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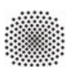
INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART



Universität Stuttgart

3D-Surface Metrology

Chromatic confocal spectral interferometry (CCSI)
Supported by: DFG (OS 111/21-1)

Atraumatic functions preserving precision surgery of the human temporal bone (COCHLEA)
Supported by: BMBF (01 EZ 0405)

Combined optical-tactile metrology for Microsystems
Supported by: BMBF (FKZ 16SV1945)

Hybrid micro-optic sensor which uses the chromatic-confocal focus detection principle
Supported by: BMBF (FZK: 02P D2551)

Multiscale Measurement Strategies: Indicators for the detection of microscopic defects
Supported by: DFG (OS 111/18-2)

In-process measurement of micrometer scale tools
Supported by: VDI/VDE-IT Berlin (16IN0373)

Application of Liquid-Crystal-Displays for digital holography

Chromatic confocal spectral interferometry (CCSI)

E. Papastathopoulos, K. Körner, W. Osten

Chromatic confocal spectral interferometry (CCSI) is a novel technique for topography measurements which combines the techniques of spectral-interferometry and chromatic-confocal microscopy. This hybrid method allows a white-light interferometric detection with high numerical aperture (NA) in a single-shot manner. To our knowledge, CCSI is the first interferometric method which simultaneously uses a confocally filtered and chromatically dispersed focus for detection, and allows the retrieval of the depth position of reflecting or scattering objects from the phase (modulation frequency) of the interferometric signals acquired. For the chromatically dispersed focus, the depth range of the sensor is decoupled from the NA of the microscope objective.

The discrepancy of the limited axial-range in previously reported spectral interferometry (SI) schemes can be visualized as follows. The reference field contains a planar wavefront, while the detection-wavefront acquires a rigorous curvature, when the object lies beyond the depth-of-focus, if aberration effects are neglected. This curved wavefront can be mathematically described by the axially symmetric Zernike polynomial of the second order. Optical interference between those two fields leads to a reduced contrast of the modulated spectral signal. In the CCSI scheme presented here, the axial-range of the detector is expanded due to the chromatically-dispersed foci (40µm axial range with 0.8 NA reported) by means of a diffractive optical element – DOE (Fig. 1). If the object lies within the dispersed focus spectrum, a sharply focused spectral-component λ_o gets reflected and this induces a high-contrast wavelet in the spectral domain. The amplitude of this modulation remains constant within the entire range of the optical spectrum employed and the axial-range of the detector is decoupled from the limited depth-of-focus. The signals acquired from CCSI comprise interference wavelets in the optical spectrum domain. The modulation frequency is then used to detect the longitudinal position of a reflecting or scattering object.

In the current project, the principles of this new spectral interferometry method were both experimentally and theoretically addressed. The CCSI principle has been implemented in two prototype setups: a Linnik-type interferometer (0.8 NA) and a fiber based interferometer (0.95 NA). Finally, on the basis of topography measurements performed on technical objects, the applicability of this method for the optical detection of objects with rough surfaces and limited reflectivity was demonstrated.

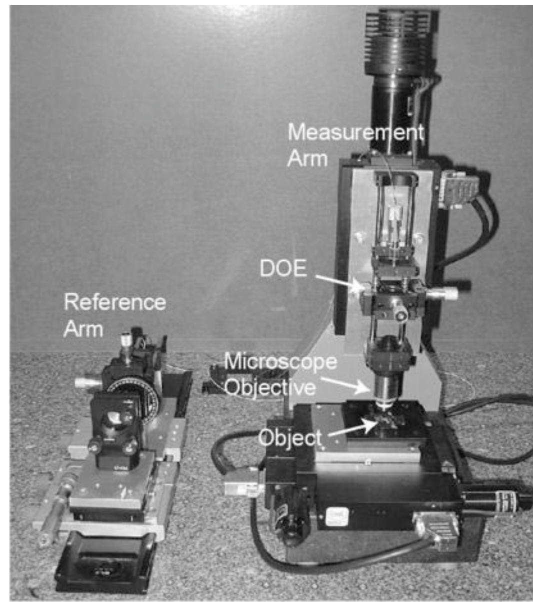


Fig. 1: Fiber-based interferometer with a chromatically dispersed focus, an achromatic reference and detection in the optical frequency domain, utilizing a grating spectrometer.

