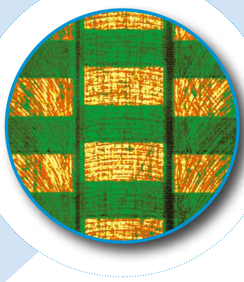
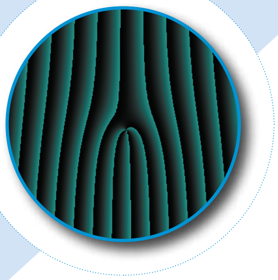
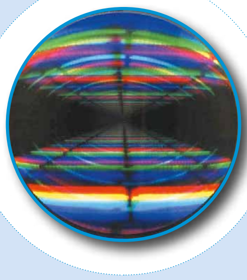
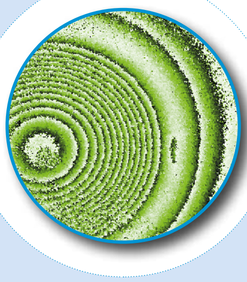
annual report
2017 / 2018

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART









Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

Prof. Dr. W. Osten
Prof. Dr. A. Herkommer

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ANNUAL REPORT 2017/2018

Dear Reader,

It was a great honor for me to take over the Chair for Applied Optics at the University Stuttgart in September 2002. Following in the footsteps of my esteemed predecessor, Prof. Hans Tiziani, who had led the institute to a high national and international reputation, it was a challenge for all employees and especially for me to maintain this position of the institute and to further improve it. Looking back on almost 17 years, I dare to say that we have done well. The years were filled with many activities in different fields and enriched with fruitful national and global cooperation. Let me take the opportunity to mention here several of our achievements briefly.

Our common activities were always based on the motto "Continuity and Renewal". Therefore, we have continuously renewed and extended our research topics and laboratory equipment. This especially due to the grown challenges for an institute covering a wide bandwidth of optical technologies and pursuing activities in several scientific fields such as optical inspection and metrology, optical systems design, nano technologies, sensor technologies, digital optical technologies and bio-medical technologies. To sustain our joint work with leading semiconductor companies and suppliers of photo-lithography equipment, we improved our cleanroom and nano-inspection facilities considerably by the implementation of a 100 square meter class 100 cleanroom and a 50 square meter climatized nano fabrication and measurement center. There we installed state-of-the-art equipment as the FEI™ Helios NanoLab for nano imaging and fabrication, the Nano Measurement and Positioning Machine NPMM 200 for sub-nm positioning of various sensors across a field with a diameter of 200 mm, the high end plasma etching system SI 500 for the processing of diffractive optical elements written with our two continuously improved Circular Laser Writing Systems CLWS 300, equipment for spectroscopic ellipsometry and scatterometry, and a two-photon maskless nano-lithography system for the fabrication of ultra-smooth micro-optics. A considerable part of the costs for all these devices and infrastructure was sponsored by the German Research Association in the framework of competitive calls for proposals. With this infrastructure and driven by many inspiring ideas of the members of the staff, we could acquire numerous interesting research projects with a funding amount of more than 36 Million Euro from various funding bodies such as the German Federal Ministry of Education and Research (BMBF), the German Ministry for Economic Affairs and Energy (BMWi), The German Research Assosiation (DFG), the Baden-Württemberg Foundation, the European Union (EU), and many German and international industrial customers. Our thanks go to all these partners for the long-term and fruitful research cooperation with many remarkable results. In the previous 7 research reports and the present edition the reader can find many interesting facts about our past and current activities. To the most important results, I would count the 37 doctoral theses which have been successfully completed so far. 15 phd theses are still on the way and are planned to be finished over the next 2 years. For us as members of a university institute it is responsibility and pleasure as well to report about our latest achievements in peer-reviewed national and international scientific journals, conference proceedings and reports. With the intention of presenting our findings to the international community, we have published several hundred publications over the past 17 years. Many of them have found a very positive response. But it was by no means our intention to produce paper only. Approximately 100 patents were filed over the years. Products such as the Tilted Wave Interferometer, produced and worldwide distributed by the company Mahr, and software solutions as the simulation tool MicroSim and the open source metrology software itom are meanwhile widely used. The awarding of numerous prestigious awards testifies to the high international recognition of our results. In 2020 the institute will celebrate its 60th birthday. If we look back on this long and successful history and are aware of the fact that the institute has always reacted very constructively to new challenges – the installation of the new chair "Optics Design and Simulation" with the support of renowned German companies from the optics branch may serve as a proof, then we all can look only positively into the future of the ITO.

Stuttgart, July 2019

Wolfgang Osten

Farewell to Prof. Wolfgang Osten

In October 2018 another era of the ITO ended with the retirement of Prof. Wolfgang Osten. The big footsteps he left behind are hard to be filled, but we hope to find a new and motivated director, who will be able to guide the institute in the same positive manner as Wolfgang Osten did.

So this annual report is also an opportunity to say "Farewell and Thank You" to Wolfgang Osten for the almost 17 years he has dedicated to the ITO. It is impossible to list up all the projects he has initiated with different partners and funding sources. This has not only financed the work of so many scientists and PhD-students at the institute, but equally important, the research ideas and scientific advice of Wolfgang Osten has made the projects successful. It was his overwhelming effort over all those years which kept the ITO visible and on top of the research on optical metrology in Germany, as well as internationally. One of his guidelines ever was "striving for excellence in research and teaching, together with a good balance of continuity and systematic renewing". He did follow this guideline via an immense invest of his time and his mind. Being a university professor and head of such a vivid institute is always an almost unsolvable balance of being a scientist, manager, editor and politician at the same time. By being an active part of the university administration, and at the same time participating in many research councils of DFG, BMBF, BMWi, Photonics BW and many others, he managed to keep the ITO at the front of the most current research and often even guiding the direction optical metrology should go for. It is this effort that allowed the ITO to grow and prosper over the past 17 years.

Wolfgang Osten often called the ITO his family, and like a good father he was able to keep the staff and scientists motivated and in line with the high-set targets. As a reward several high ranked prizes have be won by the ITO over the years. It is well worth to mention that Wolfgang Osten just recently has been selected for three of the most prominent prizes in optics: The Rudolf Kingslake Medal and Prize of The International Society for Optics and Photonics SPIE in 2018, the Chandra S. Vikram Award of the International Society for Optics and Photonics SPIE, and the Emmett N. Leith Medal of the Optical Society of America OSA. He deserved it!

Fig. 1: *OSA-President Ursula Gibson handing the Emmett N. Leith Medal of the Optical Society of America to Prof. Wolfgang Osten in Munich on June 25th, 2019.*

"Congratulations to these honours" and "Thank you for the last 17 years". We wish you all the best and good health in the coming years and are looking forward to see you at the ITO.

Prof. Dr. Alois Herkommer
(in the name of the ITO staff)

Looking forward

The future of the ITO is slightly hidden behind a certain fog of uncertainty regarding the nomination of the new institute director. In the meantime, we try to keep the ITO-ship on its well-set course and use the impressive ground-speed initiated by Wolfgang Osten.

It is not only the ground speed, but also the momentum he initiated, which is helpful to keep on track. One of the biggest, most expensive and most accurate pieces of mass at the ITO is the Nano-Positioning and Metrology Machine NPMM 200. At the end of 2018 the machine has successfully passed the test procedures and has proven to provide repeatability below the nanometer-level and accuracy in the order of a few nanometres in its large metrology volume. We will now look for research and industrial partners, which utilize this extreme amount of accuracy and versatility. This impressive machine, together with the existing FEI Helios NanoLab 600, the tilted wave interferometer TWI 60 and the Super-Inkjet-Printer SIJ-S030 will be the basis for our planned centre for nano-machining and measurement. As a further extension of this centre we will install a two-photon polymerization direct laser writing system at the ITO to continue and extend our activities in printed optical systems and sensors on a micro and nano-scale.

This activity (among many others) has once been started within the cooperative network SCoPE. Also in the future we will try to support and extend such interfaculty projects, activities and especially the educational program, represented by the master program in Photonic Engineering that was established in spring 2013. As a further post-graduate initiative out of SCoPE we have applied for a DFG graduate school "Towards Graduate Experts in Photonic Quantum Technologies", which will extend optical engineering into the quantum world.

This reflects our ongoing strong commitment to high-quality teaching on different levels (bachelor, master, Phd). Our consecutive bachelor-master course in medical technology – a joint and challenging project of the University of Stuttgart and the Eberhard Karls University Tübingen – is running very successful in both the bachelor and the master level. Based on that success an application for a DFG graduate school on tissue-differentiation has been applied for, aiming for a close collaboration between engineers in Stuttgart and medical experts in Tübingen. Within that project, and generally as a member of the Faculty of Mechanical Engineering the institute represents the University of Stuttgart in the field of Applied Optics in research and education. And we are visible: In 2019 we had the honour to represent the University of Stuttgart at the Hannover-Trade Fair and at the Lindau Nobel Laureate Meeting via an initiative of Baden-Württemberg International. So together with our national and international partners, we are positively 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. Our overall research focus "Optical Metrology and Systems Design" is unchanged.

