavior of the samples while increasing the vibration “loading” and also to record the conditions under which the first, non visible with naked eye, crack appears.

Surface deformation topology was studied with DHSPI in order to acquire information about all the alterations caused on the canvas dummies by the vibration “fatigue”. The results have shown that the method not only locates the inborn first non visible cracks, but also predicts its appearance, before it appears. This is possible through the observation of the surface deformation described by the interference fringes of the digital holographic technique, taking advantage of the fact that the surface is deformed according to the content of the internal bulk of the object.

The applied acceleration under which the first crack appear is quite high, but this was expected as the test painting was a new construction made for the specific experiments. While continuing the cycles of vibrations the elongation of the cracks and the indication of the future direction of propagation and tended interconnection patterns were also recorded. Crack growth diagrams, provided by analysis of DHSPI measurements, are illustrating the behaving of the cracks elongation while increasing vibration “loading”. Risk areas, located before any vibration loading, have also proved to be the most probable to develop cracks and defects.

The preliminary tests carried out, on the transportation of canvas paintings have been successful in detecting cracks and defected areas and also monitoring their propagation with high precision. Lab simulations of transporting in combination with DHSPI monitoring has revealed the amplitude of oscillation where the first cracks appear on new canvas paintings and also the way these cracks grow. During the tests it was also feasible to locate areas at risk of future deterioration. The full-field property allowed the overall mapping of cracking patterns to be deducted visualising further ‘the way things break” opening new possibilities in deformation studies of solids objects.

8084-19, Session 6

Infrared digital holography applications for virtual museums and diagnostics of cultural heritage

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Infrared (IR) digital holograms have some advantages compared to those ones recorded with a visible radiation source. Firstly, thanks to the long wavelength used, the distance between the camera and the object can be reduced about a fourth with respect to that of visible holograms. Moreover, the high output power of IR laser sources and the lesser sensitivity to seismic noise, when compared to the setup exploiting the visible spectrum, make them suitable for the recording of large objects.

In this work we acquire the holograms of a bronze replica of the Benvenuto Cellini “Perseus” sculpture, about 33 cm high, using a 110 W-CW CO_2 laser, emitting at 10,6 µm, and an ASi thermal camera with 640 × 480 pixels with 25 µm pixel period..

A sequence of holograms is recorded rotating the statuette with an angular step of 3 degrees.

Then, we reconstruct them optically with a circular display consisting of 9 Holoeye LCOS spatial light modulators(SLMs) (pixel period 8 micrometers) using an illumination wavelength of 532 nm. The final reconstruction is obtained from 9 holograms captured for different observation angles. This kind of reconstruction allows to obtain a 3D imaging of the statuette that could be exploited for virtual museums.

Potential difficulties in the visible reconstruction of IR holograms could be caused by the possible optical aberrations involved. Generally, if a hologram is reconstructed with a wavelength different than the one used in the recording process, the resulting image is affected by some aberrations that depend on the wavelength ratio of reconstructing to-recording light as well as on the scale factor of the hologram, due to the dissimilar values of the pixel pitch in the recording camera and in the SLM array. In order to verify that such aberrations do not affect the 3D display, we estimated the aberration coefficients, such as coma, astigmatism, distortion, and curvature of field, that result from the reconstruction in the visible range of holograms recorded with a wavelength 20 times larger. The results show that the wavefront aberration is negligible (<1 wavelength) and does not substantially affect the reconstructed images, giving the chance of a reliable IR-recording/visible-light reconstruction system.

IR digital holograms can be also exploited for non- destructive diagnostics of cultural heritage. The use of long IR wavelengths reduces the sensitivity of interferometric measurements, and, therefore, IR holography is well suited for measuring optical path variations (and, therefore, deformations) avoiding multiple wavelengths methods needed in the visible region.

Possible applications include the detection of damage such as chipping in frescoes, the presence and the extent of micro-cracks in statues, the determination of the deformations due to changes in environmental parameters. Moreover, the system could be usefully employed as a diagnostic tool for assessing a posteriori the restoration, or to evaluate the presence of residual stresses induced by restoration work.

8084-20, Session 6

Application of digital image correlation (DIC) for tracing of canvas painting deformation

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Canvas paintings are complex, multilayer structures composed of hygroscopic materials of different properties. Therefore they are sensitive to fluctuations of relative humidity in their surroundings. During storage in unstable environment significant distortions of the plane of the painting can appear. They affect aesthetic value of the picture but also, when repeat, lead to permanent damages. Buckling, waving, and sagging occur due to the expansion of its components, whereas contraction in various layers causes cracking or cleavage. In case of any discontinuities in the whole structure or in separate strata, these effects become more complicated and pronounced. These local discontinuities may be inherent to the painting technique or caused by a damage. Crackles, interlayer delamination, cuts, tears, gaps, but also repairs and patches fall into the latter category.

To monitor the deformation of a painting surface induced by its environment, a method capable of tracing in-situ general distortions and local displacements is necessary. Thus, the technique should combine large field of view with a sub-millimeter resolution and accuracy in three dimensions. It is essential to use a method capable of recording in-plane and out-of-plane displacements simultaneously. The aim of this paper is to present preliminary results of using 3D Digital Image Correlation (DIC) technique for this task. In the method the images of an object in two states: before and after its exposure to environmental changes are captured. For each state of an object two images are registered simultaneously by two cameras viewing the object from slightly different directions. In 3D DIC the application of digital image correlation combined with stereovision methods provides the maps of out-of-plane and in-plane displacements of and within an object which have occurred between acquisitions of images.

A model painting on canvas was used as the object under examination. It was made of commercially primed fine plain weave canvas stretched over a keyed wooden stretcher. To create discontinuities in its structure, cuts and gaps of various size were made and then repaired and filled in with different techniques. Then the sample was subjected to environmental stress caused by rapid changes of relative humidity in a custom designed glass climate chamber. During the experiment DIC data were collected every 20 seconds together with the relative humidity (RH) and temperature values. After processing, the displacement maps were correlated with humidity data and combined into video animations for convenient inspection. For quantitative analysis the diagrams of displacements of chosen points of the surface were generated. We will show that the 3D DIC may be used for tracking humidity-induced deformations of a painting as a whole and for examining local displacements caused by discontinuities present in the structure of the canvas support.

8084-21, Session 6

Study on the currently accessible technology for 3D printing of color objects from the reproduction quality standpoint

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In this paper a new 3D measurement system along with the study on 3D printing technology is presented from the perspective of quality of reproduction. In the first part of the paper the 3DMADMAC SPECTRAL system which integrates 3D shape with additional color and angular reflectance measurement capabilities is presented. The shape measurement system is based on structured light projection with the use of a DLP projector. The 3D shape measurement method is based on sinusoidal fringes and Gray codes projection. Color is being measured using multispectral images with a set of interference filters to separate spectral channels. Additionally the set up includes an array of compact light sources for measuring angular reflectance based on image analysis and 3D data processing. All three components of the integrated system use the same grayscale camera as a detector. The purpose of the system is to obtain complete information about shape, color and reflectance characteristic of measured surface, especially for cultural heritage objects - in order to use their models in 3D copying application. In the second part of the paper the 3D printing technology will be tested on artificial objects as well as on real measured cultural heritage ones. Testing on artificial objects allows to assess measurement and color accuracy of reproduction by selected 3D printing technology. Testing on real objects sheds some light on how current 3D printing technology can be applied into cultural heritage.

8084-22, Session 6

S. Peter Martyr (Rieti, Italy): a study case for 3D color laser scanner (RGB-ITR)

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Since several years our laboratory in ENEA Frascati Research Center is involved in development of laser scanners for Cultural Heritage investigation problems. Actually the best result obtained in this field by our laboratory is a 3D Red Green Blue Laser scanner, called RGB-ITR: the main feature of this scanner, further then measuring distances, is the ability to capture remotely (up to 20m with a sub-millimetric resolution) color information by three calibrated laser sources: this information is collected for each point sampled by the instrument and is not affected by external light sources' influence. Moreover the ability to acquire color and distance information at the same time and for each point decrease drastically the post production pipeline of a complete mesh. In this work the results of a complete scan of S. Peter Martyr in Rieti will be presented, highlighting the efficiency and robustness of color calibration algorithms introduced for a correct color representation.

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8085-01, Session 1

3D Imaging: how to achieve the highest accuracy

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The generation of 3D information from images is a key technology in many different areas, e.g. in 3D modeling and representation of architectural or heritage objects, in human body motion tracking and scanning, in 3D scene analysis of traffic scenes, in industrial applications and many more. The basic concepts rely on mathematical representations of central perspective viewing as they are widely known from photogrammetry or computer vision approaches. The objectives of these methods differ, more or less, from high precision and well-structured measurements in (industrial) photogrammetry to fully-automated non-structured applications in computer vision.

Accuracy and precision is a critical issue for the 3D measurement of industrial, engineering or medical objects. As state of the art, photogrammetric multi-view measurements achieve relative precisions in the order of 1:100000 to 1:200000, and relative accuracies with respect to retraceable lengths in the order of 1:50000 to 1:100000 of the largest object diameter. In order to obtain these figures a number of influencing parameters have to be optimized. These are, besides others: physical representation of object surface (targets, texture), illumination and light sources, imaging sensors, cameras and lenses, calibration strategies (camera model), orientation strategies (bundle adjustment), image processing of homologue features (target measurement, stereo and multi-image matching), representation of object or workpiece coordinate systems and object scale.

The paper discusses the above mentioned parameters and offers strategies for obtaining highest accuracy in object space. Practical examples of high-quality stereo camera measurements and multi-image applications are used to prove the relevance of high accuracy in different applications, ranging from medical navigation to static and dynamic industrial measurements. In addition, standards for accuracy verifications are presented and demonstrated by practical examples and tests.

8085-02, Session 1

Practical target detection and accuracy indicator in digital close range photogrammetry using consumer grade cameras

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There is a large body of literature on the calibration of consumer grade digital cameras and circle target detection, location. Target detection and location with subpixel accuracy had been investigated as a star tracker issue, many centering algorithms have been carried out. It is widely accepted that the least squares modeling of ellipse fitting is the most accurate algorithm. However, there are still problems for practical close range photogrammetry. These problems are reconfirmation for target detection and location with subpixel accuracy based on real data and an indicator for estimating the accuracy of normal close range photogrammetry using consumer grade digital cameras. With this motive, empirical testing of several algorithms for target detection, subpixel location and an indicator were investigated in this paper using real data acquired with 7 consumer grade digital cameras which have 7 mega pixels to 1.47 mega pixels.

As the first topic, target detection and location was investigated as follows; 5 thresholding algorithms which were proposed by Otsu, Zhou, Wong, Snow and Trinder were considered since target detection is influenced by thresholding. Subpixel location method is divided into following 3 phases by bottom up procedures. Simple centroid and weighted centroid algorithm were investigated in the first phases using the 5 thresholdings. The first feature of note in the first phase was that automatic threshold method which has proposed by Otsu shows the most robust accuracy among the 5 thresholdings. Therefore, the automatic thresholding was adopted in following phases. On the other hand, it was reconfirmed that simple and weighted centroid method shows almost the same accuracy.

As the second phase, ellipse fitting was investigated using detected edge points by scan-line method and linear model method. Scan-line method is edge detection method with pixel, but scan-line method has ability to detect edge point with subpixel using weighted centroid method by generating mask around the edge points. Similarly, linear model method is edge detection method with subpixel using mask, and the method has possibility to improve accuracy adopting weight for the edge points. There are 4 kinds of ellipse fitting method in the second phase, but it should be considered that these methods are influenced by number of edge points and mask size. Therefore, circumference of the circle target was divided into 16, 32, 64, 128, 256, and 5×5, 7×7, 9×9, 11×11, 13×13, 15×15 mask size were generated respectively. As a brief summary for the second phase, the weighted scan-line method doesn't show significant differences for the mask size, and more than 128 edge points show the most stable and the highest accuracy.

The third phase is ellipse fitting with star operator. In order to detect subpixel edge points, third polynomial and lagrange function were investigated along search lines radiating from initial center position to edge points which were detected by the scan-line method. Furthermore, circumference of the circle target was divided into 16, 32, 64, 128 and 256. As the brief results for the phase 3, it can be said that both function show the highest accuracy in the case of 128 or 256 edge points. However, it is concluded that third polynomial is better from the view point for procedure of detecting inflection point along search lines.

Figure1 shows brief summary for target detection and location. It should be noted that the proportional accuracy in Figure 1 were computed using 128 edge points except simple and weighed centroid method. It can be seen that simple centroid method shows high accuracy as same as other method. Ellipse fitting with star operator shows the most accurate algorithm, but it is inferred that simple centroid method is convenient method from the view point of procedure aspects. In other words, simple centroid method has ability as same as other algorithms.

As the second topic, an indicator for estimating the accuracy was investigated since general indicator which is introduced by vertical photo model has risk of underestimation. Several symmetric and non-symmetric stereo models were taken using the 7 consumer grade digital cameras.

For example, Figure 2 shows proportional accuracy for the symmetric stereo model. It can be seen obviously that the general indicator has risk of underestimation. Figure 3 shows one of non-symmetric model. It can be seen that the base height ratio is dominant parameter in stereo model.

Therefore, it is concluded that accuracy should be estimated using the indicator which is introduced by conversion photo model.

8085-03, Session 1

Digital methodologies for 3D acquisition and representation of mosaics

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In the last two decades, the improvements and widespread of digital technologies and methodologies aimed at acquiring data and rebuild faithful replicas of reality have suggested different and interesting applications in the field of Cultural Heritage. Digital collections and exhibitions are actually offering new opportunities to Institutions called to preserve and promote artistic, historical and cultural heritage and to communicate and share knowledge among different users and scholars. But despite these recent improvements, many Institutions still aren't encouraged to adopt digital procedures as a standard practice to collect data upon their heritage. The reasons for this lack are mainly due to the high costs connected to their use and to the absence of standard procedures that guarantee the consistency and the durability of digital data that need to be used in different contexts and for different purposes that can change through time.

For these reasons, artefacts and artworks which present evident intrinsic complexities such as for example, mosaics, are still not widely investigated. One of the most peculiar characteristics of mosaics that often limits their 3d digital survey is the complexity of their geometry that can be detected at two main scales of observation. Looking at an overall scale, mosaics generally cover floors or walls which have predominant two-dimensional geometries that can be assimilated to flat or curved (vaults, columns, etc.) surfaces. At this scale, due to aging factors, the overall supporting geometry of mosaics can change through time if affected by architectural degradation that can cause lesions, collapses or swellings. At a smaller scale, mosaic surfaces are constituted by single tesserae whose geometry is very complex and therefore needs to be acquired using different approaches and methodologies. At this close-up scale, the offset, non-coplanarity, self occlusion of single tesserae need to be acquired using more accurate instruments. In addition to these aspects, as far as their colour and reflectance characteristics, the use of translucent materials (such as glass or marble) and metal finishing (gold leaf) of tesserae, can underline lacks and difficulties when collected using technologies and instruments that use light as mean to recognize the position of 3d points in space.

Purposes

The aim of this paper is to show the results of a research conducted in order to find the most appropriate digital methodology and procedure to be adopted to collect geometric and radiometric data upon mosaics that can straightforward both the preservation of the consistency of information and the management of huge amount of data.

The case study presented in this paper is the "Flight of the Doves" mosaic of Renato Guttuso and Romolo Papa (1957-59), which belongs to the Modern Mosaics Collection preserved at the Art Museum of Ravenna and whose geometric characteristics are extremely complex if compared to the byzantine ones, both from the small and to the overall scale.

One of the most immediate applications of digital 3d survey of mosaics is the substitution of plaster casts which were usually required by the Superintendence of Ravenna in order to add the third dimension to pictorial or photographic surveys before restoration interventions. In addition to this purpose, digital 3d surveys of mosaics allow to document their conservation conditions, to conduct restoration interventions in digital environment in order to speed and perform more reliable evaluations. Moreover, 3d reality-based models of mosaics can be used in 3d information systems or for digital exhibitions and reconstruction aims.

