annual report
2019 / 2020

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

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ANNUAL REPORT 2019/2020

Dear Reader,

an appropriate headline for this issue may be “bridging the gap”: In the end of 2018 Prof. Wolfgang Osten has retired and it has taken almost full three years until on October,1st 2021 I could finally hand over the key to the new director of the Institute: Prof. Stephan Reichelt.

Although Prof. Wolfgang Osten has left the ITO with great momentum, large ground speed and a well-set course, three years are a long time. As an intermediate head it was not always straightforward to navigate the ITO through this period. Keeping research successful, while not being allowed to make long-term strategic decisions is not simple, and some worldwide virus did not make things easier for us. But nevertheless, we managed well. Our democratic board of group leaders has proven to be a successful instrument to keep the institute on track and the skills of our financial officers and secretaries was solid ground. Thus, the research, teaching and administrative burden could be distributed on several shoulders, and I need to express my deep acknowledgements to the persons owing these shoulders. Without the group leaders, without the secretaries this would not have been possible. They are the reason, why we could keep our headcount and revenue constant. “Thank you!”.

One of the main research pillars has certainly been our activity in the field of two-photon direct laser writing. We have been able to acquire a Nanoscribe-GT printer at the ITO in 2019 and the machine is heavily booked since then, helping us to demonstrate the possibilities of this fascinating technology. Among other projects we have been able to demonstrate the smallest 3D-printed spectrometer worldwide, only having a footprint of 0.1mm x 0.1mm.

These activities in 3D-printing have once been started within the cooperative network SCoPE and have ever grown since then. In 2020 within SCoPE we have also gained funding for a new DFG graduate school GRK2642 “Towards Graduate Experts in Photonic Quantum Technologies“, which will extend engineering into the quantum world. This graduate school is a perfect extension of our master program in Photonic Engineering that was established in spring 2013 and is still a successful model to provide higher education in the field of optics and photonics. This reflects our ongoing strong commitment to high-quality teaching on different levels (bachelor, master, PhD) and different fields. Our master program in mechanical engineering MGT and supporting lectures in several other programs of the faculty are well accepted by the students and extend to the PhD-level, e.g. via the SFB1244 on “adaptive buildings”. Also, the consecutive bachelor-master course in medical technology, a joint and challenging project of the Universities of Stuttgart and Tübingen, is running very successfully and has fostered the DFG-graduate school GRK2543 “Intraoperative issue differentiation” together with the University of Tübingen. Those important projects allow us to transfer our competency in optical design and optical metrology into neighbouring research fields, such as physics, medical technologies or architecture, not only theoretical, but with prototypes and demonstrators.

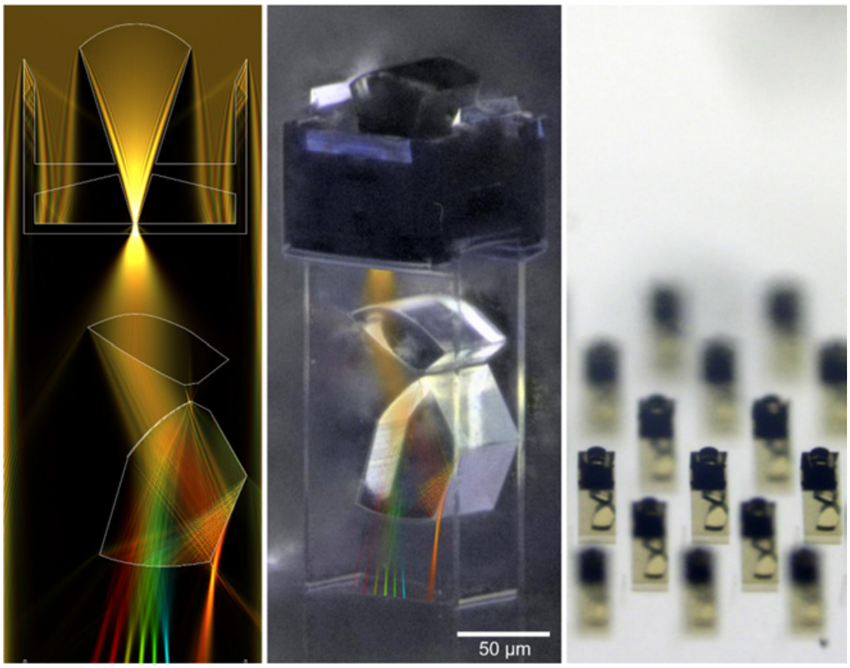

Fig. 1: 3D-printed miniature spectrometer for the visible range with only a 100 × 100 µm^2 footprint. See Toulouse et al. in Light: Advanced Manufacturing 2 (1), 1-11 (2021).

State of the art optical metrology equipment is another pilar we try to maintain and strengthen. The Nano-Positioning and Metrology Machine NPMM 200 is certainly the most massive instrument, and we started further DFG-funded research to fully employ the accuracy of a few nanometres in the large metrology volume. This impressive machine, together with the existing FEI Helios NanoLab 600, the tilted wave interferometer TWI and the Nanoscribe GT will be the basis for our planned centre for Nano-machining and measurement. As a further extension of this centre, with the help of the BMBF, we were able to acquire a Zygo NexView interferometer and a Mahr Nanofocus confocal system to continue and extend our activities in printed optical systems and sensors on a micro and nano-scale.

All those instruments and research activities are only possible via our funding partners, such as the German Federal Ministry of Education and Research (BMBF), the German Ministry for Economic Affairs and Energy (BMWi), the German Research Association (DFG), the Baden-Württemberg Stiftung, the VECTOR-foundation, the European Union (EU), and many German and international industrial partners and customers. Our thanks go to all these partners for the long-term and fruitful research cooperation with many remarkable results.

So, in summary we managed the “gap” well, which is also due to the loyalty of the above partners. However, for almost three years, a director of the institute especially representing optical metrology was missing. It is therefore a great relief to now have Prof. Dr. Stephan Reichelt at the ITO, taking care of the further path of the institute. Thus we are looking forward to extend our research on the exploration of new optical measurement, imaging and design principles and their implementation in new components, sensors and sensor systems. Welcome Stephan! May you have a good start here in Stuttgart.

For me it was a great pleasure and honour to guide the ITO through this intermediate period, and I want to say “thanks” again to all the members and partners of the institute for the wonderful support!

Stuttgart, October 2021

Alois Herkommer

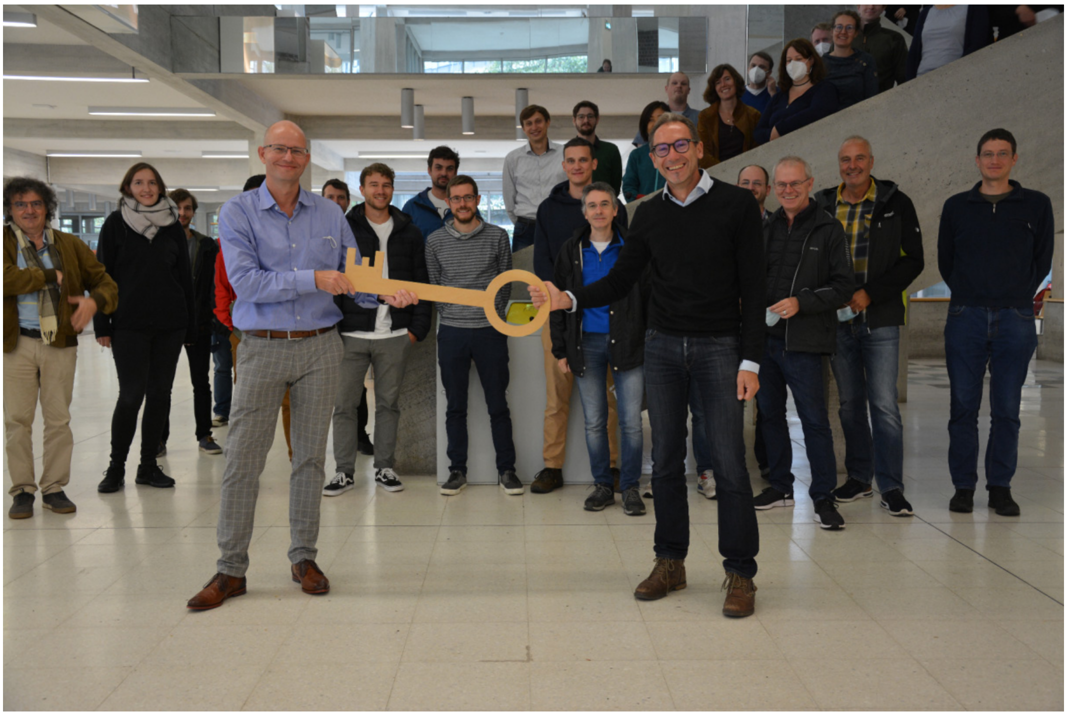

Fig. 2: Handing over the key for the Institute from the intermediate director Prof. Alois Herkommer to the new director Prof. Dr. Stephan Reichelt (picture: ITO)

Dear Reader,

It was just about two weeks ago that I symbolically received the key to the ITO from Prof. Alois Herkommer. I have now been appointed as the new director of the Institute of Applied Optics (ITO) at the University of Stuttgart with its more than 60 years of tradition and impeccable reputation.

A warm and extremely cordial welcome at the ITO makes it easy for me to take on the new tasks and challenges. Needless to say, I am extremely excited and honored to have now the privilege of leading the ITO into the future.

Three years have passed since the retirement of Prof. Wolfgang Osten, who led and managed the institute in a very successful way. He continued to shape the institute and made it what it is today. Through numerous initiatives, programs and cooperations, the international visibility and networking of the ITO was further expanded under his leadership. Regional, national and international cooperation with research institutes and industrial partners were always in his focus. Equally remarkable is his claim in teaching and scientific education to provide all graduates with a sound base for their professional life.

Three years are a relatively long time that had to be bridged. This task was mastered with excellence by Prof. A. Herkommer and Dr. T. Haist, who shouldered ad-interim the responsibility for the institute and professorship. Likewise, my thanks go to the entire ITO team, the group leaders, financial accountant and secretary, teaching and technical staff and all the scientific members! They have all made outstanding contributions to keeping the institute on track and ensuring that our field has been continuously staffed and represented in research and teaching.

The ITO is an institute that has now been successfully managed over three generations. Numerous graduates of ITO are or were employed in the optical industry or science and have made significant contributions to the field. For me personally, the institute means a lot. As you may know, the spirit and culture of the institute have shaped me both professionally and personally. I am very grateful that Prof. Hans Tiziani gave me the chance to start my research career here at ITO back then.

Now new challenges await me – it is about shaping research and education in applied optics and fulfilling administrative and management tasks in the university environment. After several professional stations, the path to ITO is a familiar and yet new one for me - a kind of homecoming, but in a new role and with a backpack full of ideas and plans. I am confident that I can contribute to the research, teaching and management of the institute with my professional experience gained as a PhD student and postdoc in a university environment, as an application manager in a start-up company and as an R&D manager in the optical industry.

What will the future bring? It is important to me to continuously expand ITO's traditional research fields. Optical metrology and sensor technology for industrial and scientific applications, design and simulation, each from the nano to the macro scale, and combined with a strong technology portfolio for structuring on the nano, micro and meso scale stand for the ITO - this will remain so! Our claim is to be your first point of contact when it comes to solving fundamental or application-specific problems in applied optics for which you need a research or development partner. New exciting fields will emerge that can be summarized under the umbrella term Digital Reality. My goal is to establish a focus in the field of imaging technologies that combines digitization, human-machine interfaces and artificial intelligence. This requires creative, digital-analog optical designs and system architectures.

This edition of the annual report reflects our exciting research activities carried out during the bridging phase. My thanks go to all third-party funders who made this research possible: BMBF, BMWi DFG, AiF, ZIM, Baden-Württemberg Stiftung, all our industrial partners and the good cooperation with all the research institutes and institutions involved.

Take a look at the articles in which we explore the many ways in which light and photonic technologies can be used in fundamental and applied research within our three pillars of Optical Metrology, Optical Design and Simulation and Advanced Nano-Micro Fabrication Technologies.

I am happy, curious and excited - and especially looking forward to a good collaboration with you. And above all: Enjoy reading this report!

Stuttgart, October 2021

Stephan Reichelt

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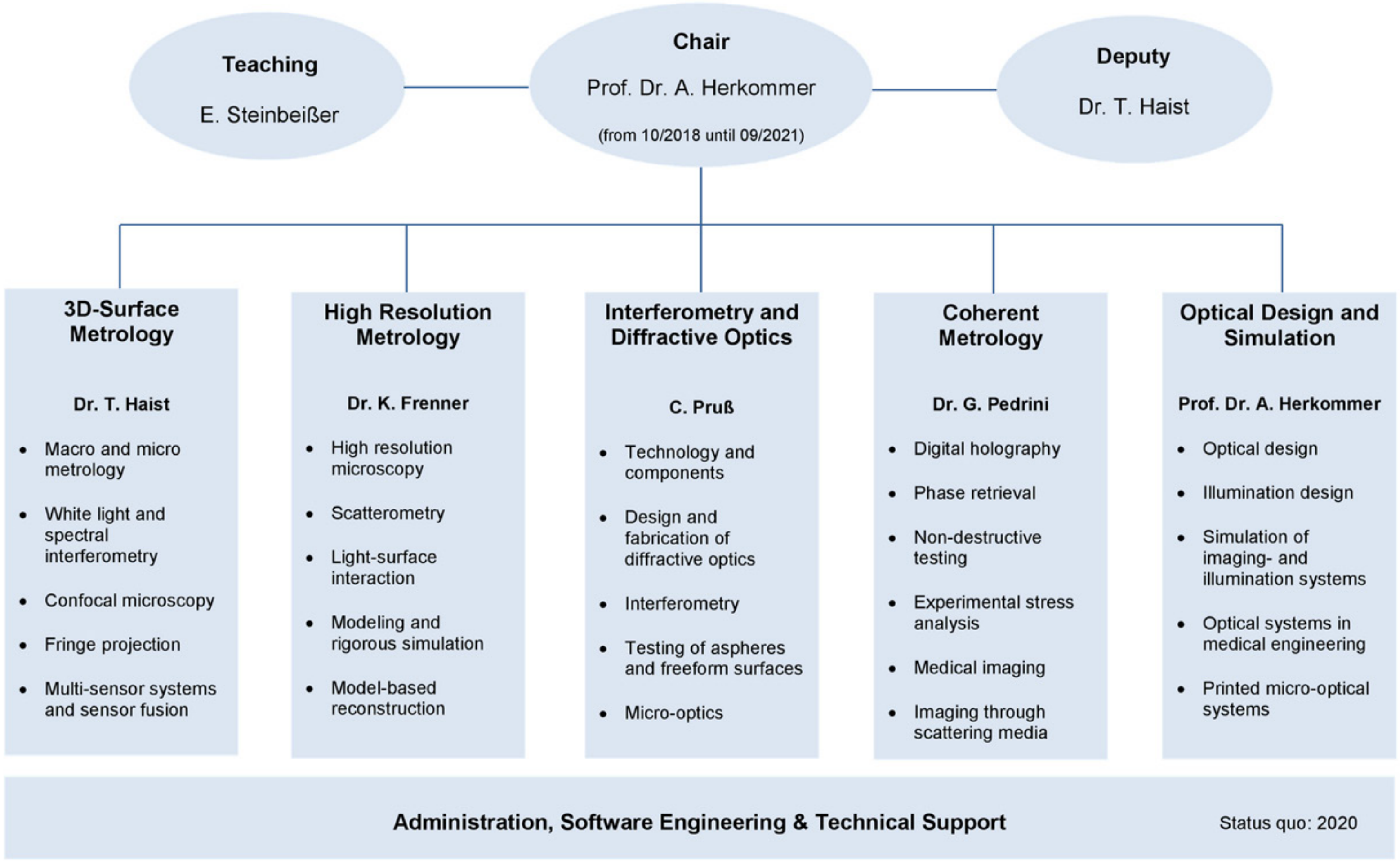
ITO Team (October 2021)


Teaching
E. Steinbeißer
Chair
Prof. Dr. A. Herkommer
(from 10/2018 until 09/2021)
Deputy
Dr. T. Haist
3D-Surface Metrology
Dr. T. Haist
Macro and micro metrology
White light and spectral interferometry
Confocal microscopy
Fringe projection
Multi-sensor systems and sensor fusion
High Resolution Metrology
Dr. K. Frenner
High resolution microscopy
Scatterometry
Light-surface interaction
Modeling and rigorous simulation
Model-based reconstruction
Interferometry and Diffractive Optics
C. Pruß
Technology and components
Design and fabrication of diffractive optics
Interferometry
Testing of aspheres and freeform surfaces
Micro-optics
Coherent Metrology
Dr. G. Pedrini
Digital holography
Phase retrieval
Non-destructive testing
Experimental stress analysis
Medical imaging
Imaging through scattering media
Optical Design and Simulation
Prof. Dr. A. Herkommer
Optical design
Illumination design
Simulation of imaging- and illumination systems
Optical systems in medical engineering
Printed micro-optical systems
Administration, Software Engineering & Technical Support
Status quo: 2020

Studying Optics

Traditionally our curriculum is primarily directed towards the students in upper-level diplom courses of **Mechanical Engineering, Cybernetic Engineering, Mechatronics, and Technology Management**. Since the academic year 2011/12 this courses are offered as master courses and an increasing number of master students is going to join our lectures.
This applies especially for the new master programme “**Micro-, Precision- and Photonics Engineering**” which enjoys great popularity also by students from other universities even from other countries.
Since the academic year 2009/10 we also offer our optics courses within the new bachelor and master program “**Medical Engineering**”, and since 2012 also within the new master program “**Photonic Engineering**”.
We also welcome students from other courses, such as “Physics” and “Electrical Engineering” and “Information Technology”.

The following list should give you an overview about the lectures given at the ITO.
Be aware that not all lectures are suitable for all courses and that most lectures are held in German language.

Core subjects in Bachelor and Master Courses (6 ECTS - Credit Points):

- **Fundamentals of Engineering Optics**

  Lecture: C. Pruß
  Exercise: C. Bett, A. Harsch, E. Steinbeißer

- **Optical Measurement Techniques and Procedures**

  Lecture: M.L. Gödecke
  Exercise: S. Hartlieb, S. Ludwig, E. Steinbeißer

- **Optical Information Processing**

  Lecture: Dr. K. Frenner
  Exercise: Dr. K. Frenner

- **Fundamentals of Optics (only for B.Sc.)**

  Lecture: Prof. Dr. A. Herkommer
  Exercise: F. Rothermel, J. Klein, M. Wende

- **Optical Systems in Medical Engineering**

  Lecture: Prof. Dr. A. Herkommer
  Exercise: F. Rothermel

- **Development of Optical Systems**

  Lecture: Prof. Dr. A. Herkommer
  Exercise: S. Lotz, C. Reichert, S. Thiele

- **Optical Sensors for Autonomous Systems**

  Lecture: Dr. T. Haist
  Exercise: Dr. T. Haist

Elective subjects in Bachelor and Master Courses (3 ECTS - Credit Points):

- **Optical Phenomena in Nature and Everyday Life**
  Lecture: Dr. T. Haist
- **Image Processing Systems for Industrial Applications**
  Lecture: Dr. T. Haist
- **Optical Measurement (only for B.Sc.)**
  Lecture: C. Pruß, Dr. T. Haist
- **Polarization Optics and Nanostructured Films**
  Lecture: Dr. K. Frenner
- **Introduction to Optical Design**
  Lecture: Prof. Dr. A. Herkommer, F. Rothermel
- **Advanced Optical Design**
  Lecture: Dr. Ch. Menke
- **Illumination Systems**
  Lecture: Prof. Dr. A. Herkommer
- **Current Topics and Devices in Biomedical Optics (only for B.Sc.)**
  Seminar: Prof. Dr. A. Herkommer

Additional studies:

- **project work and thesis within our fields of research**
  (you will find a list of all student project works at the end of this annual report)

- **practical course "Optic-Laboratory"**
  - ⇒ speckle measurement
  - ⇒ holographic projection
  - ⇒ digital microscopy
  - ⇒ computer aided design of optical systems
  - ⇒ measurement of the spectral power distribution
  - ⇒ Köhler illumination
  - ⇒ 3D measurement with stereo vision

- **practical course "Optical Measurement Techniques"**
  - ⇒ high contrast microscopy
  - ⇒ digital holography
  - ⇒ 2D-interferometry and measurement
  - ⇒ quality inspection of photo-objectives with the MTF measuring system
  - ⇒ ellipsometry

- **common lab for mechanical engineering (APMB)**

Activities of the SPIE Student Chapter “Univ. Stuttgart”

A. Toulouse, A. Birk, F. Rothermel, S. Hartlieb

Since February 2018 our insitute holds the majority of an “SPIE Student Chapter”, a self-organized gathering of students in the field of optics and photonics. The chapter was founded by Maria Laura Gödecke as our former president together with 16 other members and our faculty advisor Christof Pruss. We are funded by the international society for optics and photonics (SPIE) and can now, despite the Corona pandemic, look back on two further eventful years.

In March 2019, we invited Dr. Peter de Groot from Zygo Corporation, a legend in interferometry, to our institute. Dr. de Groot gave a talk about “Adventures in optical metrology” which was filled with ups and downs in the lab – tailored for us PhD and Master students. The following get-together gave room for discussions, ideas and opinions.

The main event in 2019 was a four-day field trip to Freiburg in autumn. Along with team-building activities like a hike to the Schauinsland or sightseeing of a mine we visited the Fraunhofer Institute for Physical Measurement Techniques (IPM, Fig. 1). We were welcomed by former ITO PhD-student and chapter member Dr. Dominik Buchta and Holger Kock, head of communication and media at IPM. Afterwards, Dr. Benedikt Blaesi from the Fraunhofer Insitute for Solar Energy Systems (ISE) gave us insights into their sophisticated cleanroom technology and solar cell research. Our next stop was the Department of Microsystems Engineering (IMTEK) of the University of Freiburg where Prof. Wallrabe gave us a short lecture to introduce the institute and Dr. Rohrbach and Dr. Breunig amazed us with a lab tour. The research at all three institutes was very different yet equally interesting and broadened our view on applied optics and photonics once more.