Stuttgart, July 2019

Alois Herkommer

Fig. 2: *The NPMM-200 constructed at the Technical University Ilmenau passed testing at the end of 2018 and is ready to be used (picture: ITO).*

Fig. 3: *Deputy research minister of Baden-Württemberg being fascinated by ITO-printed optics at the Lindau Nobel Laureate Meeting 2019 (picture: Staatsministerium Baden-Württemberg)*

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Institute structure

Research projects

■ 3D-Surface Metrology

■ Active Optical Systems and Computational Imaging

■ High Resolution Metrology and Simulation

■ Interferometry and Diffractive Optics

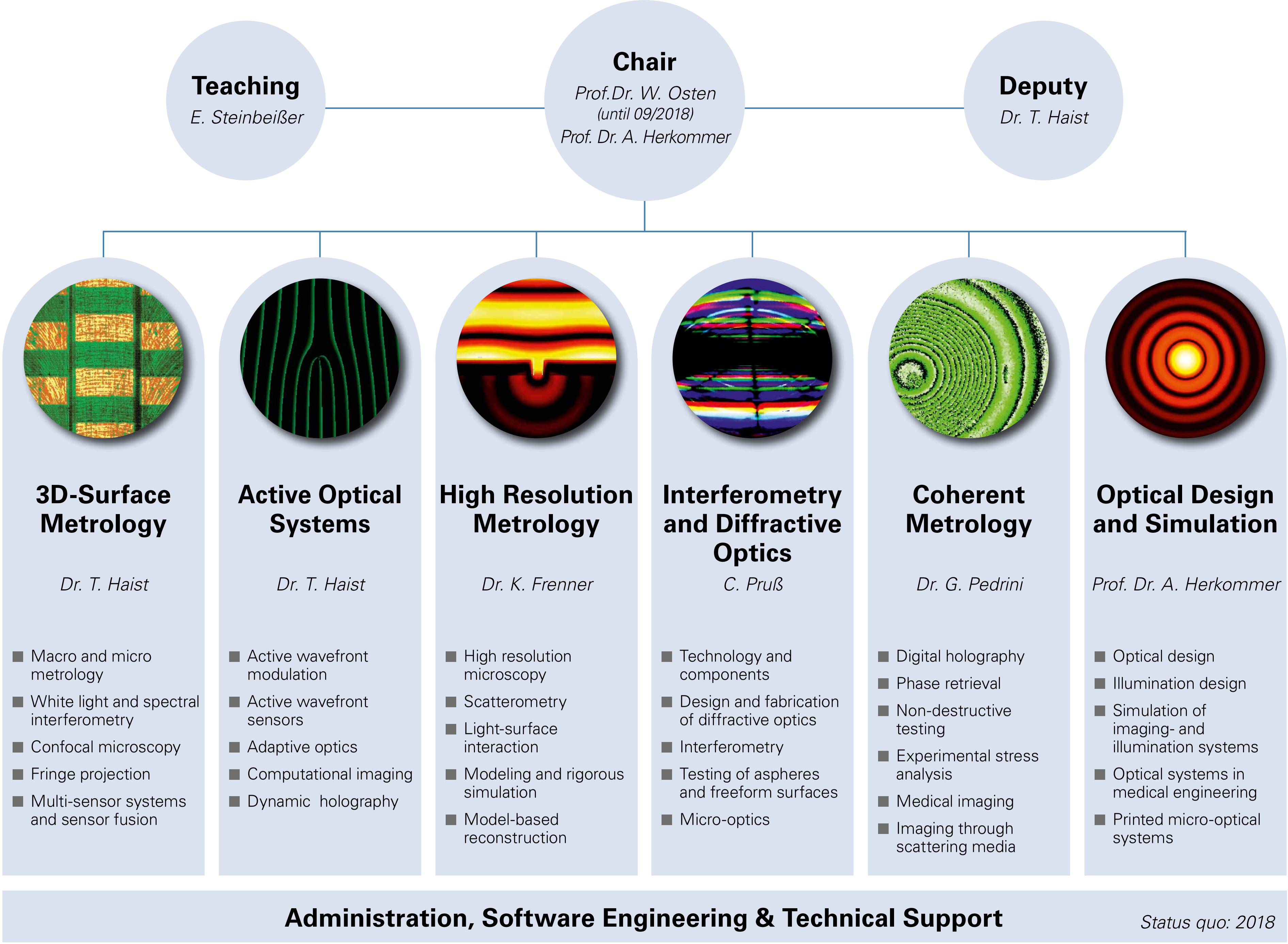
Coherent Metrology

Optical Design and Simulation

Publications 2017 – 2018

Colloquia & Conferences

Team and structure



Teaching
E. Steinbeißer

Chair
Prof.Dr. W. Osten
(until 09/2018)
Prof. Dr. A. Herkommer

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

Active Optical Systems

Dr. T. Haist

- Active wavefront modulation
- Active wavefront sensors
- Adaptive optics
- Computational imaging
- Dynamic holography

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: 2018

Staff of the Institute

Status quo: June 2019

Director

Prof. Dr. Wolfgang Osten	retired since Oct. 2018	

Director (temporary - since Oct. 2018 / Endowed Professorship for Optical Design and Simulation)

Prof. Dr. Alois Herkommer	+49 (0) 711 685-69871	herkommer@ito.uni-stuttgart.de

Administration and Secretary

Heidrun Kempf	+49 (0) 711 685-69873	kempf@ito.uni-stuttgart.de
Christina Vogelmann	+49 (0) 711 685-66074	vogelmann@ito.uni-stuttgart.de
Daria Benefeld	in parental leave	
Katja Costantino	left on 31.03.2018	

Studies

Erich Steinbeißer	+49 (0) 711 685-66068	steinbeisser@ito.uni-stuttgart.de

Research Assistants

3D-Surface metrology

Dr. Tobias Haist (leader)	+49 (0) 711 685-66069	haist@ito.uni-stuttgart.de
Simon Amann	+49 (0) 711 685-69875	amann@ito.uni-stuttgart.de
Andreas Faulhaber	+49 (0) 711 685-69888	faulhaber@ito.uni-stuttgart.de
Flavio Guerra	+49 (0) 711 685-66071	guerra@ito.uni-stuttgart.de
Simon Hartlieb	+49 (0) 711 685-60814	hartlieb@ito.uni-stuttgart.de
Michael Tscherpel	+49 (0) 711 685-61608	tscherpel@ito.uni-stuttgart.de
Tobias Boettcher	left on 31.03.2019	
Marc Gronle	left on 30.04.2017	
Dr. Klaus Körner	left on 30.09.2017	
Johann Krauter	left on 31.12.2018	
Haiyue Yang	left on 31.12.2018	

Active Optical Systems *(on hold since Dec. 2018)*

Dr. Tobias Haist (leader)	+49 (0) 711 685-66069	haist@ito.uni-stuttgart.de
Quynh Duong-Ederer	left on 31.10.2017	
Christian Lingel	left on 28.02.2017	

High resolution metrology and simulation

Karsten Frenner (leader)	+49 (0) 711 685-66065	frenner@ito.uni-stuttgart.de
Claudia Bett	+49 (0) 711 685-69804	bett@ito.uni-stuttgart.de
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Maria Laura Gödecke	+49 (0) 711 685-66623	goedecke@ito.uni-stuttgart.de
Alexander Gröger	+49 (0) 711 685-60863	groeger@ito.uni-stuttgart.de
Huiyu Li	left on 31.01.2019	

Interferometry and diffractive optics

Christof Pruß (leader)	+49 (0) 711 685-66066	pruss@ito.uni-stuttgart.de
Rolf Beißwanger	+49 (0) 711 685-60488	beisswanger@ito.uni-stuttgart.de
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Robin Hahn	+49 (0) 711 685-69879	hahn@ito.uni-stuttgart.de
Antonia Harsch	+49 (0) 711 685-69870	harsch@ito.uni-stuttgart.de
Thomas Schoder	+49 (0) 711 685-66064	schoder@ito.uni-stuttgart.de
Alexander Bielke	left on 15.04.2017	
Cherry May Mateo	left on 31.10.2017	
Johannes Schindler	left on 30.06.2017	
Oliver Schwanke	left on 30.06.2017	

Coherent metrology

Dr. Giancarlo Pedrini (leader)	+49 (0) 711 685-66078	pedrini@ito.uni-stuttgart.de
Stephan Ludwig	+49 (0) 711 685-69892	ludwig@ito.uni-stuttgart.de
Igor Alekseenko	left on 31.08.2018	
Dominic Buchta	left on 30.04.2019	
Dr. Daniel Claus	left on 30.09.2017	