Methodologies

Within this research, different acquisition methodologies have been tested and compared, each one showing different peculiarities, advantages and disadvantages. In particular, triangulation (Minolta VIVID 900 and ROMER G-Scan RX2) and time of light (Leica HDS6100) laser scanners, as well as a high resolution photogrammetry technology (Menci ZScan, camera NIKON D700, focal length 24 mm) have been used in different survey conditions in order to compare precision and accuracy of geometric acquisitions and correlate them with time data processing required by the different procedures.

The results of the application of these technologies and methodologies have always been compared with the different levels of detail of the restitutions, ranging from the ones adopted for simple visualization via the web or virtual exhibitions aims, to the ones adopted for metric evaluations of reliefs, placement and orientation of single tesserae.

The characteristics of each instrument and technology have been tested in different survey conditions upon the same artifact; their peculiarities have highlighted abilities and lacks depending, in particular, on the reflection characteristics of glass and dark tesserae. The reduction of noise without losing detail related to the shape of single tesserae and their relief above mortar was one of the main goal of each acquisition.

The small dimensions of occlusions has highlighted the ability of each technology to survey the geometry of mortar or to supply the lacks of information during post processing phases.

Post processing simplifications of detailed geometry have been compared with acquisitions conducted using less accurate and precise technology, in order to evaluate the most suitable procedure to contain the heaviness of files and therefore ease the management of huge amount of data.

Each survey technology has highlighted different approaches with color acquisition; the more accurate and precise technologies have always needed the subsequent survey of color using high resolution images. The texture mapping of 3d models of mosaics has required a particular attention in the preservation of the precise correspondence between the images of tesserae and their 3d shapes.

8085-04, Session 1

Self-calibration for a camera-projector pair

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Three-dimensional scanners based on structured light projection have become a common method for the measurement of the spatial position of object surface in the space. Different methods are known for such measurement systems, one of the most common being the fringe profilometry [1]. The measurement of surfaces of object basically consists in the measurement of the three-dimensional coordinates of a relevant number of points with respect to an arbitrary reference frame. This kind of measurement requires the knowledge of some parameters of the measurement systems, which have to be determined with a calibration procedure. The calibration procedure can be performed in different ways: some of them require elaborate procedures and accurate devices acting as calibration target, such as those reported in [2],[3], although typically achieving accurate results. Other calibration schemes can be performed in a reduced time yet with slightly worsened accuracy [4]-[6]. Some calibration procedures model the camera and projector pair as they were a pair of cameras as those of a binocular stereo-vision system [7]-[8]. An interesting proposal exists [9] for the self-calibration of a camera-projector pair, which is based on the projection of sequences of sinusoidal fringe patterns, in both vertical and horizontal directions, and with a number of poses of the two devices.

The proposed paper applies the idea of the stereo-like calibration to a camera-projector pair self-calibration techniques in order to evaluate the parameters of the pin-hole models attributed both to the camera and to the projector. The proposed calibration procedure requires only one pose of the two devices (namely the scanner has not to be moved to different poses) and can be performed projecting reference points onto an arbitrary and unknown surface. The algorithm proposed in the paper operates a minimization of the epipolar error: such error is assumed as the cost function to be minimized using an iterative algorithm. The algorithm chosen for the minimization is the Nelder-Mead simplex method.

The proposed procedure has been implemented and tested both with numerical test and experimentally for the calibration of a 3-D scanner composed of a desktop NEC NP62 projector and an Imaging Source DMK 21F04 monochrome camera. Numerical and experimental results have been also compared with those obtained with the 8-point algorithm and the subsequent decomposition of the fundamental matrices into extrinsic and intrinsic parameters [10],[11]. Moreover, the auto calibration method can be used for the quick tune up in loco of a system previously characterized in laboratory: under this point of view it is possible to narrow the search interval for the parameters and adopting a bounded numerical minimization algorithm.

Figure 1 and Figure 2 show some of the simulation results versus the standard deviation of the noise superimposed onto pixel coordinates of calibration points.

Table I shows the some of the experimental results obtained for both the 8-points algorithm and the algorithm proposed in this paper; for both of them the unbounded and the bounded versions of the two algorithms have been considered.

REFERENCES

[1] Y. Hu, J. Xi, J. Chicharo, Z. Yang, "Improved Three-step Phase Shifting Profilometry Using Digital Fringe Pattern Projection", Proceedings of CGIV'06 Conference, 26-28 July 2006, 161-167.

[2] H. Liu, W. Su, K. Reichard, S. Yin, "Calibration-based phase-shifting projected fringe profilometry for accurate absolute 3D surface profile measurement", Opt. Commun. 216 (1-3) (2003) 65-80.

[3] L.-C. Chen, C.C. Liao, "Calibration of 3D surface profilometry using digital fringe projection". Measurement Science and Technology 16, 1554-1566 (2005).

[4] Z. Xiaoling, L. Yuchi, Z. Meirong, N. Xiaobing, H. Yinguo, "Calibration of a fringe projection profilometry system using virtual

phase calibrating model planes", Journal of Optics A: Pure and Applied Optics, 7 (2005), pp. 192-197.

[5] R. Anchini, C. D'Argenio, C. Liguori, A. Paolillo, "An easy and accurate calibration procedure for 3-D shape measurement system based on phase-shifting projected fringe profilometry", IEEE International nstrumentation and Measurement Technology Conference (I²MTC), Victoria, Vancouver Island, Canada, May 12-15, 2008, pp. 2044-2049.

[6] C. D'Argenio, G. Di Leo, C. Liguori, A. Paolillo, "A simplified procedure for the calibration of a fringe pattern profilometer" IEEE Instrumentation and Measurement Technology Conference, 2009 (I2MTC '09). Singapore 5-7 May 2009, 652-657, Digital Object Identifier: 10.1109/IMTC.2009.5168531.

[7] W. Gao, L. Wang, Z. Hu, "Flexible Calibration of a Portable Structured Light System through Surface Plane," Acta Automatica Sinica, Vol. 34, No. 11, November 2008, pp. 1358 - 1362.

[8] M. Bevilacqua, C. Liguori, A. Paolillo, "Stereo Calibration for a Camera - Projector Pair", Proceedings of IEEE International Instrumentation and Measurement Technology Conference (I²MTC), Austin, TX, USA, 3-6 May 2010, pp. 492-497, ISBN 978-1-4244-2833-5, ISSN 1091-5281.

[9] J. Tian, Y. Ding, X. Peng. "Self-calibration of a fringe projection system using epipolar constraint", Optics & Laser Technology, Volume 40, Issue 3, April 2008, Pages 538-544.

[10] R. Hartley, "In defence of the 8-point algorithm". IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 19, No. 6, June 1997.

[11] P. R. S. Mendonça, R.Cipolla, "A simple technique for Self-Calibration", Proc. IEEE Conf. on Computer Vision and Pattern Recognition, Fort Collins, Colorado, USA (June), volume I, pages 500-505, 1999.

8085-05, Session 1

Power-saving modulation technique for time-of-flight range imaging sensors

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The emergence of time-of-flight range imaging as a robust and flexible depth sensing technology is enabling a wide variety of new applications in areas such as automotive safety and natural user interfaces. A number of these potential applications have stringent electrical power constraints that are difficult to meet with the current state-of-the-art camera systems. The authors have developed a technique to significantly reduce the power consumed by the image sensor, thereby lowering overall system power.

Time-of-flight range imaging cameras measure both distance and intensity simultaneously for every pixel in an image. An amplitude modulated light source illuminates the scene of interest, and distance is measured by detecting the phase shift in the modulation envelope of the back-scattered light. The phase shift is measured using a specialized gain-modulated image sensor that is operated at the same frequency as the illumination source (typically in the range of 10-100 MHz).

Sensor gain modulation contributes a significant proportion of the total image sensor power consumption. With the development of higher spatial resolution range image sensors that operate at higher modulation frequencies (to achieve better distance precision), this proportion is likely to increase.

In most range image sensor implementations, a differential "two-tap" pixel structure is employed to provide high frequency gain modulation. Each pixel contains two modulation gates that are driven with complimentary digital (square) waveforms. While the capacitive load of each individual modulation gate is small, globally modulating the cumulative capacitance of a full pixel array can demand a considerable amount of power. Transient power supply disturbance due to digital switching can also cause significant interference with other sensitive parts of the system.

The average sensor modulation power can be estimated as $P = 2NCfVV$ where N is the number of pixels in the sensor (number of columns x number of rows), and f, V and C are the modulation frequency, voltage and gate capacitance respectively. If we consider a QVGA resolution sensor (320x240 pixels) with a modest modulation gate capacitance of 20 fF, the modulation drive circuit will consume 3.3 W when operating at a voltage of 3.3 V and a frequency of 100 MHz. To offer some perspective, this level of power consumption would be prohibitive if such a camera were to be used for any battery or USB powered applications.

We have developed a sensor modulation scheme that is more power efficient than the standard mode of operation. A proof of concept implementation has been built using a PhotonICs PMD 3k-S time-of-flight image sensor from PMD Technologies GmbH (Siegen, Germany). With this system we have demonstrated a 93-96% reduction in modulation drive power over a range of frequencies from 1-11 MHz, thereby significantly reducing the total power consumption of the image sensor. This is illustrated in figure 1, which shows the average modulation drive current for the high-to-low switching transition, versus frequency, for both operating modes. Unfortunately due to limitations of the existing modulation driving electronics we were unable to obtain meaningful results at frequencies beyond 11 MHz.

Under power-saving modulation, the electrical waveform shape is inherently different to that of the standard square waveform. It is therefore necessary to also evaluate the optical response and imaging performance for both operating modes. Among the various metrics we consider, range accuracy (or linearity) is predominantly influenced by modulation waveform shape. The actual versus measured phase and resulting linearity error for one particular modulation frequency is plotted in figure 2. In this case the power-saving mode exhibited a 79% reduction in RMS linearity error compared to the standard mode of operation. Indeed at all test frequencies, power-saving operation significantly improved measurement accuracy.

In this paper we will outline the problem and describe the new power-saving implementation. We will then show experimental results that detail the electrical response of the system, including plots of voltage and current drive signal delivered to the sensor. Finally we will present a comparison of the optical response, the resulting modulation contrast levels, and the imaging performance (accuracy and precision), for both standard and power-saving modes of operation. Some of these results, and the details of the implementation, are currently the subject of a patent submission, so although they cannot be disclosed here, a full description will be provided in the final manuscript.

8085-06, Session 1

Real-time image processing of TOF range images using a reconfigurable processor system

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Perception of the environment in 3D has always been an important sensory input for many application areas such as robotic, automotive, industrial, medical and multimedia applications. In principal there are three methods mainly used to acquire 3D information: Stereo vision (SV) systems, laser range scanners (LRS) and time-of-flight (TOF) cameras. SV systems usually rely on the principle of establishing correspondences. The major disadvantages of SV systems are the correspondence problem, the limited field of view and the allocation problem. The LRS deliver one scanning line of accurate distance measurements often used for navigation tasks. The major disadvantage of LRS systems is the use of mechanical components and that they do not deliver 2D intensity images and range data at the same time. TOF cameras combine the advantage of active sensors and camera based approaches as they provide a 2D image of intensity and exact distance values in real-time. Compared to SV systems TOF cameras can deal with prominent parts of rooms like walls, floors, and ceilings even if they are not structured. In addition to the 3D point cloud, contour and flow detection in the image plane yields motion information that can be used for e.g. car or person tracking.

State of the art is to use a 4-phase shift algorithm for TOF cameras to determine the range value correctly. The optical signal is sampled four times per period at equal intervals. The corresponding sampling points permit the unique determination of all relevant parameters of the incoming optical echo's wave form. The sample points are not acquired during only one single period but summed over several hundreds or thousands of periods, which considerably increases the signal to noise ratio and hence finally the accuracy of the measurement. The most time critical operation of the 4-phase shift algorithm is the arctangent function. As the arctangent function is called for each individual pixel to determine the range value, the processing time increases with the number of present pixels. In this paper a 204 x 204 pixels PMD TOF camera (PMD[vision]® CamCube 2.0) is used with a maximum frame rate of 25 fps. Hence the arctangent function will be called 41,616 times per range image. Using a standard microcontroller (Altera NIOS soft processor clocked at 50 MHz) it takes around 800 µs to calculate the arctangent function. So the total processing time of one range image would take 33.3 s, which is not acceptable in an industrial environment.

It has been projected that by 2010, more than 40% of all field programmable gate arrays (FPGA) designs will contain a microprocessor. Platforms, which consist of a microprocessor core that is coupled with a reconfigurable functional unit (RFU), are defined as reconfigurable processors. These reconfigurable processors offer the possibility of extending the basic instruction set of the microprocessor by introducing custom functional units on the RFU. In this paper we propose a hardware algorithm for 3D-TOF photonic mixer device (PMD) cameras which is realized as a custom functional unit on the RFU of a reconfigurable processor in a FPGA. The hardware algorithm is based on look-up-tables (LUT) and a search algorithm. Our approach is customized for TOF data processing in the millimetre range and the performance is significantly better than the state-of-the-art cordic algorithm. Compared to a RISC microcontroller solution using the same clock frequency a speed-up factor of 4,000 is obtained in this paper. Using a higher clock frequency an even better performance can be achieved.

To our knowledge there is no other hardware algorithm with the same performance. The proposed approach will significantly reduce the system costs of TOF cameras as state-of-the-art is to use high performance microcontroller in combination with a FPGA. This is an important achievement as the current 3D TOF cameras are far too expensive for common industrial applications. On the conference more detail of the hardware algorithm and performance measurements will be presented.

8085-30, Poster Session

3D documentation of historical sites and buildings for interdisciplinary works

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The continued use of existing structures is of great importance because the built environment is a huge economic and political asset, growing larger every year. The assessment of existing structures is now a major engineering task. The structural engineer is increasingly called upon to devise ways for extending the life of structures whilst observing tight cost constraints. Historical immovables which are also existing structures should be assessed elaboratively in order to preserve cultural heritage and repair historical structures.

The main purpose of this paper is to explain the steps carried out to provide 3D visual input data for designing a semantic 3D model for part(s) of Seddülbahir Fortress from laser scanning data.

The fortress of Seddülbahir, the "Dam of the Sea", was built in the mid 17th century at the entrance to the Dardanelles, on the European side by Hadice Turhan Sultan, the mother of the Ottoman Sultan, Mehmet IV. The fortress was constructed as a part of the Ottoman defense against Venetian naval incursions into the Dardanelles during the long war over Crete and the eastern Aegean. Since that time Seddülbahir has protected the Ottoman, and later Turkish lands, against threats to the Dardanelles, the strategic waterway which leads to the capital of Istanbul on the Bosphorus.

Located on the shore above Cape Hellas, the Ottoman fortress of Seddülbahir was instrumental in the Ottoman defense during the famed Gallipoli campaign of World War I. It was also severely damaged by Allied artillery fire during this campaign. After World War I and the withdrawal of British troops from the Gallipoli region, the fortress was returned to the Ottoman government. The fortress and the site served as a Turkish naval outpost until 1997 when the team, KaleTakımı, began a preliminary survey of the site immediately after demilitarization.

The fortress of Seddülbahir is a large site; encompassing a total landscape of nearly 24.000m2 and containing a building mass of approximately 4.200m2. The fortress is scanned using a Leica HDS 3000 scanner, and for the registration of the point clouds Leica Cyclone Register has been used. The entire site is scanned with a point distance of 5mm. Because the distance between the points in the point clouds are small the amount of data gathered is really huge (8GB for the entire site), which makes it hard to work with the data. On the other hand this dense data gives us the opportunity to evaluate the structural, archeological and architectural situations of the entire site.