Gladly, we started 2020 right away with two in-person activities before the pandemic struck Germany. In January, we held a Workshop to test and experiment with an optics kit developed at the ITO (BMBF-project BaKaRoS). Afterwards, our traditional annual recruiting event, a winter barbecue, took place.

As a second event in 2020 we visited the Carl Zeiss AG in Oberkochen (Fig. 2). Here, we could spend time both in the in-house museum of optical history and were introduced to R&D at Zeiss Semiconductor Manufacturing Technology (SMT) by Dr. Sonja von Hodenberg. Furthermore, Nils Haverkamp showed us around at Quality and Research (IQR) where we discussed challenges in industrial measurement tools.

Unfortunately, the rest of the year was rather quiet and most of our plans had to be postponed. Thus, 2020 ended with the elections of a new set of chapter officers and many plans. Though strictly online until now, we were able to recruit several new members, especially from the Photonics Engineering Master’s program, which is a great source of young academics for both our chapter and our institute. We look forward to the next years to broaden our minds with more scientific and industrial field trips, networking opportunities and thank the ITO and SPIE for their support of our chapter.

Andrea Toulouse (president), Alexander Birk (vice-president), Florian Rothermel (secretary), Simon Hartlieb (treasurer), Christof Pruss (faculty advisor) + 16 student members

Supported by: SPIE – The international society for optics and photonics.

SPIE. STUDENT CHAPTER
UNIVERSITY OF STUTTGART

Fig. 1: SPIE-Chapter at Fraunhofer Institute for Physical Measurement Techniques (IPM).

Fig. 2: Field trip to Zeiss Headquarters in Oberkochen.

The research groups

3D-Surface Metrology

The objective of the group is the analysis and the implementation of new principles for the acquisition of optical 3D-surface data of engineering and biological objects over a wide scale. Our main focus is on the enhancement of the metering capacity by a combination of physical models and optimized system design.

Current research activities are:
- 3D-measurement applying fringe projection and deflectometry (macroscopic and microscopic)
- adaptive techniques using spatial light modulators
- confocal microscopy
- white light interferometry
- spectral interferometry
- sensor fusion and data interpretation strategies

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High Resolution Metrology and Simulation

The goal of this research group is the investigation of the interaction of light with 3d object structures in the micro and nano domain. Along with experimental research, one major aspect is the rigorous modelling and simulation as an integral part of the active metrology process. The analysis of all information channels of the electromagnetic field (intensity, phase, polarisation state of light) allows us to obtain sub-wavelength information about the structure.

Current research areas:
- modelling and rigorous simulation
- computational electromagnetics
- inverse problems
- high resolution microscopy
- scatterometry
- optical metamaterials

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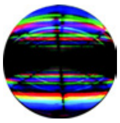

Interferometry and Diffractive Optics

The goal of our research activity is to explore new measurement concepts using diffractive optics. One important application is the testing of optical surfaces, in particular, aspheric lenses. For this purpose we design and produce computer generated holograms (CGH). At the same time, we develop flexible measurement techniques for aspheres and freeform surfaces that aim to replace static null correctors. In addition to CGH for interferometry, our in house production facilities allow us to produce diffractive elements and micro-optics for a wide variety of applications such as imaging systems, UV-measurement systems, beam shaping applications and wavefront sensing.

Our research areas include:
- testing of aspheric and freeform surfaces
- design, fabrication and testing of hybrid refractive/diffractive systems
- interferometry and wavefront sensors
- tailored optics for metrology applications
- fabrication of diffractive elements and micro-optics

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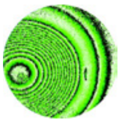

Coherent Metrology

Our research objective is the analysis and application of methods based on coherent optics for the measurement of 3D-shape and deformation and to determine the material properties of technical objects and biological tissues. Aside from the quantitative measurements of form and deformation, methods for non destructive material testing are also analysed and applied.

Research areas include:
- computational imaging
- imaging through scattering media
- holographic microscopy
- experimental stress analysis
- shape measurement

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Optical Design and Simulation

Focus of the group is the classical optical design of imaging and illumination systems, as well as ray-based and wave-optical system simulations. Main research targets are the development of novel tools for simulation and optimization and the design of innovative complex optical systems for industrial or medical purposes. A strong recent focus is the 3D-printing of micro-optical systems via two-photon-polymerization.

Current research topics are:
- imaging design
- illumination design
- optical simulations (ray-tracing and wave-optical)
- phase space methods in optical design and simulation
- complex surfaces in optical system design
- design, simulation and manufacturing of 3D-printed micro-optical systems
- optical systems for biomedical applications

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3D-Surface Metrology

Tissue Differentiation Using Model-based Optical Sensor Systems

V. Aslani, T. Haist, A. Herkommer

The primary goal of interventional procedures in surgery is to combine minimal invasiveness and high effectiveness with short treatment duration and low complication rates. A central aspect in oncology is the differentiation between malignant target structures and the surrounding tissue during surgery. Frozen section diagnostics is considered the gold standard of intraoperative tissue differentiation. During this procedure, the tissue is taken to a laboratory immediately after resection, cut in layers, stained, and examined histopathologically. The surgery usually has to be interrupted until the result is available. In addition, therapy (tumor resection) and diagnosis (histological examination) are separated both spatially and temporally.

In order to enable maximal functional preservation for the patient, a small volume identification of the tumor borders is necessary. The central topic of this research project is the discrimination of tissue boundaries based on elastic parameters using optical methods. This approach is based on the fact that tumor tissue has a different morphology than healthy tissue. The increased growth of tumor tissue results in a denser but less organized structure of the malignant tissue and to changes in the extracellular matrix (ECM). The increased density of the extracellular matrix leads to changes in the elastic parameters of the tissue. This serves as an approach to tissue differentiation, as the elasticity is quantifiable.

The goal of this research project is the development of multimodal optical sensor systems, which enable the identification of deeper functional tissue structures. In this context, depth-resolved optical sensor principles that have already been successfully tested conceptually (1, 2) are to be evaluated with respect to miniaturization and, if necessary, combined in order to record a detailed response of the tissue to an applied force. Furthermore, tissue differentiation can be supported by high-resolution optical detection of cell and tissue structures as a complementary tumor detection feature (hypervascularization and closer meshed ECM).

The measurement of elastic parameters using optical coherence tomography (OCT) has already been demonstrated by many research groups in the biomedical field. The foundation of the measurements is an exact recording of the movement of the tissue in response to an applied force. In the project further measurement methods, such as digital holography or triangulation, will be investigated and evaluated. The elastic parameters will be compared to and verified with theoretical simulation models. The aim of the research project is to develop a sensitive multimodal miniaturized probe for endoscopic use, which allows determining the elastic parameters of the tissue at hand.

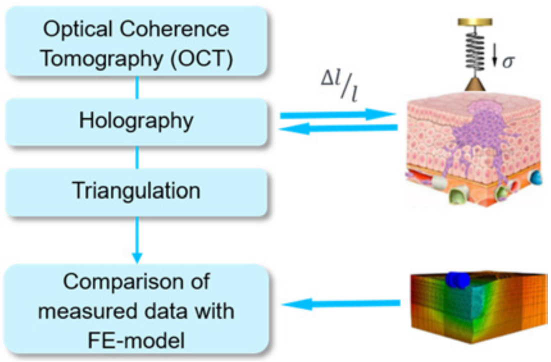

Fig. 1: Methods and solution approaches.

Supported by: The work described in this report was conducted in the framework of the Graduate School 2543/1"Intraoperative Multi-Sensory Tissue-Differentiation in Oncology" (project A1) funded by the German Research Foundation (DFG - Deutsche Forschungsgemeinschaft).
Project: „Diskriminierung tieferliegender Gewebestrukturen mittels modellgestützter optischer Sensorik" (GRK2543/1, A1)

References:

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(2) K. Mohan, A. Oldenburg: Elastography of soft materials and tissues by holographic imaging of surface acoustic waves. In: Optics express 20 (17), S. 18887–18897 (2012).

Project SEE3D – Current status and designated topics

A. Faulhaber, T. Haist, Y. Baroud, S. Simon

The Project “***SEE3D***” was previously briefly introduced in the preceding report. In cooperation with the IPVS, we are creating ***“fast and energy efficient three-dimensional panoramic views”*** for a service robotic platform (e.g. clinic, health or nursing applications). The objectives are to research a new concept and methods which incorporate fast FPGA-based image processing as well as multiple camera 360° panoramic view and depth estimation. Additionally, we further continue to investigate methods of detecting vital signs via cameras, e.g. heart rate via imaging plethysmography (iPPG).

In the following, we give you a glimpse at some designated topics of our recent research works starting with the most essential for the project – the panoramic view. Together with the IPVS, we have built a prototypical setup, see Fig. 1, consisting of ten small and low-cost cameras that are connected over custom serial connectors to three FPGA-enabled embedded boards of type Snickerdoodle (krtkl inc.). The embedded devices incorporate a Zync SoC FPGA, ARM processor and Wi-Fi and stream the cameras image data over-the-air to a host PC or server that composes a seamless 360° panoramic image of the robots’ surroundings by image stitching. Image compression and encoding, as well as computer-vision pre-processing is also done on the embedded hardware.

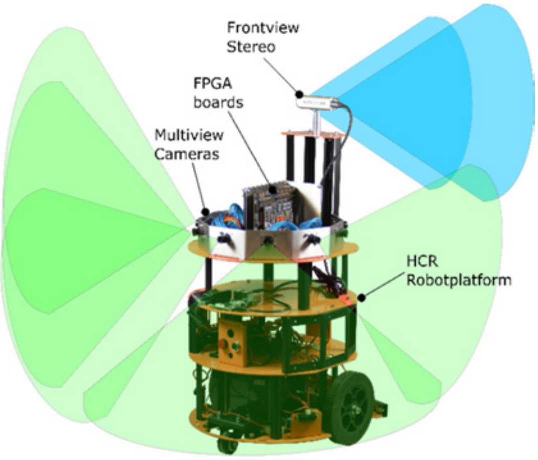

Fig. 1: Mobile robotic platform prototype with multi-camera embedded sensor system and commercial Intel RealSense stereo front view.

Furthermore, the subsequent part of the project includes measuring and estimating the depths of most parts of the panoramic view. Firstly, this is partly implemented by using the panoramic view and its overlapping camera image sections using multi-stereo vision. Secondly, we are using additionally ten cameras with different field-of-views combined with Laser-based point cloud projections as active stereovision system. The latter is generated using laser diodes, expanding optics and computer-generated holograms (CGH) lithographically printed as diffractive optical elements (DOE) to generate thousands of laser spots onto the object field.

Besides analyzing and comparison of commercially available stereovision sensors as robot addition, we’re also looking into training neural networks (CNN) to learn how to do stereovision based on artificially generated rendered scenes and depth information. The supervised learning yields decent results but needs refinement especially in circumstances of low object texturing.

Another project part is the vital signs detection. The key vital signs are the cardiovascular- and pulmonary systems. We first concentrated on measuring the heart rate with a two-camera method using specific wavelength filters previously research by us (1,2). We also tested different algorithms to improve the setup. Moreover, we also measured breathing rates using an off-the-shelf stereo camera.

Supported by: Baden-Württemberg Stiftung gGmbH
Project: “SEE3D”
In cooperation with: Institut für Parallele und Verteilte Systeme (IPVS), Universität Stuttgart

References:

(1) F. Würtenberger, et al., „Optimum wavelengths in the near infrared for imaging photoplethysmography“, IEEE Transactions on Biomedical Engineering, 66(10), 2855-2860, 2019.

(2) F. Würtenberger, L. Lachenmaier, A. Faulhaber, et al., „Kamerabasierte Erfassung von Vitalparametern”, tm - Technisches Messen, 86(7-8), 354-361, 2019.

Optical measurement systems for large scale and wide-span building deformations

F. Guerra, T. Haist, S. Hartlieb, P. Wilhelm, A. Steinitz, K. Hoppe

For the active control of large scale structures, especially high-rise buildings and bridges, fast and accurate measurement of local deformations is required. We present different approaches (1-3, unpublished) for highly accurate and fast vision based measurement techniques and first experimental results for the control of an adaptive structures prototype frame equipped with hydraulic actuators (Fig. 1). Deformations are detected at multiple discrete points based on a photogrammetric approach with additional holographic spot replication. The replication leads to effective averaging of most error contributions, especially discretization and photon noise.

For the application on already existing large structures it is desirable to have a continuously running measurement system which achieves fast, low latency (milliseconds) and highly accurate (sub-mm) coordinate measurements of multiple points. Our first two approaches use active elements (LEDs), whereas the third method uses edges (4) or corners.

Active illumination is important for operation during nighttime. Replacing one camera by multiple cameras would leads to a larger field of view but comes with the difficulty to keep the cameras completely fixed (position and orientation) over time. Longer focal lengths of the imaging optics improve resolution, accuracy and precision but reduce the field of view at the same time.

Therefore, we developed a second optical system for wide span structures such as bridges. It consists in a holographic wide-angle system that combines the accuracy of a long focal length with the advantage of a wide-angle lens for imaging extended scenery. But instead of a wide angle lens, we use a computer-generated hologram (CGH) in front of the lens to diffract light from specific angular locations. This method is tested in laboratory conditions, as well as outdoors with a real bridge. Within this method accuracy can be further improved when using a multi-image method (5). This app-roach uses an optical replication scheme which is also implemented with a CGH. It replicates each image coming from one angular position into multiple images (1, 2, 3, 5).

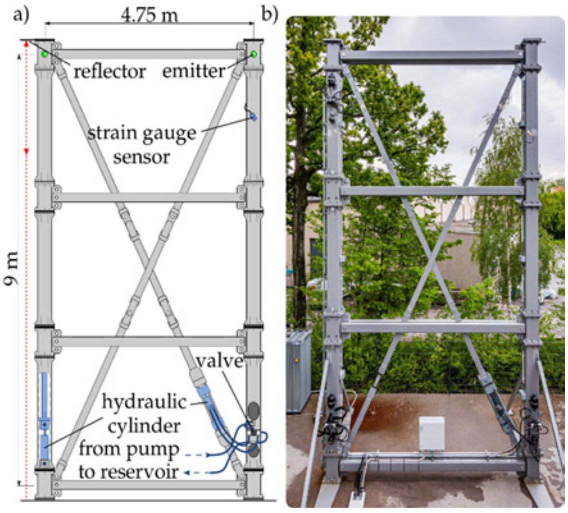

Fig. 1: Adaptive structures prototype frame. It represents three stories of one side of a lightweight adaptive high-rise structure.

Measurement uncertainties or accuracies should preferably be reported based on the extension of the measurement field or with respect to the elemental sensing element (pixel). Typical reported precisions are in the range from 0.1 to 0.01 pixels for extended targets (6).

Within that application the obtained measurement uncertainty is 0.0077 for method one and ~4/100 pixel for method two, which translates to 10-50 µm in object space at 10 m distance spanning 10 m width.

Supported by: DFG German Science Foundation
Project: Collaborative Research Center 1244 (SFB) “Adaptive Skins and Structures for the Built Environment of Tomorrow” / project B02.

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Single-shot full-field confocal microscope with a diffractive hyperspectral imager

R. Hahn, T. Haist

Optical metrology is an indispensable tool for maintaining high quality standards despite increasing production speeds. To ensure that quality control can be carried out not only on a sample basis, but also in large quantities, fast measuring systems are required. So-called single-shot measuring systems are able to capture the height information of a sample surface within a single camera frame. However, the height information in most commercial single-shot systems is only captured at a point or a line on the surface. For a full-field sample measurement, a scan of the sample surface is required.

In the ZIM-funded project “Mobimik”, a full-field single-shot confocal measurement system has been developed. To achieve this goal, a chromatic confocal sensor with a rotating microlens array was developed. The chromatic focal shift is realized by an hyperchromatic lens. A new type of hyperspectral sensor was to be used as the detector. This sensor has an extended Bayer pattern with 25 spectral channels. The filters used in front of the pixels are designed as interferential filters. In a systematic characterization (1,2), however, large, possibly manufacturing-related irregularities of the different spectral channels were observed. The characterization was performed with a specially constructed monochromator, which filters out a narrow band from a continuous spectrum of a white light laser. The camera to be examined was illuminated collimated by the monochromator and the wavelengths were systematically varied.

Since the examined camera did not meet the specifications, a new type of hyperspectral single-shot sensor was developed in the course of the project. The sensor is based on a diffractive optical element, allowing a flexible adjustment of the spatial and spectral resolution. In first tests the sensor was capable to detect spectral shifts of less than 3 nm.

By integrating this this novel sensor into the chromatic confocal microscope, a single-shot 2.5-D measurement is possible.

With this system shown in Figure 1, sample displacements of < 1µm were detected in initial tests. The axial measuring range is 100 µm, but can be increased significantly by adapting the design.

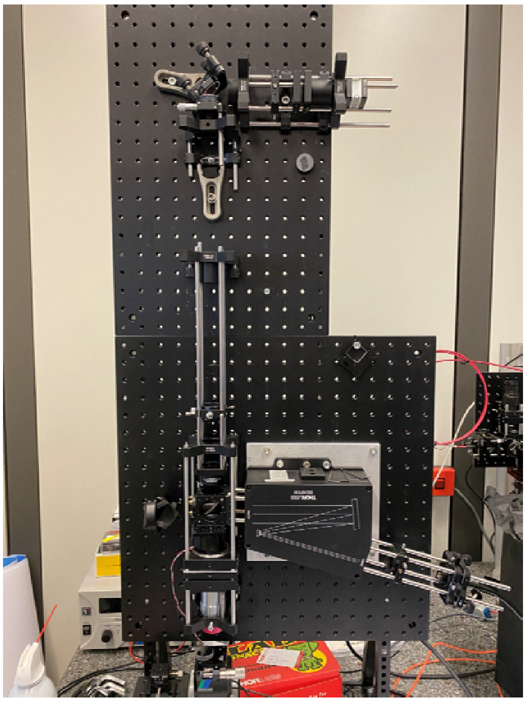

Fig. 1: Chromatic confocal microscope including a rotating micro lens array and the hyperspectral imaging approach based on a DOE.

In summary, in the course of the project a full-field single-shot topography sensor and a promising new approach for flexible hyperspectral imaging has been developed.

Supported by: German Federal Ministry for Economics Affairs (BMWi) within the ZIM project “Mobimik” (16KN075722)
In cooperation with: twip optical solutions GmbH and the Reutlingen University.

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Characterization of homogenization components for future satellite-based push-broom spectrometers

T. Haist, M. Tscherpel, S. Hartlieb, S. Amann

In this joint project we investigated the behaviour of slit homogenization components for future NASA CO2 monitoring satellites. Such components are envisioned for reducing the measurement uncertainty of spectroscopic push-broom measurements if an inhomo-geneous scene (e.g. road and forest) is imaged into the entrance slit of the spectrometer.

The optical behaviour of such devices is indeed quite complex due to the wavelength dependent multiple interferences that occur.

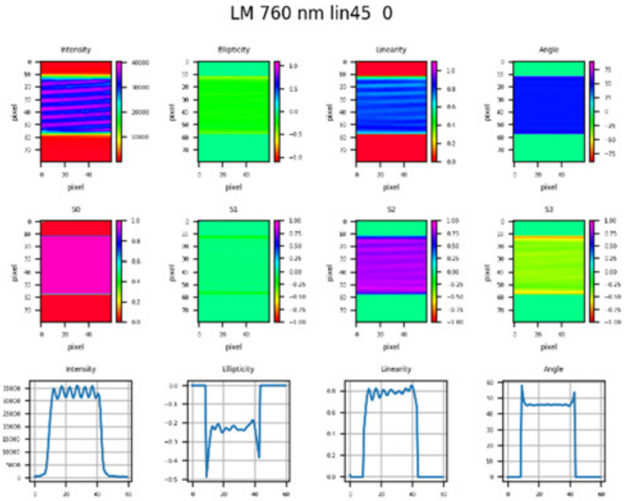

Fig. 2: Typical measurement example for polarimetric results.

For the investigations we realized a breadboard enabling temporal coherent and spatial incoherent measurements for different input intensity and polarization distributions at NIR and three different SWIR wavelengths (up to 2,3 µm). Lasers are used as sources for the temporal coherence (spectroscopic application) and to enable enough optical power to illuminate the high resolution image sensors which are necessary to achieve highly resolved recordings of the output intensity distributions after the device. Speckles and detector noise are reduced to below 1% by averaging in combination with a rotating and a fixed diffusor.

For the imaging polarimetric measurements at these wavelengths a rotating quarter-wave method has been implemented. Three computer-controlled polarization elements (polarizers and quarter-wave plate) are used to measure spatially resolved Stokes vectors for different input polarizations.

Different devices have been characterized this way and also expected mounting tolerances in the final instruments have been investigated.

Supported by: NASA
In cooperation with: University of Oklahoma

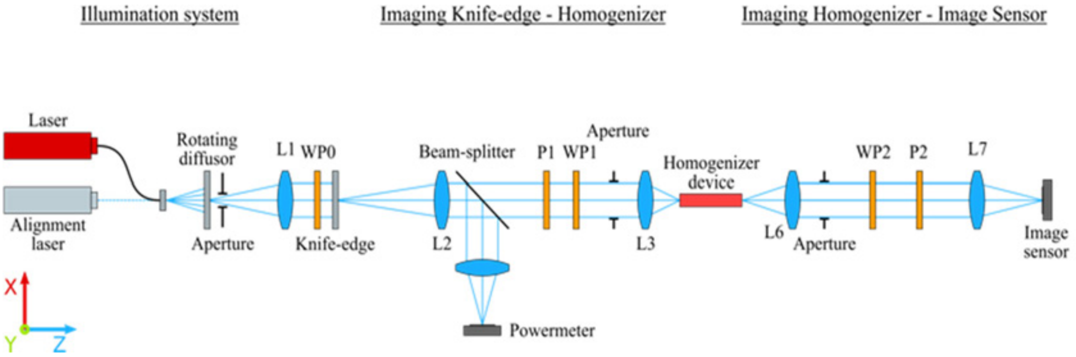

Fig. 1: SWIR Imaging polarimeter for high resolution characterization of components.