Optical Design and Simulation

Prof. Dr. Alois Herkommer (leader)	+49 (0) 711 685-69871	herkommer@ito.uni-stuttgart.de
Simon Thiele (supportive leader)	+49 (0) 711 685-66609	thiele@ito.uni-stuttgart.de
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Carsten Reichert	+49 (0) 711 685-69805	reichert@ito.uni-stuttgart.de
Florian Rothermel	+49 (0) 711 685-66094	rothermel@ito.uni-stuttgart.de
Andrea Toulouse	+49 (0) 711 685-66648	toulouse@ito.uni-stuttgart.de
Bo Chen	left on 30.09.2018	
Denise Rausch	left on 07.04.2017	
Ann-Kristin Scheibe	left on 31.03.2019	

Software Engineering and Technicians

Heiko Bieger	+49 (0) 711 685-66070	bieger@ito.uni-stuttgart.de
Ralph Knoll	+49 (0) 711 685-66067	knoll@ito.uni-stuttgart.de
Andreas Lorenz	+49 (0) 711 685-66089	lorenz@ito.uni-stuttgart.de

Guest Scientists

Ms. Jingdnan Liu	Beijing Institute of Technology, China	03.03.2016 until 28.02.2017
Mr. Swapnil D. Mahajan	M.S. University of Baroda, India	01.10.2016 until 30.09.2017
Mr. Vismay Trivedi	M.S. University of Baroda, India	15.09.2017 until 30.10.2017
Ms. Kanami Ikeda	The University of Electro-Communications, Tokyo, Japan	18.10.2017 until 04.03.2018
Dr. Elena Achimova	Academy of Sciences of Moldova	07.02.2018 until 31.03.2018 07.10.2018 until 22.11.2018
Dr. Vladimir Abaskin	Academy of Sciences of Moldova	07.02.2018 until 31.03.2018 07.10.2018 until 22.11.2018
Ms. Veronica Cazac	Academy of Sciences of Moldova	18.06.2018 until 01.07.2018
Mr. Alexei Meshalkin	Academy of Sciences of Moldova	18.06.2018 until 01.07.2018

Mr. Haichao Wang	Shanghai Institute of Optics and Fine Mechanics	15.09.2017 until 15.09.2018
Mr. Vincent Pollier	Institut d'Optique, Paris	01.10.2017 until 31.03.2018
Mr. Benjamin Le Teurnier	Institut d'Optique, Paris	01.06.2018 until 31.08.2018
Dr. Dajiang Lu	Shenzhen University, China	13.09.2018 until 13.10.2018
Dr. Meihua Liao	Shenzhen University, China	13.09.2018 until 13.10.2018
Dr. Zewei Cai	Shenzhen University, China	13.09.2018 until 13.10.2018
Mr. Shri Kumar Rishav	Indian Institute of Space Science and Technology, Kerala, India	since June 2018

Foreign Guests visiting the Institute: 2017 – May 2019

February 2017:

Pieter Kappelhoff	hitech, Den Haag, Netherland
Dr. Paul Montgomery	UNISTRA, Strasbourg, France

March 2017:

Dr. Daniel Krekel	Saint-Gobain, Sekurit, Herzogenrath

May 2017:

Dr. Yu Fu, Nanyang	University, Singapore
Prof. Yoshio Hayasaki	Utsunomiya Univ., Utsunomiya, Japan

June 2017:

Prof. P. Almoro	University Philippines, Manila, Philippines
Prof. Dr. Wei Wang	Heriot Watt Univ., Edinburgh, GB
Dr. Yu Fu	Nanyang University, Singapore
Prof. Dr. Qian Kemao	Nanyang University, Singapore
Prof. Dr. Ping Jia	President Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), Changchun, China
Prof. Dr. Min Gu	RMIT University, Australia
Prof. Dr. Yuhong Bai	Changchun Inst. of Optics, Fine Mechanics and Physics (CIOMP), Changchun, China
Dr. Po-Chi Sung	Photomechanics Laboratory, National Tsing Hua University, Taiwan

September 2017:

Prof. George Barbastathis	MIT Boston, USA
Prof. Wim Coene	TU Delft, Delft, The Netherlands
Prof. Arie den Boef	ASML, Feldhoven, The Netherlands
Prof. Miguel A. Alonso	Univ. Rochester, Rochester, USA
Prof. Anand Asundi	Nanyang Tech. Univ., Singapore
Prof. Chris Dainty	National Univ. of Ireland, Galway, Ireland
Prof. Jane Jiang	Univ. Huddersfield, Huddersfield, GB
Prof. Malgorzata Kujawinska	Univ. of Technology, Warzaw, Poland
Prof. James C. Wyant	Univ. of Arizona, Tucson, USA
Prof. Mitsuo Takeda	Utsunomiya Univ, Utsunomiya, Japan
Prof. Paul Urbach	TU Delft, Delft, The Netherlands
Dr. Pietro Ferraro	Institute of Applied Sciences & Intelligent Systems, Naples, Italy
Prof. Demetri Psaltis	EPFL Lausanne, Lausanne, Swiss
Prof. Partha Banerjee	Univ. Dayton, Dayton USA
Prof. Fernando Mendozza Santoyo	CIO, Leon, Mexico
Prof. Yongkeun Park	KAIST, Daechon, Korea
Prof. Guohai Situ	Shanghai Institute of Optics and Fine Mechanics, Shanghai, China
Prof. Yoshio Hayasaki	Utsunomiya Univ., Utsunomiya, Japan
Prof. Zhanghe Zhou	Shanghai Institute of Optics and Fine Mechanics, Shanghai, China
Dr. Bernard Kress	Microsoft, Mountain View, USA
Prof. Byoungho Lee	Seoul National Univ., Seoul, Korea
Prof. Ignacio Moreno	Univ. Miguel Hernandez, Elche, Spain
Prof. Pascal Picart	Univ. Le mans, Le Mans, France
Prof. Chris Evans	Univ. of North Carolina, Charlotte, USA
Prof. Peter de Groot	Zygo Corp., Middlefield USA
Prof. Armando Albertazzi	Univ. Florianopolis, Florianopolis, Brazil
Prof. Sen Han	Shanghai Univ. For Science and Technology, Shanghai, China
Dr. Pablo Ruiz	Lougborough Univ., Loughborough, GB

Prof. Toyohiko Yatagai	Utsunomiya Univ., Utsunomiya, Japan
Dr. Nadya Reingand	Patent Hatchery, Baltimore, USA
Dr. Eugene Arthurs	SPIE, Bellingham, USA
Dr. James Trolinger	Metro Laser, Laguna Hills, USA

March 2018:

Ulf Merbold (Astronaut)	Stuttgart, Germany
Prof. Dr. Hannes Merbold	Chur, Schwitzerland

May 2018:

Dr. Joe Howard	NASA, Washington, USA

September 2018:

Mr. AiWei	Huawei, Shenzhen, China
Mr. LuYong	Huawei, Shenzhen, China
Mr. Shao	Huawei, Shenzhen, China
Hua Fan	Qilu University of Technology, China

October 2018:

Prof. Amir R. Ali	GUC, Cairo, Egypt

February 2019:

Prof. Arie den Boef	ASML, Feldhoven, The Netherlands
Prof. Peter de Groot	Zygo Corp., Middlefield USA
Prof. Sen Han	Shanghai Univ. For Science and Technology, Shanghai, China

May 2019:

Prof. Ming-Jyh Chern	NTUST (Taiwan Tech), Taiwan

Project partners

Project collaboration with the following companies and organisations
(and many others):

Academy of Sciences of Moldova	Chisinau, Moldova
ASML Netherlands B.V.	Veldhoven, Netherlands
Carl Zeiss Meditec	Oberkochen
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
Cascade Microtech GmbH	Thiendorf
Centre Spatial de Liege	Liege, Belgium
Centre Suisse d'Electronique et de Microtechnique	Zurich, Switzerland
Daimler AG	Stuttgart
ESA / ESTEC	Noordwijk, Netherlands
Fraunhofer ENAS	Chemnitz
Fraunhofer IAO	Stuttgart
Fraunhofer IOF	Jena
Fraunhofer IOSB	Karlsruhe
Fraunhofer IAP	Potsdam
Genotec GmbH	Waiblingen
Hahn-Schickard	Stuttgart
Holoeye AG	Berlin
IAE SB RAS	Novosibirsk, Russia
ILM	Ulm
IMS Chips	Stuttgart
International Thermonuclear Experimental Reactor, ITER	Cadarache, France
KARL STORZ GmbH & Co. KG	Tuttlingen
Laboratoire d'optique appliquée, IMT, EPFL	Neuchâtel, Switzerland
Leica Microsystems CMS GmbH	Wetzlar
Mahr GmbH	Jena, Göttingen
Nanoscribe GmbH	Eggenstein
Physikalisch Technische Bundesanstalt	Braunschweig
Polytec GmbH	Waldbronn
Robert Bosch GmbH	Gerlingen
Shenzhen University	China
Sick AG	Waldkirch
Sick Stegmann GmbH	Donaueschingen
Staatliche Akademie der Bildenden Künste Stuttgart	Stuttgart
Statice	Besancon, France
Tampere University of Technology	Tampere, Finland
Trumpf GmbH + Co. KG	Ditzingen
Tsinghua University	Peking, China
Université de Franche-Comté	Besancon, France
University of Eastern Finland	Joensuu, Finland
VTT Technical Research Centre of Finland	Espoo, Finland