This paper will focus on laser scanning data of the North Tower and the work carried out for detection of stones from the point clouds. Since the North Tower is built up of mortar and stones, that are seriously damaged because of the weather conditions, vandalism and location of the fortress (very close to the sea and lies close to the geological fault line that passes through Sarköy) , it is really hard to detect the stones and the mortar channel.

The output data of this work will be used as input for a 3D CityGML model of North Tower for different groups of interest like structural engineers, archeologists and architects for;

- Examining the structural health of the structure
- As built documentation for restoration and renovation projects
- As base data for 4D model
- Archeological archive

8085-31, Poster Session

Three-dimensional surface topography based on digital fringe projection

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Extraction of three-dimensional profilometry of surface- an active and interesting subject in recent years- is an important task in a great number of measurement applications such as automatic inspection, machine vision, reverse engineering, 3D object recognition and robot control. The principle of the measurement is elucidated with the scheme depicted in Fig. 1. A video projector projects a single fringe pattern of parallel lines on the object, which are deformed in uneven parts of the surface. Then the deformed lines are captured by a digital camera. The acquired image data is analyzed in order to extract the phase information. There are various techniques to evaluate phase data embedded in the deformed lines pattern since these techniques can be essentially classified into two basic types: phase shifting and the Fourier transform.

In phase shifting method, three or more phase stepped image are needed so the main advantage of FTP over PSP is that FTP use only one frame to reconstruct 3D profile of the surface; hence it is suitable for dynamic object. In line projection techniques, we use FTP analysis. FTP is one of the most successful techniques for fringe pattern analysis that first introduced by Takeda in 1982. The fringes intensity on the test surface is given by (1):

Where the phase $\phi(x,y)$ contains the desired information of surface, A(x,y) and V(x,y) represent background of line pattern. Introduce spatial carrier frequency in x and y direction. The Fourier spectrum of the carrier modulated fringe pattern will exhibit three distinct peaks. The central peak represents the zero frequency or DC component of the spectrum. One of the two outer parts of the spectrum can be windowed off the rest, shifted to zero frequency and inverse transformed. Therefore by using a proper 2D band pass filter the utmost information of surface can be extracted.

By using FTP algorithm, the phase of the deformed lines that consists of surface's height information is extracted. Because of arc tan function has a range between π and-π, FTP gives the phase wrapped in this range. Eventually by applying efficient 2D phase unwrapping algorithms the 3D profile of the test surface can be reconstructed. In this article, we review three different phase unwrapping algorithms based on different quality maps which the path of phase unwrapping is guided according to the quality map. The key step of the quality guided method is to construct a suitable map to guide the unwrapping path. The advantage of these algorithms is high accuracy by means of unwrapping pixels from high reliable areas to low reliable ones. Therefore the propagation of phase unwrappng error can be limited.

The exprimental demonstration include the 3D recounstruction of real human face. Fig. 2(a) showes the deforme lines pattern on a real human face. Fig. 2(b) present wraped phase map that computed based on FTP algorithm. Fig. 2(c) demonstart unwrapped phase map based on gray scale mask and flood fill algorithm. Eventually the 3D profilometry of Fig. 2(a) is shown from different views in Fig. 3. This technique occupy a special place as a full-field metrological means with non-complex set-up and processing algorithms that is easy to implement in outdoor and industrial environment.

8085-32, Poster Session

Large material stack-yard 3D reconstruction based on sequential stereo imagery and projected-contour

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Fast and accurate 3D reconstruction of large material stack-yard is an important job in material (such as coal, ore and grain) load-and-unload and logistics management for industrial dock or warehouse. Currently, the relevant technologies mainly are developed from non-contacting optical methods, such as LiDAR (light detecting and ranging), photogrammetry and light-section. Challenges in stack-yard 3D reconstruction include: complex and irregular 3D shape, poor surface texture and low material reflectivity, thus its 3D reconstruction and measurement always becomes quite difficult with a required precision by LiDAR or traditional photogrammetry technologies. Light-section, solid-equipped with single camera and light-projecting unit, is useful on reconstruction of small bulk-flow (e.g. bulk-stack on moving belt), but in large-size stack-yard, local-reconstructing on multi-station or dynamic-reconstructing from moving-platform, and 3D integration from local-surface's 3D units is required.

In the paper, an improved method integrated with projected-contour scanning and sequential stereo cameras imaging is proposed. Instead of only one 3D projected-contour reconstructed by traditional light-section from a concrete position and pose, a certain local-yard would be scanned by projected-contour freely and sequential image pairs collected by stereo-camera unit in a static working state, then a set of 3D contour for the complex yard surface can be reconstructed. Based on different working state's 3D contour-set of stack-yard surface, larger area stack-yard's 3D surface can be combined easily and in low error as well. The most important issue of yard 3D reconstructing is single 3D contour generation from stereo image unit. To achieve single 3D projected-contour reconstruction from stereo image by the proposed method, three key points are discussed. 1, relationship of image edge gradient vector and epipolar-line is utilized to obtain edge corresponding point in stereo imagery. This point can reduce the calculation of stereo imagery's corresponding point of projected-contour remarkably, while no local-window searching and matching along epipolar-line of stereo imagery and contour centerline extracting in each image are needed. Besides, it is also very useful to fulfill robust matching of stereo imagery's corresponding contour feature. 2, collinear equations of stereo imagery and least square forward intersection are used in 3D point calculation, instead of the basic triangulation of projected-plane and image point's 2D coordinate in light-section. 3, contour spatial features, such as contour width on yard surface, co-plane constraint of 3D point-set in one plane of projected-contour and 3D point-set's one-dimensional array, are used to generate 3D contour by object space analysis. This is special and new idea of the paper proposed method, relevant steps include: fitting the projecting plane with co-plane triangle-set judging and RANSAC (random sampling consensus) principle from one contour edge's 3D point-set; 3D point filtering by the threshold of contour max width on yard surface, and perpendicular point calculating on the fitted spatial projecting-plane as fitted 3D centerline of single contour; one-dimensional sorting and filtering based on the crossing line of projecting plane and reference plane (assumed as ground-plane in general). After these mathematic model and algorithm analysis, experiment is fulfilled with terrain sand model and calibration frame indoor. Based on 2mega-pixel stereo imagery, 3D contours can be reconstructed more than 5 per second and average length of reconstructed part is near 70% to the covered length of projected-contour, distance deviation of 3D point-set to standard plane is 0.6mm, and angle error is limited in 0.9 degree for two perpendicular-crossed planes of the calibration frame. In this way, stack-yard 3D could be reconstructed and measured fast and reliably based on this paper's work.

Next, we'll continue relevant research and development as following: 1, in order to project best contour-feature on stack-yard surface, suitable laser projector choosing, including large laser-power (1W at least) and wavelength under the circumstance of strong sunshine and atmosphere's sunlight absorbing characteristic should be considered comprehensively; 2, to obtain remarkable contour feature in camera image and reduce noise of stack-yard background and camera lens, imaging capability and sensitivity of camera should be discussed; besides, suitable filter on projector laser wavelength has also been considered together; 3, after these jobs, we'll concentrate on systematical model developing of technology product for large stack-yard 3D reconstruction and measurement.

8085-33, Poster Session

A fast reconstruction and mesh simplification applied in FEM of dental model

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A method for quickly reconstruction of dental model based on rotate scanning using structured light match technology and an algorithm of mesh simplification of the 3d surface model of dental using section lines sampling was proposed in this paper, which can provide regular surface mesh points for finite element method (FEM) of dental model. Experiments show that the method and algorithm could apply accurate surface mesh model which can provide excellent model support for finite element biomechanical model analysis.

Stress analysis of teeth and dental arch is an important branch in the research area of dental biomechanics. As it is difficult to measure the stress of teeth and dental directly, three dimension FEM is commonly used to simulate and analyses the stress situation which needs digital dental model and regular mesh model that can express the surface of the digital dental model. So quickly 3d reconstruction and mesh simplification technique are the two essential foundations of FEM.

(1) Quickly reconstruction

With the development of 3d photography and computer technology, all kinds of contacting and non- contacting digitizing methods of dental model such as stereo photography, laser scanning, moire fringes, structure light scanning, microscopically CT, infrared sensor scanning, photo elastic modeling, etc. are coming forth. But getting the total digital model of dental model using these methods is complicated, which relies on the means of multi-angle and multi-directional scanning and registration.

This paper provides a method of rotate scanning based on structured light scanning technology, which can get the complete 3d point cloud data of the dental model quickly and automatically. In this paper a rotate stage driven by stepper motor is designed to archive the target of automatic registration. How registration works is as the following: pieces of point cloud acquired using the rotate stage is with relationship of rotating around the axes of the stage. And the relationship can be presented by the position of the axes in the coordinate system of the scan equipments and the rotate angles. The axes position can be calibrated before scanning and the angles can be recorded by the computer, so pieces of point cloud can be aligned to a unified coordinate system by applying the transformation matrix made up of the axes position and the angle parameters.

(2) Mesh Simplification

The digital surface model (DSM) of dental has high-density points, while the data used in FEM should be organized as regular mesh. So DSM should be simplificated in order to get the regular mesh data. An algorithm using section lines sampling with fixed angles to divide mesh was proposed. The algorithm works as follows: taking the vector of the axes of dental model as main vector, then setting multiple parallel cutting planes in the direction perpendicular to the main vector, next calculating intersection points of cutting planes and the DSM of dental model, then connecting the intersection points on the same cutting planes into section lines based on neighbors and tangent, then generating a group of planes taking the main vector as the axis, and the group of planes must intersect with each section lines, the intersection points on the same cutting plane and on two cutting planes adjacent to each other make the final result of mesh simplification. The procedure above can be summarized as: cutting planes setting, points of section line acquiring, discrete points tracking, sampling planes setting, regular mesh point interpolation.

Several comparison experiments are designed to test the method and the algorithm. The experiments has implied that the time of reconstructing the model of one single tooth was less than 5 minutes, and the relative accuracy of the point cloud could achieve 1/10000 of the scanning distance.The experiments has also implied that the mesh model acquired by the algorithm proposed in this paper have low simplification ratio and high consistency compared with the DSM, which can meet the needs of the surface mesh model used in FEM. An in additional, the time of the procedure from getting DSM of the tooth model and generating the mesh model of the tooth model is less than 30 minutes.

The method of quickly 3d reconstruction proposed in this paper can provide accurate DSM of the tooth model, which can be used in digital tooth model preparing system, accurate tooth measurement and etc. The mesh simplification algorithm in this paper can provide surface mesh model used in FEM, which can improve efficiency of getting the surface 3d models of the tooth model compared with the method of CT and further provide the surface mesh model to the FEM.

8085-34, Poster Session

Infrared digital holography for 3D display

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Current and newly-developed 3D displays have the disadvantage that they either force the user to wear special eyewear, limit the number of simultaneous viewers, discard completely certain depth cues (such as blurring) thus causing fatigue, or else encode only a small number of distinct different views of the 3D scene. There is only one known family of techniques that can capture a full 3D scene in a single shot, including phase information, and re-project that light field perfectly thus overcoming all of the above disadvantages: the family of holographic techniques. All other methods are only 3D under a whole lot of conditions. However, unfortunately, holographic techniques for the time being present also a number of drawbacks. Conventional holograms are not dynamic. By replacing the conventional holographic plate with a digital camera and an optoelectronic 2D screen, we can capture and display only holographic images. In order to overcome some other disadvantages, we capture 3D scenes at infra-red wavelengths. IR digital holograms have some plus compared to those ones recorded with a visible radiation source. Firstly, thanks to the long wavelength used, the distance between the camera and the object can be reduced of about a fourth with respect to visible holograms. Moreover, the high output power of IR laser sources and the lesser sensitivity to seismic noise, when compared to the setup exploiting the visible spectrum, make them suitable for the recording of human-size objects. In this paper we present a sequence of holograms which are recorded rotating the object with a fixed angular step. Then they are optically reconstructed using a spatial light modulator using an illumination wavelength of 532 nm. The final reconstruction is obtained from different holograms captured for different observation angles. This kind of reconstruction allows to obtain a 3D imaging of the object. Moreover, using holograms of different objects, we can synthesize numerically 3D scenes to be displayed.

8085-35, Poster Session

Robust Sharp Features Infer in Point Clouds

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A novel sharp features extraction method is proposed in this paper. First, we calculate the displacement between the point and its local weighted average position and we label the point with salient this value as the candidate sharp feature points and we estimate the normal direction of those candidate sharp feature points by means of local PCA methods. Then we refine the normal estimated by inferring the orientation of the points near the candidate sharp feature region and bilateral filtering in the normal field of point clouds. At last we project the displacement between point and its local weighted average position along the direction of normal .We use value of this projection as the criteria of whether a point can be labeled as sharp feature. The extracted discrete sharp feature points are represented in the form of piece-wised B-Spline lines. Experiment on both real scanner point clouds and synthesized point clouds show that our method of sharp features extraction are simple to be implemented and efficient for both space and time overhead as well as it robust to the noise ,outlier and un even sample witch are inherent in the point clouds.

8085-36, Poster Session

Longitudinal resolution improving of 3D range imaging Lidar through redundant detection and intensity distribution analysis

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To improve the poor longitudinal resolution of 3D range imaging Lidar system, the redundant detection is employed. The intensity distribution curve of light reflected by the detected object is fitted by the intensities in neighboring images, and by using the curve, the objects can be located more precisely. By this method, the longitudinal resolution can be improved from 1.2m to about 0.15m.

3D detecting is one important application of Lidar. Currently, the mature technology is by 3D scanning, and products have already been applied. However, the scanning unit will make the whole system heavier, and the scanning precision will get worse because of mechanical abrasion. Moreover, it has strict demands on laser, such as high frequency, large pulse energy, small divergence angle and narrow pulse width, and this will increase the cost.

To avoid the disadvantages above, the method of 3D range imaging Lidar is put forward, and the experimental prototype is designed. Through control of the gating timing, the system can detect objects in different layers, and in conjunction with the push-broom of airborne platform, it can detect objects in 3D space. It does not need scanning unit, and the demands for Laser are much lower. In addition, every time an image is taken a large area is detected, so it can detect more efficiently than 3D scanning Lidar. 3D rang imaging Lidar is a promising technology to develop.

Longitudinal resolution of 3D range imaging Lidar depends on the laser pulse width and the exposure time of ICCD, both of which cannot be infinitesimal, and so compared with 3D scanning Lidar, its longitudinal resolution is lower. To fix this serious disadvantage and insure the detecting efficiency meanwhile, redundant detection is employed and parameters are appropriately set to make sure that one object will appear in two and just two neighboring images in time sequence. The intensities of the object in the two images are different. By using the intensities and distances corresponding to the offered gating time, the distance corresponding to the highest intensity, which is the most precise location of the object, can be determined. The mathematical principle of this method is described in detail, in which section the intensity distribution of light reflected by one single object is analyzed and the formula to calculate the most precise location of the object by using the intensities in the two images captured is deduced.

The intensity distribution curve is shown in Fig.1 and Fig.2, where c is velocity of light, wL is the width of laser pulse, wG is the exposure time of ICCD, and d is the precise location of the object to detect. The abscissa is the time ICCD begins to be exposed, and the ordinate is the intensity of light received. In Fig.1, wL is larger than wG, and in Fig.2 the opposite. The distribution curve is verified by experiments with the time ICCD begins to be exposed extended a small step every time a single image is captured. The flat section of the curve will affect precise locating of detected objects, so wL and wG are assigned the same value and the curve will change to the shape shown in Fig.3, where w stands for both wL and wG.

The formula to calculate the precise location of detected objects is expressed as eq.1. where, t1 and t2 are the time ICCD begins to be exposed, and L1 and L2 are intensities of the object in the two images.

Actual detection results show that by this method the longitudinal resolution of 3D rang imaging Lidar system can be improved from 1.2m to about 0.15m.

8085-37, Poster Session

A novel color coding method for structured light 3D measurement

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This paper presents a novel color-coded method which is applied to the structure light system of three-dimensional measurement using fringe-pattern projections. In the industrial production, the traditional quality inspection, such as coordinate measuring machine, is so slow that it has seriously restricted the production efficiency. So research and development of an efficient, high-precision three-dimensional measurement technology has important practical significance.