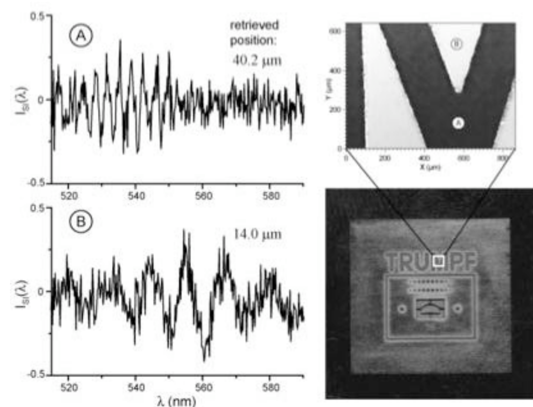


Fig. 2: An experimentally acquired interference wavelet involving a laser-processed Wolfram plate. This object is courtesy of TRUMPF. It exhibits a step structure which was measured by monitoring the modulation frequency of the interference signals from the sampled areas A and B

Supported by: DFG (OS 111/21-1)

References:

[1] Papastathopoulos, E.; Koerner, K.; Osten, W.

[2] Optics Letters 31, 589 (2006)

[3] Applied Optics 45, 8244 (2006)

[4] Proc. SPIE 6292-43 (2006)

[5] Proc. SPIE 6189-39 (2006)

Atraumatic functions preserving precision surgery of the human temporal bone (COCHLEA)

E. Papastathopoulos, K. Körner, W. Osten

In modern surgery, the implementation of navigation systems and robots has become very popular and successful. Current machine vision and navigation systems are proving inadequate techniques to provide the sub-millimetre precision required for surgery on the skull base and on the temporal bone, the bone on which the inner ear organ is located. A typical example of the concept of atraumatic operation is the implantation of a Cochlear electrode in the inner ear, in the area of the temporal bone. When manual methods are used often part of the remaining hearing ability can be destroyed. Within this scope a high-precision position system with a Hexapod-Kinematik system and a miniaturised confocal optical sensor are implemented to provide solution to this a problem.

A schematic of the sensor developed for this purpose is depicted in Fig.2. As a light source, a pigtailed laser diode was employed, which emits quasi-monochromatic light, at a wavelength of 658nm and with a 12mW optical intensity output from a single mode fiber. Due to the limited spatial dimensions in the surgically enfranchised temporal bone area, a compact sensor head was conceived on the basis of graded index optics (GRIN). It is composed of one gradient index rod lens with a focal length of 4.5 mm and a diameter of 1.8 mm, glued together using a glass rod spacer (BK7) with UV-cured adhesive. On the other side of the glass spacer the end of a single mode optical fiber was centred and fixed by adhesive. This serves both as a point-like light source and as a pinhole for the confocal detection. The overall diameter of the sensor head is 2mm. In order to avoid contamination or damage of the operated on outer shell of the Cochlea, a moderate working distance of several millimetres, here more than 4mm, is required. Following an optimised optical design the lateral resolution of the sensor is 10µm. Test measurements performed on human temporal bone tissues showed repeatability of less than 500µm for the longitudinal confocal detection.

The COCHLEA project presented here is performed in cooperation with the Institute for Process Control and Robotics at the University of Karlsruhe, with the Department (IPR) of ORL & HNS at the University Clinic in Freiburg and with the companies Richard Wolf GmbH (Knittlingen) and Cochlear GmbH (Hannover).

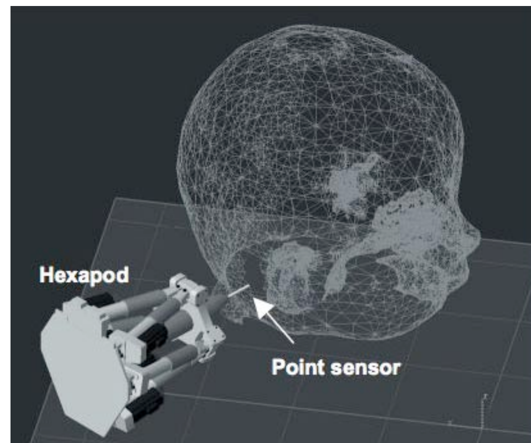


Fig. 1: Schematic representation of the optical measurement of the temporal bone region by implementing a Hexapod and a confocal point-sensor.