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: Prof. Dr. W. Osten, C. Pruß
  Exercise: A. Harsch, E. Steinbeißer

- **Optical Measurement Techniques and Procedures**
  Lecture: Prof. Dr. W. Osten
  Exercise: Dr. K. Körner, S. Ludwig, E. Steinbeißer

- **Optical Information Processing**
  Lecture: Prof. Dr. W. Osten, Dr. K. Frenner
  Exercise: Dr. K. Frenner

- **Fundamentals of Optics** (only for B.Sc.)
  Lecture: Prof. Dr. A. Herkommer
  Exercise: C. Bett, F. Rothermel

- **Optical Systems in Medical Engineering**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: C. Reichert, F. Rothermel

- **Development of Optical Systems**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: S. Lotz, C. Reichert, S. Thiele

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: 2017: Dr. K. Körner, E. Steinbeißer; 2018: C. Pruß, Dr. T. Haist

- **Polarization Optics and Nanostructured Films**
  Lecture: Dr. K. Frenner

- **Introduction to Optical Design**
  Lecture: Prof. Dr. A. Herkommer

- **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.)
  Lecture: 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

- **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)**

Founding of the SPIE Student Chapter – Univ. Stuttgart

M. L. Gödecke, C. Reichert, R. Hahn, F. Guerra, C. Pruß, W. Osten

In late 2017, we founded the student chapter with 16 members and the chapter advisor Christof Pruß (Academic Senior Councillor) at the University of Stuttgart – Institut für Technische Optik under Prof. Wolfgang Osten (Department head). The main purpose of this group is to promote optical science and engineering throughout study, research, discussions, share of knowledge and promoting other students and academic researchers to join. Exemplary activities and program over the year are regular meetings, special lectures, courses, invited guest speakers, social events and travels/field trips.

The foremost agenda was the election of chapter officers held on March 22nd 2018. The officers elected were Maria Laura Gödecke (President), Carsten Reichert (Vice president), Robin Hahn (Secretary) and Flavio Guerra (Treasurer). Prior to the elections, we held a discussion about the year's program and events. We decided to plan several technical talks with in-house lecturers as well as invited guests (NASA, Aalen University, Trumpf, etc.). In addition, we planned outreach activities like co-organizing the "Science Day" at the University, the Optics Colloquium at ITO and more. An in-house software-programming course and other teambuilding or networking events were planned as well. Activities to build connections to industry were intended by visiting optics related exhibitions and field trips to companies.

The first event was the visit of Dr. Joseph M. Howard – lead optical designer of the James Webb Space Telescope at NASA. He gave an interesting lecture about the development and testing of the Webb telescope and the Hubble space telescope followed by a lively discussion and a tour of our labs at ITO. Another event included the chapter in helping organize the "Science Day" – an outreach event for all people of all ages interested in experiencing research on campus. The next activities included the software courses on itom and blender. Colleagues Hahn and Lotz gave an introductory tutorial on how to use both software programs.

In mid-2018, we visited the industry-leader TRUMPF in Ditzingen specializing in Laser-systems for Semiconductor- and Additive Manufacturing. Dr. Matthias Wissert, Steffen Sickinger and Marc Gronle (former PhD student at ITO) introduced their departments, products and gave a live demonstration.

The second field trip was a three-day trip to Switzerland, in particular to visit the HTW Chur (University of Applied Science) and to promote scientific exchange and potential collaborations with Prof. Dr. Hannes Merbold (see fig. 1). At the HTW, both parties gave introductory and scientific lectures. E.g., we introduced the chapter, R. Hahn promoted itom and some research projects were presented (see fig. 2). A guided tour of the HTW labs and a luncheon with discussion rounded off the visit. Afterwards, we headed to ESPROS Photonics Corporation (EPC) where we met Beat de Coi (CEO) and his company focused on developing time-of-flight- and other special camera chips. Furthermore, we went to the Mirasteilas observatory to learn about astronomy and telescoping with hands-on experience and great views on the stars and galaxy. We also went hiking the Rheinschlucht as a social event ending the day with a cozy cheese fondue dinner that everybody enjoyed (see fig. 3). On the way back, we stopped at the Technorama in Winterthur for fun outreach physics and optical experiments.

In December 2018, we invited Prof. Dr. Herbert Schneckenburger from Aalen University as a Guest SPIE Traveling Lecturer to give a talk about "High-resolution optical microscopy in life sciences" at the ITO. The chapter, students and ITO staff attended the interesting talk followed by a technical discussion and a guided tour through ITO laboratories explaining current research projects.

At the end of the year, we gathered the chapter members for a winter barbeque to socialize and network around a campfire. (see fig. 4)

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

SPIE. STUDENT CHAPTER
UNIVERSITY OF STUTTGART

Fig. 1: *SPIE Chapter at the HTW Chur during the three-day field trip.*

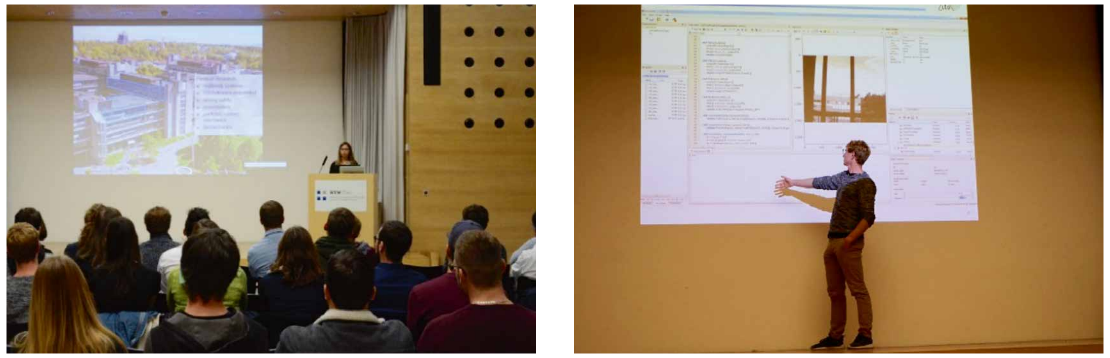


Fig. 2: *Lectures and presentations given by chapter members during the visit at HTW Chur.*

Fig. 3: *360-degree image taken during the telescope lesson at Mirastelias (left) and panoramic view of Rheinschlucht (right) while hiking in Switzerland.*

Fig. 4: *Prof. Herbert Schneckenburger as guest lecturer giving his talk (left) and the winter barbeque with bonfire (right).*

The research groups

Status quo: December 2018

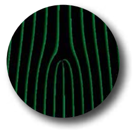
3D-Surface Metrology

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

Contact: **haist@ito.uni-stuttgart.de**



Active Optical Systems and Computational Imaging

The objective of our work is the development of flexible optical systems in order to enable new applications, especially within the field of scientific and industrial metrology. To achieve this goal, we make use of different modern light modulation technologies and computer-based methods. One focus of our work lies in the application of holographic methods based on liquid crystal displays and micromechanical systems for various applications ranging from optical tweezers to aberration control and testing of aspherical surfaces.

Main research areas:

- active wavefront modulation and sensors
- adaptive optics
- active wavefront sensors
- dynamic holography
- components, algorithms, and strategies
- waveoptical computing
- computational imaging

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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
- superlenses

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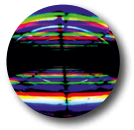

Interferometry and Diffractive Optics

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.

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 and simulation of 3d-printed micro-optical systems
- optical systems for biomedical applications

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3D-Surface Metrology

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Supported by: BMBF
Project: Verbundprojekt IRIS - Infrarotmesstechnik zur In-Line-Inspektion für gekapselte Siliziumbauelemente
In cooperation with: Polytec, Robert-Bosch GmbH, Melexis GmbH, X-Fab MEMS Foundry GmbH, IMMS gGmbH, FhG-ENAS, FormFactor

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Supported by: Baden-Württemberg Stiftung gGmbH
Project: Adascope
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Supported by: Baden-Württemberg Stiftung gGmbH
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"Itom" is freely available. The Core is licensed under the open source license LGPL.

Multipoint measurement system for the measurement of large building deformations... 36

Supported by: DFG German Science Foundation
Project: Adaptive Hüllen und Strukturen für die gebaute Umwelt von morgen (SFB 1244)
In cooperation with: ISYS, University Stuttgart

Topography measurement of micro-electro-mechanical systems below silicon caps

J. Krauter, W. Osten

Micro-electro-mechanical systems (MEMS) are used today in a variety of applications. For the fabrication of MEMS, principles of photolithography are applied. Especially for safety relevant MEMS like airbag or ESP sensors an 100 % inspection is necessary. After optical inspection the MEMS structures are protected by bonding of a silicon cap wafer. This covering or subsequent packaging can cause additional stress in the wafer stack that might influence the MEMS function. In the case of a failed electronic test, the problem cannot be localized because the cap wafer is opaque to common optical surface sensors.