Image based 3D position measurement using holographic point replication

S. Hartlieb, T. Haist, W. Osten, O. Sawodny (ISYS)

Many industrial applications such as coordinate measurement-, milling-, or turning machines rely on a very precise measurement of the relative position between the tool centre point (TCP) and workpiece (WP). The TCP position is commonly measured indirectly using encoders that are placed out of the Abbe point. Therefore, with increasing dynamic and moving mass, inertia leads to a distinct deviation between measured and real TCP position.

Optical position measurement with holographic multipoints could provide the necessary means to identify and compensate those deviations by directly measuring the relative position between light sources that are attached to TCP and WP. It was shown by Haist et al. that the holographic replication of a single point light source to a cluster of spots in image space can provide the opportunity to improve the accuracy of position measurement by the root mean square of the number of replicated spots, by averaging the centres of gravity of all spots per cluster. (1)

In this project, the multipoint method is used to measure 3D positions with highest accuracy. Therefore, a stereo camera system is designed, which consists of 2 camera systems, whose lenses are upgraded with computer generated holograms to perform the multipoint replication. Both cameras are mounted in a stiff frame (see Fig. 1). Simulations were performed to analyse the best calibration strategy (see (2)). Simulation results show, that the use of a positioning machine is suited best for the high requirements. The Nanopositioning and Nanomeasuring Machine NPMM-200 is used for this purpose. Unlike conventional calibration, simulations at different distorted lens systems show that a multivariate polynomial reaches better reprojection results than commonly used calibration functions. The polynomial maps the calibration points in object space to the measured points in image space. The measurement volume is 100 mm x 74 mm x 24 mm and the calibration grid consists of 3900 points. By taking advantage of the improved accuracy achieved by the multipoint method in combination with the highly accurate positioning of the NPMM-200, highest accuracies can be reached. The reprojection error for the whole measurement volume is $\sigma_x = 0.367$ µm, $\sigma_y = 0.373$ µm and $\sigma_z = 0.437$ µm. Conventional single spot evaluation results in a reprojection error that is 3 to 5 times worse.

The innovative points of this system are not only the very high positional accuracy but also the ability to measure orientations of multiple objects simultaneously. Furthermore, the measurement system can be retrofitted to already existing applications.

Supported by: DFG German Science Foundation
Project: Dynamische Referenzierung von Koordinatenmess- und Bearbeitungsmaschinen (OS 111/42-2)
In Cooperation with: Institut für Systemdynamik

References:

(1) T. Haist, W.Osten, et al., “Multi-image position detection”, Optics Express 22, 14450-14463, 2014.

(2) S. Hartlieb, W.Osten, et al., “Hochgenaue Kalibrierung eines holografischen Multi-Punkt Positionsmesssystems”, *tm - Technisches Messen*, vol. 87, no. 7-8, pp. 504-513, 2020.

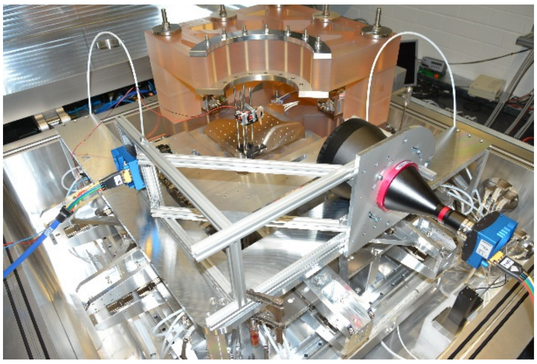

Fig. 1: Multipoint measurement setup consisting of two camera systems in a stiff frame. The setup is mounted in NPMM-200 for calibration.

Image based vibration measurement using holographic multipoint method

S. Hartlieb, T. Haist, W. Osten

The precise measurement of deformations and vibrations is needed in many industrial applications. There the use of laser Doppler vibrometer (LDV) is very common, as they offer great temporal and spatial resolution. However, as soon as multiple object points have to be measured simultaneously, LDVs are becoming impractical. Here, image based vibration measurement can offer the means to fill this gap.

In this project we use the holographic replication of a single point light source to a predefined pattern in the image plane of the camera sensor. By averaging the centers of gravity of all spots, the accuracy of position measurement can be improved by the square root of the number of replications (1). This offers the possibility to very precisely locate the position of one or multiple point light sources in object space. The idea is to attach multiple point light sources to a vibrating object and measure the transient movement of all light sources with very high resolution.

First measurements are performed using a linear piezo stage with multiple light sources attached (see Fig. 1). A sinusoidal movement of 50 Hz with different amplitudes is measured by the multipoint camera setup and a LDV for validation. The comparison of both signals shows that vibrational amplitudes of 100 nm can be resolved. In Fig. 2 the measurement of a vibration amplitude of 500 nm is plotted for the LDV and the camera setup. The standard deviation between both signals is σ = 0.099 µm, which corresponds to 0.0015 pixels in image space. Furthermore, it can be shown that, by monitoring the relative movement between static and vibrating light sources, classical band pass filtering can be omitted. To analyze the precision for high frequencies, experiments with an inertial shaker are performed. The shaker is actuated with a sweep signal from 100 Hz to 1000 Hz. Measurements of the LDV and the camera system show very good correspondence.

Supported by: DFG German Science Foundation

Project: Dynamische Referenzierung von Koordinatenmess- und Bearbeitungsmaschinen (OS 111/42-2)
In Cooperation with: Institut für Systemdynamik

References:

(1) T. Haist, W.Osten, et al., “Multi-image position detection”, Optics Express 22, 14450-14463, 2014.

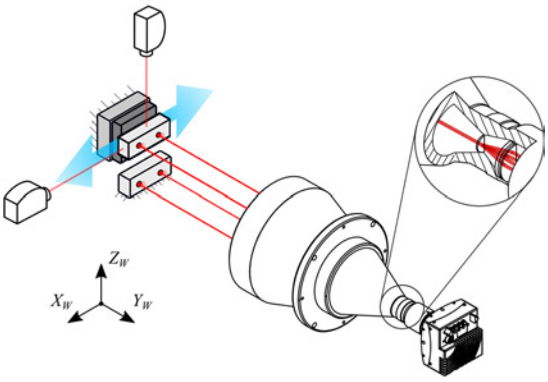

Fig. 1: Experimental setup: Two light sources are attached to a piezo stage and its position is measured by two LDV and the multipoint measurement setup.

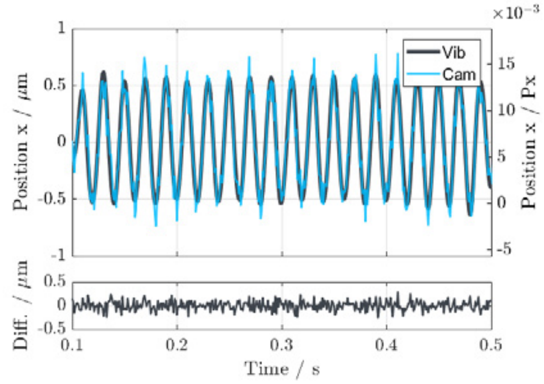

Fig. 2: Measurement of a sinusoidal piezo stage movement (50 Hz, 500 nm amplitude) with the camera and a LDV. The difference between both signals is shown in the lower plot.

High Resolution Metrology and Simulation

Machine Vision with Single Pixel Camera and Deep Learning based Signal Processing

A. Birk, K. Frenner, W. Osten

Making a machine aware of its surroundings by leveraging optical metrology – Machine Vision (MV) – is a very active research area in light of the continued push for autonomy in technical systems. Within this research project, we developed a novel approach to MV problems where the main interest is object pose recognition. Its defining features are that it works without areal optical sensors, that a Neural Network performs the data processing and that it directly extracts the relevant features such as size and positioning of objects in a 3D space. This setup offers multiple advantages compared to classic approaches: It reduces hardware requirements on the data acquisition side by simplifying the sensor, enables its use in domains where areal image sensors are very expensive or unavailable, and greatly lightens the processing side by directly returning relevant scene information, eliminating explicit image reconstruction. Thus, this approach belongs to the still sparsely covered area of image free MV methods.

The setup is based on ideas and principles from the area of Compressed Sensing (CS). The main goal in CS is to harness the inherent sparsity of information in a naturally occurring scene. This allows for a great reduction in the amount of data that needs to be captured, and a significantly simplified sensor setup. In the context of the project, this means that the setup consists only of a means to provide structured illumination and a single photodiode to capture the light that the objects in the scene reflect. We also refer to this kind of setup as a Single Pixel Camera when used to produce images. (1)

In our case however, we produce scene information from this CS data instead of reconstructed images. To do so, we employ artificial Neural Nets and Deep Learning. Over the last few years, we witnessed significant success in using these techniques in the areas of image processing, scene and object identification (2) as well as data reduction. This supported us in developing a purpose-built Neural Net for the task. Major features of our network topology include that it actively harnesses the continuous change over time in the scene and that it uses 3D time of flight information. Additionally, our training process allows for the optimization of the structured illumination patterns in the measurement setup alongside the interpreting Neural Net. This ensures we produce an optimal setup for the given application profile in a single training run.

With this method, we want to provide a flexible solution that is cheaply and easily adaptable to different MV problems. This is also why we train the setup on artificial data generated with ray tracing algorithms and only test it with real-world data, thus greatly reducing the need for actual physical measurements.

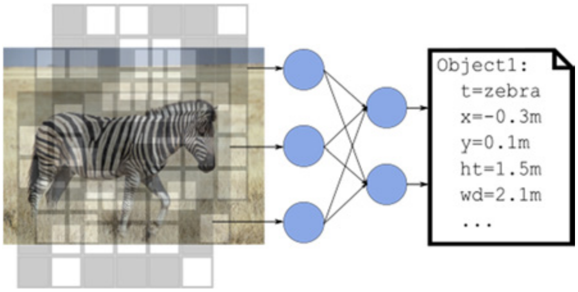

Fig. 1: High-level schematic of our approach. The scene is illuminated with different dark-light-patterns and a neural net processes the intensities of refected light to produce the desired information.

Supported by: DFG German Science Foundation and Landesministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg
Project: Single Pixel Camera with Deep ConvNet Signal Processing for Autonomous Robot Systems (GSaME F2-036)

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Laser-Based 3D-Sensor-System for Autonomous Driving in Adverse Weather Conditions with Poor Visibility

C. M. Bett, M. Daiber-Huppert, K. Frenner, W. Osten

Autonomously driven cars need a bunch of sensors to make them robust against many possible street scenarios. In adverse weather conditions (fog, heavy rain, snow) especially, state-of-the-art sensors show a very limited performance. Therefore, we are developing a sensor system to overcome these limitations in a joined research project with University of Freiburg (AIS) and Fraunhofer Gesellschaft (IPM).

The sensor system comprehends a Lidar sensor (IPM), as well as an intelligent data analysis via multimodal neural networks by AIS. ITO is developing a so-called “time-gated single-pixel-camera” (see Fig. 1) to enrich the Lidar information for specifically interesting regions of its point cloud.

Time-gated or range-gated cameras provide excellent penetration through scattering media (see Fig. 2), although this simultaneously leads to low light levels. An eye-safe pulsed laser with as much power as allowable is therefore crucial. This is why we fixed the operating wavelength at 1540 nm. In the infrared though, camera technology is not as developed as in the visible range, moreover if time gating with very short gating intervals in the nanosecond regime is considered. We want to circumvent this problem by measuring with a simple photodiode, which is fast and inexpensive. The spatial information is provided by a set of masks in front of the photodiode (see Fig. 1). The number of masks is significantly reduced compared to the equivalent number of camera pixels because the scene is well compressible with our sensor concept. The binary measurement matrix (the masks) are not predefined but trained with a neural network, in order to generate the best object recognition performance with as few masks as possible.

Supported by: Baden-Württemberg Stiftung gGmbH
Project: Laser-basiertes 3D-Sensorsystem für autonomes Fahren unter schwierigen Wetter- und Sichtbedingungen „Clear-View-3D“ (BW-Stiftung)
In cooperation with: Institute for Autonomous Intelligent Systems (AIS), University of Freiburg,
Fraunhofer Institute for Physical Measurement Techniques (IPM).

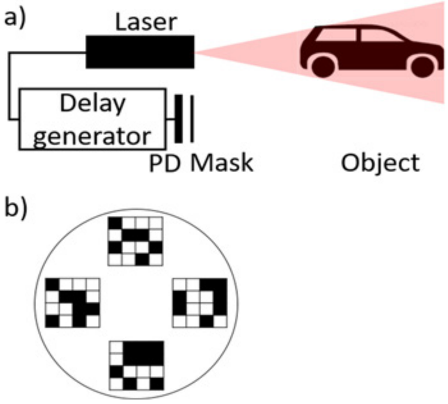

Fig. 1: An infrared pulsed-laser illuminates the object. The photodiode is triggered after some variable delay time (depending on the distance of interest). The masks in front of the photodiode (PD) enable spatial detection (a). Possible implementation of the masks on a rotating disc (b).

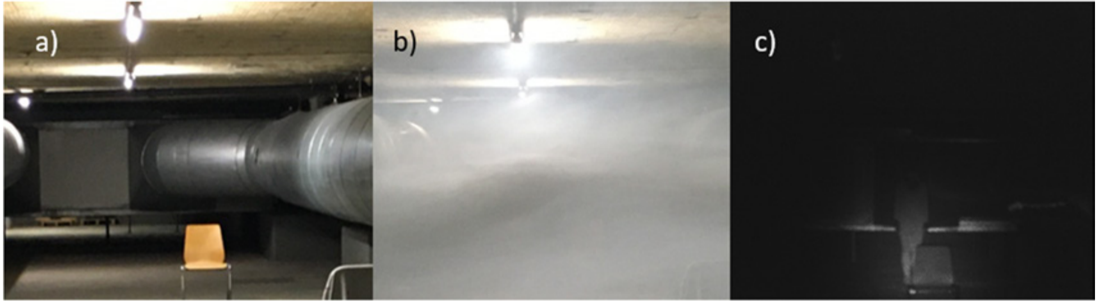

Fig. 2: Time gating enables detection through fog: Laboratory environment without fog (a). With fog, the chair and a person standing behind it cannot be detected by a conventional camera (b). This becomes possible with a time-gated camera (WiDySenS 640V STP, 100ns gating) (c).

White-light Mueller-matrix Fourier scatterometry for the characterisation of complex periodic nanostructures

M. L. Gödecke, K. Frenner, W. Osten

With the structure dimensions on modern semiconductor chips having reached the nanometer scale and the circuit designs becoming ever more complex, process monitoring is facing veritable challenges. Due to its fast and non-destructive operation mode, model-based optical scatterometry ranks among the most important measurement techniques in high-volume semiconductor manufacturing. As the feature sizes are too small for direct optical imaging, scatterometry retrieves them indirectly by comparing measured data to simulated signatures and searching for the closest match. However, the design complexity of state-of-the-art devices generally requires large parameter spaces for the structural modeling. As a result, the reconstruction procedure is often complicated by ambiguities due to low sensitivities and high cross-correlations.

In the framework of a DFG funded project, the so-called white-light Mueller-matrix Fourier scatterometry was proposed as a novel measurement approach. It combines the well-known techniques of Fourier microscopy, Fourier spectroscopy, and Mueller polarimetry into one apparatus and allows for the measurement of a sample's full Mueller matrix with simultaneous angle and wavelength resolution. By means of a rigorous simulation study, it was demonstrated that in comparison to conventional techniques, the increased information content of the measurement result provides a more stable regularisation to the inverse problem of scatterometry (1).

In order to demonstrate the practical feasibility of the proposed sensor concept, a prototype version of the sensor was designed and implemented. The calculation of a sample's Mueller matrix currently requires four measurements at different angular orienttations of polariser and analyser. System imperfections are removed by performing reference measurements on a calibration target. Fig. 1 shows exemplary measurement results obtained on a sub-wavelength silicon line grating and compares them to the best matching simulation results (2).

The accuracy of the measurement procedure was verified by performing additional SEM and AFM measurements. Fig. 2 shows cross-section SEM images of two different silicon line gratings together with true-to-scale sketches of the reconstructed profiles. The good agreement highlights the method's sensitivity and implies that systematic measurement errors are negligible.

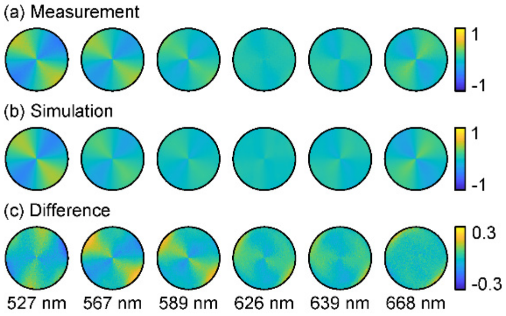

Fig. 1: Mueller matrix element m_{13} at all angles and at different wavelengths, measured on a silicon line grating with a pitch of 150 nm. The black circles mark the maximum NA of 0.8.

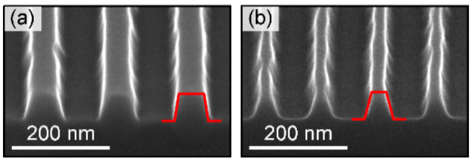

Fig. 2: Cross-section SEM images of different silicon line gratings. (a) 150 nm pitch, (b) 116 nm. The red profiles illustrate the results of the model-based reconstruction.

Supported by: DFG German Science Foundation
Project: Schnelle Weißlicht-Müller-Matrix-Scatterometrie zur Charakterisierung von Nanostrukturen mit großem Parameterraum (OS 111/49-1)

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(1) M. L. Gödecke, K. Frenner, W.Osten, “White-light Mueller-matrix Fourier scatterometry for the characterization of nanostructures with large parameter spaces”, Proc. SPIE 113250V, 2020.

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Tissue Differentiation using IR Spectroscopy

F. Fischer, K. Frenner, A. Herkommer

During the proliferation of tumour cells the proportions of tissue components such as nucleic acids and lipids change which also yields changes in its optical characteristics (1). Thus, the spectra of tumourous and healthy tissue differ and it is possible to distinguish them from one another. The spectroscopic examination of organic material has commonly been conducted with FTIR spectrometers, but they are gradually being replaced by modern IR-spectrometers that are based on the principle of attenuated total reflection (ATR).

In this project, we are developing a new method to use ATR spectroscopy in combination with highly sophisticated and exceptionally brilliant quantum cascade lasers (QCLs) to downsize the optical set-up and accelerate the acquisition time. The overall goal is to miniaturize the spectrometer and to implement it in a conventional endoscope in order to assess the completeness of tumour resections already during surgery and consequently shorten the overall time in the operating room.

Previous work has shown that this abundance of signals is not necessary to distinguish between malignant and benign tissue spectra, because the main information lies in specific biomarker regions (1, 2). That is why we want to use only few narrow bandwidth DFB lasers as a light source.

Hence, it is necessary to find the most relevant data points in the mid infrared spectrum of tumourous tissue beforehand. To do so, at first measurements have been undertaken in the PA&T laboratories in Reutlingen, in which we recorded FTIR spectra from organoids of bladder carcinoma (fig. 1) - further investigations of samples from healthy organoids are pending. The samples are then analysed and discriminated using different techniques like linear discriminant analysis (LDA) and neural networks. Afterwards, plenty of different feature selection methods have been investigated to find the most informative biomarkers including cross-validation, random forests and correlation based statistical approaches. Even though the aforementioned classification algorithms are not obviously suitable for feature selection purposes, especially the latter shows pronounced potential to outperform any existing feature selection algorithm, when being slightly modified, such that a recursive pruning of the input nodes in a neural network is feasible. The result of this algorithm is an embedded feature selection method that is also able to cope with non-linearity (in contrast to e.g. LDAs).

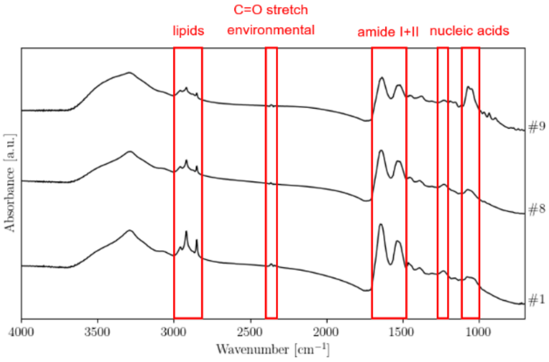

Fig. 1: Measured spectra of bladder carcinoma organoid. The red regions indicate possible biomarker areas.

This years' focus lied on the development of this feature selection algorithm. By the use of so-called callbacks – executions of certain code snippets during training phase of the model – we have been able to evaluate and modify the input features at a certain stage of optimizing the classification. At each callback, we are able to measure the feature importance and delete the less important features. The training then continues until it reaches the next callback.

A paper with the theoretical background and the results of comparing it with other algorithms is to be submitted within the next few weeks.

Supported by: DFG German Science Foundation
Project: Intraoperative multisensorische Gewebedifferenzierung in der Onkologie (GRK 2543 – A2)
In cooperation with: Universität Tübingen

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3D rigorous speckle simulator using surface integral equation method and multilevel fast multiple method

L. Fu, K. Frenner, M. Daiber-Huppert, W. Osten

We have developed a 3D rigorous speckle simulator using surface integral equation (SIE) method to calculate light scattering from large area surfaces. Since only the surface of the object is discretized, this method shows great advantages over volumetric approaches such as the finite difference in time domain method and the frequency domain finite element method. Integral equations derived from the Maxwell's equations are normally formulated in Stratton-Chu's way. To solve the coupled electric and magnetic surface integral equations using, e.g. PMCHWT formulation (1), we mesh the surface using triangular elements and use Rao-Wilton-Glisson rooftops as basis functions.

To reduce memory and computation costs for large objects, we use an iterative solver GMRES (2) sped up by multilevel fast multiple method (MLFMM) (3). Furthermore, a simple preconditioner out of the diagonal elements of the impedance matrix is implemented. The simulator was programmed in Fortran 90 and the tests were performed on a Xeon server (2× Xeon E5-2627, 3.5GHz with 12 threads using MKL OMP algorithm). Smooth spheres and square surfaces out of silver with a refractive index of 0.0552-i4.01 at the wavelength of 600 nm are meshed with a size smaller than $\lambda/10$ and were calculated. In fig.1, time consumed for a LU decomposition solver (routine ZGESV in Intel MKL) and the preconditioned iterative solver combined with MLFMM versus unknowns is plotted. The former can be well fitted by $N^{2.5}$ (the non-integer power is induced by the parallelization of the solver), while the latter can be approximately fitted by $\log(N)N^{1.5}$. The improvement with the latter is huge when the number of unknows is large. Using the LU direct solver to solve 3.93×10^5 unknowns, an estimated time would be 102 hours (the problem is already beyond the memory capacity of the server), which is obviously not a realistic CPU time. Instead, only 199 minutes were used by the MLFMM solver.