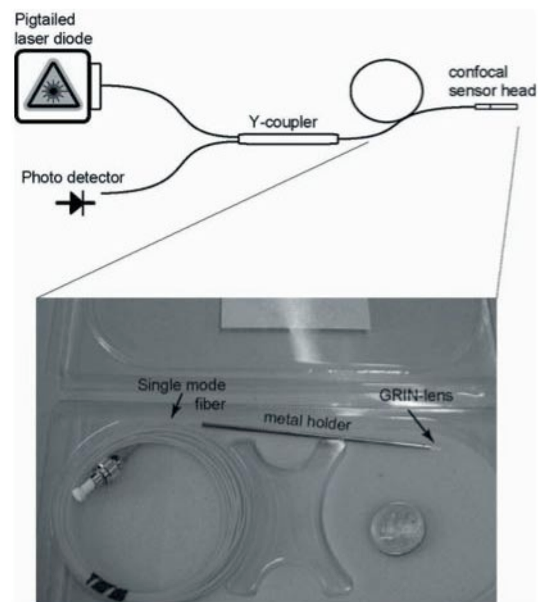


Fig. 2: Schematic representation of the confocal optical sensor (upper) and a photograph of the miniature sensor head (lower frame).

Supported by: BMBF (01 EZ 0405)

References:

[1] Ngan, C. C.; Raczkowsky, J.; Knapp, F.; Klenzner, T.; Papastathopoulos, E. ; Koerner, K.; Schipper, J.; Woern, H. "Micro scaling of robot treatment for skull base operations", Invited paper by IJCARS (in press)

Combined optical-tactile metrology for Microsystems

R. Berger, K. Körner, W. Osten

Microsystems Technology has high potential in research and industry. MEMS [1] and MOEMS [2] devices are in the micrometre to millimetre range. As the structures get smaller, the tolerances become also smaller and even reach the nanometre scale. The structures themselves are often small holes, gratings or other geometrical elements with high aspect ratios in silicon, plastic or metal. For quality inspection the distances, radii, depths and angles of these structures are of interest.

In the BMBF-project µgeoMess measurement systems are developed, which are suitable for a wide range of the above measurement tasks. As we know that there will be no single measurement principle, which can perform these measurements, we investigate a modular combination of three different measurement techniques. On the one hand, there are two optical measurement techniques, which give the 2D- and 3D-profile of the object respectively. Because a field for example as large as 0.6 mm x 0.8 mm can be measured, it is a fast technique to inspect MEMS and MOEMS. For the 2D-investigation there is a light optical microscope, which can record a digital image and perform the digital image processing. To get the 3D-profile, there is a white-light-interferometer, which can achieve nanometre resolution in the vertical dimension. The two optical measurement systems are combined in a compact measurement tool. This is possible by using a special microscope objective, similar to a Mirau objective, which was designed by one of the project partners. We separate the optical wavelength spectrum into two parts to operate the system. In the blue spectral region the beam splitter in front of the last lens surface is transparent and the objective can be used for 2D-measurements as a usual microscope objective. When using light above the blue spectral range, the light will be reflected at the beam splitter and the objective works as a Mirau interferometer. To change between the 2D- and 3D-measurement modes, it is only necessary to switch on another LED in the illumination device. There is no need to move mechanical parts or to modify the optical system. With these two measurement techniques it should be possible to investigate most of the geometrical characteristics of MEMS and MOEMS. But small holes and undercuts can not be detected by these usual optical measurement devices. For this reason, there is also a novel tactile micro probe, which can also be positioned in the micro holes. The probe is a piezo resistive silicon cantilver with an integrated measurement tip. This combination of the two optical techniques with the tactile measurement technique will result in a compact and complete solution for most of the measurement tasks in Microsystems Technology.

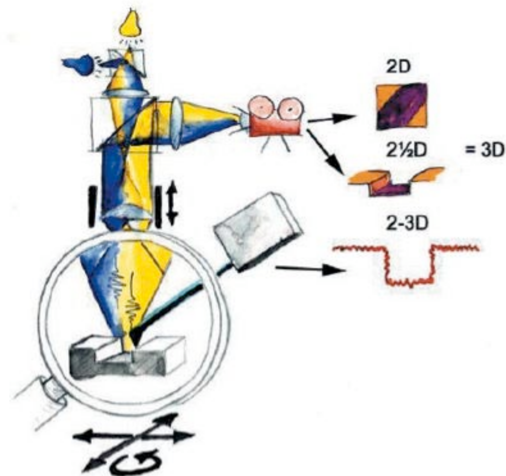


Fig. 1: Schematic of the interaction between the three different measurement principles: the optical microscope with digital image processing; white-light interferometry and the tactile probe.