In our project, a short-coherent interference microscope for high resolution topography measurement of micro-elecotrmechanical systems (MEMS) hidden under silicon caps has been developed. It is based on a Linnik white-light interferometric configuration.

In order to eliminiate the spherical aberration introduced by the cap (to first approximation a plane parallel plate) we used objective lenses (Olympus, 50 x, NA=0.65) with correction collars. The light source is an LED at a wavelength of 1.55 µm and a spectral bandwidth (FWHM) of 100 nm. In this spectral region (SWIR) silicon is transparent and, therefore, light backscattered from the MEMS surface can be detected. For the detection we use a cooled Raptor ninox 640 InGaAs sensor with a resolution of 640 x 512 pixels.

A detailed simulation using raytracing for obtaining the wavefront in the exit pupil followed by PSF and interference computation has been realized. For the evaluation, a standard lock-in method followed by a heuristic method for the elimination of ghosts steps has been used.

The precision of the method is below 5 nm (standard deviation). The main problem concerning the accuracy is the deviation that is introduced by caps with spatially varying thicknesses. Due to the large refractive index of silicon (at 1.55 µm) typical variations lead to strong deviations in the topography of several micrometers. If one measures also the topography of the cap (possible by using an extended axial scanning) correction of the measurment results are possible and deviations in the range of 500 nm can be expected.

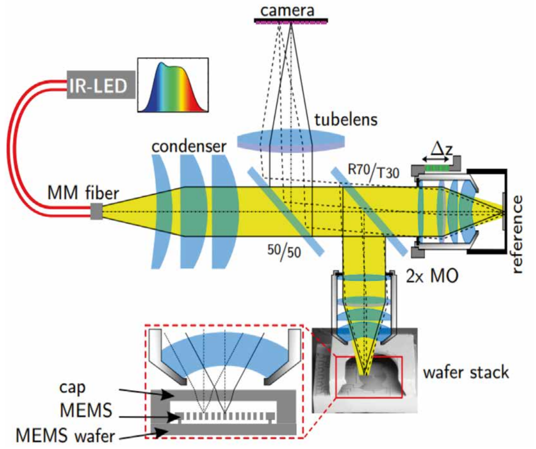

Fig. 1: *Short coherence microscope in the SWIR.*

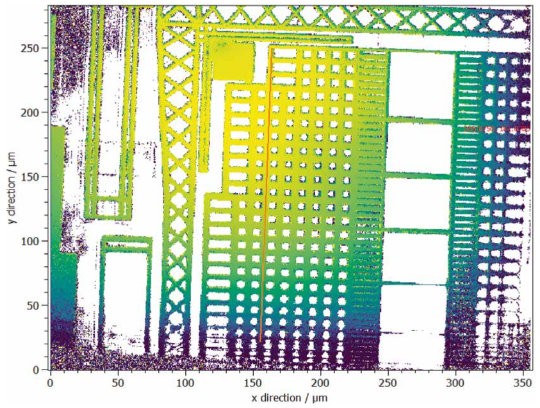

Fig. 2: *Topography measurement (correct) of a MEMS below a silicon cap.*

Supported by: BMBF
Project: Verbundprojekt IRIS – Infrarotmesstechnik zur In-Line-Inspektion für gekapselte Siliziumbauelemente
In cooperation with: Polytec, Robert-Bosch GmbH, Melexis GmbH, X-Fab MEMS Foundry GmbH, IMMS gGmbH, FhG-ENAS, FormFactor

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References:

[1] Krauter, J. and Osten, W. "Nondestructive surface profiling of hidden MEMS by an infrared low-coherence interferometric microscope," J. Surf. Topogr. Metrol. Prop. 6(1), 15005, IOP Publishing (2017) [doi:10.1088/2051-672X/aaa0a8].

New approaches for the combination of confocal microscopy and short coherence tomography

T. Boettcher, D. Claus, M. Gronle, T. Haist, W. Osten

In high-precision inspection, a lot of different measurement tasks have to be accomplished even on a single specimen. Almost every task can be solved by specifically designed measurement devices. But nowadays there are components only manufactured in small batches or even as single pieces. To provide inline inspection capability, a suitable measurement sensor has to be fast, adaptive to the specimen as well as highly precise.

Most often, the topography of a manufactured product is of interest. There are several well-known topography measurement principles. The most prominent are Scanning White Light Interferometry (SWLI), triangulation-based sensors and Confocal Microscopy (CM), whose strongest drawback is the need for a mechanical (axial) scan.

There are, some promising ideas for single-shot devices based on either technology, most of them feasible only as point sensors. The mostly investigated scheme of those is Chromatic Confocal Microscopy (CCM), where the mechanical axial scan is substituted by a chromatically encoded focal range and a spectrometer as a detector. Hence, it provides single-shot height measurements with high lateral as well as axial resolution only limited by the objective's Numerical Aperture (NA).

The approach discussed here overcomes the issue of having to laterally splace the object between consecutive recording positions in CCM. It is based on an area sensor in combination with a wavelength tuneable light source and a Digital Micromirror Device (DMD) for adaptive lateral addressing. Thus, each object point can be illuminated by only those wavelength, which are in focus, allowing laterally dense measurement with low crosstalk. In addition, an achromatic reference arm allows for a second measurement mode, Chromatic Confocal Spectral Interferometry (CCSI)

Fig. 1 shows a wide-field measurement of a resolution standard by Halle in CCM mode. Also without a full wavelength scan, information about the object's shape can be gained by extracting the defocus value from the blurred point images.

To reach higher positional resolution compared to the CCM mode, a new CCSI evaluation method was developed, depicted in fig. 2: The high-frequency part of the Fourier transformation of the CCSI signal is inversely transformed point by point. At focus position, all resulting phase ramps should be zero. Hence, the position of the lowest phase sum is extracted as measurement value.

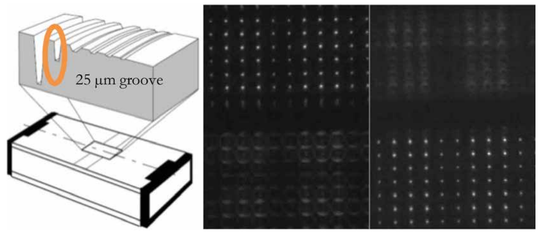


Fig. 1: *CCM measurement of depth resolution standard.*
Mid: selected wavelength focussed at lower surface.
Right: selected wavelength focussed at upper surface.
Contrast enhanced.

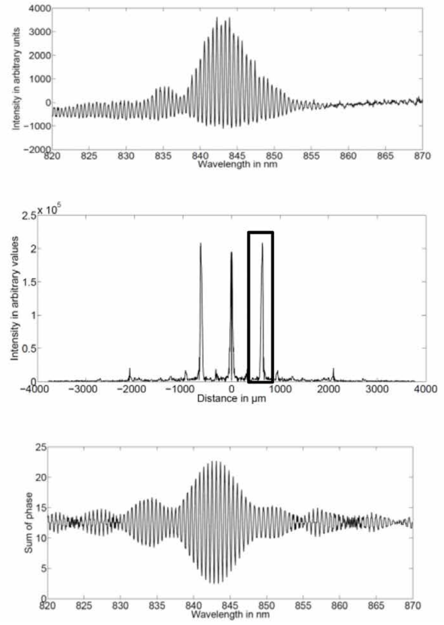


Fig. 2: *Zero Phase Evaluation for CCSI measurements. Upper: recorded signal. Mid: Fourier transform. High-frequency part highlighted. Lower: Sum of phase ramps after pixelwise inverse Fourier transform of highlighted part.*

Supported by: Baden-Württemberg Stiftung gGmbH
Project: Adascope
In cooperation with: Fraunhofer IOSB Karlsruhe

References:

[1] Claus, D.; Boettcher, T.; Pedrini, G.; Taphanel, M.; Hibst, R.; Osten, W. Proc. SPIE 10677, DOI 10.1117/12.2314914, 2018

[2] Claus, D; Boettcher, T; Osten, W. Proceedings SPIE Photonics West, 2019.

Fast and energy-efficient acquisition of three-dimensional panoramic views

A. Faulhaber, T. Haist, W. Osten, S. Simon

In the field of service and care robotics, the robust panoramic acquisition of complex three dimensional scenes with 3D depth information in rooms in video real-time is still a challenge and only conditionally solved. From a fundamental point-of-view, mobile robotic systems are limited by their limited electrical power capacity in particular, when large scenes with high resolution are to be recorded with active lighting (robustness) and high data volumes. Furthermore, the complexity of corresponding hardware/software acquisition systems continues to be a challenge in terms of practical applications. These challenges – robust panoramic acquisition of complex three-dimensional scenes, limited electrical performance of mobile systems and the complexity of corresponding hardware/software acquisition systems – are to be addressed by the “Multi-Stereo – Multi-Projection Methodology” proposed in this project.