Nevertheless, once the surface becomes rough, the convergence of current simulator becomes slow. This is due to the increased condition number of the impedance matrix. To solve this problem, a more efficient preconditioner such as Schur-complement preconditioner should be implemented, which is under process.

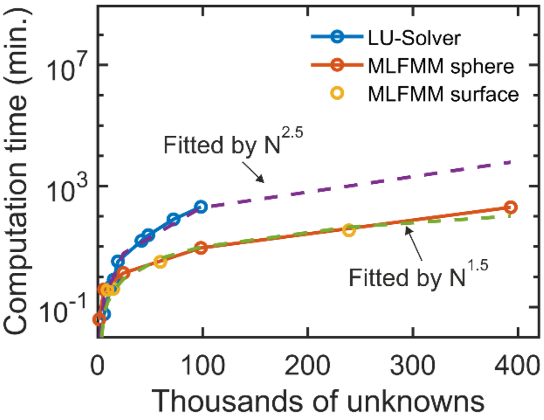

Fig. 1: (a) Comparison of computation cost by using an LU decomposition solver and a GMRES iterative solver sped up by MLFMM. Dashed lines are fittings.

Supported by: DFG German Science Foundation
Project: Rigorose Simulation von Speckle Feldern bei großflächigen rauen Oberflächen mit schnellen Algorithmen auf der Basis von Randelementmethoden höherer Ordnung (OS 111/51-1)

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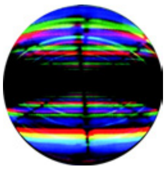
Interferometry and Diffractive Optics



Advances in Freeform Metrology

A. Gronle, C. Pruß, C. Schober, R. Beißwanger

Aspherical and freeform optics are essential parts of many modern optical imaging systems. For their precise manufacturing accurate form measurement is needed. The EMPIR FreeFORM project was dedicated to improve both the manufacturing and measurement capabilities of institutes and companies.

For the optimization of full-field measurements with a Tilted-Wave Interferometer (TWI), we use our custom TWI Monte Carlo simulation environment. One main challenge during the measurements is to distinguish between an error caused by a misaligned surface and a topography error. This problem is known from the interferometric inspection of spheres, where a radius error and a defocused position cannot be distinguished. For aspherical or freeform surfaces, the ambiguities are much more complex due to their more complex geometry. Correlations between surface geometry and positioning errors have been investigated. External measurements of the surfaces position can help to reduce the resulting uncertainties (1).

Another severe problem in the development of measurement systems is the lack of a reference measurement system. Therefore, interlaboratory comparisons serve to evaluate measurement systems. Newly developed reference surfaces made from thermo invariant materials with complex surface forms were used in two round robin comparisons with participating institutes from all over Europe and beyond. Five specimens were investigated: a two-radii specimen, a convex toroid, a concave toroid, an asphere with 3 µm steps and a freeform TIMM2. ITO participated in this round robin comparison with measurements on the TWI (specimen 1, 2 and 3) and the NPMM (specimen 4 and 5). Measurements performed with TWIs at PTB and Mahr, show very good agreement with our measurements, see figure 2, published in (2). The measurements done by the NPMM were used to verify newly developed reference algorithms, developed within the project (3).

Fig. 1: Participants of the Freeform Measurement Training held at ITO with the aim to promote exchange between developers, users and research institutes.

Supported by: European Union’s Horizon 2020 research and innovation programme and the EMPIR Participating States
Project: EMPIR project 15SIB01 FreeFORM
In cooperation with: Physikalisch Technische Bundesanstalt and others.

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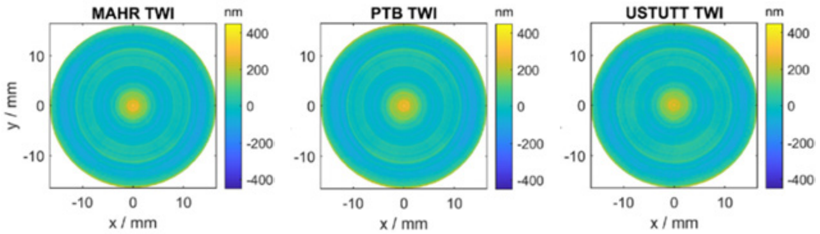

Fig. 2: Round Robin comparison of a two radii specimen. Measurements with TWIs at ITO, PTB and Mahr. (2)

Combination of subapertures for precise measurement of aspheric surfaces using a Tilted Wave Interferometer

A. Gronle, C. Pruß, W. Osten

Large aspheric optical components can be found e.g. in lithography systems or remote sensing with telescopes like the E-ELT. Manufacturers need a potent metrology to be able to produce such optics with high precision. The aim of the project “TWI-Stitch” was to develop a fast and contactless method for the measurement of large optical components with a high lateral resolution.

To be able to capture large diameters, individual subapertures distributed over the measurement area are recorded. After the measurements, they are stitched together.

In case of an aspheric surface, the subapertures themselves are not rotationally symmetric. The Tilted Wave Interferometer (TWI) is capable of measuring such freeformed surfaces due to its illumination array which provides a number of waves that are mutually tilted. This allows choosing subapertures with diameters in the range of the interferometer aperture, even if their departure from a best fit sphere is hundreds of microns. We could show that with this approach, the number of required subapertures can be reduced by up to 90% compared to a standard interferometer.

The interferometer needs to be tilted in order to capture subapertures at the edge of the surface, as shown in figure 1, especially when steep surfaces with comparably small radii are to be measured. Adaptions on the design of the interferometer were made to make it more stable. Experiments have shown, that tilts up to 12° are possible without losing stability. After tilting the interferometer, the surface under test is rotated to measure all subapertures with the same radial distance from the surface’s center.

Figure 2 shows the topography of three subapertures, which are stitched together in order to get an overall result.

Supported by: AiF
Project: TWI-Stitch: Kombination von Subaperturen zur hochgenauen Vermessung asphärischer Flächen unter Verwendung eines speziell angepassten Tilted Wave Interferometers. IGF Vorhaben 18592 N.
In cooperation with: Technische Hochschule Deggendorf and Mahr GmbH.

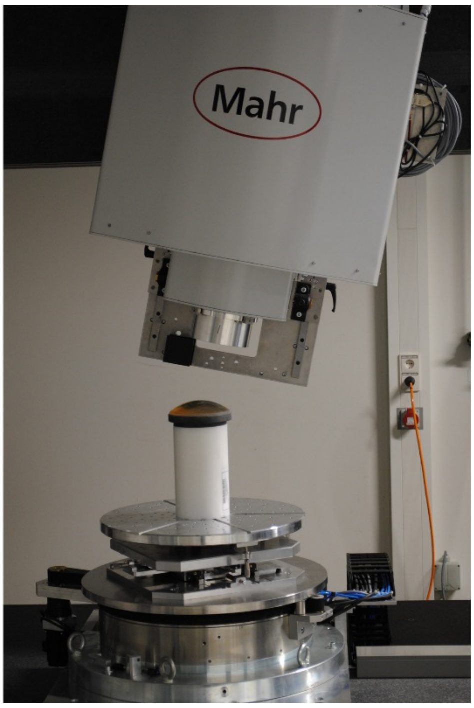

Fig. 1: Testsurface and a TWI, tilted for subaperture measurements

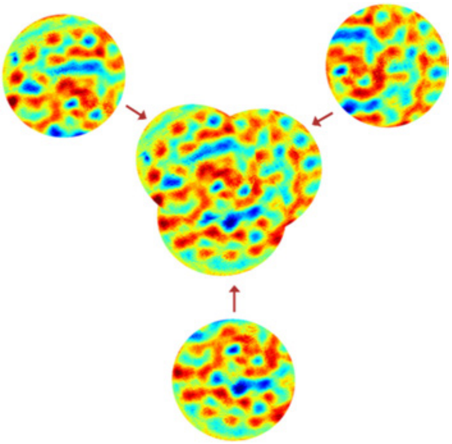

Fig. 2: Three subapertures and the stitched result

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Fizeau-type Tilted Wave Interferometry

R. Beißwanger, C. Schober, C. Pruß, A. Herkommer

With the manufacturing possibilities for optics given today, the use of sophisticated optical elements, like aspheres or freeform surfaces, is very attractive and affordable for modern optical systems. Such elements can improve the optical performance or enable a smaller from factor.

Accompanied, there is the need of precise and fast measurement of such elements. Especially small batch sizes demand a high flexibility in measurement systems.

Tilted Wave Interferometry (TWI) accounts for these three major demands: Precision, short measurement time and flexibility (1) - (3). TWI provides full field measurement with high lateral resolution in a measurement time of typically less than 30 seconds. Moreover, no lead time (like in CGH Interferometry) is required before measurements. A commercial version of TWI is available from Mahr GmbH (4) and the capability of TWI was demonstrated in several round robin test (5).

Major improvements where achieved with the 3rd generation of the TWI, the TWI in Fizeau configuration (figure 1) (6), (7). The main advantage is the common path principle: except for the distance between objective and specimen, measurement and reference beam paths are almost the same. Thus, a major part of the errors in the common path cancel out in the interferogram signal, i.e. in the difference between the two paths. This was demonstrated in simulations with a disturbed optical element in the common path of the interferometer. Also stability with respect to temporal fluctuations like air turbulences and acoustic disturbances increases, as shown in figure 2. In our setup, the phase noise, caused by temporal environment fluctuations is 3 times lower than in the standard Twyman-Green-TWI version.

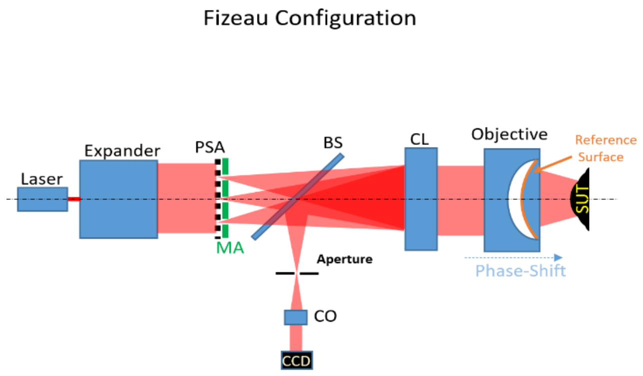

Fig.1: Tilted Wave Interferometer in common path Fizeau configuration.

An example of measurement with the new TWI Fizeau is shown in figure 3. The sample was a freeform surface that has an overlaid sine grid with a 1 mm spatial frequency. The results are in very good agreement with measurements made by the NPMM-200.

Because of the advantage of common path principle, the 3rd generation also paves the way to a full field of further developments. For example, the high stability of the Fizeau interferometer allows to use heterodyne techniques with multiple wavelengths (multi wavelength interferometry MWLI) (8). MWLI can contribute to the unambiguousness of error description and numerical stability and thus pushing the limits of TWI further.

In cooperation with: Mahr GmbH

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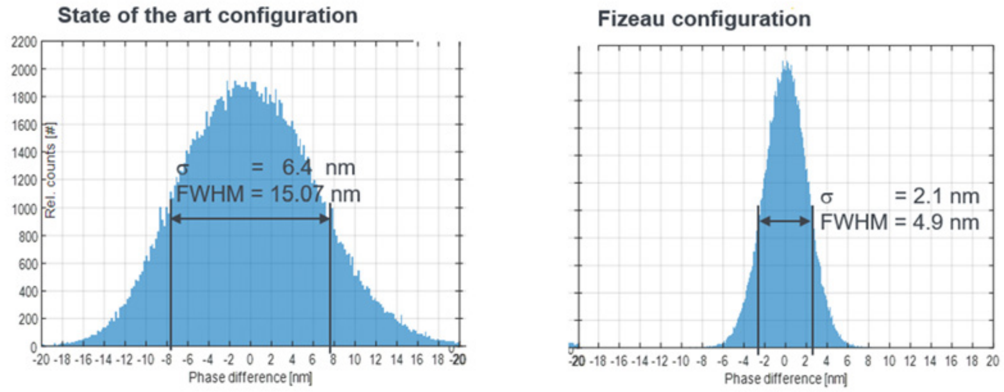

Fig.2: Measured phase-noise for state of the art TWI (left) and 3rd generation Fizeau configuration (right).

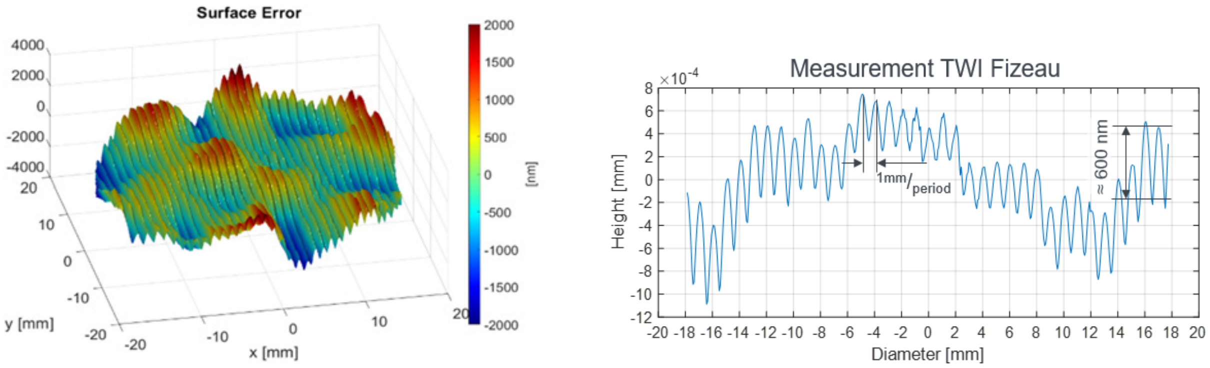

Fig.3 a) and b): Measurement with Fizeau-TWI. The Specimen has an overlaid sine grid with nominal amplitude of 600nm and nominal period of 1/mm.

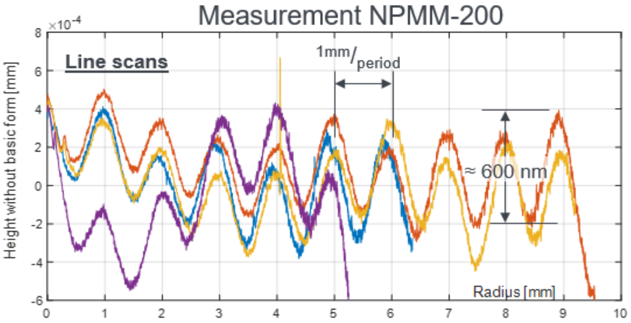

Fig.3 c: The measured parameters where confirmed with measurement with the NPMM200.

Nanopositioning and Nanomeasuring Machine NPMM-200: Large Volume High Precision at ITO

C. Schober, C. Pruß

Nanometer precision metrology and positioning in a large volume is interesting for many research areas such as form metrology, system calibration tasks or lithography. The nanopositioning and nanomeasuring machine NPMM-200 built by the TU Ilmenau provides an ideal platform for research in this field.

Since end of 2018 the machine has undergone the final tests and is in use. The machine enables sub nanometer resolution positioning in a large measurement volume of 200 x 200 x 25 mm^3. For the realization of this resolution six interferometers measure the movement of the sample carrier (“mirror-corner”). The interferometers are fixed in a measurement frame made of ZERODUR glass ceramic. In this measurement frame different types of sensors can easily be attached (1). The easy exchange of the sensors enables a plentitude of possibilities for the use of the machine.

A research field of the machine is surface shape metrology. Using a fixed focus sensor to sense the sample surface the machine is controlled to track the sample surface while it is scanned in x and y. Therefore, the influence of the linearity error of the sensor can be minimized. The sample height is calculated from the position of the machine and the residual sensor signal. The sampling rate of the system is 8192 Hz. With this focus sensor we made measurements of a calibrated step height sample with 5 mm step height. We could show a repeatability of 60 pm for these measurements. The absolute difference between the step height measurements on the same sample at the ITO and the TU Ilmenau was 2 nm. We are also working on the measurement of freeform optics with this principle. The measurement setup of a freeform sample measured for the CCUP High Level Expert Meeting is shown in figure 5. The measurement result contains 5943100 measurement points. After subtracting the best fit surface the remaining rms error of the sample is 33.5 nm (2). Other round robin experiments are detailed in (3), where we contributed to a measurement comparison with other measurement institutes in measurement of new reference surface structures.

Another sensor in use for areal surface metrology is our custom-built white light interferometer. It is made with a special thermal system construction made of invar alloy (4). There it is possible to do measurements of large surfaces with precise stitching of subapertures.

Beside the surface measuring there is the possibility to use the machine for the calibration of sensors or optics. The machine was also used to do a calibration of the distortion of a large telecentric lens for the use in precise

Fig. 1: The NPMM-200 at ITO. Machine in the opened vacuum chamber for thermal isolation. The measurement frame is made of ZERODUR.

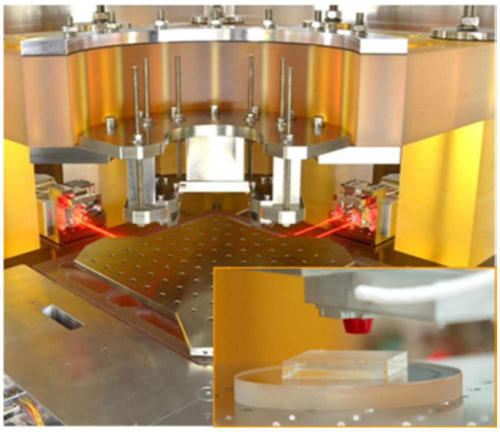

Fig. 2: Measurement frame of the NPMM-200. Three interferometers for x-y movement and z-rotation and the flexible sensor mount visible. Inlet: Focus sensor measuring a test sample.

machine position monitoring (5,6 and fig. 4). The lens was attached to the measurement frame of the machine and the target, a light source, was moved taking advantage of the nanometer precision of the NPMM positioning system.

The machine and its step-height measurement capabilities were further used to cross check the calibration of measurements of other measurement systems. We used the height measurement as check for AFM measurements. There we measured an AFM reference-artefact with a nominal height of 113nm ± 3%. The measurement of the NPMM was 113.70 nm and the standard deviation of ten measurements was 0.15 nm. The agreement between the vendor specifications and the NPMM-200 measurement results is excellent (7).

Supported by: DFG German Science Foundation
Project: Os 111/44-1
In cooperation with: Technische Universität Ilmenau

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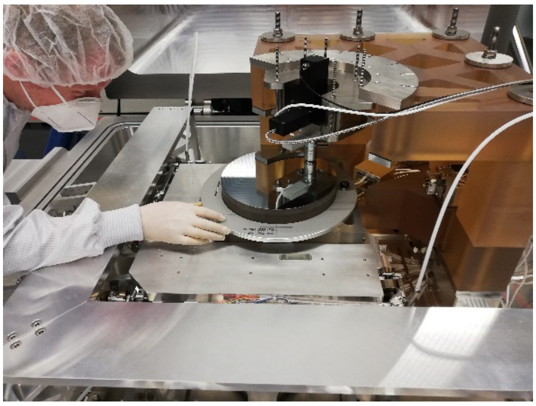

Fig. 3: Placing a large 6" mirror in the machine as sample for measurement with the focus sensor.

Fig. 4: Calibration of a large telecentric lens. The objective is attached to the measurement frame and the precision positioning is used for calibration.

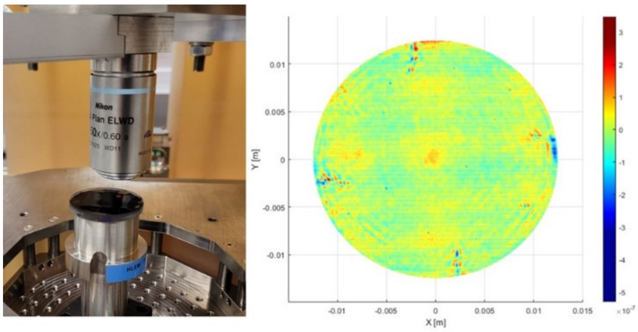

Fig. 5: Measurement of a freeform sample for the CCUPOB High Level Expert Meeting. The measurement is done with the focus sensor and a long working distance objective. The residual rms value of the sample is 33.5 nm.

Single-shot interferometry for testing an astronomical mirror

K. Treptow, C. Pruß, C. Schober, A. Herkommer

Standard temporal phase shifting interferometry based on piezo elements cannot be used in unstable environments. Floor vibrations and air turbulences lead to large measurement uncertainties. Single-shot interferometry provides a remedy here. Using the light polarisation and using a polarization-sensitive camera, all interferograms can be captured instantaneously, basically eliminating the problem of instabilities.

The polarization camera contains a special micro grid polarizer in front of the CMOS sensor chip. The polarizers with 0°. 45°, 90° and 180° orientation define a super pixel. With suitable circular polarization states of the reference and test beam of our Twyman-Green interferometer, each of the polarizer orientations results in one phase shift, thus the phase can be determined with one camera picture only.

We used this setup to determine the surface error of a spherical astronomical mirror with Ø=50cm and R=16m. The surface error is the deviation of the mirror surface from its perfect spherical shape.

Because of the large distance between the mirror and the interferometer setup, the measurement took place in a strongly disturbed environment.

Vibration errors are suppressed by single shot measurements. Air turbulence can be mitigated by averaging a series of measurements (e.g. 1200 data sets). The interferometer setup was calibrated by the "Jensen-test".

The mounting stage enables a rotation of the mirror around the optical axis. This feature is used to measure the mirror in 4 rotated positions to separate gravitational deformations from mirror shape.