Structured light three-dimensional measurement technique has a faster measurement speed and high precision, which is widely used in three-dimensional profile measurement. The novel coding method described in this paper is based on this technique. And the main devices of the measurement system consist of a projector and a camera only. The projector projects encoded fringe pattern to the measured object surface in proper order, while the camera in sequence to obtain the deformation fringes modulated by the object surface simultaneously, so each of the projection fringe patterns is encoded by those time-series images, which is called the time coding method. Then, through the fringes decoding and data processing program, the three-dimensional shape information of the detected objects is obtained. With the time coding method, in order to obtain high spatial resolution, it normally takes more projection fringe patterns. But with the increase of projected fringes in number, the projection number of the fringe pattern images is bound to increase. Thereby the measurement time is increased, and the measurement efficiency is reduced. Therefore, in order to improve the measurement efficiency with time coding, this paper proposed a novel coding method with color fringe pattern. That is, each original fringe pattern of the projection fringe images projected onto the measured object surface is subdivided further into several color fringes by several specific colors, and the sub-fringes can be distinguished from each other by those colors automatically. Then the fringe patterns consisted of the color sub-fringes are projected onto the measured object surface in sequence and shot by a camera using of time coding method. Thus the number of the measured fringe patterns is increased and more measured data can be obtained through the fringe pattern processing, in other words, under the premise of the same projection number, the number of the fringe is increased, or the measurement efficiency is improved.

But the introduction of colored fringes also brings a lot of difficulties in image processing, in which the most important is the color crosstalk. Because of it, the edge of fringes will be hard to identify correctly, and the bright fringes will affect the darker fringes, which resulting in the extraction accuracy of fringe center. Ultimately it will seriously directly affect the measurement accuracy. Therefore, in order to solve the problem, this paper adopts the red (R), green (G), blue (B) primary colors and the white color (W) to subdivide the original fringes, and sinusoidal fringe patterns, a complementary fringe pattern image corresponding to the original fringe patterns image and other related image processing methods are also used to separate color fringes accurately, which can quickly and effectively solve the color crosstalk problem and get a better processing fringe pattern by reducing edge effects and improving the edge quality of those fringes.

Then based on the above ideas and measurement methods, a three-dimensional measurement system is built, and the main system equipment consists of a high-resolution CCD (Charge-coupled Device) and a digital projector based on digital light procession (DLP). A mathematical model of the measurement system is also established in the paper. And before the measurement, a direct linear calibration method with lens distortion correction of the camera and the projector is applied to calibrate the parameters of structured light system consisting of the projector and the camera. Namely, it uses the cross ratio invariance principle to correct the lens distortion of the projector and the camera, and the internal or external parameters of the system are obtained by the direct linear calibration method. Then the system parameters are optimized through the bundle adjustment method. Finally, a standard metal hemisphere with spraying was measured, and the accuracy of the measurement system is analyzed by comparing with a standard data obtained by a coordinate measuring machine (CMM) with higher measurement accuracy. Experimental results show that the method reduces the number of image projection with high horizontal measurement resolution, and the measurement accuracy of the depth direction is about 0.25mm.

8085-38, Poster Session

Three-dimensional contour reconstruction of push-broom range-gated Lidar data: case studies

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To accomplish a wide area survey, a push-broom range-gated imaging Lidar system (PR-Lidar), named DeepView, is newly developed by Beijing Institute of Technology (BIT). Since the use of 'push-broom' for wide-area applications represents a novel idea, not yet explored in practice, new 3D reconstruction technique is needed to be developed with the purpose of: 1) reducing the effect of range ambiguity in the raw data not only in longitude direction but also in transverse direction; 2) reducing the dependence on complicated and empirical imaging processing to maintain the efficiency for large data volume; 3) working stable even when the system is operated under a defocusing condition, which is essential for those scenes with a large range of depth, or for system with a constant focus length; 4) reconstructing the range information in an explicit data form (e.g., 3D contour) to merit quantitative analysis.

This article suggests the use of a cross-layer constraint (CLC), originated from the intrinsic relation between time slices (or range slices) of PR-Lidar data, to accomplish the above requirements. Three outdoor scenes are fully studied to demonstrate the validity of CLC method, by using the data released by the DeepView. It should be noted that all three experiments are conducted in a defocusing condition to demonstrate the robust of CLC.

In the first scene with a simple building corner, we present a close investigation on the intensity of each reflecting surface flows through the time-slice stack (Fig. 1a) to derive the model of CLC. Two cross-layer constraints are found to resolve the range ambiguity of a reflecting surface as follows: 1) the intensity profile of a reflecting surface is Gaussian-shaped (Fig. 1c), and its peak determines the most probable longitude location of this surface; 2) the region of a reflecting surface in time-slice Ii will be replaced by a background region (zero intensity) in the time-slice Ii+N or Ii-N, and the boundary of this background region well confines the fuzzy boundary of corresponding surface (Fig. 1b).

By combining above two constraints, the CLC model to resolve range ambiguity in time-slice Ii is as follow:

(1)

Where Ci is the reconstructed contour area, N is number of cross layers, S is the level of background noise, and is the binarization of time-slice I using the threshold S. This CLC model is physical-based and thus does not need any prior knowledge of the scene. In addition, it only involves simple calculations and set operations, voiding complicated and empirical imaging process.

In the second scene, the derived CLC model is applied to reconstruct a car with enough depth contrast and semi-transparent glasses to test the capacity of resolving range ambiguity. Many key details(e.g., thin glasses) mixed by the effect of range ambiguity are successfully decoupled, and thus a more informative 3D contour of car is created with depth resolution about 0.7~0.9m at 60m.

In the third case, the use of CLC is successfully extended to a push-broom process, where a large complicated scenario (Fig. 2a) is reconstructed by aligning two small adjacent time-slice stacks (Fig. 2b,2c). The contours of two time-slice stacks match well (Fig. 2d). Building corner, trees, oil barrel on the top of building, and several reference targets are well discriminated and are in good agreement with their real locations as shown in Fig. 2e, where a deviations smaller than 25cm is achieved. This proves that the CLC method is stable against reflectance variation within the scene.

Therefore, the major conclusion is that when the range-gated Imaging Lidar is extended by push-broom mode and the data is reconstructed by using the CLC method, a wide area survey is possible.

8085-07, Session 2

Accurate documentation in cultural heritage by merging TLS and high-resolution photogrammetric data

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Several recording techniques are often used simultaneously in Cultural Heritage Documentation projects. The main purpose of the documentation and conservation works is usually to generate geometric and photorealistic 3D models for both accurate reconstruction and visualization purposes.

The recording approach discussed in this paper is based on the combination of photogrammetric dense matching and Terrestrial Laser Scanning (TLS) techniques. Both techniques have pros and cons, and criteria as geometry, texture, accuracy, resolution, recording and processing time are often compared.

TLS techniques (time of flight or phase shift systems) are mostly used for recording large and complex objects or sites. Point cloud generation from images by dense stereo or multi-image matching can be used as an alternative or a complementary method to TLS. Compared to TLS, the photogrammetric solution is a low cost one as the acquisition system is limited to a digital camera and a few accessories only. Indeed, the stereo matching process offers a cheap, flexible and accurate solution to get 3D point clouds and textured models. The calibration of the camera allows the processing of distortion free images, accurate orientation of the images, and matching at the subpixel level. The main advantage of this photogrammetric methodology is to get at the same time a point cloud (the resolution depends on the size of the pixel on the object), and therefore an accurate meshed object with its texture. After the matching and processing steps, we can use the resulting data in much the same way as a TLS point cloud, but with really better raster information for textures.

The discussion will review the automation of the processing steps (registration, segmentation, and reconstruction), the assessment of the results, and the deliverables (e.g. PDF-3D files). For the visualization of the models, we propose to show solutions proposed in the Cloudcompare software (EDF, Opensource).

Two projects processed by our group in Strasbourg are used as case studies for this paper:

- The Gallo-roman Theatre of Mandeure (France, figure 1);

The Medieval Fortress of Châtel-sur-Moselle (France, figure 2), where a network of underground galleries and vaults has been recorded.

8085-08, Session 2

A parallel point cloud clustering algorithm for subset segmentation and outlier detection

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Optical 3D scanning is a state-of-the-art technique to capture three-dimensional surfaces in order to apply metrological evaluations or for the digital reconstruction of real world objects by polygonal meshing. Along with the increasing distribution of 3D scanners the applications become wider too. Measuring industrial items for quality inspection, scanning large statues for cultural heritage documentation and capturing factories in order to update the digital plant layout are typical tasks we are focusing.

Depending on the objects size, resolution and data density very large data sets with many millions of points are produced. The application of optical 3D metrology in online inspection systems as well as the processing of large data sets requires automatisms for data pre-processing such as filtering, segmentation or outlier detection. Especially the automatic segmentation of connected subsets is discussed here. A large set of data points is subdivided by our algorithm (see Figure 1) which enables us to perform a piecewise data analysis on the resulting parts in the main and post-processing steps. Whereas post-processing means outlier removal in order to perform a robust object detection and surface or geometry approximation.

Thus, we present an extremely fast point cloud clustering technique which is suitable for outlier detection, object segmentation and region labeling for large multi-dimensional data sets. The basic data structure is a binary tree similar to a kd-tree which enables us to detect connected subsets very fast. For example, a point set with two million coordinates is analyzed within 3 seconds and 15 million points within 35 seconds on Intel Core2 processor. It handles arbitrary n-dimensional data formats, e.g. with additional color and/or normal vector information since it is implemented as a template class. The algorithm is easy to parallelize which further increases the computation performance on multi-core machines for most applications.

We consider the following major tasks: building an appropriate data structure for n-dimensional point data sets, performing efficient range queries, analyzing local neighborhoods, identifying and evaluating subsets with regards to different applications. Finally, we discuss highly efficient nearest neighbor query strategies at the example of a variety of different point cloud models from industrial measuring tasks.

8085-09, Session 2

Integration of range and image data for building reconstruction

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In the last few years, three-dimensional reconstruction of buildings and urban areas has become a fundamental part in a growing number of applications, such as urban planning, map updating, 3D city modeling, and environmental monitoring. Traditionally, these products were manually performed, with hours of work of experienced users; the development of new techniques to a commercial level has made possible the development of new solutions and new products.

In particular, LiDAR and image matching techniques have achieved good results in airborne applications, because of their speed and accuracy in point cloud generation; these techniques have allowed dense point cloud to be achieved over urban ad rural areas in an efficient way. Nevertheless, neither technique assures complete and reliable results. Laser scanning techniques have non-negligible drawbacks due to the impossibility of directly obtaining radiometric information and the exact position of the object breaklines; on the other hand, image-matching techniques cannot assure that a point cloud is achieved without blunders in all conditions and they are not able to guarantee good results in bad-textured areas. For these reasons, the great part of planes devoted to 3D city model and map production have been equipped with both these acquisition systems and both data are usually collected over the same area.

Once the point cloud has been acquired, several semi-automated and manual interventions have to be applied in order to classify, segment and model the surveyed points to achieve a complete 3D model of buildings and urban areas. Then, the image information allows adding the texture to the model and refining the products obtained by point clouds. On the other hand, when a map has to be produced, an almost complete manual (and time consuming) plotting is still required even if commercial and academic software have tried to simplify this process.

Research has been concentrated in the improvement of the automation of both these processes to achieve 3D models or maps in a semi- or fully-automatic way. Several algorithms have been already proposed to classify, segment images or point clouds, and to automate the modelling of specific objects. These approaches are usually semi-automatic and the automation increases only when the algorithms are devoted to very specific applications.

Other authors have already suggested how to combine the use of LiDAR data and image information to reach highly versatile systems and new applications (Ackermann, 1999; Brenner, 2003), exploiting their complementary natures. In this way, new solutions of integration between these techniques have been investigated. Some papers consider this integration as a possibility of sharing the point clouds generated by these two kinds of instruments; other papers consider the integration as a possibility of improve (Alshawabkeh, et al. 2004) one technique through the other. Only a few papers have described this integration considering it as a sharing of radiometric and ranging information (McIntosh and Krupnik, 2002): anyway, the integration is usually performed after the data processing of each technique separately. A complete and automatic integration between laser scanner acquisitions and multi-image matching techniques has never been implemented.

Starting from the former works, a new integrated approach has been developed. This procedure is focused on the possibility of overcoming the individual weakness of each technique through their cooperation: this integration plays a main role in the proposed approach, fusing the image matching techniques and the point cloud data processing. These techniques work independently and the shared information is used as feedback to improve the reliability of the algorithms and to increase the completeness of their results.

The final goal of the approach is the automated extraction of the information requested in the 3D city modeling and in the map production or updating. This process considers RGB images and DSM provided by point clouds: until now, any multi-spectral image and multi-echo point cloud has been considered. The workflow of the algorithm is summarized in Figure 1.

The data are initially classified in order to extract man-made objects (buildings, roads, etc.) from vegetation and bare soil. In this step, images and point clouds are processed together, integrating the achieved results to improve their completeness and reliability.

The edge extraction is performed only in correspondence of roads and buildings; this process is focused on the regions characterized by high curvatures of the LiDAR data in order to define the breaklines in these areas.

Then, these edges are matched in the space according to a multi-image approach and they are filtered using the LiDAR information: blunders are deleted and the edges with a geometric correspondence are divided from the edges due to shadows or radiometric variations. In this way, the edges are only extracted along the breaklines of man-made objects, allowing their outline determination.

Finally, the edges are smoothed in order to regularize their shapes and to use them as input data in the modelling of buildings and roads or as starting point in the map production.

This approach has already achieved good results in terrestrial applications (Nex and Rinaudo, 2010) and it has given its first promising results in aerial applications too (Lingua et al., 2010), increasing the reliability of the results respect to a “single-technique” approach.

In this paper, the description of the last improvements of the approach (in the classification and edge extraction processes) for aerial applications and the achieved results will be presented and discussed more in detail.

This paper is a part of a more complex and ongoing work: the CIEM (3D Cartographic Information Extraction and Management) project, a Marie Curie - COFUND project at the Foundation Bruno Kessler - FBK in Trento.

8085-10, Session 2

Performance analysis of different classification methods for hand gesture recognition using range cameras

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Interactions between humans and computers are typically carried out using keyboards, mice and joysticks. In addition to being different from the natural human way of communicating, these tools do not provide enough flexibility for a number of applications such as manipulating objects in a virtual environment. In order to improve the human-computer interaction, an automatic hand gesture recognition system could be used. Hand gesture recognition is the process by which gestures made by the user are recorded by a camera and automatically recognized in real-time by computer software. Hand gesture recognition has gained popularity in recent years, and could become the future tool for humans to interact with computers or virtual environments.

Different approaches can be found in the literature related to hand gesture recognition. Early approaches make use of markers on the fingertips. An algorithm is then used to detect the presence and the colour of these markers in order to identify the fingers. Gesture recognition is currently performed through supervised classification processes where different features are used to represent the hand gestures and different classification methods are applied to predict the class membership. The reference gestures are stored in a database and the current gesture is matched with the most similar one available in the database. To perform the classification, a huge number of classifiers such as neural network, support vector machine, graph matching, inductive learning system, voting theory, hidden Markov model, mean-shift algorithm, chamfer distance or dynamic Bayesian network are used. Extensive training and testing are performed after acquisition of a high number of datasets from multiple users. A confusion matrix is generally presented to show the success rate.

Though several methods have been described in literature, a comparative study using the same hand gesture database is not available. The objective of the current research is to conduct a performance analysis of different classification methods using the same database of hand gestures obtained with a range camera. The motivation is to identify the appropriate hand model and classification method to be used for a desktop application where oil and gas reservoirs will be manipulated in a virtual environment making use of hand gestures only with images collected using a range camera.