At the Institute, we focus on the analysis of different measurement errors in white light interferometry. When measuring mirrorlike, tilted objects and performing a phase measurement, we found a correlation between the slope of the object and the phase information in the interference data, at each pixel of the camera. This can result in phase step errors in the topography map of the object under test. The aim is to get a detailed understanding and to provide solutions to the effects that introduce measurement errors [3].

Supported by: BMBF (FKZ 16SV1945)

Footnote and reference:

[1] MEMS: Micro-Electro-Mechanical-System

[2] MOEMS: Micro-Electro-Optical-Mechanical-System

[3] Berger, R.; Sure, T.; Osten, W. "Measurement errors of mirrorlike, tilted objects in white-light interferometry" to be presented at SPIE Optical Metrology, June 2007.

Hybrid micro-optic sensor which uses the chromatic-confocal focus detection principle

A. Ruprecht, C. Pruss, H. J. Tiziani, W. Osten

An increasing demand for the checking of small mechanical and optical precision component tolerances requires improved measurement techniques. In particular, components with a complex geometry are difficult to assess using state-of-the-art tactile measurement systems. Optical measurement systems are non-contact and therefore have the advantage that no mechanical forces occur during the measurement which could distort or displace a miniaturized sensor head and alter the result.

Mahr GmbH, a measurement system manufacturer, the Institut für Mikrostrukturtechnik (IMT) at the Forschungszentrum Karlsruhe, Boehringer Ingelheim microParts GmbH and the Institut für Technische Optik were partners in the research project HymoSens (hybrid micro-optical sensors). The main focus of the project is to develop a miniaturized micro-optical sensor. The sensor makes use of the chromatic-confocal measurement principle and as this technique does not use a mechanical depth scan the sensor was designed without any moving parts. A diffractive element is included to achieve the necessary chromatic axial splitting of the light. The diffractive micro optic was produced by ITO using a photolithographic processes and reactive ion etching to form the structure in thin substrates of fused silica.

A disadvantage of previously designed micro optic sensors [3] is the open beam arrangement. Therefore a part of the light used is reflected at the end of the fibre and by the lens surfaces. This leads to a background intensity in the signal that can disturb the signal evaluation. Here a monolithic layout of the sensor is the best solution, with only very small refractive index changes, in order to minimize reflections. The resulting design is represented in Fig. 1. Here, the numerical aperture is 0.5 and the working distance is 1 mm.

A diffractive lens (DOE) is the last optical element in the ray path, with the diffractive structure is located at the inner side of the DOE. Because of this the final surface of the sensor is a plane surface which can be easily cleaned. For this sensor, a super luminescent diode was used, which emits light in the near infrared region between 790 nm and 850 nm. Such a sensor can be optimized to have focus spots close to the diffraction limit. Calculated focus plots are shown in Fig. 2. The diameters of the circles in the plot are equal to the diameter of the Airy disc of an equivalent diffraction limited focus spots.

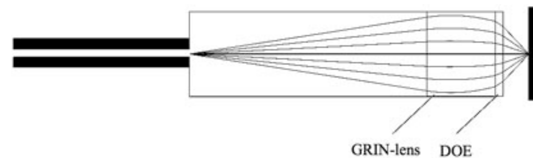


Fig. 1: Principle of the optical setup for the miniaturized point sensor. The elements are an optical fibre, a GRIN lens and a diffractive lens (DOE).

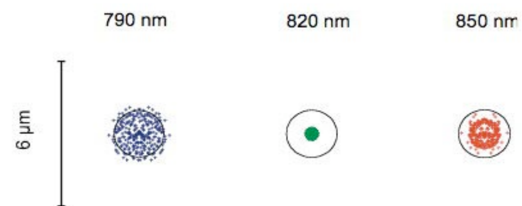


Fig. 2: Focus plots of the raytracing simulation of the setup in Fig. 1.

Supported by: BMBF (FZK: 02P D2551)

References:

[1] Ruprecht, A. K.; Wiesendanger, T. F.; Tiziani, H. J. "Chromatic confocal microscopy with finite pinhole size", Optics Letters 29 (18), 2130-2132, 2004.