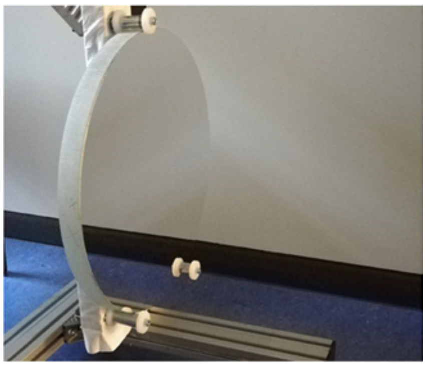

Fig. 1: Astronomical mirror with diameter 50 cm.

The surface error is shown in figure 2. A small amount of spherical aberration and a pronounced dip in the centre can be observed.

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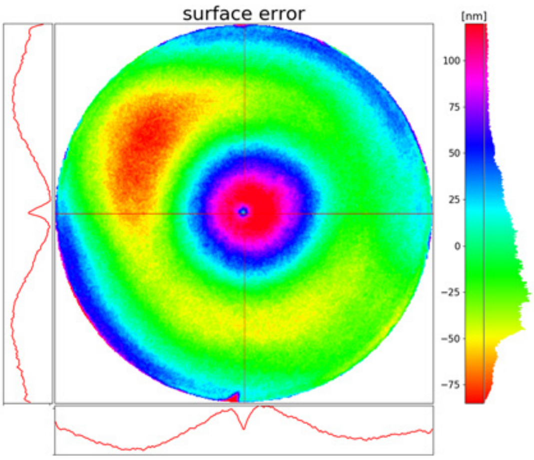

Fig. 2: surface error of the astronomical mirror.

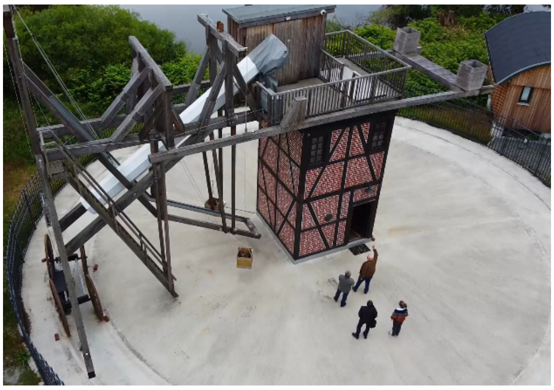

Fig. 3: Reconstruction of the 27 foot mirror telescope of Hieronymous Schroeter of 1793 in Lilienthal.

In cooperation with: TELESCOPIUM-Lilienthal Foundation e.V.

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New process chain for encapsulated diffractive lenses

M. Zach, K. Treptow, C. Pruß, C. Schober, S. Wagner, A. Zimmermann, A. Herkommer

In optics design, the combination of refractive and diffractive optical elements allows to generate arbitrary, complex wave fronts and can be used to compensate chromatic and spherical aberrations or creating specific features like multiplexing or arbitrary beam shaping. Refractive and diffractive functionality can be integrated into only one surface, leading to highly compact systems. In the AiF-project Redolis3D, an optimized new process chain is developed to enable low-cost manufacturing of compact optical systems including curved DOE (1). The basic system design encapsulates the DOE to yield a robust optical system with only plane surfaces facing outside.

The base technology is injection compression molding. We use a combination of laser direct writing lithography in photoresist and UPM (ultra-precision machining). UPM at our partner Hahn-Schickard generates the basic, curved shape in metal on which we generate the diffractive structures directly using laser direct writing lithography in photoresist.

The UPM surface exhibits a high reflective surface, which will lead to disturbing interferences during the lithography process. For this reason, an anti-reflective coating layer is applied prior to the photoresist layer. As always, the process steps have to be monitored. This requires investigations and adaptions of the measurement equipment, e.g. the thin film thickness metrology that is typically not prepared to measure on non-flat surfaces. The laser lithography process on the substrate using the circular laser writing system (CLWS300F) is the next step in the process chain. The CLWS is a laser-direct writing system developed at ITO that can be used to structure curved substrates. A key feature is the autofocus system that also works on tilted surfaces (2). The resulting photoresist master is used to create a tool insert using Ni electroplating. By means of injection compression moulding, the curved DOE are transferred into a thermoplastic transparent material. We demonstrate the potential of the method with a zero optical power element working in the near infrared that can be used e.g. in chromatic confocal microscopy.

Supported by: Aif, project REDOLIS 3D in cooperation with Hahn-Schickard, Stuttgart, within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Minitry of Economic Affairs and Energy based on a enactment of German Parliament.

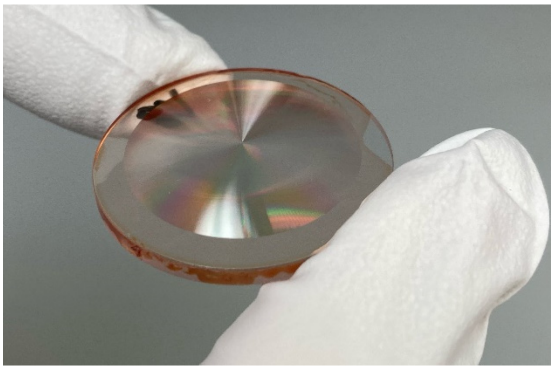

Fig. 1: diffractive structure on a curved element, produced with the CLWS developed at the ITO.

Fig. 2: brass master insert

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Grating Reflectors Enabled laser Applications and Training (GREAT)

A. Savchenko, C. Pruß

Innovative Training Networks (ITNs) are part of the European HORIZON 2020 program and aim to build up networks of early stage researchers (ESRs). Within the ITN GREAT (Grating Reflectors Enabled Laser applications and training) 15 ESRs located in different institutions are working on the design, fabrication and implementation of Grating Waveguide Structures (GWS) in high power laser systems.

A GWS is a combination of a planar waveguide and a subwavelength grating and exhibits unique properties. Under specific illumination conditions such as incidence angle, polarization and wavelength resonance effects can be observed [1]. These can be tailored and make GWS a powerful solution for high-power laser beam shaping, combining and polarization control [2].

At ITO, we investigate the fabrication of circular and segmented GWS with reflectivity as high as 99.9% based on designs provided by project partner IFSW ("Institut für Strahlwerkzeuge"). Circular GWS (binary grating with circular lines) will replace either end-mirrors or output couplers in thin-disk laser resonators ensuring extraction of cylindrical vector beams (radially or azimuthally polarized) directly from a laser cavity. It is achieved by suppression of undesired polarization state and due to the circularity of grating lines cylindrical vector beams are generated inside of a resonator. Segmented GWS will be used as polarization converters transforming incident linear polarized beam into cylindrical vector beam with efficiency higher than 90%.

These structures are fabricated by means of laser interference lithography and subsequent plasma etching. For the fabrication of the intracavity elements the "in-house" built Scanning Beam Interference Lithography (SBIL) setup is used where a rotated substrate is scanned by a small (tens of µm) interference pattern. As a result, a circular grating is produced, see fig. 1. For extracavity converters a Stepped Mask Interference Lithography Exposure (SMILE) setup will be used. This setup is based on a classical Lloyds mirror setup with one rotational degree of freedom added to the substrate. A special rotational mask covers part of the substrate resulting in only a segment of the substrate being exposed. This allows to produce segmented grating elements with arbitrary grating line orientation to realize polarization converters as sketched in fig. 2.

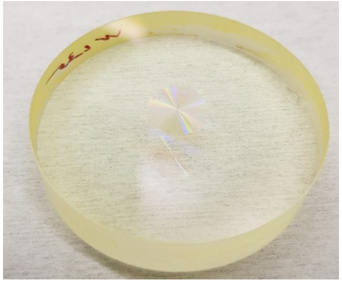

Fig. 1: Example of circular grating patterned by our SBIL setup.

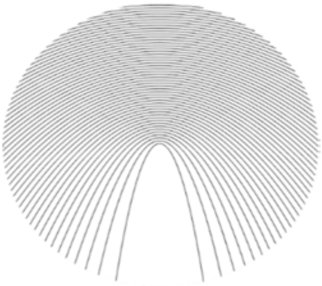

Fig. 2: Gratings line orientation for polarization converter.

Supported by: European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813159.
Project: ITN GREAT
In cooperation with: 15 academic and scientific partners from France, United Kingdom, Finland and Germany.

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Optical compensation of eccentricity errors in rotary encoders

R. Hahn, M. Dombrowski, D. van Weeren, C. Pruß, W. Osten

The increasing degree of automation makes it possible to meet the demand for high throughput and accuracy in almost all areas of today's production. High-resolution rotary encoders are an essential component of today's robot systems. The functional principles of such encoders range from magnetic, inductive, capacitive to optical. For highest demands in precision, typically optical encoders are chosen.

The key element of any encoder is the encoder disk. This has uniformly arranged radial slots. The disk is centered on the shaft to be monitored and a photodiode evaluates the number of passing slits through a readout grid. The slits are illuminated by a diode in transmission. Fig. 1 shows a schematic representation of the system.

The high quality of today’s lithographic processes guarantees a high accuracy of the slit pattern. However, a major part of uncertainty results from unwanted eccentricity between the center of fabrication of the slit pattern and the shaft to be monitored.

The approach pursued in this project is the in-situ fabrication of the encoder structures. This avoids the encoder eccentricity entirely, since the mechanical axis defines the encoder axis. In our demonstrator, the encoder was produced using an ablation process. As alternative approach, new photosensitive materials were investigated that change their transmission upon illumination. Here, the application dictates that no additional wet chemical development process is required. Results of the investigations have been shown in our last ITO report (1).

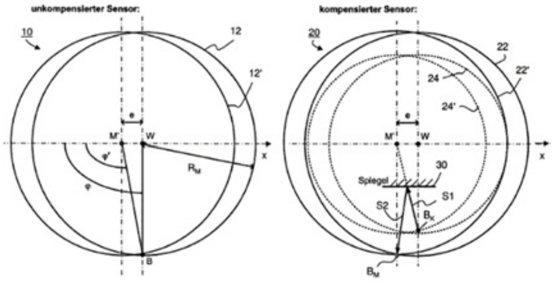


Fig. 1: Left: An eccentricity error e leads to a wrong readout position B in a standard encoder. Right: The eccentricity is optically compensated such that the angle is read a the correct position B_M.

Residual eccentricities might remain, e.g. due to an unstable axis of rotation. A new optical scheme that is depicted in fig. 1 can solve this problem. Here, the readout beam is deflected by an auxiliary track on the encoder disk such that the readout position moves together with the eccentric encoder disk, making sure that the readout spot is always reflected to the correct angular readout position B_M. Fig. 2 shows the resulting effect on the readout error.

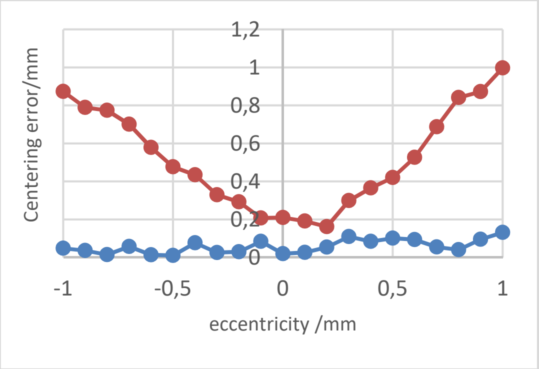


Fig. 2: Comparison of readout error due to eccentricity: red: uncompensated, blue: compensated.

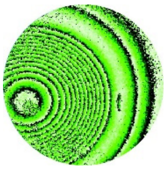
Supported by: BMBF
Project: 13N10854
In cooperation with: SICK AG, Allresist, Acsys, STVision.

References:

(1) R. Hahn, M. Dombrowski, C. Pruß, W. Osten: “Resist characterization for developer free lithography processes”, ITO report 2017/2018.

(2) Hopp, D., Pruß, C., Osten, W.; German patent *DE102009040790B4, 2012.*

Coherent Metrology



Optical real-time 3D data acquisition in difficult visibility conditions for autonomous driving

A.Gröger, G. Pedrini, D. Claus, I. Alekseenko, A. Herkommer

We investigate the possibility of a macroscopic realization of optical coherence tomography (OCT) in combination with digital holography (DH). The major feature of OCT is the interference of signal and reference light. The signal interacts with the object under observation and the reference light has to be delayed according to the object distance and the coherence length of the light source. Therefore, the optical path length of the reference light has to be adjustable. For a macroscopic version of OCT, this places considerable demands on the reference arm design, since huge path lengths differences (i. e. 20-100 m) have to be realized in a short period of time. In our approach, we tackle this problem by the use of several single mode fibers with different lengths and a galvo scanner interfacing the reference light into one fiber at a time. Signal and reference light are recombined onto a CCD detector forming a digital hologram in image plane configuration with the object being imaged on the detector by a lens. The fiber ends are bundled together and located at the pupil plane of the imaging lens. Figure 1 shows the reference arm as part of the experimental setup.

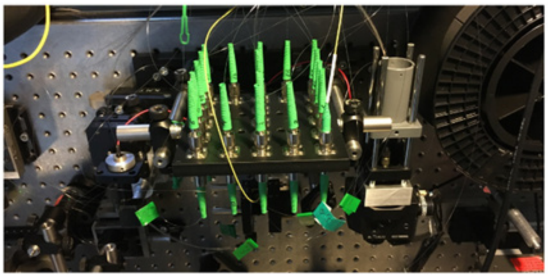


Fig. 1: Reference arm including beam expander, galvo scanner, fiber bundle with connectors and fibers of different length on a reel, light is entering the galvo scanner from the left side through a beam expander.

The purpose of this project is to evaluate the combination of OCT and DH as a new approach for environment perception in autonomous driving vehicles under adverse weather conditions. We use the coherence property of light to separate the scattered photons, which disturb the image formation, from ballistic photons, which carry object information. Furthermore, the inherent amplification of a weak object signal by a strong reference is supposed to enhance the performance of such a setup, potentially giving it an edge over competing technologies such as LiDAR and time-gated imaging. In addition, digital holographic processing enables the reconstruction of the amplitude and phase information from the object wave. With two-wavelength digital holography, the shape of macroscopic objects can be determined by evaluating the phase information of the synthetic wavelength. In summary, such a system has the capability to detect the distance, texture and shape of an object covered in fog. With our fog chamber, (see: Research Fog Chamber for large scale scattering media experiments) we are able to characterize the performance of our concept and compare it to state of the art technologies.

Figure 2 shows experimental results with a Siemens star as textured object placed at a distance of 17 meters. The lower part of the target is covered by fog. After digital holographic processing, the part covered by fog becomes visible.

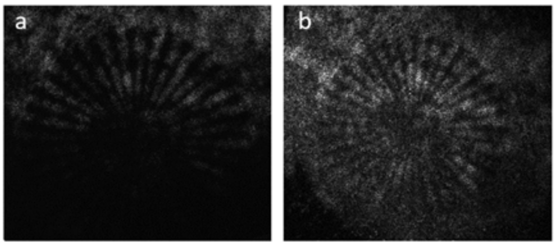


Fig. 2: Siemens star as target inside the fog chamber; a) digital hologram with the lower part of the target covered by fog, b) reconstructed image, the whole pattern appears.

Supported by: Baden-Württemberg Stiftung gGmbH
Project: Optische Echtzeit-3D-Datenerfassung bei erschwerten Sichtbedingungen für die Anwendung im Straßenverkehr
In cooperation with: ILM, Ulm

Research Fog Chamber for large scale scattering media experiments

A.Gröger, G. Pedrini, A. Herkommer

One of the fundamental problems in modern optics is sensing through scattering media. For decades, a challenging field on a rather small scale is imaging through all sorts of biological tissue, where absorption and scattering disturb the image formation. A related problem on a larger scale is represented by sensing through heavy rain or dense fog for environment perception in autonomous driving vehicles. Today many research projects for autonomous driving focus on the development of a sensing system with redundant full capability characteristics, i.e. capturing the environment under all weather conditions. Therefore, the characterization and comparison of newly developed sensors such as FMCW LiDAR, time-of-flight, IR camera systems and long distance digital holography in a controlled environment is of great interest. For that purpose, we build a research platform featuring a 27 meters long fog chamber with a diameter of 0.6 meters, an industrial ultrasonic humidifier, a monitoring and controlling system and a remote controlled car as movable object carrier. Figure 1 shows the inside of the fog chamber.

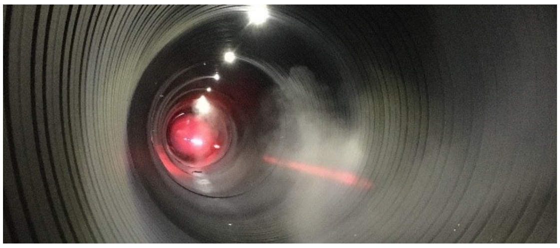


Fig. 1: View inside the fog chamber; fog is entering through multiple inlets along the bottom of the chamber, the beam of the HeNe-Laser is scattered by the fog droplets.

With the average droplet size of the ultrasonically generated fog of approximatly 5-10 µm, the scattering characterisics inside the fog chamber are equal to that of natural fog. Depending on the humidity, fog dissipation happens on seconds time-scale, therefore, a laminar flow with multiple inlets along the chamber and extraction at one end is implemented. The meteoroligical visibility can be adjusted from 1000 meters down to 1 meter by the use of a throttle, regulating the ratio of fresh air and fog. A 5 mW HeNe-Laser is used to continousliy measure beam attenuation in a one-way propagation setup to determine the visibility as feedback for the control system. In Figure 2 the object carrier inside the fog chamber is shown.

With our infrastrucure we are able to charaterize the performance drop of different sensor types, i.e. time-gated sensing and LiDAR and investigate the benefits of different approaches, such as long distance coherence gated digital holography (see: Optical real-time 3D data acquisition in difficult visibility conditions). Furthermore, our research platform is available for external projects.

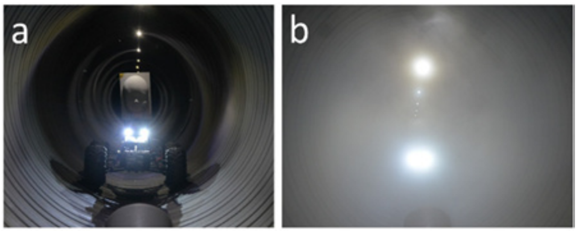


Fig. 2: a) object mounted on remote controlled car inside the fog chamber, b) object covered in dense fog.

Supported by: Baden-Württemberg Stiftung gGmbH
Project: Optische Echtzeit-3D-Datenerfassung bei erschwerten Sichtbedingungen für die Anwendung im Straßenverkehr

With friendly support by Dieter Höhn and Institute of Thermodynamics and Thermal Process Engineering

Developments in scatter-plate microscopy

S. Ludwig, G. Pedrini, W. Osten

Imaging through scattering media is a challenging task but has a wide range of possible applications, especially in medical and biological science. Our approach to image through visually opaque material regards the scattering medium not as an obstacle but as the actual imaging element. Exploiting the optical memory effect, we developed the scatter-plate microscope: a technique enabling lensless imaging with variable magnification, numerical aperture and working distance [1]. Instead of a bulky, complex and expensive objective, the scatter-plate microscope uses a simple ground glass diffuser to image microstructures. The intensity distribution produced by such a diffuser resembles a random pattern but the details of a illuminated object hidden behind the diffuser can be reconstructed by cross-correlating this pattern with the previously recorded speckle pattern generated with a point source illumination (point spread function (PSF)).

So far, the method was just realized with monochromatic but spatially incoherent sample illumination. However, we could demonstrate that even with spatially coherent sample illumination scatter-plate microscopy can be realized. Moreover, we could apply the method to realize microscopic imaging through temporal modulated scattering layers (Fig.1) [2].

We further realized scatter-plate microscopy as a single-pixel imaging tool [3-4]: By applying random patterns displayed by a digital micro mirror device (DMD) as scatter-plates, we could retrieve the PSFs of many patterns from diffraction theory (Fig.2). The correlation of the single-pixel intensity signal with these PSFs allows image retrieval (Fig.3). By comparing image results retrieved with different PSF-wavelengths and different distances between the point sources and the DMD, our single-pixel approach can realize both chromatic and depth resolved imaging.

Supported by: DFG German Science Foundation
Project: High-resolution microscopy using a scattering layer (OS 111/49-1)
Sino-German Centre for Research Promotion (CDZ) (GZ 1391)

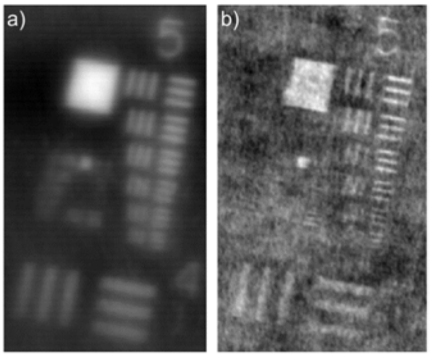


Fig. 1: Image of group 5 of the USAF-target acquired via scatter-plate microscopy through a rotating ground glass diffuser and spatially incoherent (a) resp. spatially coherent sample illumination (b).)

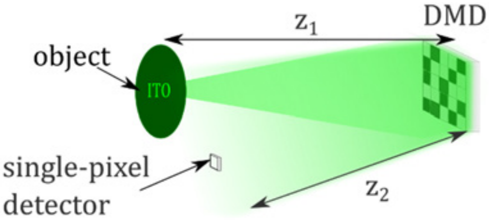


Fig 2: Schematic setup of single-pixel scatter-plate microscopy

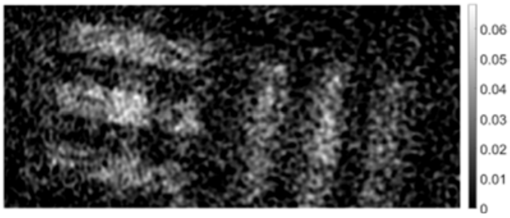


Fig. 3: Image of group 2 element 2 of the USAF target acquired with the single-pixel scatter-plate microscope

References:

(1) A.K. Singh, G. Pedrini, M. Takeda, and W. Osten; "Scatter-plate microscope for lensless microscopy with diffraction limited resolution", Scientific Reports, vol. 7, no. 1, p.10687, 2017.