The range camera used in this research is a time-of-flight camera (SR4000) meaning that the time taken for the light to travel from an active illumination source to the objects in the field of view and back to the sensor is measured. The camera provides both range and 2D intensity images at the same time using an integrated sensor. It has a low resolution of 176 × 144 pixels. Once the image is acquired, the range information is used for generating the x, y, z coordinates for each pixel in the camera space. The range camera produces images at a rate of up to 54 frames per second.

In this performance analysis, the five static gestures as shown in table 1, made of the number of raised fingers in a one-hand gesture are first considered. In addition, the gestures representing the following actions “grasping”, “translating and rotating,” and “releasing” will be added to the previous ones. The recognition is analyzed by considering the orientation of the hand gesture and the distance between the gesture and the camera.

The following feature vectors are considered: feature vectors extracted from principal component analysis, hand shape and its distance transformation image and statistical and geometrical parameters. Principal component analysis is used to extract feature vectors by defining an orthogonal space and projecting an image into that space. This method was used by Malassiotis and Strintzis (2008). Zhi and Ray (2009) represent the hand image by an edge image and a distance transformation image. A combination of statistical and geometric features has been used by Rashid et al. (2009). The statistical features are made of the seven Hu-moments derived from second and third order moments.

The following classifiers have been applied: K-nearest neighbour, chamfer distance, support vector machine and Bayes classifier. While support vector machines (SVMs) are considered by Liu et al. (2008), Malassiotis and Strintzis (2008) use the k-nearest neighbour. Zhi and Ray (2009) as well as Liu and Fujimura (2004) use the chamfer matching method to measure the similarities between the candidate hand image and the hand templates in the database.

This paper starts with a literature review of most recent classification techniques used for hand gesture recognition. The SR4000, range camera used is then described as well as the training and testing databases collected. Every classifier used to categorize the gestures considering each of the hand models is considered. The assessment is made in terms of overall recognition rate. The best feature vector and classification method are then implemented in a real-time application where the recognition time is analyzed.

This study provides the confusion matrix of every classification performed. For example, the recognition made by using k-nearest neighbour as classifier and principal component analysis feature vectors is presented in table 2.

For this classification, 150 images were used in the training database and 1311 images in the testing database. The overall recognition rate is 89.32%. Because 10.68% of the images were incorrectly classified, this study suggests as future work a new and more representative feature vector using the 3D data provided by the range image. The suggested representation of the hand gesture which has to be built from the segmented point cloud is supposed to contain five angles from 0° up to 180° between the five fingers of the hand and the palm plane and four angles from 0° up to 90° between the planes containing the five fingers which are perpendicular to the palm plane.

REFERENCES

Liu, X. and Fujimura, K. Hand Gesture Recognition Using Depth Data. In Proceedings of the sixth IEEE International conference on automatic face and gesture recognition, 17-19 May 2004, Soc pp529-34.

Liu, H., Ju, Z., Zhu, X. and Xiong, Y. Dynamic grasp recognition using time clustering, Gaussian mixture models and hidden Markov models, In Proceeding of the First International Conference, ICIRA 2008, 15-17 Oct. 2008, Springer-Verlag pp669-78.

Malassiotis, S. and Strintzis, M.G. Real-Time Hand Posture Recognition Using Range Data. Image and Vision Computing, 26(7), 1027-37, July 2008, Pages 1027-1037.

Rashid, O.; Al-Hamadi, A. and Michaelis, B. A Framework for the Integration of Gesture and Posture Recognition using HMM and SVM. International Conference on Intelligent Computing and Intelligent Systems 20-22 Nov. 2009, IEEE pp572-7.

Zhi, L. and Ray, J. Real Time Hand Gesture Recognition using a Range Camera. Conference on Robotics and Automation (Acra), December 2-4, 2009, Sydney, Australia.

8085-11, Session 3

Artefacts for surface measurement

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Flexible manufacturing technologies are supporting the routine production of components with freeform surfaces in a wide variety of materials and surface finishes. Such surfaces may be exploited for both aesthetic and performance criteria for a wide range of industries, for example automotive, aircraft, small consumer goods and medial components. In order to ensure conformance between manufactured part and digital design it is necessary to understand, validate and promote best practice of the available measurement technologies. Similar, but currently less quantifiable, measurement requirements also exist in heritage, museum and fine art recording where objects can be individually hand crafted to extremely fine levels of detail.

Optical 3D measurement systems designed for close range applications are typified by one or more illumination sources projecting a spot, line or structured light pattern onto a surface or surfaces of interest. Reflections from the projected light are detected in one or more imaging devices and measurements made concerning the location, intensity and optionally colour of the image. Coordinates of locations on the surface may be computed either directly from an understanding of the illumination and imaging geometry or indirectly through analysis of the spatial frequencies of the projected pattern. Regardless of sensing configuration some independent means is necessary to ensure that measurement capability will meet the requirements of a given level of object recording and is consistent for variations in surface properties and structure. As technologies mature, guidelines for best practice are emerging, most prominent at the current time being the German VDI/VDE 2634 and ISO/DIS 10360-8 guidelines. This paper considers state of the art capabilities for independent validation of optical non-contact measurement systems suited to the close range measurement of tabletop sized manufactured or crafted objects with examples drawn from work at UCL, UKAEA and NRC.

8085-12, Session 3

Illumination waveform optimization for time-of-flight range imaging cameras

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Time-of-flight range imaging sensors acquire an image of a scene, where in addition to standard intensity information, the range (or distance) is also measured concurrently by each pixel. An amplitude modulated light source illuminates the scene, and light is reflected from objects back to an image sensor, where the propagation time (flight time) introduces a phase shift in the illumination modulation envelope. The pixels within the image sensor are gain modulated at the same modulation frequency as the illumination source, correlating the received illumination waveform with the sensor reference waveform. From multiple (typically four) correlation measurements, the phase shift is calculated in order to determine the flight time, and hence object range for each pixel.

The phase measurement often assumes that the correlation waveform is sinusoidal, whereas typically the illumination and image sensor are amplitude modulated with digitally generated rectangular waveforms, leading to a triangular shaped correlation waveform. During sampling, harmonics within this triangular waveform are aliased onto the fundamental frequency component, resulting in a linearity error in the range measurement that is commonly corrected through calibration and post processing.

The calibration step can be avoided by removing the aliased harmonics from the correlation waveform. One simple means of achieving this is to employ sinusoidal amplitude modulation of the illumination source. Such modulation increases the complexity of the electronic drive circuit and can be difficult to achieve at high frequencies using LEDs. A similar reduction of selected harmonics can be achieved by reducing the duty cycle of the existing rectangular illumination modulation waveform. When four correlation measurements are used to calculate the phase shift, odd order harmonics are aliased onto the fundamental frequency component, corrupting the phase measurement. Of these aliased harmonics, the third order harmonic has the greatest amplitude, and therefore contributes the largest error. The harmonic content can be altered by reducing the rectangular illumination modulation waveform duty cycle. For example at 33% duty cycle the third order harmonic is minimized, with a corresponding reduction in the range measurement linearity error due to the less significant contribution from the fifth order and higher odd harmonics.

Figure 1 illustrates the measured RMS phase linearity error at different duty cycles using a laser diode as the illumination source and a Canesta XZ422 range imaging camera. For comparison purposes, measurements were made using both the standard homodyne configuration and applying a harmonic cancellation technique - where phase encoding is applied during the data acquisition to remove the odd order (aliased) harmonic components [1]. The standard configuration shows significantly smaller linearity error for illumination duty cycles near 33%, while the harmonic cancellation method maintains good linearity independent of the duty cycle used.

As the duty cycle is reduced, the average optical power also decreases, degrading range measurement precision. To overcome this issue it is suggested that the peak modulated illumination power be increased to maintain constant average optical power. In this case, while applying perfect rectangular modulation, the amplitude of the fundamental frequency component of the correlation waveform is proportional to sinc(π.dutycycle). This relationship is evident in the measured data in Figure 2, where the average optical power of the laser diode source remains constant while the duty cycle is changed. The results show an improvement in the measured amplitude, hence range measurement precision, for shorter duty cycle values. The harmonic cancellation technique also shows an attenuation of the measured amplitude inherent to the phase encoding method used.

By reducing the duty cycle the illumination modulation waveform to approximately 33%, while maintaining constant optical power, both the range measurement linearity and precision of a range imaging camera can be improved. However, in practice LEDs are frequently used as the illumination source, which, due to their limited rise and fall times, are unable to generate perfectly rectangular modulation waveforms. Despite this limitation, the same concepts can be applied to existing range imaging cameras by minimizing the most significant aliased harmonic and maximizing the peak amplitude. Figure 3 shows the resultant amplitude modulated illumination waveform of the onboard LED array on the Canesta XZ422 range imaging camera, where the LED drive signals have been adjusted in the camera software to minimize the third order harmonic. Range linearity measurements will be provided in the final paper using a linear actuator to precisely move a target over a 3.5m distance, using the XZ422 range imaging camera with the onboard LED array and the optimized drive signal timing.

[1] A. D. Payne, A. A. Dorrington, M. J. Cree, and D. A. Carnegie, “Improved measurement linearity and precision for AMCW time-of-flight range imaging cameras,” Applied Optics, vol. 49, pp. 4392-4403, 2010.

8085-13, Session 3

A descriptive geometry based method for total and common cameras fields of view optimization

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Adjusting cameras position and orientation is a crucial problem for many applications. In general, authors choose experimentally and empirically the cameras position and orientation by playing potential geometrical configurations using simulation. This process requires a lot of time to adjust approximately the field of view of the cameras around the monitored scene in terms of common and total fields. This is due to the fact that the desired optimal solution has relatively a small interval of variation. Indeed, a large variation in a camera's field of view results in a small displacement and/or orientation of the camera. Considering a multi-camera system, the objective is to optimize automatically both the total field of view of the vision system and the common field of view of all the cameras. In this paper we consider a vision system composed with two cameras. This work is a part of the PANsafer project (Towards a safer level crossing), supported by the French National Agency of Research (ANR).

Considering a vision system composed with two cameras, the goal is to determine the optimal position and orientation of the cameras in order to cover the desired area. The optimization process concerns the total fields of view of the vision system, but also the common field of view of the cameras for stereo vision use. The proposed method starts by maximizing the field of view of each camera with respect to the desired area. Depending on the obtained position of the cameras, one can then maximize the total field of view of the cameras by minimizing the common field of view, or minimize the total field of view of the cameras by maximizing the common field of view. Thus, if the cameras are close, the objective will be to maximize the total field of view by keeping the common field of view greater than a limit. Inversely, if the cameras are far, the objective will be to maximize the common field of view by keeping the total field of view greater than a limit.

The field of view of each camera being modelled by a pyramidal representation, the proposed method is decomposed so as the optimization process performs into several 2D domains. Using descriptive geometry, these domains are obtained by projecting the field of view on horizontal and vertical planes. Therefore, optimizing the total and common fields of view consists of optimizing the surface of the 2D domains.

The proposed optimization method is based on a descriptive geometry approach that performs on projection planes, while preserving the most useful properties. Three projection planes are defined for each camera: horizontal plane, vertical orientation plane, vertical projection plane.

The horizontal plane is simply the ground plane. The intersection of this plane with the field of view of each camera corresponds to the base of view of the camera. The ground plane contains the base of the polyhedron representing the common field of view of the two cameras. As the polyhedron is convex, maximizing the surface of its base leads to the maximization of its volume. The optimization process within this plane is based on two parameters: the gravity centre and the surface of the base of view.

Before defining the vertical orientation plane, it is important to precise that the objects to be detected and tracked enter the scene by two opposed sides (road sides considering the environment of a level crossing). The vertical orientation plane corresponds to the vertical plane representing the area limit to be monitored for each side to each the objects enter the scene. Initially, this plane may be far from the field of view of the camera so as there is no intersection between them. To reach this plane, intermediate vertical orientation planes are considered so as the first one intersects the field of view of the camera. The camera is then submitted to an orientation procedure for each vertical orientation plane: once the camera is oriented using a vertical orientation plane, another vertical orientation plane that intersects the field of view of the camera is considered to perform the same procedure until reaching the desired plane. As for the ground plane, the orientation procedure is based on the gravity centre and surface of the intersection between the field of view of the camera and each vertical orientation plane.

The vertical projection consists in projecting vertically and orthogonally the total/common field of view of the cameras. Based on the polyhedron convexity property, this projection leads to optimize (maximizing/minimizing) the common/total field of view, and allows to be sure that we obtain a sufficient height of view in order to detect big objects like trucks.

The whole optimization method is composed of three stages. In the first one, each camera position is determined separately using its corresponding ground projection plane. The process consists of moving the gravity centre of the base of view of the camera (intersection between the ground plane and the field of view of the camera) towards the desired point (centre of the surface of the desired area), using a centralization technique. The second stage consists in optimizing the position and the orientation of each camera separately using the ground and orientation projection planes conjointly. This is achieved thanks to the centralization technique and a surface maximization procedure. In the third stage both cameras are moved simultaneously using the ground and vertical projection plane conjointly. This process is achieved by optimizing the total and common surfaces simultaneously, considering the height constraint imposed by the vertical plane projection.

The proposed approach is tested to monitor the area of Figure 1, using a vision system composed with two cameras. Figure 2 shows the optimization processes corresponding to the three stages of the whole optimization algorithm. In Figure 2-1 (first stage), we can see that the centralization technique leads the gravity centres of the horizontal surfaces to the desired positions. Figure 2-2 (first stage) shows that the horizontal surface covered by each camera increases during the centralization process. Figure 2-3 (second stage) shows the optimization of the field of view of each camera (in terms of horizontal and vertical surfaces) during the orientation stage. In Figure 2-4 (third stage), one can see the evolution of the total/common horizontal and vertical surfaces, where DTHD and DTVD are the desired total horizontal and vertical surfaces, respectively, and DCHD and DCVD are the desired common horizontal and vertical surfaces, respectively. We can see that the obtained surfaces are very close to the desired ones.

8085-14, Session 3

Experiences of image sequence orientation in close-range photogrammetry

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Automatic image orientation of close-range image blocks is becoming of increasing importance in the practice of photogrammetry. The competition of laser scanning for 3D recostruction is indeed pushing also photogrammetric software companies to develop tools for markerless image orientation (see for instance the recent release of Photomodeler 2010 by EOS company). While image orientation based on interactive measurement of tie points does not require any preferential block structure, when automation is desired the use of sequences can help carried out this task. Moreover, sequences are directly captured by cameras mounted on vehicles, either in the case of MMTs and aircrafts.

Automatic orientation of image sequences has been widely investigated in the Computer Vision (CV) community. Here the adopted approach is generally named "Structure from Motion" (SfM), or "Structure and Motion." These both refer to the simultaneous estimation of the image orientation parameters and 3D points of a sequence from a set of image correspondences. These methods usually start with a robust identification of interest points on the images, then a subset of images (generally an image pair or a triplet) is oriented, and all the other images are progressively concatenated up to a final bundle adjustment. Some of these methods are termed "uncalibrated", meaning that interior orientation parameters and distortion coefficients are initially unknown, but derived during the processing or from the image EXIF information. Such approaches, that disregard camera calibration data and the absence of a bundle adjustment with all the statistical analysis of the recovered parameters do not ensure an accurate reconstruction, which is a requirement for photogrammetric projects. The major contribution of SfM is therefore viewed in the photogrammetric community as a powerful tool to provide a dense set of tie points as well as initial parameter values for the bundle adjustment.

Although developments from a theoretical side continue, there are a number of questions that are still open. Some of these have more to do with old-fashioned but sound photogrammetry than with feature extraction and matching. In this paper, after a brief description of two SfM strategies, results of a series of image sequence orientation cases will be shown. Based on the characteristics of the sequences, that refer to different cases in terms of imaging geometry, object texture and shape, a discussion will be made about the problems faced and the strategies implemented to overcome them. The goal of the paper is therefore more of a discussion on “photogrammetric engineering” rather than on theoretical issues.