Many standardized, simple and self-calibrating miniature image acquisition and projection modules will be installed on a mobile robot platform. Analogous to human vision, both massive data compression and highly variable resolution are used to keep the data rate and thus the energy consumption on the robot reasonable low. The computing operations necessary for the large amount of data are FPGA-based processed on the robot side due to the high energy-efficiency of embedded systems.

The projection, which in the case of large rooms or scenes at high data rates classically represents the main limitation in terms of high-energy consumption, is optimized by means of a sparse coding and computer-generated phase holograms in combination with panoramic optics - also in terms of energy consumption.

The Multi-Stereo – Multi-Projection approach (fig. 1) can significantly improve the robustness and measurement uncertainty of environmental topographies compared to classic stereo vision. The processing can be optimized by machine learning approaches (e.g. Deep Neural Networks).

The project is in collaboration with the Institut für Parallele und Verteilte Systeme (IPVS) under supervision of Prof. Sven Simon. They will be concentrating on the implementation of the FPGA embedded system connected to the camera sensors, the real-time image pre-processing, image compression/ encoding and bi-directional communication to a host computer via wireless network.

We, at the Institut für Technische Optik (ITO), are mainly working on the overall design and simulation of sensor array composition and how the multiple sensors and projectors are to be arranged. In addition, we will design the projection modules using lasers and diffractive optical elements (DOE) to generate point-clouds for individual scene illumination. The DOEs will be manufactured at our Institute. Additionally, we will investigate possibilities to incorporate the previously researched topics on remote pulse measurements and other vital sign surveillance [1].

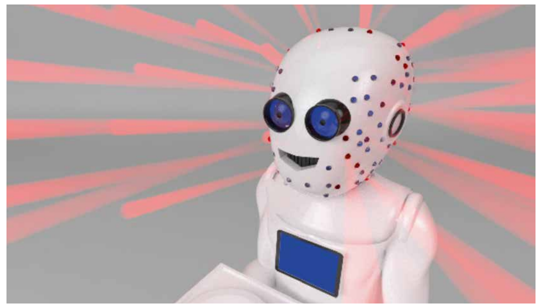


Fig. 1: *Concept image of a service robot incorporating the Multi-Stereo Multi-Projection modules. The laser holographic point-cloud projections are displayed in red; the cameras are blue dots on the head.*

Supported by: Baden-Württemberg Stiftung gGmbH
Project: „Schnelle, energieeffiziente Erfassung 3-dimensionaler Panoramen“(SEE3D)
In cooperation with: IPVS, University of Stuttgart

References:

[1] Würtenberger, F.; Haist, T.; Reichert, C.; Faulhaber, A.; Boettcher, T.; Herkommer, A. “Optimum wavelengths in the near infrared for imaging photoplethysmography”, IEEE Trans Biomed Eng, 2019.

Status of the OpenSource Measurement and Automation Software “Itom”: Release 3.2

R. Hahn, M. Gronle, J. Krauter, H. Bieger, A. Faulhaber, W. Osten

Itom is an open source software suite for operating measurements systems, laboratory automation and data evaluation. Its development started in 2011 at ITO in order to provide a software that can be easily used to control optical systems, create and execute data evaluation algorithms in **Python** and/or C++, communicate with hardware components or easily create individual user interfaces.

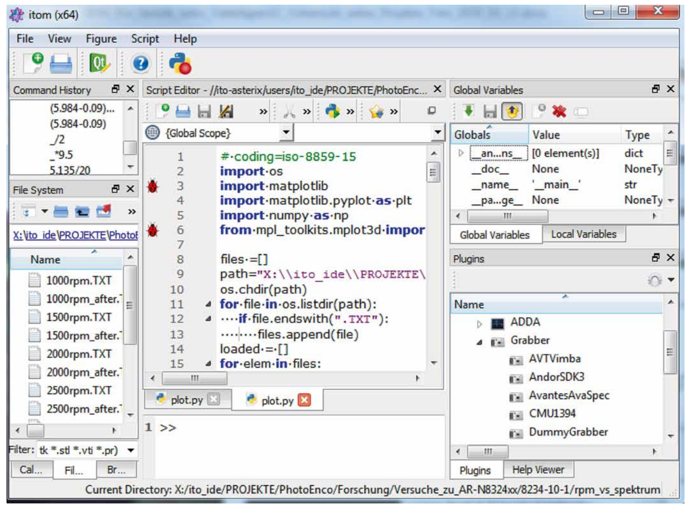
Many requirements were taken into account during development: The software (fig. 1) is intended to offer both inexperienced users and experienced users added value in hardware control and data evaluation. Despite the desired simplicity, **itom** is able to carry out fast and complex data evaluations.

The fully integrated **Python** engine enables fast and easy prototyping of algorithms and system control routines. The uniform plugin interface offers the possibility to replace or add new hardware without time-consuming programming. Hardware and software plugins are written in C++ and can integrate any third-party components as well as CUDA or other parallelization techniques.

In addition to classic data and image processing, **itom** is also ideally suited for setting up neural networks. This is made possible by the fully integrated scripting language **Python**, which can be extended with a variety of packages such as Tensorflow and Keras.

During the reporting period, a large number of new functions were implemented in the core application of plugins and plots. The new setup version 3.2 contains a completely revised **script editor**, which offers with the **Python** package **jedi** a very helpful functionality for code completion. In addition, the 2D graph offers a **volume intersection functionality** (fig. 2), which allows a cross-section through all planes of a 3D image stack. A connection method for actuator and DataIO instances has been implemented, allowing the user to connect a **Python** function to a plugin emited signal. Furthermore small helpful functions like a Clear All Button or a **Drag & Drop Plugin initialization** functionality were introduced.

More than 70 different plugins for hardware and algorithms have been created and published until now. Beside specific plugins for different camera vendors like Ximea, PCO, Pointgrey, Allied Vision or IDS Imaging, **itom** also provides generic plugins like GenICam or Microsoft MediaFoundation to acess a further high number of cameras.



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import·os
import·matplotlib
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files·=[]
path="X:\\ito_ide\\PROJEKTE\
os.chdir(path)
for·file·in·os.listdir(path):
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```
1 >>
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Current Directory: X:/ito_ide/PROJEKTE/PhotoEnco/Forschung/Versuche_zu_AR-N8324xx/8234-10-1/rpm_vs_spektrum

Fig. 1: *Main Window of the Software.*

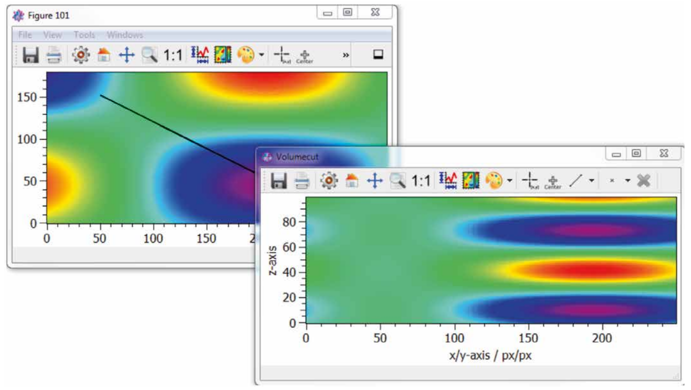


Fig. 2: *Volume cut through a 3D dataObject.*

“Itom” *is freely available under* ***http://itom.rocks*** *or* ***http://itom-software.org****. The Core is licensed under the open source license LGPL.*

References:

[1] Gronle, M.; Lyda, W.; Wilke, M.; Kohler, C.; Osten, W. „itom an open source metrology, automation , and data evaluation software“, Appl. Opt. 53, 2974-2982 (2014).

Multipoint measurement system for the measurement of large building deformations

F. Guerra, T. Haist, W. Osten

The precise measurement of positions is of utmost importance in a multitude of image-sensor based optical measurement systems. A new method to improve the accuracy using photogrammetry is the multipoint technique [1, 2]. This report summarizes briefly the work conducted based on the application of the multipoint technique for deformation measurement of large adaptive buildings. This means that the building to be measured can also be actuated in order to adapt its form. Therefore, its deformation state supervised by a closed loop control system.

Because of the adaptivity of the building, the demand to the system is to get sub-millimetre accuracies concurrently obtaining 3D measurement data in real-time (100 Hz). This means that starting from image acquisition passing on to image processing up to sending data to the computer, may only take approximately 10 ms.

Using the multipoint method helps to overcome conventional problems given to the nature of pixelated sensors. Among these is discretization, noise and a limited quantum well capacity. Multipoint technique addresses these problems by spot-replication which can be seen as a sort of "spatial multiplexing". The working principle simply uses a computer-generated hologram (CGH) in front of the camera lens. The CGH's holografic structure acts as a grating which replicated the number of emitter positions seen by the camera sensor. The CGH we developed has N=21 replications for each object point (see fig. 1). Multipoint technique can theoretically reduce discretization and noise errors by a factor of √N, where N is the number of replicated spots. In laboratory we showed that this factor depends on the calibration quality, the carefulness of the setup as well as the complete absence of air turbulences and mechanical vibrations.