[2] Lücke, P.; Last, A.; Mohr, J.; Ruprecht, A.; Osten, W.; Tiziani, H. J.; Lehmann, P. "Confocal microoptical distance-sensor for precision metrology", Optical Sensing, Proc. SPIE Vol. 5459-22, Strasbourg, 27-30 April 2004.

[3] Ruprecht, A. K.; Pruss, C.; Tiziani, H.J.; Osten, W.; Lücke, P.; Last, A.; Mohr, J.; Lehmann, P. "Confocal micro-optical distance sensor: principle and design", Optical Metrology, Proc. SPIE Vol. 5856-15, Munich, 13-17 June 2005.

Multiscale Measurement Strategies:
Indicators for the detection of microscopic defects

T. Wiesendanger, W. Osten

The increasing importance of technical components in the micro- and nanoscale raises the need for fast and economical characterisation techniques.

The limited space-bandwidth-product of optical sensors however enforces a compromise between a large measurement field, a high measurement resolution and a short measurement time. The aim of the research project funded by the DFG is to provide such measurement strategies.

A measurement strategy deploying a smart combination of sensors is the proposed solution to this problem (cf. Fig. 1). Based upon an initial global assessment of remaining areas of measurement uncertainty, local measurement techniques with different configurations are explored. All the measurement data is registered and merged into one consistent data set. The process of data acquisition is repeated until the measurement uncertainty is sufficient to decide whether the object under study is inside or outside of specifications.

The scheduling of the measurement process, especially the decision about where to place the higher resolved measurements, is performed by the application of defect indicators on the global measurement results.

In the context of this project several indicators are being studied: One example is the laterally resolved fractal dimension or the confocal axial response.

These strategies are being applied to the detection of topographic defects and a fast characterization of microlens-arrays (cf. Fig. 2, Fig. 3).

Future work will focus on a new measurement set-up to incorporate the strategies in the field of wafer scale testing.

Fig. 1: Schematic illustration of the applied measurement strategy

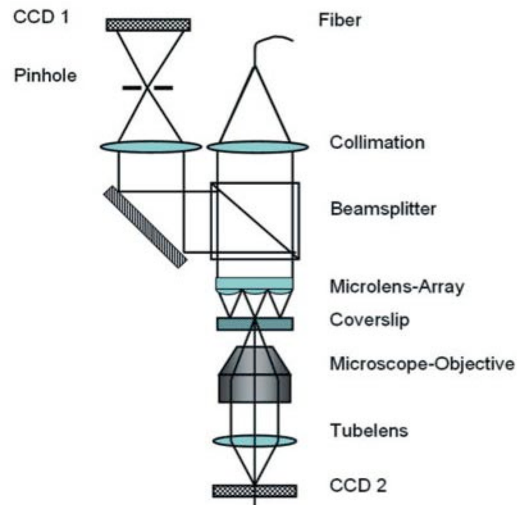


Fig. 2: Example: Measurement of defects on a Si-Wafer

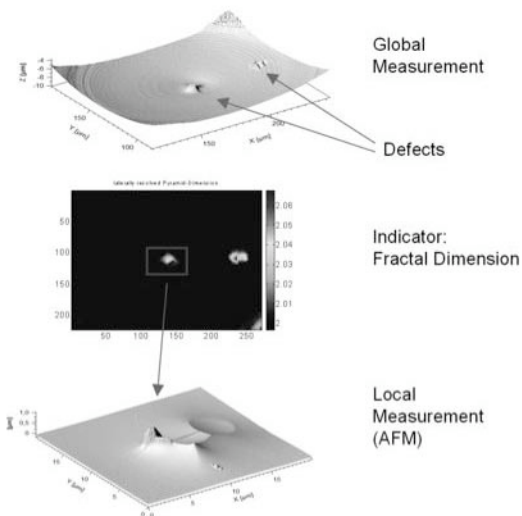


Fig. 3: Set-up for the fast characterization of microlens arrays

Supported by: DFG (OS 111/18-2)

References:

[1] Wiesendanger, T. ; Osten, W.; Pannekamp, J.; Regin, J.; Westkämper, E. "Neue multiskalige Mess- und Prüfstrategien für die Produktion von Mikrosystemen" In: Mikrosystemtechnik Kongress 2005. GMM, VDE, VDI, (eds.), VDE Verlag Berlin, Germany; pp 677-680.