The first two case studies were oriented by using the SfM approach developed at the University of Parma, Italy.

The first sequence has been taken in a tunnel to provide the rock mechanics experts with a dense DSM to be used to study the tunnel stability. The time constraint for image acquisition was a prerequisite, since escavation in the tunnel could only be stopped for a few minutes. With a specially designed device, from each camera station six images were taken to cover a section of the tunnel vault. Moving forward with the camera, a new set of six is acquired which overlaps with the previous. Overall a total of 6x130 images were oriented along 6 separate strips, put toghether later still with an automated procedure.

The second sequence is made up of stereo-images captured from a MMT van along a countryside road. The imaging geometry is completely different and very unfavourable. Also the backgroud is not rich in details that could be easily traced along the images. The goal in this case was to study whether a photogrammetric orientation might replace GNSS data during outages. A total of 91 image pairs along a road stretch of almost 300 m were oriented with camera station errors largely below 1 m.

The last two case studies were afforded by using ATiPE. They concern a long image sequence taken from inside the well-known Piazza Navona in Rome with a calibrated SLR camera, and a block taken over an archeological site in Honduras (Copan). In the last case, images were captured by using a camera mounted on a mini-helicopter. These examples will be shortly discussed because they have been already presented in previous papers.

The core of the paper is represented on the next section. Here some relevant topics which concern the orientation of image sequences in close-range are discussed.

These topics will include first an analysis of the block structure. At the time of analogue metric cameras (especially in the field of Cultural Heritage documentation), terrestrial blocks were organized in a manner very similar to the aerial ones. Then, the introduction of semi-metric reseau-cameras first, and then of digital sensors, was coupled to block configuration with convergent imagery. The use of image sequences comes from CV, but today it has become popular in photogrammetry as well. A sequence can be considered as the elementary image structure in close range, as the strip is in aerial photogrammetry. This is true especially in the case of large objects’ survey. Are there rules for the organization of the sequences among them (overlaps, cross-strips, scales, tie point redundancy, ...).

The second topic will concern the use of ground constraints, compared to the one of inner constraints (free-block adjustment). Also the integration of both at different stages will be analysed.

Different SfM methods utilise feature- and also area-based matching techniques. These are capable of providing different precisions, which deserve a detail discussion including a comparison with: processing time, strategy for point transfer, interest operators to be used, image normalisation. Another question in this topic is related to the use of stereo or multi-photo matching techniques.

A further topic is related to the possibility of a preliminary image processing in order to improve performances of matching techniques.

Eventually, some issues about ouliers rejection and bundle adjustment model and strategy will be addressed.

These topics will be discussed and documented on the basis of the reported examples.

Automation of orientation in close range photogrammetry seems to become a totally overcome problem in a few years. The same process occurred in the past for automatic aerial triangulation. On the other aim, this paper points out that there are many issues which still deserve analysis and discussion in the scientific community. This is really important today, where researchers exploits results obtained from two parallel worlds (Photogrammetry and Computer Vision), but with poor occasions of common discussion and comparison between them.

8085-15, Session 3

Geometric investigation of a gaming active device

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While 3D imaging systems are widely available and used for surveying, modeling and entertainment applications, clear statements about their characteristics, performances and limitations are still missing. The VDI/VDE and the ASTM-E57 committees are trying to set some standards but the commercial market is not reacting properly. Since many new users are approaching these 3D recording methodologies, clear statements and information to know if a package or system satisfies certain requirements before investing are fundamental for those who are not really familiar with these active sensors.

Recently small and portable active sensors came on the market, like TOF range-imaging cameras or low-cost triangulation-based range sensors. A quite interesting active system was produced by PrimeSense and put on the market thanks to the Microsoft Xbox project with the name of Kinect. The Kinect sensor consists of an IR emitter and a CMOS camera, coupled to produce in real-time dense 3D point clouds of the irradiated scene based on the light coding principle. The article reports the geometric investigation of the Kinect active sensors, considering its performances, the accuracy of the retrieve range data, the influence of light and scene materials and the possibility to use it for 3D modeling application.

8085-16, Session 4

Industrial photogrammetry: challenges and opportunities

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Optical 3-D measurement systems based on photogrammetric methods are increasingly and successfully being applied in industrial applications, covering different sectors like automotive or aerospace industries, research facilities like particle accelerators but also emerging technologies like renewable energy.

The systems are utilized throughout the whole product lifecycle - ranging from applications in R&D, development, testing, manufacturing and final quality control.

Like the whole market for optical three-dimensional technologies it is a rapidly growing technology sector. As the boundaries to other optical technologies like laser triangulation sensors, white light scanning or even tactile measurement systems are narrowing, an overview of technologies used and the relevance of photogrammetric solutions in the different applications and sectors will be given.

The paper then describes state of the art and recent developments in camera technology, calibration, software and tooling utilized in industrial photogrammetric systems. Special emphasis is given on systems for dynamic measurements with regards to the growing demand in in-line, tracking and positioning applications. Here the technology offers unique possibilities and advantages that are difficult or sometimes even impossible to be realized with traditional measurement technologies.

The third part focuses on the requirements for industrial testing and inspection relating to robustness, speed, accuracy and handling, but also in post-processing like CAD or GD&T analysis and reporting. Many inspection processes and dimensioning schemes were designed for classical CMM measurements and are not easily adapted to new technologies. Tolerances and thus required measurement accuracies can be quite different for features in the same drawing. Some of these features like natural edges are hard to measure accurately with optical technologies. Here very often additional optical tooling is required to match the specifications, in turn limiting the classical advantages of photogrammetry like speed and ease of use.

Another topic in this part is related to acceptance and certification of optical technologies. Here the definition of standards like VDI 2634 has led to a significant improvement. The perception of photogrammetry as a tool used by experts has changed. In some areas photogrammetric measurements are even an industry standard today, especially in large volume measurements

There are numerous successful installations of photogrammetric systems in industrial applications. Several examples have been selected to demonstrate the variety of installations. These application reports will include the technical background of the application, technical realization and a summary of the benefits to the users compared to other technologies.

Examples from different industries haven been chosen to give a broad overview in testing and inspection applications, dynamic and static measurements and integrated or stand alone solutions.

8085-17, Session 4

Integration of photogrammetry and acoustic emission analysis for assessing concrete structures during loading tests

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Loading tests of concrete structures are often used in civil engineering to prove the load bearing capacity of structural elements in cases, where a numerical assessment is not possible or requires an enormous effort. Especially the behaviour of constructions with no or little ductility is difficult to evaluate because of their low advance notice of failure. This applies for instances to components without shear reinforcement. In this context the term "advance notice" refers to the determination of the ultimate test load, the exceeding of which causes irreversible damages of the tested structure. The idea of instrumental load test monitoring by modern measurement methods is the detection and assessment of smallest structural changes in the tested structure in order to release an immediate warning and to stop the experiment. This way, intolerable damages or even the complete destruction of the structure during the load test can be avoided with sufficient certainty. The combination of complementary monitoring techniques enables a significant improvement of the information quality during the loading tests, so that the real-time evaluation of the measurement results may allow for the definition of objective criteria for the ultimate test load.

The paper focuses on space- and time-resolved crack detection in concrete structures by combining photogrammetric techniques with acoustic emission analysis. In the experiments presented here, reinforced concrete is investigated in tensile, bending and shear tests. For the photogrammetric measurements, the surface is textured by a random pattern. A consumer-grade digital camera is used to observe the region of interest during the loading tests. In a sequence of images, cracks are detected by detecting discrepancies in local displacement vector fields, which are obtained from matching algorithms applied to consecutive images. The analysis is based on a two-dimensional distortion of the concrete samples, as movements in depth direction are considered negligible. The results obtained from the photogrammetric measurement system were validated by strain gauges. In several tensile tests, local displacements could in fact be measured before the development of cracks, although the advance notice time was too short to admit an intervention. Thus, the distinction between the detected cracks or even the evaluation of the ultimate test load of the concrete sample exclusively on the basis of visual crack detection turned out not possible.

Comparing the measured principal deformation strain with acoustic emission analysis allows the combination of the internal and external condition of the structure. Therefore critical areas of concrete samples are equipped with several acoustic emission sensors to monitor the crack formation and propagation. The plastic deformation of concrete structures is connected with the gradual development of cracks and is located in the area of their tips. The associated acoustic emission spread throughout the entire body in shape of an elastic wave from the place of development. Parameter-based acoustic emission analysis is used to record specific parameters in real time, like the duration or energy of the acoustic signals and enables the distinction between bending or shear cracks depending on the signal energy. During the loading tests, information about crack growth can be used to derive the time of transition from stable to instable phase. The acoustically detected shear crack can now be monitored in the images to track his growth and to interrupt the experiment if necessary. Thus, shear cracks can be localized temporally and locally on the surface and inside the structure. Detailed information about crack width and crack edge displacement will be examined in further investigations.

In a next step, the detected cracks are checked for certain properties providing information about the condition of the structure. Indicators with high level significance referring to structures with no or low advance notice of failure constitute a focal point of further research.

8085-18, Session 4

Vibration measurement of a model wind turbine using high speed photogrammetry

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To meet the growing demand for sustainable energy, wind turbines have to be made more powerful and efficient. A design challenge is the aero-elastic stability limit of the blades. This can be analyzed by the vibrations that occur on the blades during operational conditions. In this study high speed photogrammetry is used to measure blade vibrations of a model wind turbine during a wind tunnel experiment.

By placing circular retro-reflective targets on the blades of the wind turbine and taking images with two synchronized high speed cameras, the motion of the blades is captured. High speed cameras produce a large number of images in a short time, making manual target measurement impractical. This study concerns automation of target measurements in high speed images and investigates the accuracy of reconstructed object coordinates.

A method is developed for target detection and tracking by exploiting the knowledge about the circular motion of the targets. The targets are detected in the images using a histogram thresholding segmentation. Since the targets describe a circular motion, a circle is used as model to track the position of the targets in the sequence of frames. To measure the center of the circular targets with sub-pixel precision, the edges of the targets are detected and a circle is fitted to the edges.

To reconstruct the object coordinates the Direct Linear Transformation (DLT) is used in two steps. In the first step, the DLT parameters are estimated using the corresponding targets in the first image of each sequence. In the second step, the object coordinates of the targets are computed by performing a forward intersection in all successive image pairs.

An experiment was conducted in a wind tunnel with a model wind turbine rotating at a speed of about 260 rpm. Images were acquired at a frequency of 500 frames per second for the duration of 1.6 seconds using two synchronized high-speed cameras in a convergent setup.

A total of 32 targets were successfully measured and tracked in the two image sequences, and 3D object coordinates were computed for all targets. An evaluation of the reconstructed targets showed a positional accuracy of 1.3 millimeter.

Using the images of the experiment, a robustness analysis was carried out for the developed method for automatic target measurement and tracking. From this analysis, it could be concluded that targets can be precisely measured and tracked in high speed images works, even in the presence of outlying features or noise. The target tracking and establishing correspondence could be performed successfully for an acquisition frequency of 125 Hz and higher.

The vibrations of each target were obtained by applying a Principal Component Analyses (PCA) to its reconstructed 3D track. The PCA provides the axes of maximum and minimum variation of the 3D track of a target. The first two axes represent the plane of rotation while the third axis signifies the direction of vibration. The measured vibration had a maximum amplitude of 6 mm, with an accuracy of 0.56 mm. In conclusion, the experimental results demonstrate the capability and accuracy potential of high speed photogrammetry for vibration measurement of wind turbines.

8085-19, Session 4

Use of 3D range cameras for structural deformation measurements

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Three-dimensional (3D) range imaging camera systems are a recent development for close-range imaging applications. They operate based on the phase-shift principle to determine the distance between the target and the camera. Each pixel in the sensor frame independently measures distance and amplitude information of the scene which is realized through CCD/CMOS lock-in pixel technology. The range and the amplitude information are obtained simultaneously by sampling the returned modulated optical signal at every element location of the solid-sate sensor. The use of range cameras has been reported for applications such as robotic and machine vision, hand gesture recognition for human-computer interaction, 3D sensing for automated vehicle guidance and wheelchair assistance, outdoor surveillance, and biometric applications such as facial recognition through enhanced depth mapping.

One close-range high-precision application for which range cameras are well suited is the measurement of structural deformation. Structural deformation measurements are particularly important for civil engineering in order to assess the strength of beams, columns, slabs etc. under different loading conditions. Moreover, the structures used in buildings and bridges are subject to fatigue while exposed to various environmental forces leading to strength deterioration. Therefore it is necessary to assess the health of the structures in order to mitigate any impending danger of structure failure. One method of assessing the health of the structures is by measuring the beam deflection under external loading in a laboratory setting. Figure 1 shows the schematic representation of simply-supported beam at the zero load and loaded states. When a beam is subjected to the load, the beam bends as shown in Figure 1 (Right). The quantification of the beam deflection is the subject of interest of this research.

Beam deflections can be measured using 1D laser transducers, photogrammetric systems comprising multiple digital cameras and terrestrial laser scanner systems. The use of a miniaturized range camera for structural deformation measurement can be considered superior to the terrestrial laser scanner for a number of reasons. First, a range camera's 3D point cloud data are captured simultaneously rather than sequentially, which facilitates faster field operation. Second, its compact size allows greater accessibility in congested sites. Third, a range camera is many times cheaper than a scanner system. A range camera is advantageous over a multiple-camera photogrammetric system because it can directly obtain the 3D information of the scene using only one camera without having to undergo tedious processing steps required for the stereo-photogrammetry. Lastly, the range camera is a viable alternative to the 1D laser transducer because it can provide a dense point cloud of the surface unlike the single-point measurement of a laser transducer.

However, range camera data suffers from various systematic error sources. Some rangefinder biases like the rangefinder offset, cyclic and clock-skew errors can be corrected using physical models whose parameters are determined by self-calibration. However, scene-dependent errors such as the internal scattering artefact and multi-path errors are difficult to model with a physical basis in complex 3D scenes. Nevertheless, the results of empirical experiments on the scattering effect have shown that the SR4000 range camera is less affected by the scattering errors by an order of magnitude less than the earlier-generation SR3000 camera. Therefore the use of the SR4000 has been investigated for potential use in structural deformation measurements.

The beam deflection at any loading state is equal to the vertical measurement at that loading state minus the vertical measurement at the zero load state. If it is explicitly assumed that the scene-dependent biases are equal at all the measurement states, then the subtraction method cancels out any un-modelled scene-dependent errors associated with the vertical measurements.

A deformation measurement test has been conducted on two concrete beams, one with and one without steel-reinforced polymer sheets, in an indoor testing facility. A hydraulic-actuator having a maximum force capacity of 250 kN was used to apply load to the beam at the rate of 1 mm displacement of the beam per minute up to the point of the failure. The failure of the beam was observed at a nominal deflection of 65 mm.

The deflection measurements from the range camera are compared with those from a Leica HDS 6100 terrestrial laser scanner, which is a well proven technology for deformation measurements. The result shows that the measurement precision and accuracy for the deformation test for both the concrete beams are within 1 mm. Figures 2 and 3 show the overlay of deflection curves from the terrestrial laser scanner and the range camera, and the deflection errors of the range camera, respectively, for one of the concrete beam tests. Further tests on the concrete beam with the steel-reinforced polymer sheets has shown that even 3 mm deformation can be reliably detected with measurement precision of 0.3 mm and an accuracy of 0.4 mm. These results clearly indicate the high metric potential of 3D range cameras in spite of their coarse imaging resolution and low single point accuracy.