Due to the high speed, and the 3D measurement of buildings (two cameras), there is a multitude of conditions which help to close the control loop fast. First of all, the light emitters applied onto the buildings nodal points, directly shine towards the camera. The cone of light slender to not waste any light into the environment at the same time being wide enough in order to always shine into the camera lens, despite movements of the building itself (see fig. 2). This reduces camera's integration time. Another fundamental piece is the image processing algorithm. It has to efficiently track every nodal point of the building, despite of any occurring obfuscation of the light emitter. Alas, spot tracking is one method used to reduce the amount of data which has to be processed for every image. Because of a high (image) sampling rate, prior knowledge is used for searching spots in just a restricted area of the actual image. In the end, multi-threading helps to use efficiently the embedded computer used within this project. In total there are two stereo cameras, one for each embedded computer.

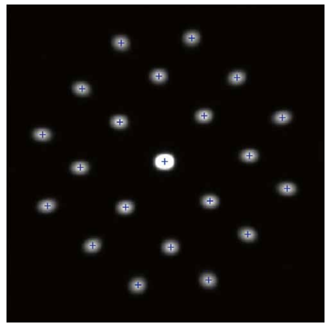


Fig. 1: *Example image of one light emitter seen through the CGH used for the multipoint technique.*

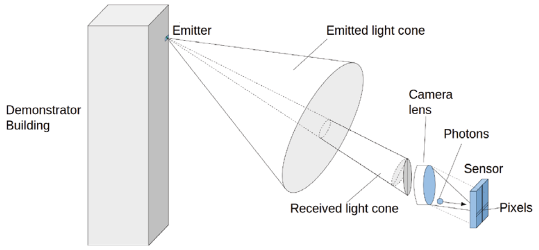


Fig. 2: *Geometric specification for efficient usage of the light by each emitter despite the building's movements.*

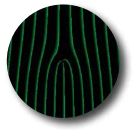
Supported by: DFG German Science Foundation
Project: Adaptive Hüllen und Strukturen für die gebaute Umwelt von morgen (SFB 1244)
In cooperation with: ISYS, University Stuttgart

References:

[1] T. Haist, M. Gronle, D. A. Bui, B. Jiang, C. Pruss, F. Schaal, W. Osten "Towards one trillion positions," Proc. SPIE 9530, Automated Visual Inspection and Machine Vision, 953004 (22 June 2015); doi: 10.1117/12.2184636.

[2] T. Haist, S. Dong, T. Arnold, M. Gronle, W. Osten "Multi-image position detection," Opt. Express 22, 14450-14463 (2014).

Active Optical Systems and Computational Imaging



Ultraprecise Measurement of Positions and Orientations using holographic multipoints

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 TCP and WP.

To reconstruct the position of a single object point (e.g. the TCP) with a camera vision system, a commonly used technique is to calculate the center of gravity (COG) of the corresponding grey values in the spot image. Typical root mean square (RMS) deviations of this technique range between 1/10 and 1/100 of a pixel [1]. These accuracies can be improved further by upgrading the optical lens-camera-setup with a computer generated hologram (CGH) in front of the lens. The CGH replicates the spot image of a point lightsource to a predefined pattern on the detector (see fig. 1). So each punctual lightsource in object space is represented by a cluster containing N replicated spots. By averaging the subpixel positions of all N spots, the statistical errors such as discretization and photon noise can be reduced by the square root of N. With this technique, a RMS deviation of 0.0028 pixels has been reached in former experiments [2].

To optically measure and compensate the dynamic 3D positioning errors of machines, the multipoint method is applied in a real-time stereo setup (see fig. 2) consisting of two telecentric lenses, two highspeed cameras and LED´s attached to TCP and WP of a coordinate measurement machine (Mahr MFU 100). The goal is to measure 3D positions in a volume of 100 x 100 x 50 mm³ with an accuracy of 1 µm at a speed of 500 Hz.

To achieve this accuracies, different calibration methods were investigated. First option is a calibration target consisting of an illuminated chrome mask. A Second option is the precise meandering of a lightsource in objectspace, which was carried out with two different positioning machines. The calibration with a linear 2D stage (Uhl Precision Positioning Systems) reached accuracies of 0.6 µm and a similar calibration carried out with the Nano Measurement and Positioning machine (NPMM) reached 0.36 µm in objectspace.

The current setup at MFU 100 consists of one telecentric lens with a hologram. 2D measurements in an area of around 70 x 100 mm² were carried out with a speed of 150 Hz. For slow movements the comparison between optical multipoint measurement and the encoder signals of MFU show, that both signals differ in the range of 2 µm. Future work will consist of extending the measurement area to 3D, implementing the algorithm on FPGA and optimizing the CPU / GPU algorithm.

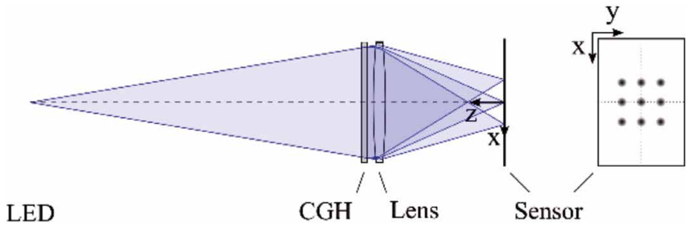


Fig. 1: *By the use of a hologram (CGH) the punctual lightsource of one LED is replicated to a cluster of N = 9 spots on the sensor.*

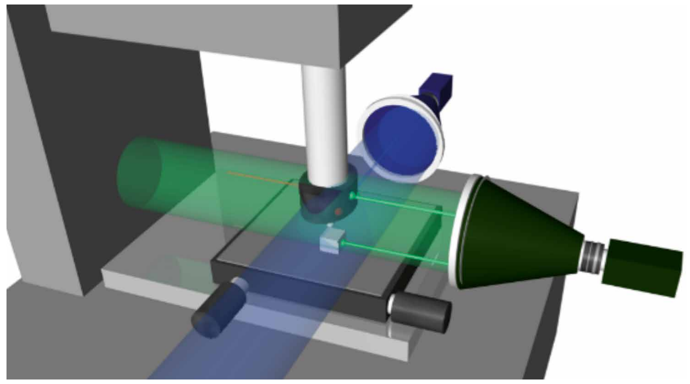


Fig. 2: *Scheme of a stereo setup consisting of two telecentric lenses, two highspeed cameras and for each lens one LED at TCP and one at WP [T. Haist].*

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

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[1] Shortis, M. R.; and Clarke, T. A. “Practical Testing of the Precision and Accuracy of Target Image Centring Algorithms”, Proc. SPIE, 2598:65–76, 1995.

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Large hybrid DOE-based object-sided telecentric lens system with field-dependent deconvolution

M. Gronle, A. Faulhaber, T. Haist, C. Pruß, W. Osten, Y. Baroud, S. Simon

Telecentric imaging is a corner stone of image-based geometrical measurement techniques and industrial image processing. Object-sided tele-centricity leads to constant magnification independent of the distance of the object and invariant geometrical appearance for three-dimensionally extended objects. In general, image-based tele-centricity achieves best accuracies concerning the measurement of positions. The main problem of telecentric imaging is that the front element of the objective lens has to be at least as large as the object field leading to extreme expensive optical systems using refractive lenses.

We show the cost effective realization of a double telecentric imaging system for large object fields. Two small off-the-shelf lenses and one large diffractive optical front-element (DOE) are combined to achieve a small telecentricity error in combination with low distortion for a limited spectral bandwidth over a large object field at low cost. We lithographically manufactured the DOE, which can serve as a master element for replication purposes to decrease costs. A nonlinear intrinsic camera model can further reduce remaining distortion. Furthermore, a high-speed deconvolution algorithm suppresses chromatic aberrations due to incoherent illumination.

We designed the system for a circular object field of 150 mm diameter in combination with a 1" image sensor (FLIR GS3-UC-41C6M) at a wavelength of 532 nm and an F-number of 6.3. The working distance is 420 mm and the magnification –0.092. Fig. 1 shows the basic design of the system. High spatial frequencies in the DOE would considerably increase the difficulty of manufacturing. Therefore, the focal length of the DOE was chosen to be long compared to the size of the object field. As a result, the overall length of the system was increased. Based on the paraxial design, a rotational symmetric DOE (Binary 2 surface in Zemax) replaced the first telescopic lens and two refractive lenses realized the second lens group. At our Institute, we manufactured the DOE in-house with our laser-lithographic grayscale process. The DOE has a diameter of 180 mm, being larger than the desired object field size.