(2) S. Ludwig, P. Ruchka, G. Pedrini, X. Peng, and W. Osten, "Scatter-plate microscopy with spatially coherent illumination and temporal scatter modulation," Opt. Express **29**, 4530-4546 (2021)

(3) S. Ludwig, G. Pedrini, X. Peng, and W. Osten, "Single-pixel scatter-plate microscopy," Opt. Lett. **46**, 2473-2476 (2021)

(4) S. Ludwig, G. Pedrini, X. Peng, and W. Osten, "Ensemble cross-correlation for image retrieval from the intensity signal recorded by a single pixel", Proc. SPIE 11782, 2021.

Residual stress evaluation of ceramic coating under industrial conditions by laser ablation and digital holography

G. Pedrini, A. Calabuig-Barroso, W. Osten

Ceramic coatings are commonly used to improve the wear or heat resistance of many technical components, but due to their deposition process, e.g. plasma or high velocity oxygen fuel spraying, rather high residual stresses can build up within the coating and underneath. The reason for that are differences in the coatings and substrates expansion coefficients, inhomogeneous temperature distribution during the process and the quenching of splats. The mechanical hole drilling technique can be used for the detection of residual stresses in coatings. The residual stresses are locally relieved due to the material removal process, which leads to a deformation of the surface around the hole. These deformations, measured as relaxed strains through strain gauges rosettes, in combination with appropriate calibration data (separately determined by simulation for the layer composite), allows the quantitative determination of the residual stress depth profile. The disadvantage of the strain gauges is that they can only be used on flat and relatively smooth surfaces, where the rosette is applied.

We propose an approach (see Fig.1(a)) to avoid the mechanical drilling operation and the application of strain gauges, where a pulsed laser is used for the object machining (ablation process) leading to 3D residual deformation by stress relaxation which are measured by an optical system based on digital holographic interferometry. The residual stresses at different depth of the coating are calculated from the deformations obtained after incremental loading, the profile (shape, depth) of the machined surface and the material parameters. The technique can be used for determining residual stresses under industrial conditions. The Atmospheric Plasma Spraying (APS) is placed on a robot arm that can move in the space between the optical measuring system and the object to be coated. The distance between the sample and the measuring system is approximately 0.8 m. The APS and the measuring system are inside a cabin that is hermetically closed during the coating process. The robot for coating and the optical systems are shown in Fig. 1(b). The purple light is due to the high temperature plasma glow. During the coating process the temperature of the object arises up to 400 °C.

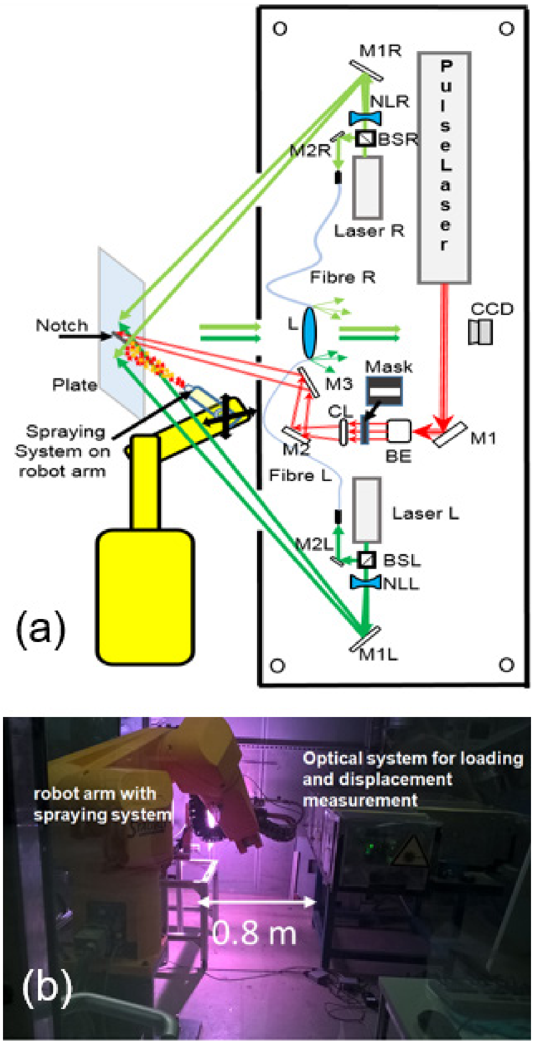


Fig. 1: (a) Set-up for laser machining and displacement measurement. (b) Coating system mounted on a robot arm and optical system.

Figure 2 shows residual stresses inside a coating measured with the new developed holographic method (from 30 µm to 130 µm) and the traditional micro hole drilling method (HDM). In spite of the fact that the DHI measurements seem to underestimate the residual stresses measured with the HDM, there is a similar behaviour for the common depth interval. In principle it is possible to use laser ablation and digital holography also for depth of 200 µm or more but we were not able to perform laser ablation of notches having depths larger than 130 µm.

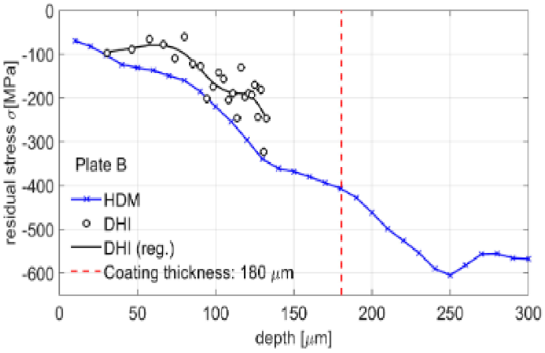


Fig. 2: Residual stresses inside a coating measured by the micro hole drilling method (HDM) and laser ablation combined with digital holographic interferometry (DHI) The coating thickness for this plate is approximately 180 µm (dashed vertical line).

Figure 3.(a) shows a phase map (modulo 2π) corresponding to the in-plane displacements produced by laser loading just after coating. The temperature of the surface monitored by a pyrometer was 360 °C. The plate was then cooled down at 215, 98, 24 °C, and phase maps corresponding to displacements produced by application of the same laser loading were determined (see Fig. 3(b)–(d)). From the phase maps, it is possible to calculate the in-plane displacements. In Fig. 3(a), there are few fringes and, thus, the displacement and the residual stresses are small. The displacement increases (more fringes in the phase maps) when the temperature decreases, thus the residual stresses are produced when the coating cool down. The phase maps recorded at higher temperature have lower quality (more noise). This can be explained by considering that it was not possible to keep the temperature constant during the measurements. At 360, 215, and 98 °C, we had changes of ±15 °C, ±10 °C and ±5 °C, respectively. These temperature instabilities produce changes of the coating microstructure degrading the quality of the results.

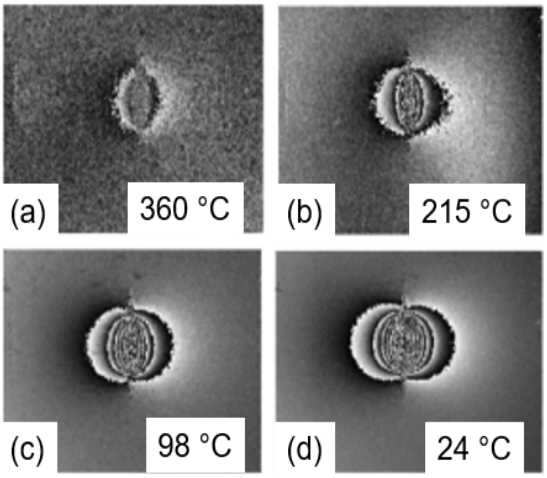


Fig. 3: Phase maps mod (2π) obtained by measurements at different temperatures.

Supported by: DFG German Science Foundation
Project: Ermittlung von Eigenspannungen in beschichteten Oberflächen (OS 111/37)

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(1) G. Pedrini, V. Martínez-García, P. Weidmann, M. Wenzelburger, A. Killinger, U. Weber, S. Schmauder, R. Gadow, W. Osten, “Residual stress analysis of ceramic coating by laser ablation and digital holography”, Exp. Mech. (2016) 56: 683.

(2) P. Weidmann, U. Weber, S. Schmauder, G. Pedrini, W. Osten, “Numerical calculation of temperature and surface topology during a laser ablation process for ceramic coatings”, Meccanica (2016) 51: 279.

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(4) I. Alekseenko, G. Pedrini, V. Martínez-García, A. Mora, A. Killinger, A. Kozhevnikova, S. Schmauder, R.Gadow, W. Osten, “Residual Stress Evaluation in Ceramic Coating Under Industrial Conditions by Digital Holography”, IEEE Transactions on Industrial Informatics, 16, 1102–1110, (2019), DOI: 10.1109/TII.2019.2939972

Feasibility study of digital holography for erosion measurements under extreme environmental conditions inside the ITER Tokamak

G. Pedrini, A. Calabuig-Barroso, G. Jagannathan, M. Kempenaars, G. Vayakis, W. Osten

The ITER Project (see Fig. 1) is the next step in the transition from experimental studies of plasma physics to full-scale electricity-producing fusion power stations. It fuses the hydrogen isotopes deuterium and tritium into helium thereby releasing a high energy neutron. In order to start the fusion reaction the temperature has to be about 150 million Kelvin, creating a plasma. Because there is no material that could withstand such high temperatures, the plasma is guided, contactless, by magnetic fields within the vacuum chamber. However, these fields are not fully closed, resulting in partial plasma contact particularly in the divertor region. This leads to wear effects, affecting the overall performance and reliability of the Tokamak and potentially generating metallic dust. Thus, there is a need for the regular measuring of the erosion and deposition at the wall once the Tokamak starts operating. An erosion and deposition monitor able to measure the changes in the surface shape with a depth resolution of 10 µm is planned. The measurement will be done not on the whole internal surface of the Tokamak but on two surfaces of the divertor that endure high rates of erosion and deposition, each monitored area has a size of 10x30 cm². Due to the high temperature and radiation it will not be possible to have the measuring system inside the Tokamak, for this reason the measurements will be performed remotely. Hence the opto-electronic instruments (detector, laser, controlling electronics) will be located at a distance of about 40 m from the surface to be measured.

We have shown that long distance shape measurements in challenging environmental conditions can be done by two (or multi) wavelength digital holography and thus this technique could be used for the erosion monitoring inside the Tokamak. Fast acquisition of holograms to reduce the influence of strong vibrations persisting inside the Tokamak has been developed (see Ref. 1).

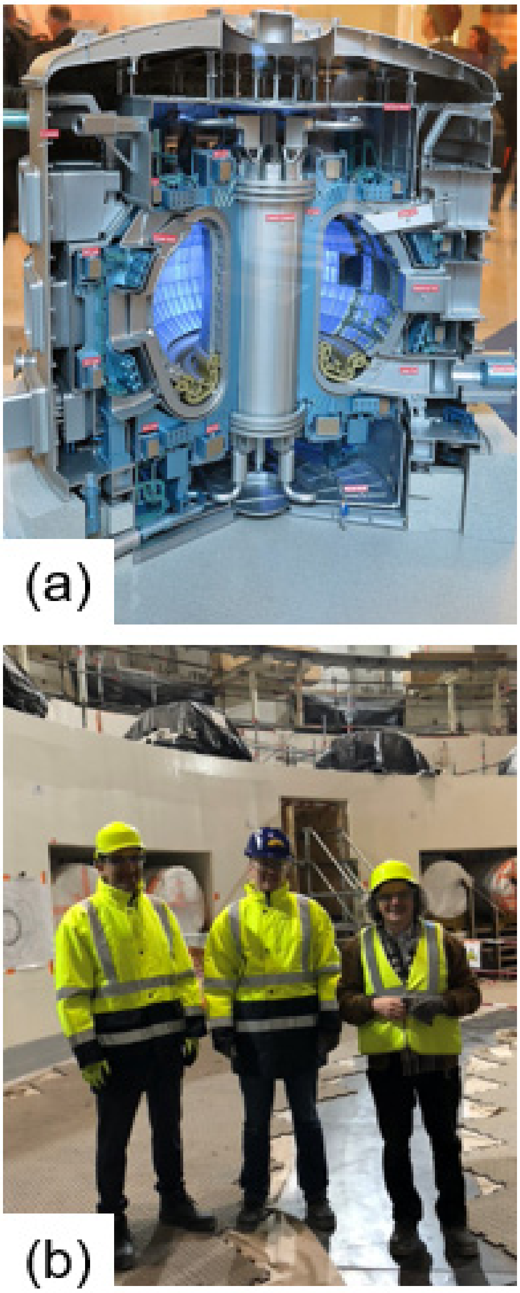

Fig. 1: (a) CAD model of the Tokamak (https://en.wikipedia.org/wiki/ITER). (b) Inside the Tokamak pit, during construction, ITO visit to ITER, March 2020.

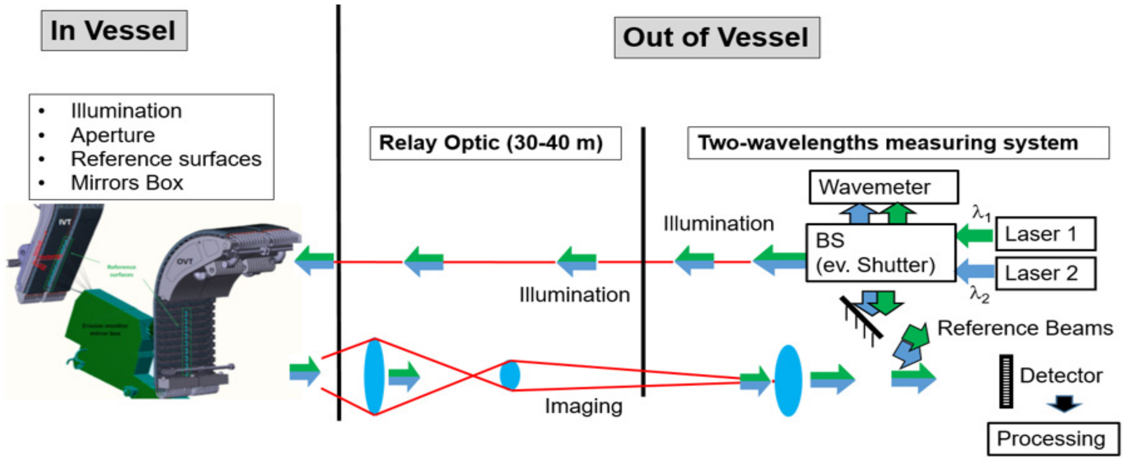

Fig. 2: Scheme of the planned erosion monitor system.

It is planned to use the two-wavelengths holographic system developed at ITO for the measurement of the erosion inside the TOKAMAK. The planned scheme of the erosion monitor is shown in Fig. 2.

Supported by: ITER.

Disclaimer:
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References:

(1) G. Pedrini, I. Alekseenko, G. Jagannathan, M. Kempenaars, G. Vayakis, W. Osten, "Feasibility study of digital holography for erosion measurements under extreme environmental conditions inside the International Thermonuclear Experimental Reactor tokamak [invited]," Appl. Opt. 58, A147-A155 (2019)

Lensless light-field imaging through diffuser encoding

Z. Cai, X. Peng, G. Pedrini, W. Osten

Microlens arrays are commonly used for light-field imaging. However, the use of a microlens array generally suffers from an intrinsic trade-off between spatial and angular resolutions. We demonstrate that the diffuser can efficiently angularly couple incident light rays into a detected image without needing any lens (see Fig. 1). To characterize and analyse this phenomenon, we establish a diffuser-encoding light-field transmission model, in which four-dimensional light fields are mapped into two-dimensional images via a transmission matrix describing the light propagation through the diffuser. Correspondingly, a calibration strategy is designed to flexibly determine the transmission matrix, so that light rays can be computationally decoupled from a detected image with adjustable spatio-angular resolutions, which are relaxed from the resolution limitation of the sensor. The proof-of-concept approach indicates the possibility of using scattering media for lensless four-dimensional light-field recording and processing, not just for two- or three-dimensional imaging.

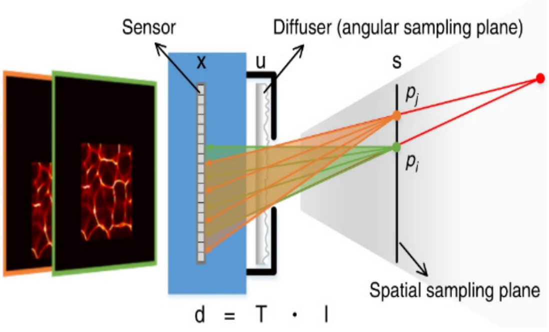

*Fig. 1: Schematic diagram of lensless light-field imaging through diffuser encoding. **s**, **u**, and **x** are coordinates on the spatial sampling plane, angular sampling plane, and sensor plane, respectively; **d** is the vector describing the sensor detection; **l** is the vector describing the objective light field; and **T** is the light-field transmission matrix.*

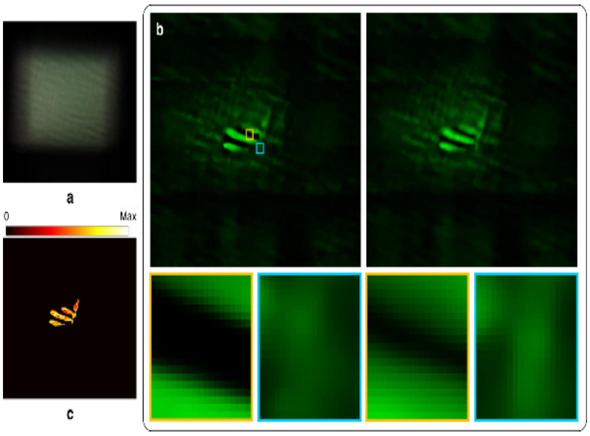

Fig. 2: Light-field imaging for a small plant. (a) Captured raw image; (b) In-focus slices of the focal stack at different depths and enlarged segments related to regions marked by the yellow and cyan boxes; (c) Depth map

The experimental data of a small plant (provided by Antipa, N. et al. DiffuserCam: lensless single-exposure 3D imaging. Optica 5, 1–9, 2018) were used to test our approach. The results are shown in Fig. 2.

Supported by: Sino-German Centre (GZ 1391)

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Phase retrieval using 3D Fourier transforms of volume diffraction pattern

G. Pedrini, D. Claus

Figure 1 shows simulations of a wave diffracted by a sample illuminated by temporal coherent light. v(x,y,z) is the complex amplitude of the wavefield inside a volume (see Fig. 1.(a)) and its 3D-Fourier transform is $V(f_x,f_y,f_z)=FT\{v(x,y,z)\}$. Figure 1.(b) shows that the 3D power spectrum:$|V(f_x,f_y,f_z)|$ is concentrated around a paraboloid. Sections of the power spectrum in longitudinal and transversal planes are shown in Figs. 1.(c, d), and enlarged parts in the insets.

In Ref. 1, we have shown that is possible retrieving the phase of a wavefield from a volume diffraction intensity pattern by application of a paraboloid constraint in the reciprocal 3D-space. The algorithm is described in Fig. 2.

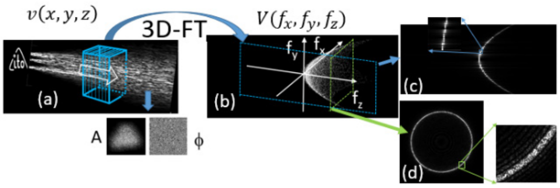


Fig. 1: Propagation of a wave diffracted by a complex sample (a), 3D power spectrum (b) and sections (c, d).

The volume intensity (128 diffraction patterns) was recorded by a CCD mounted on a translation stage. After retrieving the phase of the volume wavefield by using the proposed algorithm, it is possible to propagate the wave and reconstruct the image of the sample. The results of the reconstruction of the USAF test target used in the experiment is shown in Fig. 3.(b) and the enlarged part of the reconstruction in Fig. 3.(c).

Supported by: DFG German Science Foundation Sino-German Centre (GZ 1391).

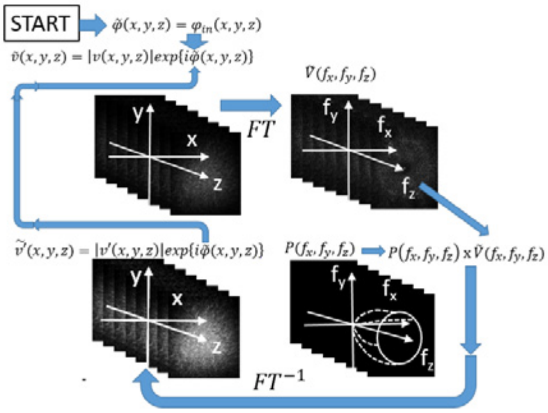


Fig. 2: Algorithm for phase retrieval

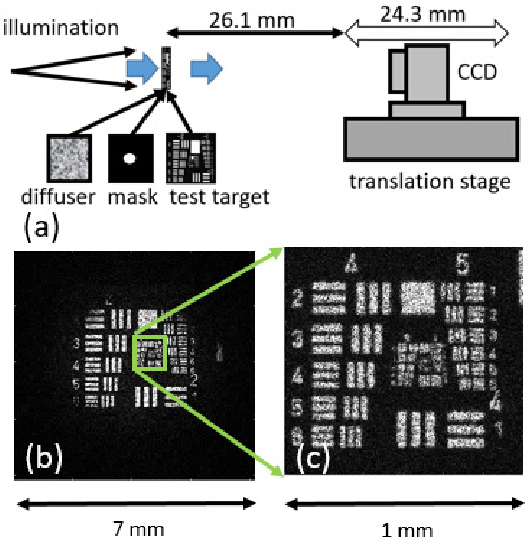


Fig. 3: Setup for the recording of the volume intensity (a). Reconstruction of the test target with the proposed method after 300 iterations (b). Enlarged part of the reconstruction (c).

References:

(1) G. Pedrini, D. Claus, "Phase retrieval using 3D Fourier transforms of volume diffraction pattern," Opt. Lett. 46, 1716-1719 (2021).

Compact lateral shearing holographic microscope for label-free diagnosis of diseases affecting red blood cells

A. Anand, C. Patel, G. Pedrini

Diseases affecting cells (malaria, thalassemia, sickle cell anemia etc) are widespread, especially in Africa and Asia. Golden standard of detection of these diseases is still based on inspection of blood smears, treated with reagents under a bright field microscope by a trained technician. So, an automatic, label-free and field portable microscope for their diagnosis will greatly benefit health care professionals.

Digital quantitative phase microscopy can be used for cell identification. For this purpose, interference patterns (holograms) are recorded on digital arrays and reconstructed numerically yielding the cell thickness profile.