8085-20, Session 5

Low-cost human motion capture system for postural analysis onboard ships

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Human postural stability is a multidisciplinary topic involving several sciences and disciplines, since it has a profound impact on many aspects of everyday life. How individuals maintain balance, employ correct and efficient postural strategies, are able to prevent falls and occurrence of severe injuries are questions that relate to medicine and neurophysiology, biomechanics and robotics, as well as occupational safety, ergonomics and sport applications. Many different disciplines use motion analysis techniques for recording human movements and posture, including medicine, biomechanics, computer animation, virtual reality, etc. Both research and commercial applications involve measurement, modelling and motion capture of the whole body or single parts (as human face). Consequently, different approaches and systems have been developed and they vary depending on the requirements. Systems for body measurement and motion capture can be roughly classified in direct measurement techniques (mechanical, magnetic, acoustic and inertial trackers) and optical methods (structured light systems, laser scanning, image-based techniques). Among the wide range of existing methodologies and technologies, the choice of instrumentations and sensors depends on the requirement of the specific experimentation.

Postural stability is a critical matter as far as the naval and commercial ship sector is concerned, since ship motions heavily influence human performance and can negatively affect safety of personnel working on deck. In any motion environment, losing balance is a likely event and potentially its occurrence increases with worsening sea conditions.

Several models have been proposed for predicting loosing of balance events, named Motion Induced Interruptions (MIIs) in naval jargon, or simulating the postural behaviour of a crewmember onboard sailing vessels. The commonly used model proposed by Graham assumes the individual to react as a rigid body and underestimates the human capacity to counteract external disturbances (i.e. ship motions). More complex postural models have been proposed but have to be validated.

Validating theoretical models necessitates many experiments to be conducted, in order to obtain relevant (statistically) data and infer significant results. A general procedure should require having one or more ships completely available for executing a set of trials in different environmental conditions, testing many individuals involved in several tasks. This would be an "optimum" for obtaining data in a real environment, without the limitation on motion magnitude imposed by motion simulators, but would result in unbearable costs. In this field, the location where the experiments have to be conducted differs substantially from any conventional ashore laboratories. The need of capturing the motion of an individual standing on a ship during its daily service does not permit to employ the optical systems commonly used for human motion analysis. These sensors are not designed to operate in disadvantageous environmental conditions (water, wetness, saltiness) and with not optimal lighting.

The solution proposed in this study has consisted in developing a motion acquisition system that could be (i) easily usable onboard ships while accomplishing their daily mission and (ii) handled even by only one person for minimising the encumbrance onboard.

These characteristics and drawbacks have led to set up an “ad-hoc” motion capture system, whose peculiarities were:

- ease to use and calibrate even in disadvantageous conditions, as on a ship’s deck;
- speed in setting up in different configurations and removing it in order to not hinder the normal execution of onboard tasks;
- flexibility for being employed on a movable platform, in cramped spaces, in unfavourable lighting conditions (also in the dark);
- taking up a minimal amount of space;
- to be integrated with sensors for measuring ship’s motions;
- to be portable on different platforms, without interfering with onboard work.

Taking into account the specified requirements, the measurement system has been realised by using two different methodologies: (i) motion measurement with Inertial Measurement Unit (IMU) and (ii) motion capture with videogrammetry.

The used inertial sensor is a lightweight, portable system composed by a master and up to ten small inertial units. This kind of device is particularly suitable for biomechanics, rehabilitation, and all the applications that need to acquire human movement without any mechanical interference or constraint. The developed image-based motion capture system is made up of three low-cost, light and compact video cameras and different kind of supports.

Before the execution of onboard trials, laboratory tests have been conducted for testing and validating the proposed motion acquisition system. A comparative analysis has been conducted between the inertial and videogrammetric methodologies; to this purpose, suitable devices and own-developed software procedures have been realised. Moreover, experiments using a commercial optical system have been performed in order to test the overall accuracy and reliability of the presented motion acquisition system.

In this paper, the whole process of planning, designing, calibrating, and assessing the accuracy of the motion capture system is reported and discussed. The motivations that were at the basis of setting up this “ad hoc” acquisition system are analysed. Results from the laboratory tests and preliminary campaigns in the field are presented.

8085-22, Session 5

Shadow correction in high dynamic range image for generating ortho photos

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High dynamic range imagery is widely accepted in remote sensing. With the spread of aerial digital camera such as DMC (Intergraph Z/I Imaging, 12bit), ADS40(Leica Geosystems, 12bit), RMK-D(Intergraph Z/I Imaging,14bit) and UltraCamD(Vexcel Imaging, 12bit), high dynamic range image is enormously expected for generating minuteness ortho photo in digital aerial photogrammetry. However, high dynamic range image (12 bit; 4,096 gray level) is generally compressed into 8 bit depth digital image (256 gray level) due to huge data, and peripheral such as monitor and printer. This means that many image data is eliminated from original data, and it is faced with a new shadow problem. In particular, influence of shadow in urban area cause serious problem for generating minuteness ortho photo and house detection. Therefore, shadow problem comes down to image compression problem.

There is a large body of literature on image compression techniques such as logarithmic compression and tone mapping algorithm. However, logarithmic compression tends to cause lost of detail in the dark and/or light areas. Furthermore, the logarithmic method intends to operate the full scene. This means that high-resolution luminance information cannot be brought out. While tone mapping algorithm has ability to operate the full scene and the local scene, background knowledge is requested. In order to resolve the shadow issue in digital aerial photogrammetry, shadow area should be recognized and corrected automatically without lose luminance information.

With this motive, practical shadow correction method was investigated in this paper using 12 bit real data acquired by DMC. Detail procedures and analysis will be discussed in this paper, but following is remarkable feature in the proposed method.

1) Segmentation

High dynamic range image is converted into gray scale image at the first step, and the gray scale image is segmented into 4 categories automatically including the shadow areas using automatic threshold method which has proposed by Otsu.

2) Correction

After automatic recognition of the shadow areas using feature of histogram for the 4 categories, the shadow areas are identified and corrected using statistical values. Furthermore, edge line around the shadow areas are erased by smoothing. Finally, corrected image is converted into 8 bit image.

Figure 1 shows corrected image by logarithmic method, tone mapping algorithm and the proposed method. It can be seen that the inside of shadow areas are corrected and clearly visible in the proposed method instead of barely visible in logarithmic method.

On the other hand, while tone mapping algorithm shows the same results compare with the proposed method, it should be noted that each shadow area is identified in the proposed method. This means that the proposed method has ability to detect house or changing subjects in the shadow area for post procedures. In particular, detection of house and changing subjects in urban area is important issue in digital aerial photogrammetry. Consequently, it is concluded that the proposed method is effective shadow correction method in digital aerial photogrammetry.

8085-23, Session 5

An approach for the calibration of a combined RGB-sensor and 3D-camera device

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In applications such as mobile robotics, range cameras offer many advantages compared to established devices such as laserscanners or stereo-cameras. An important advantage is their mono-sensorial simultaneous of data capture. The resolution of a typical 3D-camera is 25Hz in time and 204x204px in space. This allows using this type of sensor to observe dynamic 3D processes or acquire data on a mobile platform. Mobile robots may also be interesting for applications in agriculture, e.g. in precision farming. Here, in addition to 3D-data, there is often a necessity to get color information (RGB plus possibly NIR) for each 3D-point. This facilitates to segment and classify plants and their background. It may also be useful to distinguish plants (to be harvested) and obstacles (to be circumvented).

Common 3D-cameras are not able to capture color data. Therefore it is necessary to combine a 3D-camera and an additional RGB-sensor. A rigorous system calibration is needed to get the right color for each 3D-point. This paper will present calibration methods and discuss their accuracy potential. Based on a spatial resection and bundle adjustment, the algorithms determine the translation and rotation between the two sensors and the interior orientation of the used sensors. Using the collinearity equation and the calculated orientation parameters, it is possible to calculate the 2D-position on the RGB-sensor for each 3D-point to get its color information.

The developed calibration principles can be divided into two types. Type 1 work with the 3D-camera treated as ‘passive’. In this case, the relative orientation parameters between the two devices are determined in a bundle block adjustment with multiple images of the 3D camera and the RGB camera. Only the 2D intensity data of 3D-camera is used for calibration, i.e. the 3D-camera alone is not used for 3D-point calculation. Type 2 makes more use of the capabilities of the 3D-camera. The 3D-camera is used here in an active way to get 3D-data for calibration. Methods based on single 3D-point or 3D-object tracking are developed to get calibration data. When tracking a single 3D-point, the target is measured via ellipse fit in two images. After finding more than three corresponding points, we are able to estimate parameters of transformation. Further methods works with 3D objects. The advantage of them is to fit known 3D-objects into a 3D-point cloud and get an adjusted 3D-position. In comparison with a planar ellipse fit 3D-objects increase the depth accuracy. 3D-objects could be spheres, edges or corners. For this objects, many single points of 3D-camera are used to estimate the parameters of it. For instance, we are able to calculate different planes and intersect them to get an edge. Redundancy and the known geometry model can be used to find outliers and improve the accuracy of a 3D-object the accuracy of calculated edges and corners are often better than that of a single 3D-point. Capturing planes in 3D-camera data may show some problems, for instance multi-path or scattering. So another type of 3D-object should be used. Spheres also allow finding corresponding points on two sensors, and it is possible to interpolate the range of it. Errors such as multi-path or scattering are smaller or not existing with this configuration.

The accuracy of calibration depends strongly on accuracy of the 3D-points. Type 1 calculates 3D-points via bundle block adjustment and delivers highly accurate 3D-points (sigma-0: 0.03mm, standard deviation of translation: 0.7mm, standard deviation of rotation: 0.005 degrees) through high redundancy, multi-image processing and adjustment. This accurate but complex method offers a very good accuracy for calibration parameters and will be used as reference for further methods. Type 2 gets 3D-points via range data and geometry models obtained from the 3D-camera. It is easier to get 3D-points, but the accuracy of a single point (standard deviation in depth: 0.5-1cm) is worse than with type 1. For this reason, the precision of the calibration parameters is also degraded (standard deviation of translation: 3mm; standard deviation of rotation: 0.5 degrees).

3D-objects like spheres or corners have not been tested yet, but will likely improve the single point accuracy and thus the precision of the calibration parameters. The reason for this is the fit of a mathematic model into a point cloud with the object parameter precision being much better than the single point precision due to the redundancy in the fitting process.

8085-24, Session 5

Least squares embedded particle filter for model-based 3D object tracking

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1 Abstract

Tracking the pose of a known 3D object from image is a common computer vision task with a variety of applications from manufacturing to augmented reality.

In this paper a novel model-based 3D tracking approach, called the least squares embedded particle filter (LSPF) is proposed.

The proposed approach uses edges as features to track and uses distance transform to measure the model-to-image distance.

Firstly we show how to use the distance transformed image to track 3D object with least squares and particle filter respectively. The complementarily aspects of the two approaches are analyzed. Finally, to design a robust tracker combining the advantages of probabilistic approaches and deterministic approaches, LSPF is proposed by embedding least square into a particle filtering framework to guide the particle set toward the peaks of the distribution.

Experiments on simulated and real video sequences show the good accuracy and robustness of the resulting tracker. It has the ability to track full 3D pose of the objects with roughly 80% fewer particles; converges fast to the correct pose in the circumstances of large displacements, partial occlusion, light changes, shadows and dense clutter.

2 Methodology

Classic registration approaches for model-based tracking try to find the pose which provides the best alignment between the projected edges of a 3D model with the edges of the image.

In many related works, the distance measurement for edge registration is performed by 1D searching along normal to the projected lines of the model. Instead in this paper, we use distance transform because it is more efficient than normal searching.

Given the distance transformed image, least squares and particle filter based 3D tracking approaches are described respectively. The least squares based 3D tracking approach (LS for short) is deterministic, while the particle filter based one (PF for short) is probabilistic.

In LS optimization, a few iterations lead to the minimum of the cost function with good accuracy.

However, this bottom-up approach presents some limitations. It is of low robust and can fall in a local minimum. The deterministic nature of the approach makes it fail in case of occlusion (partial occlusion, complete occlusion, self-occlusion due to aspect changing), dense clutter, large displacements, or fast movement. LS approaches are fundamentally uni-modal in that they calculate a single pose for each frame, which then provides a single prior pose for the next frame; if the estimate is sufficiently incorrect, tracking will fail. Moreover, as for any registration approach, the frame to frame motion needs to be small for the tracker to converge, and it would benefit from temporal filtering.

Particle filter provides an alternative approach to propagating pose estimates. It uses a set of hypothesis on the possible camera poses (the particles). In this paper, the confidence level (likelihood) of each particle in the PF tracker is evaluated in the distance image. The ability of the particle filters to deal with non-linearity and multi-modal non-Gaussian statistics suggests the potential to provide improved robustness. By estimating the density of probability, several modes can simultaneously be hold.

Nevertheless, the accuracy depends linearly on the number of particles. A balance has to be found between increasing tracking accuracy and reducing computational time. Since the space of all possible poses is large, one difficulty is to keep a fair representation of the different modes of the state probability distribution while using few particles.

To keep the advantages of both LS and PF trackers, we proposed to embed least squares into a particle filtering framework. In the proposed LSPF approach, the LS tracker is applied to each particle of a particle filter to guide it toward the local maxima of the likelihood function (i.e. the peaks of the distribution).

In order to use the new particle set without destroying the original distribution, we adopt the importance sampling technique. Therefore, only a small number of particles are needed in LSPF although the state space is large. The decrease in the number of particles introduces a loss of accuracy that is compensated by the optimization methods which finds the mode of the distance function. Furthermore, thanks to the prediction, it reduces the number of iterations required in the LS minimization.

At the end of the LSPF in each frame, we output the most likely particle as the tracking result.

By combining deterministic and probabilistic approaches, good robustness provided by particle filter and high accuracy ensured by least squares can be simultaneously maintained.

3 Approach summary

Given the particles set at previous frame, the proposed LSPF approach performs the following steps:

(1) Resample

(2) Propagate the particles according to the motion model.

(3) Optimize each particle by LS. A set of optimized particles is obtained.

(4) Combine the propagated particle set and the optimized particle set.

(5) Weight each particle by importance sampling.

(6) Estimate the tracking result as the most likely particle.

In the above steps, hidden line removal is done for each particle in each step. Tracking initialization is implemented by a manually PnP algorithm. Image processing for each frame involves radial distortion removal, edges detection, distance transform, etc.

4 Experimental results

Experiments have been conducted on video sequences using this approach.

5 Conclusions and Future Work

By combining deterministic least squares optimization and probabilistic particle filtering approaches, we proposed a robust approach which allows tracking the 3D pose of a known object. The proposed approach has proved to be able to track object using roughly 80% fewer particles. Experiments on simulated and real video sequences show the good performance in presence of ambiguities, dense clutters, large displacements, fast motions, severe occlusions and illumination changes.

Further work will be exploring the parallel power of graphics processing units (GPUs) for hidden line removal, confidence level computing, so as to build a real-time system.

8085-25, Session 6

Comparison of single view calibration methods

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In order to resolve interior parameters of camera geometry lot of effort has been put to automate the process. In photogrammetric community the problem solution has been sought by using coded targets and applying non-linear model in order to find accurate values for interior camera parameters. An alternative approach, popular especially in computer vision applications has been to discard the targeting and use existing geometric properties of scene to solve intrinsic parameters instead i.e. parallel lines and orthogonality of line sets. However, in most cases the parameters to be solved has been restricted to linear components of camera model. In this paper we compare the accuracy of three alternative single view calibration approaches with results from multi-station, multi-image calibration. The idea is to study the accuracy and reliability of alternative mathematical models to solve intrinsic parameters of camera from single view geometry.

Utilizing parallelism of straight lines in camera calibration concentrates on finding vanishing points in perspective image. The known fact is that parallel lines on scene under perspective projection will be seen on image plane as a converging line set which will intersect in a single point i.e. vanishing point. This has been knowledged among artists for ages and used as a tool to depict perspective view on canvas. To use parallel line sets, which in addition are orthogonal to other line sets, in camera calibration have been studied since 1960's (Gracie 1968). Although the approach has become more practical and tempting with coming of digital imaging and development of digital image processing algorithms. New dawn of camera calibration with vanishing points has appeared in 1990's and beginning of 2000. The research has diverged to apply purely algebraical model (Hartley & Zisserman 2000) or geometric interpretation of relation of camera parameters and vanishing points of orthogonal line sets (Grammatikopoulos et al 2004). The later approach is more close to approach presented on 1960's with the distinction how the relation between camera parameters and vanishing points are represented.