[2] Westkämper, E.; Osten, W.; Regin, J.; Wiesendanger, T. "Multiskalige Mess- und Prüfstrategien in der Mikro- und Nanomesstechnik" VDI/VDE-Gesellschaft Meß- und Automatisierungstechnik -GMA-, Düsseldorf: Messtechnik für Mikro- und Nano-Engineering : Tagung Erlangen, 29. und 30. November 2006 Düsseldorf: VDI-Verlag, 2006 (VDI-Berichte 1950), ISBN: 3-18-091950-7

In-process measurement of micrometer scale tools

T. Wiesendanger, C. Kohler, W. Osten

The growing amount of highly integrated Microsystems, with an associated increased miniaturization, demands new high precision manufacturing processes. The newly developed manufacturing method called "Electrochemical micromachining", in particular, has the capability to fulfil some of these needs. It offers the possibility of producing stainless steel micro scaled structures with high aspect ratios in a single process step. To reach the achievable manufacturing limits adequate measurement instrumentation is necessary.

One of the big advantages of electrochemical micromachining is that the tools used are also made with the same manufacturing process as a first step. This greatly reduces the required precision of the tool blanks. However their precise position in the coordinate system of the machine and their exact shape has to be measured just before the start of process. In addition, an in process control of the tool is required to observe and correct for tool wear.

The tools are made out of tungsten wire with a diameter of 500µm and a length of several millimetres. The wire is welded in a previous step onto a machine holder. At this project stage only cylindrical tools are used, so the position relative to the machine mounted holder, the shape of the cylinder (e.g. small shape defects) and the concentricity must be measured. As a future step more arbitrarily shaped tools are planed, e.g. to create undercuts and notches. So a versatile in process measurement set-up at moderate costs is needed.

We therefore developed an image processing based machine integrated optical sensor out of standard components. The key features are:

- 10x magnification,
- object space NA 0.1,
- 0.8 x 0.6 mm field,
- 12 Bit CCD camera,
- 45 mm working distance,
- measurement resolution of 0.1 µm.

Due to the large measurement field of the sensor, tools between 10µm and 500µm in diameter can be measured with the same set-up. No change of objective is needed. One important task to guarantee a resolution of 0.1 µm was the machine integration of the sensor. This task was achieved by three design features: splitting the sensor into independent illumination and an observation parts; long working distances; and a folded optical path of the observation optics. The image in Fig. 1 shows a first test set-up of the measurement system with a test object.

Then initial measurements were performed (cf. Fig. 2, Fig. 3) to approve the image quality.

Fig. 1: Prototype of the measurement setup.

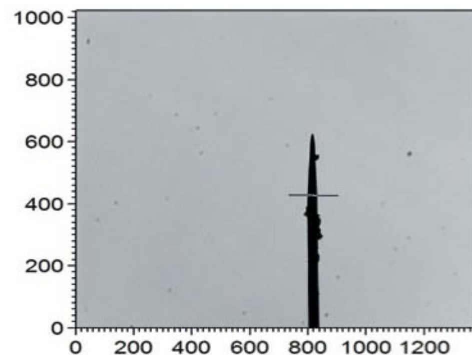


Fig. 2: Measurement of 20µm tool.

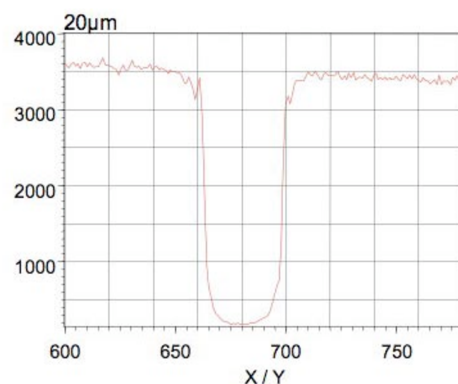


Fig. 3: Profile through the captured image of the 20µm tool (Fig. 2).

Supported by: VDI/VDE-IT Berlin (16IN0373).
Cooperation with: Institut für Zeitmesstechnik, Fein- und Mikrotechnik, Stuttgart.