A lateral shearing digital holographic microscope (see Fig. 1) was developed, built and tested. A beam from a laser source illuminates the sample. The trans-illuminated sample is magnified by a microscope objective The expanding beam is split into two laterally sheared versions by a glass plate. These to beams interfere at the digital array. The portion of the wavefront reflected from the back surface, un-modulated by object information acts as the reference for the portion of the wavefront containing object information reflected from the front surface and vice versa leading to formation of off-axis holograms. Figure 2.(a) show a recorded hologram of blood cells and Fig. 2.(b) the phase map obtained after processing the hologram. The reconstructed shapes of the cells are shown in Fig. 2.(c) and the enlarged shape of a single cell is shown in Fig. 2.(d).

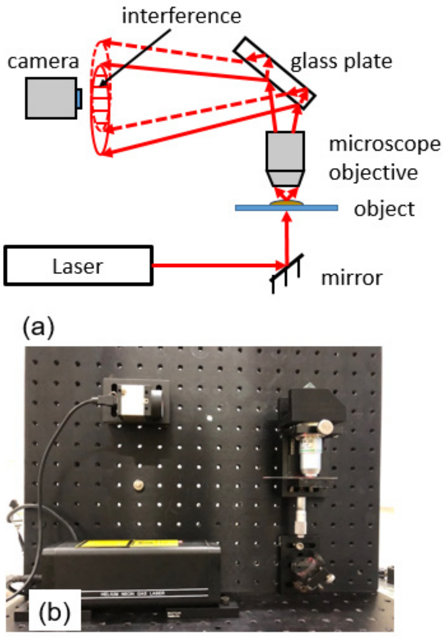


Fig. 1: Compact lateral shearing digital holographic microscope. Sketch (a) and built set-up (b).

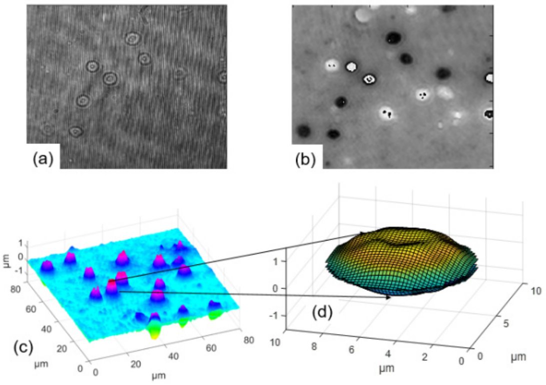


Fig. 2: Hologram (a) and phase map (b) of blood cells obtained by using the compact digital holographic microscope. Shape of the cells (c) with enlargement of a single cell (d).

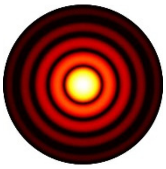
The system can also provide static and mechanical cell parameters, based on the cell thickness profile. These parameters will be used for cell comparison and identification. This would allow to have the advantages of the system for portable point-of-care diagnostic device connected to a mobile phone.

Supported by: BMBF-ICRM cooperative science program (FKZ: 01DQ17006)

References:

(1) M. Joglekar, V. Trivedi, R. Bhatt, V. Chhaniwal, S. Dubey, D. Claus, G. Pedrini, R. Leitgeb, A. Anand, "Compact, low cost, large field-of-view self-referencing digital holographic interference microscope", Optik, 245, 167615, (2021)

Optical design and Simulation



3D-printed miniature spectrometer on a 100 x 100 µm² footprint

A. Toulouse, J. Drozella, S. Thiele, A. Herkommer

The miniaturisation of spectroscopic measurement devices opens novel information channels for size critical applications such as endoscopy or consumer electronics. Computational spectrometers in the size-range of micrometres have been demonstrated, however, these are calibration sensitive and based on complex reconstruction algorithms. Herein we present an angle-insensitive 3D-printed miniature spectrometer with a direct separated spatial-spectral response in a volume of only 100 x 100 x 300 µm³ (Fig. 1, [1]).

In a first step, a ray tracing model was designed. The design freedom of 3D printing was exploited by using chirped grating periods as well as highly tilted and freeform surface geometries. The derived mechanical model was validated with wave-optical simulations (see WPM-paper in this issue) and the final design fabricated via femtosecond direct laser writing. In a post-processing step, the slit was realized with a super-fine inkjet printer making use of previously defined microfluidic structures [2]. A micrograph of the final spectrometer is shown in Fig. 1 (middle) with an overlaid wave-optical simulation for visualization.

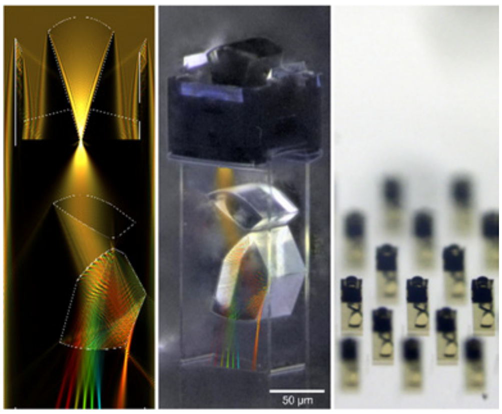


Fig. 1: Wave-optical simulation of the color separation, a micrograph of the 3D-printed spectrometer, and a fabricated microspectrometer array. A single spectrometer has a width of 100 µm.

In a second step, the performance of the spectrometer was assessed in an experimental setup consisting of a monochromator as illumination source and a microscope for magnification of the spectrometer's image plane. The measured intensity profiles along the dispersion direction are displayed in Fig. 2., also showing some residual noise. Thus, a direct spatial-spectral separation across a range of 200 nm with a resolution around 15 nm is demonstrated for the first time in this size-range.

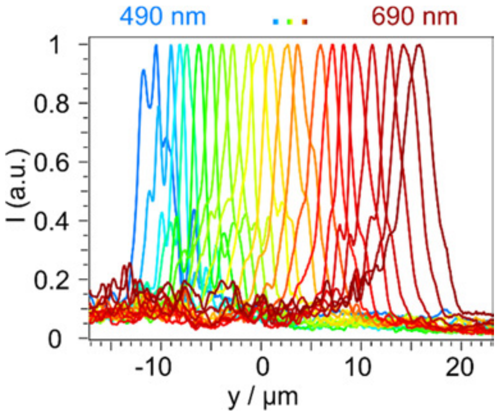


Fig. 2: Spatial-spectral response measurement. The wavelengths are separated in the image plane of the 3D-printed spectrometer [1].

In summary, we have proven the functionality of a complex optical measurement system, namely a spectrometer, on a miniature footprint using 3D-printing technology. For further details, please refer to Ref.[1] below.

Supported by: Baden-Württemberg Stiftung, Bundesministerium für Bildung und Forschung, Vector-Stiftung, Ministerium für Wissenschaft und Kunst, European Research Council.
Projects: Opterial, PrintOptics/PrintFunction, TinyEndoscope3D, SpectraScope3D, ComplexPlas, 3DPrintedOptics
In cooperation with: 4th Physics Institute, Nanoscribe, Karl Storz

References:

[1] A. Toulouse, J. Drozella, S. Thiele, H. Giessen & A. Herkommer. „3D-printed miniature spectrometer for the visible range with a 100×100 µm² footprint", Light: Advanced Manufacturing, 2(1), 1-11, 2021.

[2] A. Toulouse, S. Thiele, H. Giessen, & A. M. Herkommer. „Alignment-free integration of apertures and nontransparent hulls into 3D-printed micro-optics", Optics letters, 43(21), 5283-5286, 2018.

Magnetic actuation of 3D-printed microoptics

F. Rothermel, S. Thiele, C. Jung, A. Herkommer

Mechanical actuation enables important active features such as autofocus, zooming or tilting and thus could further increase the already wide range of applications of 3D-printed micro-optical components. Implementing existing actuation concepts for microsystems, e.g. MEMS-actuators, would however require certain steps of micro-assembly and therefore compromise the flexibility of the fabrication method.

A novel implementation of a magnetic actuation method was developed and successfully demonstrated at the ITO. The concept of this method is illustrated in Fig.1.

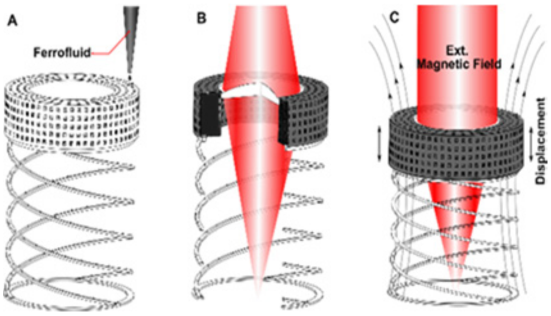


*Fig. 1: Concept for the magnetic actuation of a 3D-printed microlens. **A**. Filling of the microcavity with a ferrofluid. **B.** & **C**. Actuation of the microlens by applying an external magnetic field.*

The monolithic opto-mechanical structures consist of the optical component (microlens), an integrated microcavity and restoring mechanical elements (e.g. springs or flexures). They are entirely fabricated via two-photon polymerization. Fluid ferromagnetic substances, such as ferrofluids or magnetizable compounds of magnetic microparticles and epoxy are then filled inside the microcavity by using a super-fine inkjet method [1]. By applying external magnetic fields, which can be generated through microcoils (see Fig. 2 B), magnetic forces are induced that result in attraction of the magnetic particles inside the cavity and thus a displacement of the optical component and a compression of the spring. If the external magnetic field is deactivated, the spring will restore the original position of the microlens. Therefore, tuning the magnetic field strength enables continuous positioning of components with fast response times below 100 ms.

One application is the implementation of this method into ultra-compact endoscopic designs, such as shown in Fig. 2B. A microcoil, which is directly wound around an imaging fiber, serves as magnetic field source for the actuation of the opto-mechanical structure that is printed onto an imaging fiber tip. Further details can be found in ref. [2].

Supported by: German Research Foundation (DFG)
Project: Foerderkennzeichen HE6363/5-1 (DFG-MiMAO)
In cooperation with: 4th Physic Institute, Univ. Stuttgart

References:

[1] A. Toulouse, S. Thiele, H. Giessen, & A. M. Herkommer. „Alignment-free integration of apertures and nontransparent hulls into 3D-printed micro-optics", Optics letters, 43(21), 5283-5286, 2018.

[2] F. Rothermel, S. Thiele, C. Jung, H. Giessen, A. Herkommer, "Towards magnetically actuated 3D-printed micro-optical elements," Proc. SPIE 11816, Optomechanics and Optical Alignment, 118160I (1 August 2021)

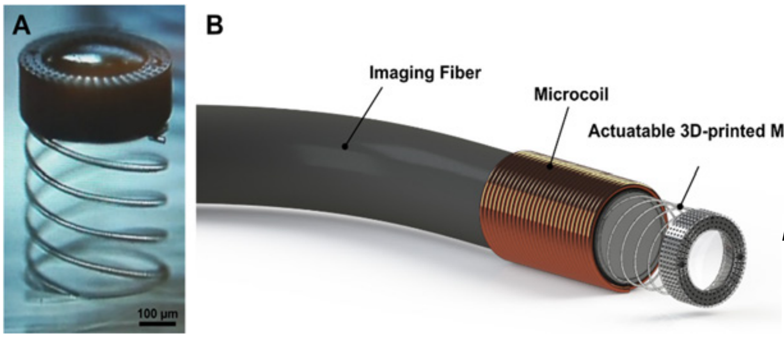


*Fig. 2: **A**. Microscope image of an actuatable micro-lens. **B.** Concept for the actuation of ultra-compact endoscopic systems.*

Optical Trapping Design Using Wave Optical Simulation

J. Drozella, S. Thiele, A. Herkommer

Optical trapping allows for the inspection and manipulation of single molecules in a given surrounding medium. In a cooperation with University of Stuttgarts PI4 and University of Grenobles CNRS a setup was developed in ref. [1], which utilizes a counter-propagating dual-fiber design in order to create necessary forces to keep single molecules or small particles at a desired spot.

Diffractive lens structures consisting of one or two lenses each, are directly manufactured on the ends of single core fibers by using a Nanoscribe high-resolution 3D printer. Different numerical apertures of the lens designs allow for different beam profiles and force distributions, as well as changes in working distances as shown in Fig 1.

Up to 210 µm of working space between two fibers was achieved, while still providing sufficient force for practical use. This allows for more comfortable access during inspection, measurement, or manipulation.

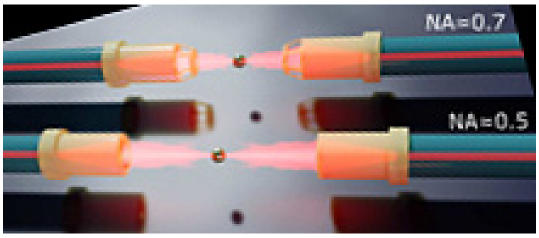


Fig. 1: Concept rendering of the optical trapping setup in a counter-propagation manner. DOEs control distance and trapping force. Image from [1].

The trapping setup showed very good trapping stability even when using low powered light sources. Especially the NA=0.5 setup provides exceptional trapping efficiency for a 1 µm diameter polystyrene sphere in water (video available in supplemental information in [1]). The measured and calculated values are about 35 to 50 times better than comparable chemically wet-etched traditional fiber tips, while allowing for significantly larger distance to the fiber at the same time. In comparison an aspherical design of similar NA would reduce the available working space by approximately 50%. Trapping was also demonstrated with a 0.5 µm diameter polystyrene sphere using the same setup, highlighting the capabilities of this design.

ITO was included in the optical design, the manufacturing on top of optical fibers, as well as scalar wave-optical simulation using the ITOM plugin WavePropagationMethods (WPM, see corresponding paper) as shown in Fig 2.

The simulation of the electric field distributions in forward direction were conducted depending on the fiber input, diffractive lens design, wavelength and the aqueous environment. The results were then provided for comparison with the experimental data, and as a basis for force calculations.

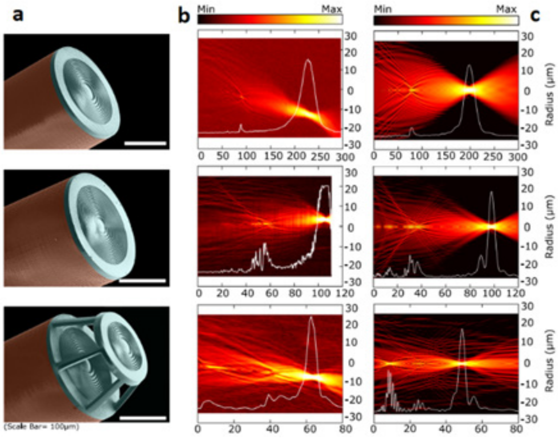


*Fig. 2: **a,** Colored scanning electron microscopy images of the manufactured lenses on fiber tips. **b,** Beam profile measurements, normalized camera pixel values. **c,** WPM simulations, log10- scaling.*

Comparing the simulation results with the measured beam profile shows a very good qualitative agreement, allowing for pre-experimental layout considerations using WPM simulations.

Supported by: Bundesministerium für Bildung und Forschung
Project: Printoptics and
BW Stiftung, Project: Opterial

References:

[1] A. Asadollahbaik, S. Thiele, K. Weber, A. Kumar, J. Drozella, F. Sterl, A. Herkommer, H. Giessen & J. Fick. „Highly Efficient Dual-Fiber Optical Trapping with 3D Printed Diffractive Fresnel Lenses". ASC Photonics 7, 88-97, 2020.

Wave Optical Simulation of 3D Printed Micro Optics in ITOM

J. Drozella, A. Toulouse, M. Wende, A. Herkommer

WavePropagationMethods (WPM) is a plugin for ITOM which is capable of processing 2D and 3D systems up to an approximate size of 1 mm^3 and simulate those using a scalar wave-optical approach [1].

It is designed to provide relatively comfortable user experience compared to extensive electro-magnetic simulation tools like COMSOL, while being significantly quicker and requiring less resources in terms of computer memory and time. This is made possible by calculating the propagating electric field using the scalar Helmholtz-equation in forward direction instead of solving Maxwell's equations rigorously.

This fast simulation is suitable for refractive, diffractive and total internal reflection calculations with the requirement on the main component remaining in a 'forward' direction. Non-linear interaction, back-reflection, as well as non-dielectric materials, or the consideration of polarization dependent effects are not in the scope of this plugin at this moment. However, parts of these topics are under development currently.

The definition of simulation models is aimed to be as comfortable as possible. Functions to translate Zemax OpticStudio designs, processing of STL-files, measured lens surface data as well as options to directly provide 2D or 3D refractive index distributions are included.

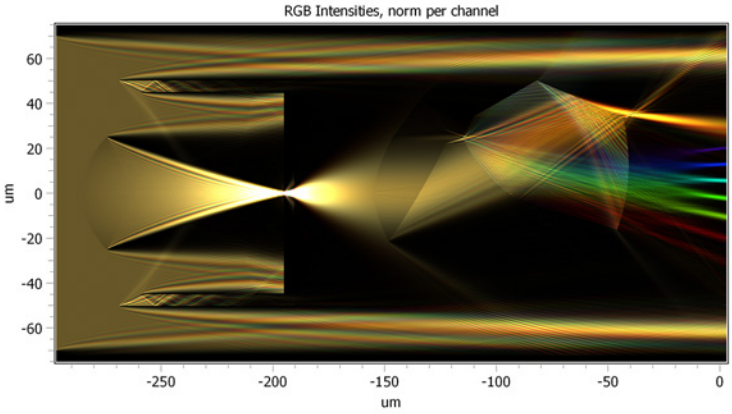


Fig. 1: Wave-optical propagation through 3D-printed miniature spectrometer [2] based on its STL file. Multiple colors are propagated separately as a plane wave input from the left. Sensor plane at z=0.

An example of processing CAD-defined systems by using STL-files to create refractive index distributions is shown in Fig. 1 for a miniature spectrometer (see paper in this issue). Here the STL system file was processed with multiple consecutive simulations using separate incoming wavelengths. Absorbing structures can be realized simply by replacing selected areas with a refractive index of 0, which are automatically extinguished during simulation. The completed simulations were color-converted using a wavelength-to-RGB-algorithm and combined to a full image in order to show the diffractive and positional effects as desired [2].

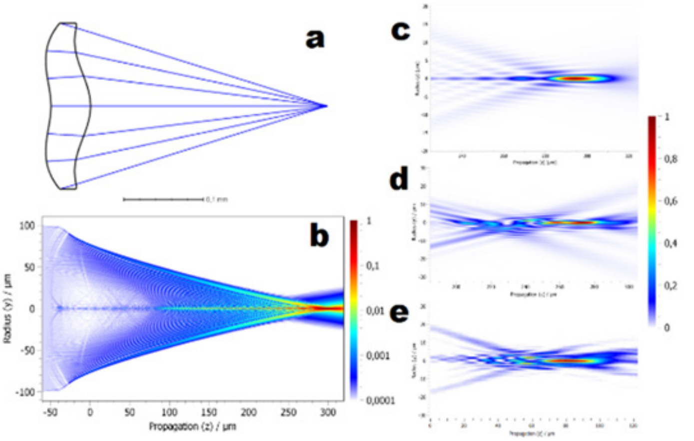


Fig. 2: ***a****, Raytracing and* ***b,*** *logarithmic intensity distribution after WPM of a perfect lens from Zemax data.* ***c****, Theoretical focus region.* ***d****, Changes to focus after replacing one of the surfaces with measurement data.* ***e****, Comparison to spot profile measurement of the manufactured lens [1]. Axes in µm, scale normalized intensity.*

By default the WPM outputs a (y,z)-plane cut of the simulated system at its center on the x-axis in order to visualize the propagating electric field (compare Fig. 2b). It is possible however to extract any sized (x,y)-plane in a desired region of interest along the propagation. This can be useful to examine beam profile or focal spot development, as well as extractions of field distributions in Fourier planes.

Due to the structure of the WPM plugin it is easily possible to replace Zemax-based system or lens descriptions with individually defined or measured data. As shown in Fig. 2. the design of a perfectly focusing lens was manufactured with a Nanoscribe 3D printer, which utilizes 2-photon polymerization to reach voxel resolutions in the magnitude of 0.1 µm. After production, the surfaces were measured using a confocal microscope and deviations due to shrinking and warping while production were recorded as z(x,y) in a CSV file format. For comparison the calculated perfect lens surfaces was replaced by the measurement data, which results in a change in focal spot shape, showing both the influence of this surface as well as the adaptability of the WPM.

A construction of fully-individual systems, using surface profiles from any python-processable source as height-values, for example computated digital holographic surface topographies, is also an option.

Current developments aim for the optional implementation of vectorial instead of scalar electric fields. This allows for polarization-dependent effects to be simulated, and a separation of the electric field components per spacial direction.

Supported by: Bundesministerium für Bildung und Forschung
Project: Printoptics and
BW Stiftung, Project: Opterial

References:

[1] J. Drozella, A. Toulouse, S. Thiele & A. Herkommer, "Fast and comfortable GPU-accelerated wave-optical simulation for imaging properties and design of highly aspheric 3D-printed freeform microlens systems," Proc. SPIE 11105, 1110506 (9 September 2019)

[2] A. Toulouse, J. Drozella, S. Thiele, H. Giessen & A. Herkommer. „3D-printed miniature spectrometer for the visible range with a 100×100 µm² footprint", Light: Advanced Manufacturing, 2(1), 1-11, 2021.

Evaluation and comparison of different materials for additive manufacturing of transparent optical components

C. Reichert, A. Herkommer

Additive manufacturing allows to produce almost any lens shape (see Fig 1 [A]), whereas in classical optics manufacturing only spherical surfaces are available at low cost for small quantities. With conventional 3D printing, it is therefore possible to manufacture novel optical design ideas (especially for illumination tasks) with manageable time and costs.

For the optical design and the later use of optical elements, it is important to know the individual optical properties of the applicable materials, like the refractive index for various wavelengths, transmission, volume scattering, reflection and temperature dependent behaviour. We evaluate the use of four different materials (VeroClear, ClearVue, LOCTITE 3820 and WaterShed) for printing optical components in the field of illumination design (see Ref. [1]).