The research work done in this area has inspired us to look at calibration approaches from the accuracy and reliability point of view. Therefore, we have implemented our own algebraical, geometric, and point wise camera calibration program code to compute parameter values with these three alternative methods and compare them with the reference values. For the reference values of comparison, camera calibration is computed with multi-station, multi-image calibration method. These values are assumed to be near "true" values and adequate for comparing accuracy of camera parameters computed with three alternative methods.

This study concentrates on solving principal point co-ordinates, principal distance (camera constant), and first parameter of radial lens distortion. As the calibration object we have used a three dimensional calibration grid, where we have over 80 retro reflecting targets. The targets are used in computation of point wise method and 3D co-ordinates of targets needed in computation are from separate mensuration. For the other two methods image observations are line pixels from edge detection. The object itself is a rectangular 3D grid, which has six aluminum bars in each three principle directions. With three vanishing points we only can resolve three camera parameters from a single view. Therefore, the radial lens distortion parameter will be solved at separate stage assuming edge lines are straight.

The authors are aware of possibility to use multiple views and this way include more parameters in computation. However, in this paper we have concentrated to study the reliability of calibration methods based on vanishing points. We do believe that using the same single view to observe the ability of different methods to solve same parameters is suitable for this purpose. After all, in many cases this is exactly the way the methods are used in practice.

REFERENCE

Gracie, G. 1968. Analytical photogrammetry applied to single terrestrial photograph mensuration. XI ISP Congress, Lausanne.

Grammatikopoulos, L. , Karras, G. , Petsa, E. 2004. Camera Calibration Combining Images with Two Vanishing Points. Int. Archives of Photogrammetry, Remote sensing & Spatial Information science 35(5), pp. 99-104.

Hartley, R. , Zisserman, A. , 2000. Multiple View Geometry in Computer Vision. Cambridge Univ. Press.

8085-26, Session 6

Planar metric rectification via parallelograms

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The identification of a parallelogram in the image plane, combined with the knowledge of camera parameters, allows metric properties to be recovered. This papers presents a methodology capable of estimating a 2D homography for perspective images of planar objects without taking any measure on the world plane. Therefore, the rectified image will have only an overall scale ambiguity

Once the vanishing line is estimated by using the corners of a parallelograms, a synthetic rotation can be determined from interior orientation parameters. This removes the projective ambiguity from the original image allowing metric properties to be measured. The solution of this problem is not unique because only the normal n to the scene plane can be estimated. However, a set of three orthonormal vectors [r, s, n/||n||] can be estimated in order to remove this ambiguity by using the normal to the scene plane.

The solution of this problem uses inhomogeneous coordinates. A point in the plane is identified as a column vector x = (x, y)T. The homogenous coordinates of a point can be obtained by adding an extra coordinates to this pair. This new last coordinate gives a new triplet x = (λx, λy, λ)T.

A projectivity is an invertible mapping from point in Pn to points in Pn. A planar projective transformation (or homography) is represented by a 3×3 matrix where H is non-singular matrix and has 8 degrees of freedom. The estimation of the elements of H with the proposed method is based on the use of a mapping that transforms the compute vanishing line into (0, 0, 1)T, therefore its canonical form. This can be computed as follows:

H = KRK^(-1)

where

R = [r, s, n/||n||]T

Obviously, as a rectangle is a special case of a parallelogram, standard procedures based on the identification of horizontal and vertical lines (e.g. those belonging to building facades can be employed). Shown in fig. is an example. The painting was rectified using the frame and the principal distance, according to the proposed methodology. The knowledge of all camera calibration parameters allowed one to remove the distortion due to the grandangular lens, used. Then, metric properties were recovered without using any distance ratio, demonstrating that no information about the world space is needed.

The method was implemented to create Metric Rectifier, a photogrammetric for the estimation of the proposed projective transformation. This package was also extended to compute unknown homographies with standard techniques, such as ground control points, rectangles with a known length ratio, and squares.

Examples are presented using synthetic and real data. In particular, the method was adapted for the automated measurement of vertical distances using two leveling staffs mounting some photogrammetric targets. They form a parallelogram in space allowing the estimation of the elevations of ground points relative to a reference datum. This is similar to the leveling process based on optical levels and graduated staffs.

A comparison was carried out by using the measurement taken with a Zeiss Ni1 level, using some displacements simulated with a regulation screw, but several numerical comparisons are illustrated and discussed, showing the potential, but also the practical limits, of this methodology: satisfactory results were achieved in experiments carried out under controlled conditions.

8085-27, Session 6

Calibration of wide-angle lens cameras using perspective and non-perspective projections in the context of real-time tracking applications

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In most close-range photogrammetry applications, the cameras are modelled as imaging systems with perspective projections combined with the lens distortion correction as proposed by Brown in 1971. In the 1980s the calibration of video cameras received considerable attention, which required the compensation of further systematic effects caused by the digitization of the analogue image signal. Modelling the image process in that manner has become the widely applied standard since then. To take advantage of the increased field of view of individual cameras, the use of wide-angle as well as fish eye lenses became common in computer vision and close-range photogrammetry, again requiring appropriate modelling of the imaging process to ensure high accuracies.

The Advanced Realtime Tracking GmbH provides real-time tracking systems with infra-red cameras, which are in some cases equipped with short focal length lenses for the purpose of increased fields of view, resulting in larger trackable object volumes. Unfortunately the lens distortion of these cameras reaches magnitudes which can not be sufficiently modelled with the customary Brown model as - mainly in the image corners - the calculation of the correction is not applicable. Considerations to avoid modelling these lenses as fish eye projections lead to an alternate and rather pragmatic approach. As the Brown model works successfully for most of the image space, except the corners, it was suspected that only slight changes to the conventional method were necessary to achieve full coverage. The lens distortion correction to compensate for the systematic displacement of image points is an iterative procedure, generally requiring increasing iteration steps in proportion to the corrections required. The number of iterations is also an indicator of the appropriateness of the correction. From the image center outwards the number of iterations might increase and then within a certain range start to fail. Allowing only points within this certain range will achieve successful calibration runs and will also enable the subsequent 3D reconstruction of object points. The drawback of this workaround is a significant reduction of the field of view of the cameras, where achieving the opposite was the original intention.

The rather straightforward extension of the Brown distortion model enables the lens distortion correction over the whole sensor area: using four instead of the proposed three radial distortion parameters combined with an iterative procedure to determine their values. The camera calibration is determined within a bundle adjustment to derive its interior parameters. The nature of this least squares adjustment is that initial values of the parameter have to be provided to achieve convergence of the generally non-linear estimation process. Starting without a priori knowledge of the camera´s interior and exterior orientation, i.e. with a distortion parameter set with values set to zero and coarse camera poses, will cause failure of the bundle adjustment. This problem can be solved by approaching the end result in a stepwise manner. As the failure in the bundle adjustment, caused by divergence of the lens distortion correction, only occurs in the far corner areas of the images, introducing an incrementally-increasing cut-off radius helps the calibration process. As a final step, using all available image points will contribute to the estimation process and will result in a parameter set which achieves an applicable and valid distortion correction for the whole image space. It is well-known that correlations between each of the radial distortion parameters is high and this was also observed if the fourth coefficient is used to model the distortion correction. The radial distortion parameters therefore need to be applied as a complete set to achieve the appropriate image coordinate correction. With this extended set of Brown parameters no cutting back in the field of view of cameras is necessary and tracking in a larger object volume is enabled.

This paper presents the modified lens distortion model, describes the iterative calibration procedure and compares tracking results in respect to the conventional approach. The results are also compared to the approach wherein the camera lens is modelled as a fish eye projection. The introduction of a fourth radial lens distortion parameter and the fish eye projection were successfully implemented and enable distortion corrections over the whole sensor area. In the case of the used c-mount wide-angle lenses higher overall accuracies were obtained compared to the conventional approach, where the fish eye approach yielded even higher accuracies and was numerically more stable.

8085-28, Session 6

Practical calibration for consumer grade digital camera with integrated high zooming lens

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Zoom lenses are widely accepted in vision system. However, the use of zoom lenses is not general in close range photogrammetry from the view point of instability by zoom setting. With the spread of consumer grade digital cameras with integrated zoom lenses, in particular high zooming lens such as 35×were appeared on the market in Japan. Digital photogrammetry using the consumer grade digital cameras is enormously expected in various application fields. There is a large body of literature on the calibration of zoom lenses. However, there is still problem for effective digital photogrammetry using the consumer grade digital cameras with integrated zoom lens. The problem is practical calibration technique of zoom lens, in particular correction of misalignment which is caused by zoom setting.

Misalignment is image displacement which is caused by the optical axis of lens does not perpendicular to the image plane. General mathematical model of camera calibration is based on the well-known collinearity condition, radial and decentring distortion are only considered as image displacement since misalignment and decentring distortion have high correlation. In order to resolve instability of zoom setting caused by misalignment, a newly calibration technique is proposed in this paper. That is, location of principal point and lens distortion (radial and decentring) is corrected simultaneously in the proposed newly calibration technique. In order to evaluate the newly calibration technique for zoom setting, calibration tests were conducted using 5 kinds of consumer grade digital camera (3 5×) , 3 kinds of high zooming consumer grade digital camera (12 30×) and single reflector camera with zoom lens (11×).

Figure 1 shows relative accuracy by the general calibration technique with 9 interior orientation parameters {principal point(x0,y0), principal distance(f), scaling(a), shearing(b), radial distortion (K1,K2) and decentring distortion(P1,P2)}, and Figure 2 shows relative accuracy by the proposed calibration technique. Similarly, interior orientation parameters in the proposed calibration technique are as same as general calibration technique, but procedure for correction of image coordinate is just different. The relative accuracy is ratio of RMS error for 86 check points to standard error which is generally accepted in normal stereo photogrammetry. Therefore, larger ratio than 1 means accuracy degradation compare with standard error.

The first feature of note in figure 2 is that the relative accuracy for all cameras is acquired in all zoom setting. In particular, it can be seen clearly for high zooming consumer grade digital cameras. It should be noted that this means instability by zoom setting is resolved. On the contrary, consumer grade cameras such as N1(3×), S710(3.6×), FX100(3.6×), W60(5×) doesn't show any significant variation compare with the general(Figure 1) and the proposed calibration technique (Figure 2). It is not evident, but it is estimated that misalignment of the consume grade cameras is adjusted by manufacturing process so that the influence of misalignment can be neglected.

Furthermore, it is verified that fluctuation of principal point agrees with P1 and P2's fluctuation. Therefore, let make it into account the relationship between misalignment and decentring distortion, it is clearly inferred that misalignment is caused by zoom setting, and it can be seen that the misalignment is corrected by the proposed calibration technique, and it is concluded that the newly calibration technique is simple and effective for all zoom setting.

8085-29, Session 6

Calibration of low-cost measurement system by using a consumer digital stereo camera

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1. Introduction

FUJIFILM Cooperation released the consumer digital stereo camera FinePix REAL 3D W1 in August 2009. Since the camera was designed to take a pair of stereo images for stereo viewing, the stereo baseline length of 77 mm is unsuitable for accurate stereo measurement. We intended to develop a low-cost and easy-operation system to measure dimensions of an object on a sub-meter scale only by using a pair of stereo images acquired by the camera without any controls, because the camera is not expensive and can obtain a pair of stereo images easily.

When a pair of stereo images is shot, the camera records not only a pair of stereo images but also the current values of the focal length of each imaging unit, the convergence angle, and the baseline length between two imaging units in a Multi-Picture (MP) format file. Whenever a pair of stereo images is shot, digital zooming of the camera is in operation. However, the camera records no information concerning the digital zooming such as the digital zoom ratio and the location of the zoomed area on the focal plane of each imaging unit. Accordingly, camera calibration including estimation of alignment between two imaging units in the camera is necessary.

The aim of our study is to evaluate calibration methods for the system and investigate geometrical features of the camera.

2. Camera calibration

2.1 Image geometry model

We adopted the image distortion model widely used in photogrammetry for each imaging unit. The model consists of a principal distance, offsets from the principal point to the center of the image frame, radial and decentering distortion components. As for alignment between two imaging units, we estimated a baseline length, two rotation angles of the left imaging unit, and three rotation angles of the right imaging unit.

2.2 Evaluated calibration methods

We examined the following calibration methods:

Method-1: Ordinary camera calibration is executed for each imaging unit to estimate its interior orientation parameters. Then relative orientation is conducted by using the obtained interior orientation parameters of both imaging units to estimate alignment between two imaging units except for a baseline length, which is estimated by using positions of the projection centers of both imaging units obtained in the previous camera calibration.

Method-2: Ordinary camera calibration is executed for each imaging unit to estimate its interior orientation parameters. Then alignment between two imaging units is estimated by using two sets of exterior orientation parameters of both imaging units obtained in the previous camera calibration.

Method-3: Both interior orientation parameters of two imaging units and alignment between two imaging units are estimated simultaneously by using the dedicated camera calibration software for the system.

2.3 Image acquisition

We adopted a calibration method using a set of calibration points distributed on the 2-D plane. A round of calibration for each focal length of ten focal lengths (6.3 mm - 18.9 mm) utilized a set of 16 convergent images acquired from four different directions with four different camera frame rotation angles of 0, +90, +180, and -90 degrees around the optical axis of the camera.

2.4 Evaluation of calibration methods

We evaluated the calibration methods by estimation errors of lengths of line segments measured without any controls. Locations of 60 points on three horizontal lines of 100 cm long and three vertical lines of 100 cm long were measured. Each line had 10 points at an interval of 10 cm and 9 line segments of 10 cm long were measured. Four pairs of stereo images were taken for each focal length. The distance from the camera to the target varied according to the focal length as unit cell size on the target so that each image scale was nearly equal.

3. Results and discussion

3.1 Evaluation of calibration methods

The measurement results indicate that Method-1 would be an undesirable method for the system. On the contrary, the results show that the measurement accuracy by Method-3 would be almost equal to that by Method-2 except for f = 13.1 mm and f = 14.8 mm. Although we had expected that Method-3 would provide the most accurate measurement results, the results show that Method-2 would be able to provide the better measurement results than Method-3.

We computed the expected accuracy from the measurement accuracy of a point position on an image by using the rules of error propagation. The measurement errors by Method-2 and Method-3 were less than 0.4 pixels on an image except for 0.45 pixels by Method-2 at f = 6.9 mm. Accordingly, we concluded that both methods would be able to provide sufficiently accurate measurement results.

3.2 Investigation of geometrical features

Variations of the estimated offsets of the principal point with varying zoom setting are considerably larger than those shown in some reports. The results show that the principal point of the left imaging unit moves rightward as the focal length increases, whereas that of the right imaging unit moves leftward. We guessed that these horizontal movements of the principal points of the two imaging units would be made by the movements of the zoomed area on the focal plane with the intention of obtaining better stereo viewing.

All estimated convergence angles except for 2.0 degrees by Method-3 at f = 6.3 mm were larger than 2.2 degrees that is the value recorded in each MP format file. The specification of the camera that the distance to "Point of Convergence" ranges from 2 m (wide) to 6.5 m (tele) means that the convergence angle ranges from 2.2 degrees (wide) to 0.68 degrees (tele). The owner's manual of the camera defines "Point of Convergence" as the point where the optical axes of the two lenses intersect, but the estimated convergence angles were inconsistent with the specification. We introduced an intersection angle that is defined as an angle formed by two straight lines passing through the center of the zoomed area and the projection center of each imaging unit. The intersection angle can be calculated from the estimated convergence angles and the estimated offsets of the principal points of the left and right imaging units. The results indicate that the angles calculated from the distance to "Point of convergence" would be consistent with the intersection angles.