Application of Liquid-Crystal-Displays for digital holography

C. Kohler, X. Schwab, T. Haist, W. Osten

The advances of liquid crystal displays offer new applications of these devices in digital holography and comparative digital holography. The increasing lateral resolution and the newly offered phase-only devices are enabling elements for new measurement setups in digital holography and micromanipulation devices like optical tweezers. [1]

Though the demands for these applications are very different, both have in common the need for a good knowledge of the modulator used for the optical reconstruction of the digital holograms [2, 3]. So as a first step of a modulator characterization the modulators complex transmission is measured i.e. the amplitude and phase transmission. But these measurements are only the first step in a complex characterization. As for example the modulator characteristic is determined by the modulator, the polarizers and the wave plates used. So the overall efficiency should be considered e.g. a phase only characteristic could be achieved but due to the settings of the wave plates an optical efficiency of 5% could occur as the polarizer and analyzer are working almost in extinction [2]. Other important factors are the surface geometry of the modulator which adds at least a defocus term and of course the modulator's fill factor which is the dominant factor for the achievable diffraction efficiency. E.g. with the LCOS modulator used almost half the incident light is scattered to higher diffraction orders. In consequence the maximum overall diffraction efficiency will be obviously lower than 50%.

As a consequence we did a first investigation of the achievable diffraction efficiencies based on the measurement of the intensities of reconstructed holograms. A hologram of a knight chess piece was recorded (s. Fig. 1) and then reconstructed in different modes:

- As a phase hologram with the modulator in phase-mostly mode (s. Fig. 2)
- As a phase hologram with the modulator in amplitude-mostly mode
- As an amplitude hologram with the modulator in phase-mostly mode
- As an amplitude hologram with the modulator in amplitude-mostly mode

The achieved diffraction efficiency of the different holograms with the distinct operation modes of the display was measured. The results of the measurements are shown in table1. As expected the phase hologram reconstructed in phase-mostly mode offers the highest diffraction efficiency.

Further steps in the SLM characterization will be the measurement of the Jones-Matrix and an optimization of digitally generated holograms based on Jones-Calculus which will lead to an even better understanding of the modulator's properties.

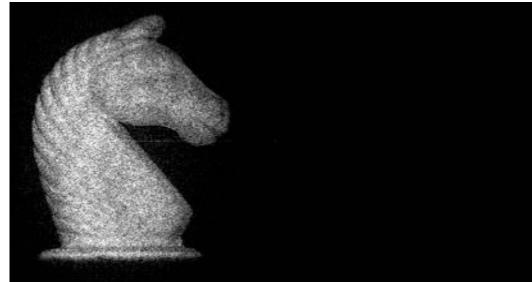


Fig. 1: Digital reconstruction of the recorded hologram of a knight chess piece.

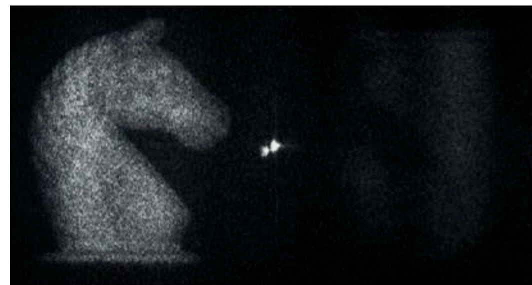


Fig. 2: Optical reconstruction of the recorded phase hologram with the display operated in phase-mostly mode.

References:

[1] Haist, T.; Schönleber, M.; Tiziani, H. J. "Computer generated holograms from 3D-objects written on twistednematic liquid crystal displays", Opt. Commun. 140, 299–308 (1997).

[2] Osten, W.; Kohler, C.; Liesner, J. "Evaluation and application of spatial light modulators for optical metrology" presented at 4a Reunión Espanola de Optoelectronica OPTOEL '05 (2005).

[3] Kohler, C.; Schwab, X.; Osten, W. "Optimally tuned spatial light modulators for digital holography" Appl. Opt., 45, 960-967 (2006).

Display-mode	Hologram transferred to the SLM	0. order [%]	+1. order [%]	-1. order [%]	Diffraction efficency [%]
AM	Amplitude hologram	0.28	0.03	0.01	10
AM	Filtered phase hologram	0.37	0.71	0.05	63
PM	Phase hologram	4.38	2.92	2.92	29
PM	Filtered phase hologram	1.25	7.69	0.81	79
PM	Filtered and shifted phase hologram	1.16	7.96	0.54	82

Table 1: Measurements from phase and amplitude holograms in AM and PM mode of the percentage of intensity in the 0., +1. and -1. orders of the reconstructed hologram relative to the laser intensity (with an error of ± 8% of the value) and the diffraction efficiency.
AM: amplitude mostly; PM: phase mostly

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