For the determination of the refractive indices, we used a commercial refractometer, which analyzes the material with seven fixed wavelengths and variable temperature. Using the measured data, we obtained the Cauchy and Sellmeier fit descriptions for different temperatures (20 to 80 °C with a step size of 10 °C). We calculated the Abbe number and show that it changes by increasing the temperature. In summary, LOCTITE 3820 and VeroClear showed a complemental behavior, as needed for achromatic lenses.

To investigate which of the polymers are best suited to build optical components, we designed two spherical and two aspherical lenses for each material using Zemax (for example see Fig. 1 [B]). All the lenses have a diameter of 25.4 mm, the shapes are plano-convex and they were printed in both flatwise and upright orientation. Using these lenses, we measured the transmission at 650 nm, determined the imaging quality by imaging a homogeneously illuminated razor blade and measured the heating behavior of the lenses while illuminating them with a white light LED.

To show the potential we created an illumination system, which produces a positive indoor lighting situation similar to the sun shining through a roof window. This was realized by 3D printing two lenses of 120 mm diameter, one containing an aspherical, and the other a freeform shape (see Fig. 1 [C] and [D]).

In conclusion we recommend fabricating printed lenses in a flatwise orientation. The lenses manufactured with VeroClear in this manner show a comparatively good image quality. LOCTITE 3820 had the highest maximum temperature and VeroClear the lowest. For applications where high transmissivity is the key requirement, LOCTITE 3820 or VeroClear could be identified as the most beneficial materials. The material VeroClear at a flatwise orientation also provides the best imaging quality.

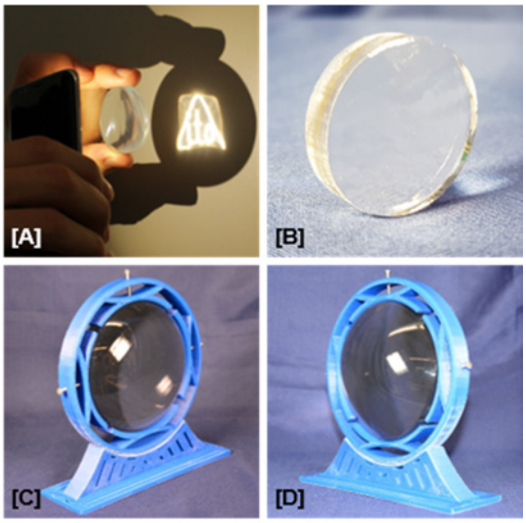


*Fig. 1: Different 3D printed lenses. **[A]** freeform lens to create the ITO logo, **[B]** plano-convex spherical lens (f'=40 mm), **[C]** aspherical and **[D]** freeform lens for illumination purposes with a diameter of 120 mm.*

Supported by: BMBF Federal Ministry of Education and Research
Project: Modulsystem zu Realisierung photonischer Anwendungen (FKZ 13N15165)

References:

[1] C. Reichert, et al., “Evaluation and comparison of different materials for manufacturing of transparent optical components in additive manufacturing”, Optical Engineering, DOI: 10.1117/1.OE.60.6.067103, 202

Enabling producibility of custom optical systems – algorithmic catalog lens substitution by continuous design optimization

C. Reichert, A. Herkommer

After the design of an optical system is completed, it should be possible to build and use it in real life. Since the design process often results in lenses that are not available in this exact geometry, they usually have to be custom manufactured. This means that high manufacturing costs and long delivery times must be expected. It is therefore advisable to use standard catalogue lenses when designing optical systems. However, it is often difficult to set up an optical system with catalog lenses from the beginning because of their predefined (individual) parameters.

We have developed an open source optical design program in C++ that replaces the individual lenses in an optical system with the most appropriate lenses from a variety of catalogues. This inevitably leads to changes in the optical system‘s behavior, since the catalog lens rarely matches the original lens in all parameters. For this reason, each replacement step is accompanied with an optimization step, wherein the aberrations caused by the replacement should be eliminated by adjusting the rest of the designed system.

The algorithm sequence is shown in Fig. 1. First, the user has to design an optical system and define system variables (V). Second, the start system will be optimized according to a merit function. Using weighted parameters, a user-specified minimum of the root mean square (RMS) spot sizes of different field positions can be achieved. Next, the algorithm uses the optimized system and exchanges the designed lens by the best-fit catalog lenses. In this process, the user can decide how many lenses are replaced using a catalog. After that, all newly generated optical systems are optimized using the merit function. The algorithm chooses the best optimized system for the next steps. This cycle repeats until all design lenses are replaced by catalog lenses.

For the optimization, we use a genetic algorithm in combination with the damped least squares method. For the replacement sequence, the user can allow many different lenses from Thorlabs, Edmund Optics (EO) and Qioptiq. The algorithm automatically includes the catalog lens in two different orientations (the same orientation as in the catalog and rotated by 180 degrees).

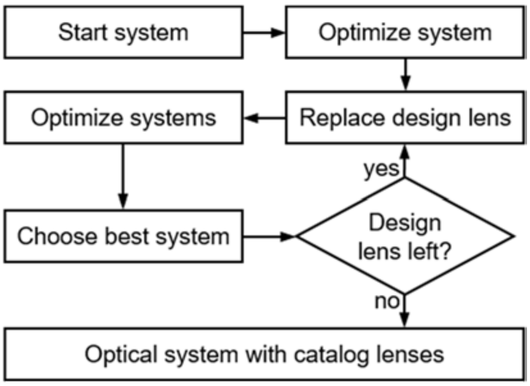


Fig. 1: Sequence of the algorithm to replace an optical design with catalogue lenses by continuous design optimization.

During the process, it is important which design lens is replaced next. For that reason, the user can decide in which sequence the design lenses should be replaced. The user has the following opportunities: From left to right, from right to left, choose design lens with highest/lowest seidel aberrations, try all replace sequences and return the best system, and give your own replace sequence to the algorithm. A simple result of the algorithm is shown in Fig. 2.

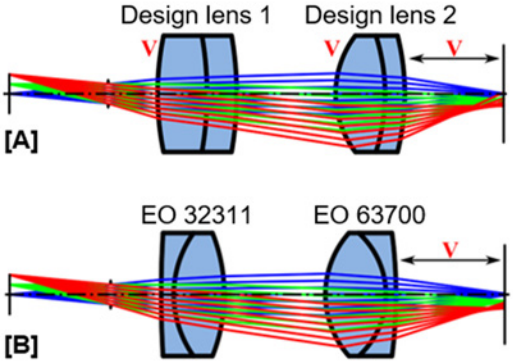


Fig. 2: The algorithm replaces design lenses from start system [A] with catalogue lenses by continuous design adaptation [B].

Supported by: BMBF Federal Ministry of Education and Research
Project: Modulsystem zu Realisierung photonischer Anwendungen (FKZ 13N15165)

Editorial work

Herkommer, A., Duerr, F.

Interdisciplinary Simulation

Advanced Optical Technologies No. 2, 2019

V. Micó, G. Pedrini, M. Lei, C. Zuo, P.Gao

Editorial: Optical Microscopic and Spectroscopic Techniques Targeting Biological Applications

Frontiers in Physics., Volume 9, Article 752435 2021
https://doi.org/10.3389/fphy.2021.752435

Awards

2019 – July 2021

W. Osten:

Chandra S. Vikram Award of the International Society for Optics and Photonics SPIE, 2019

W. Osten

Emmett N. Leith Medal of the Optical Society of America OSA, 2019

A. Toulouse, S. Thiele, H. Giessen, A. Herkommer:

Best student paper award at Advanced Fabrication “Technologies for Micro/Nano Optics and Photonics XII”, part of Photonics West 2019, for an outstanding paper on „Super-fine inkjet process for alignment-free integration of non-transparent structures into 3D-printed micro-optics“.

A. Toulouse

Innovation Prize der Purmundus Challenge “Beyond 3D printing" 2019

T. Boettcher

CC UPOB Young Scientist Award 2019, first prize.

C. Schober

CC UPOB Young Scientist Award 2019, third prize.

S. Thiele

"Preis der Freunde der Universität Stuttgart für besondere wissenschaftliche Leistungen" 2020 for his PhD-thesis "Design, Simulation und Prozessoptimierung für das 3D-Laserdirektschreiben von Mikrooptiken".

N. Fahrbach

1. Prize of the Artur-Fischer-Stiftung for the best master-thesis (2020) "Entwicklung einer kompakten low-cost Weitwinkelkamera mittels on-Chip 3D-Druck von Mikrolinsen".

H. Giessen, A. Herkommer and Simon Thiele

Gips-Schüle-Forschungspreis 2021

Membership of Editorial Boards

A. Herkommer

Member of the Editorial Board of the Journal “JPhys Photonics”

Reviewed Papers

2019

A Asadollahbaik , S. Thiele, K. Weber, A. Kumar, J. Drozella, F. Sterl, A. Herkommer, H. Giessen, J. Fick

Highly Efficient Dual-Fiber Optical Trapping with 3D Printed Diffractive Fresnel Lenses

ACS Photonics, Vol. 7, Nr. 1, pp. 88–97

Z. Cai, X. Liu, G. Pedrini, W. Osten, X. Peng

Accurate depth estimation in structured light fields

Optics Express, Vol. 27, Nr. 9, pp. 13532-13546

Z. Cai, X. Liu, G. Pedrini, W. Osten, X. Peng

Unfocused plenoptic metric modeling and calibration

Optics Express, Vol. 27, Nr. 15, pp. 20177-20198

F. Duerr, A. Herkommer

Why does interdisciplinary research matter?

Advanced optical technologies Vol. 8, Nr. 2, p. 103–104

T. Haist, C. Reichert, F. Würtenberger, L. Lachenmaier, A. Faulhaber

Kamerabasierte Erfassung von Vitalparametern (Camera-based measurement of vital signs)

TM-Technisches Messen, Vol. 86, Nr. 7–8, pp. 354-361

J. Krauter, J. Stark, W. Osten

Topography measurement on disguised microelectromechanical systems using short coherence interferometry

TM-Technisches Messen, Vol. 86, Nr. 6, pp. 309-318

M. Liao, D. Lu, W. He, G. Pedrini, W. Osten, X. Peng

Improving reconstruction of speckle correlation imaging by using a modified phase retrieval algorithm with the number of nonzero-pixels constraint

Applied Optics, Vol. 58, Nr. 2, pp. 473-478

S. Ludwig, B. L. Teurnier, G. Pedrini, X. Peng, W. Osten

Image reconstruction and enhancement by deconvolution in scatter-plate microscopy

Optics Express, Vol. 27, Nr. 16, pp. 23049-23058

G. Pedrini, I. Alekseenko, G. Jagannathan, M. Kempenaars, G. Vayakis, W. Osten

Feasibility study of digital holography for erosion measurements under extreme environmental conditions inside the International Thermonuclear Experimental Reactor tokamak ınvited

Applied Optics, Vol. 58, Nr. 5, pp. A147-A155

D. Rausch, A. Herkommer

Design of a freeform uniformity corrector lens for extended sources in elliptical reflectors

Journal of Physics: Photonics Vol.1, Nr.2, p. 24001

F. Reichenzer, S. Dörr, A. Herkommer

Transient simulation of laser beam propagation through turbulent cutting gas flow

Advanced optical technologies Vol. 8, Nr. 2, p. 129–134

J. Ritter, N. Ma, W. Osten, M. Takeda, W. Wang

Depolarizing surface scattering by a birefringent material with rough surface

Optics Communications, Vol. 430, pp. 456--460

M. Roeder, S. Thiele, D. Hera, C. Pruss, T. Guenther, W. Osten, A. Zimmermann

Fabrication of curved diffractive optical elements by means of laser direct writing, electroplating, and injection compression molding

Journal of Manufacturing Processes, 47, 2019

J. Schindler, C. Pruss, W. Osten

Simultaneous removal of nonrotationally symmetric errors in tilted wave interferometry

Optical Engineering, Vol. 58, Nr. 7, 074105

I. Shevkunov, V. Katkovnik, D. Claus, G. Pedrini, N. V. Petrov, K. Egiazarian

Spectral Object Recognition in Hyperspectral Holography with Complex-Domain Denoising

Sensors, Vol. 19, Nr. 23, 5188

S. Thiele, C. Pruss, A. M. Herkommer, H. Giessen

3D Printed Stacked Diffractive Microlenses

Optics Express, Vol. 27, Nr. 24, pp. 35621-35630

F. Würtenberger, T. Haist, C. Reichert, A. Faulhaber, T. Boettcher, A. Herkommer

Optimum Wavelengths in the Near Infrared for Imaging Photoplethysmography

IEEE Trans. Biomed. Engineering, Vol. 66, Nr. 10, 2855-2860

Reviewed Papers

2020

I. Alekseenko, G. Pedrini, V. Martínez-García, A. Mora, A. Killinger, A. Kozhevnikova, S. Schmauder, R.Gadow, W. Osten

Residual Stress Evaluation in Ceramic Coating Under Industrial Conditions by Digital Holography

IEEE Transactions on Industrial Informatics, Vol. 16, Nr. 2, pp. 1102 - 1110

L. Bremer, K. Weber, S. Fischbach, S. Thiele, M. Schmidt, A. Kaganskiy, S. Rodt, A. Herkommer, M. Sartison, S. Portalupi, P. Michler, H. Giessen, S. Reitzenstein

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Li, Huiyu

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06/2021

Rausch, Denise

Design und Analyse von Beleuchtungsoptiken auf Basis des Phasenraumkonzepts

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Master Thesis 2019-2020

Irion,Christoph

Konzeption und Konstruktion einer dynamischen Strahlablenkung zur Verbesserung der Homogenität linienförmiger Intensitätsverteilung

1/2019

Tischler, Jan-Heiko

Entwicklung, Aufbau und Bewertung eines Messplatzes für die Pulse-Phase-Shearografie

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New focused-based methods for fast microscopic topography measurement

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Hochgenaue Kalibrierverfahren von Multipoint-Positionsmesssystemen

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Analysis of Synthetic and Real Camera Image Data to Determine Facial Parameters

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Knab, Aline

Konzeption und Analyse einer optimierten spektralen Messlösung in der Austrittspupille eines Operationsmikroskops

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Untersuchungen zum Einfluss von differenten Konturformen unter verschiedenen Beleuchtungen für Mercedes-Benz-Fahrzeuge

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Detektion von niedriggradigen Tumoren in der Neurochirurgie mittels Fluoreszenz

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Rüdinger, Andrea

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Simulationsmodell zur Untersuchung der Augengefährdung durch mehrere Lidar-Systeme

4/2019

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Development of Transparent Conductive Oxides by Magnetron Sputtering for the Application in Semitransparent Perovskite Solar Cells

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Optische und mechanische Simulation der spannungsinduzierten Doppelbrechung eines LCD Moduls für automotive Anwendungen

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Simulation of a single pixel camera with deep learning methods

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Entwicklung eines genetischen Evolutionsalgorithmus für komplexe optische Systeme in Kombination mit lokaler Optimierung

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Untersuchungen zum Einfluss ringförmiger Intensitätsverteilungen auf den Laserschneidprozess

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Leuchte mit variabler Lichtverteilung

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Low-Cost-3D Visualisierung

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Klassifizierung zeitlicher Specklefrequenzen mittels Deep Learning als Erweiterung des LiDAR-Sensors zur Objekterkennung in Nebel

6/2019

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Verbrennungsanalyse am optisch zugänglichen Einzylindermotor mittels Flammenspektroskopie

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Entwicklung einer kompakten low-cost Weitwinkelkamera mittels on-Chip 3D-Druck von Mikrolinsen

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Optische Simulation und Analyse einer plenoptischen Kamera zur dreidimensionalen Untersuchung von Plasmaströmungen

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Systemcharakterisierung eines neuartigen Operationsmikroskops zur quantitativen Fluoreszenzmessung und Visualisierung von niedriggradigen malignen Gliomen

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Holistic Optimization of Optical Systems

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Detektion von Mikroorganismen mittels Machine Learning-Ansätzen unter der Verwendung eines Low-Cost Mikroskops

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Khamis, Abdallah

Mikrooptisches Lasermodul in Polymertechnologie

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Optimiertes Fügen von tranparenten Materialien mittels Ultrakurzpulslaser

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Simulation des Feinpassfehlers in starren Endoskopen

9/2019

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Optikdesign und Spritzguss eines Mikroobjektivs für die medizinische Endoskopie

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Entwicklung, Aufbau und Evaluierung eines interferometrischen Topografiesensors

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Konzeption eines hochintegrierten mikrooptischen Positionsgebers

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A deep learning approach to traffic sign classification in fog via single pixel camera

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Optimizing the Fast Multipole Method FMM

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Farid, Azra

Object detection through scattering media (fog) using polarimetric methods

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Papugy, Thataniga

Optimiertes Laserschweißen transparenter Materialien mittels strahlgeformter ultrakurzer Laserpulse

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Development of Simulation Methods to Perform Eye Safety Evaluations of Optical Display and Sensor Systems with Ray Tracing

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Analysis of tissue classification strategies in medical endoscopy using a multispectral light source

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Zimmermann, Markus

Neural Networks for Hyperspectral Image Reconstruction from Computed Tomography Imaging Spectrometer (CTIS) data

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Single-Shot Interferometrie zur Vermessung von Freiformoberflächen im einstelligen Nanometerbereich

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Bachelor Thesis 2019-2020

Tatiyosyan, Anais

Virtual diagnosis for low vision patients: an optokinetic nystagmus based contrast sensitivity test in virtual reality

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Multilayer Auswertung von reflektierenden und streuenden Medien mit dem TWIP Konfokal Mikroskop

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Digital holografische Tomografie unter Einsatz der Zwei-Wellenlängen-Methode

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Entwicklung eines Algorithmus zur Ersetzung eines Optikdesigns durch Kataloglinsen mit kontinuierlicher Designanpassung

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Entwicklung eines Ray-Aiming-Algorithmus und Simulation verschiedener Abstrahlcharakteristika von Lichtquellen

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Design and Simulation for 3D-printed whispering gallery Mode Sensors

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Phasenplatten zur Strahlformung in einem Gerät zur Zwei-Photonen-Lithographie

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Deep Learning Single Pixel Camera

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Klein, Jil

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Untersuchung verschiedener Stereokameras zur 3D-Messung und Atmungsdetektion

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Solving the inverse problem of ellipsometry with Deep Learning

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Interference adjustment with Deep Q-Learning

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Linearisierung eines Variational Autoencoders

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Kurzbauendes asphärisches 1-mm-Objektiv für die Endoskopie mittels 3D-Druck

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Brechungsindexmessungen mit 3D-gedruckten Fabry-Perot-Fasersensoren

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Object classification in fog in autonomous driving with single-pixel camera via deep learning

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Mettler, Markus

Entwicklung eines lowcost Entfernungsmessers mit Hilfe von Multispotlasertriangulation

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Virtual Reality-basierte Simulation von Augenkrankheiten

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Beleuchtung durchs Schlüsselloch: Lichtsammlung und Einbringung zur intensiven Ausleuchtung abgeschlossener Räume

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Wahl, Johannes

Analyse der Einflussfaktoren auf die Herstellung eines optischen Elements zur Polarisationsformung von Hochleistungslasern im Infrarotbereich basierend auf Gitterwellenleiterstrukturen

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Design und Aufbau eines Push-Broom-Spectrometers

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Hochgenaue Kantendetektion durch holografische Mehrbildgenerierung

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Hochgenaue Kamerakalibrierung für ausgedehnte Szenen mittels computer-generierter Hologramme

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Herstellung von Glas-Mikrooptiken auf optischen Fasern mittels 3D-gedruckter Gussformen aus Kunststoff

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Vollautomatische Radienmessung von Präzisionsoptiken für fertigungsnahe Bedingungen

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Polarimetrische Untersuchung der Haut durch Laser-Speckle

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Herstellung von „Liquid-Glass“-Mikrooptiken mittels 3D-gedruckter Gussformen aus Kunststoff

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Eggstein, Selina

Optimierung 3D-gedruckter Mikrooptiken durch iteratives optisches Design

11/2020

Optik-Kolloquium 2019

Abschiedskolloquium Prof. Dr. Wolfgang Osten

Quo vadis Optical Metrology

am 1. März 2019, Teilnehmer: ca. 200

Begrüßung und Einführung	Prof. Dr. Alois Herkommer ITO, Universität Stuttgart
Optische Messtechnik im Zeitalter der digitalen Transformation: ein längerer Blick zurück und zwei kurze nach vorn	Prof. Dr. Wolfgang Osten ITO, Universität Stuttgart
Immer komplexer - physikalische Forschung und Lehre an Universitäten	Prof. Dr. Dieter Meschede Institut für Angewandte Physik, Universität Bonn
Optical distance and displacement measurements for precision stage positioning	Peter de Groot Zygo Corporation, Middlefield, CT (USA)
Vom Photon ins Internet of Production	Prof. Dr.-Ing. Robert Schmitt Werkzeugmaschinenlabor WZL der RWTH Aachen
Schnelle Digitale Holographie für industrielle Anwendungen	Dr. Daniel Carl Fraunhofer-Institut für Physikalische Messtechnik IPM , Freiburg
Optical metrology in semiconductor manufacturing: challenges and opportunities	Prof. Dr. Arie den Boef Vrije Universiteit Amsterdam and ASML Veldhoven (NL)
Bildgebende Ellipsometrie an gekrümmten Oberflächen	Prof. Dr.-Ing. Jürgen Beyerer Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung IOSB, Karlsruhe
Digital holography for erosion measurements under extreme environmental conditions inside the ITER Tokamak	Dr. Giancarlo Pedrini ITO, Universität Stuttgart
Elektronisch-photonisch integrierte Schaltungen auf Silizium	Prof. Dr.-Ing. Manfred Berroth Institut für Elektrische und Optische Nachrichtentechnik, Universität Stuttgart
Nanopositioning and metrology machine at ITO	Christof Pruß ITO, Universität Stuttgart

Organized International Conferences: 2019 - 2020

A. Herkommer:

EOS Optical Technologies
TOM 2: Computational, Adaptive and Freeform Optics
TOM 3: Optical System Design, Tolerancing and Manufacturing
Munich, Germany, June 24-26, 2019

A. Herkommer:

EOS Optical Technologies
TOM 2: Computational, Adaptive and Freeform Optics
TOM 3: Optical System Design, Tolerancing and Manufacturing
Online meeting, September 7-11, 2020

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