We characterized the performance of the optical system by the means of experimental measurements and tests. The 1951 USAF resolution target (Edmund 58-918) with back-illumination by a LED (collimated, homogenized, filtered at λ=532 nm; FWHM=10 nm) was used to determine the imaging resolution. A pinhole (diameter = 50 µm), instead of the target, can be considered as a point source and utilizing a 3D scanning mount in x-y-z directions then allows evaluating the telecentricity error and distortion aberrations.

The imaging resolution on axis is 58,6 lp/mm at contrast 0.25 delivering 17,2 µm structure resolution. This is depleting to the field's edge down to 46,2 lp/mm. The distortion was calculated to -1.67 % (field radius = 106.1 mm) from the scanned point source spots, which is consistent to the simulated -1.2 %. The telecentricity error results to approximately 1.1’’, after evaluating different field point height deviations in z direction. Also in fig. 2, the depth-of-field for the telecentricity is depicted giving an approximate DOF = 80 mm.

The limitation of the diffraction-based objective design to mono-chromaticity is a major drawback, but we have found the field dependent real time deconvolution image processing reasonably helpful. A low-cost, high-performance field-programmable gate array (FPGA) (Xilinx Kintex 7) processes the raw data coming from the image sensor. With locally resolved point-spread-functions (PSFs), we efficiently solve deconvolution algorithms on small image kernels. Therefore, the image can be reconstructed and undistorted to increase resolution and contrast.

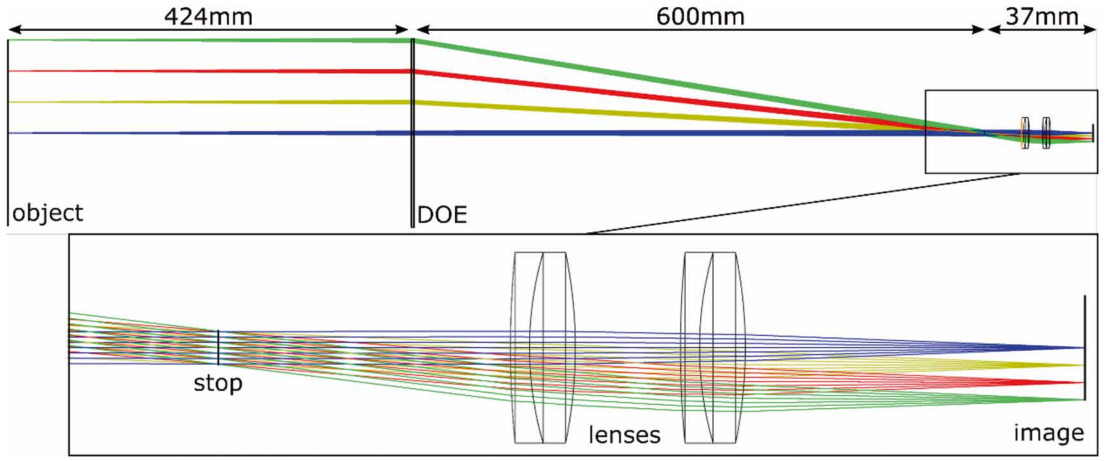

Fig. 1: *Double telecentric imaging system simulation in Zemax with DOE front element and two off-the-shelf lenses. The upper part shows the whole design layout, whereas the lower part displays an enlarged view on the imaging side.*

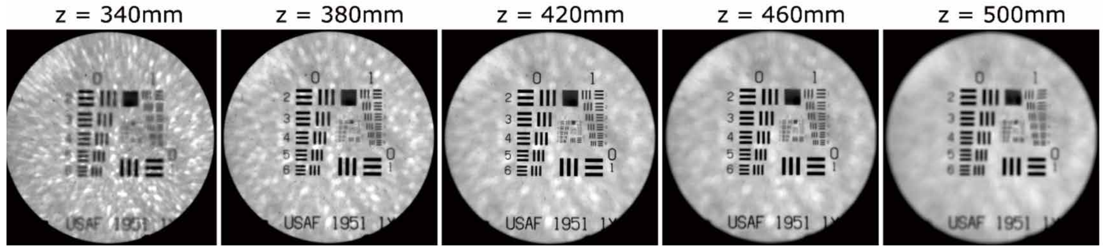

Fig. 2: *Image acquisitions of the USAF resolution target for some axial z-positions around the focal plane (420 mm). Best depth of focus region is around 80 mm.*

Supported by: Baden-Württemberg Stiftung gGmbH
Project: „Intelligent optical sensor for 2D/3D surface measurements and inspection"(IOS23)
In cooperation with: IPVS, University of Stuttgart

References:

[1] Faulhaber, A.; Gronle, M.; Haist, T.; Baroud, Y.; Osten, W.; Simon, S. "Hybrid telecentric triangulation sensor system with real-time field-dependent deconvolution," Proceedings SPIE Optical Metrology, Munich (2019).

Dynamic holography for speckle noise reduction in hybrid measurement system

A. Faulhaber, S. Haberl, M. Gronle, T. Haist, W. Osten

Measurement systems using laser based active triangulation methods on rough surfaces suffer from laser granulation. This so called speckle noise fundamentally limits the uncertainty in height measurements [1]. In this work, we investigate methods for speckle noise reduction to improve the accuracy on center-of-gravity (COG) detection in a triangulation sensor setup. The methods are based on dynamically varying the wavefront of a holographic laser-spot projection through a spatial light modulator.

In the last decades, spatial light modulators have been intensively used for different applications in optical measurement systems. Today, the elements have high enough resolutions to be used even for simple holographic applications. We generate dynamic computer-generated holograms (CGH) with a pixelated spatial light modulator by inscribing multiple holograms over time. These custom holograms change the wavefront in the Fourier plane of the projection system. Due to these changes, we can microscopically translate and deform the laser-spot in the object plane. The minimal different spot positions then allows decorrelating the minimally different speckle patterns. By averaging of the intensity field in the camera plane, as depicted in fig. 1, the decorrelated patterns can therefore reduce the speckle noise and increase the measurement accuracy of the spot's COG.

The methods for the wavefront deformation on the holograms are based on Zernike-polynomials (defocus, astigmatism, coma and trefoil) as well as donut-wavefronts (Laguerre-Gauß-Modes). For changes in angular spectrum, we used different dynamical partial apertures on the hologram, e.g. single circular segment, rotating two- and four-bladed and a random flying sub-aperture. The CGH itself, as shown exemplary in fig. 2, is a dynamically variable diffraction structure or grating with a carrier frequency (υ_0 = 6.25 mm^{-1}) for off axis holography with the overlaid wavefront deformation.

For the evaluation of the working principle of speckle reduction and for the differentiation between the various methods we used the speckle contrast C. The degree of reduction R is the ratio between the intensity-averaged speckle contrast C_I and the mean speckle contrast C of all averaged patterns [2]:

$$R = \frac{C_I}{C_q}\,, with\ [0 \leq R \leq 1]\ \ and\ \ R_{theor} = \frac{1}{\sqrt{N}} \qquad (1)$$

Our experiments show, that the principle of speckle reduction works to a certain degree. Fig. 3 and fig. 4 display the best reduction rates using coma aberration, donut-mode and rotating 30° segmented aperture. Unfortunately, the large difference to the theoretically best achievable rate is due to the combination of numerical apertures of illumination to the detection and some optical aberrations in the setup.

In this proof-of-principle study, we showed the potential for active laser-triangulation sensor setups to be improved through dynamic holography. In the future, we will investigate the time-sequential multi-spot-scanning method using various amounts of different holograms. In addition, we will further investigate the improvement in measurement uncertainty.

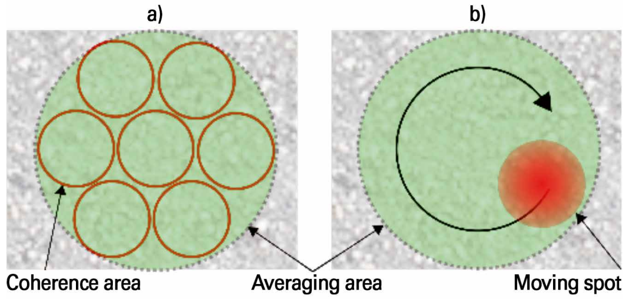

Fig. 1: *Averaging area approximating the object-sided Airy disk with speckle reduction in a) due to reduced spatial coherence and b) with spatial decorrelation of the scanning of multiple spots.*

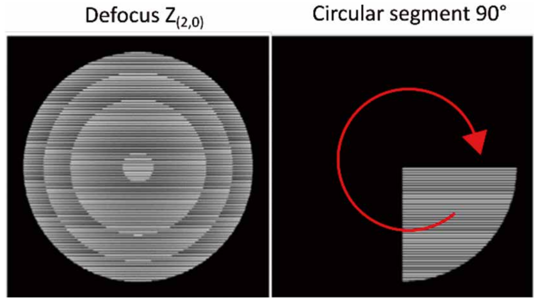

Fig. 2: *Computer generated hologram with overlaid Zernike-polynomial Defocus (left) and angular spectrum variation via rotating sub-aperture (right).*

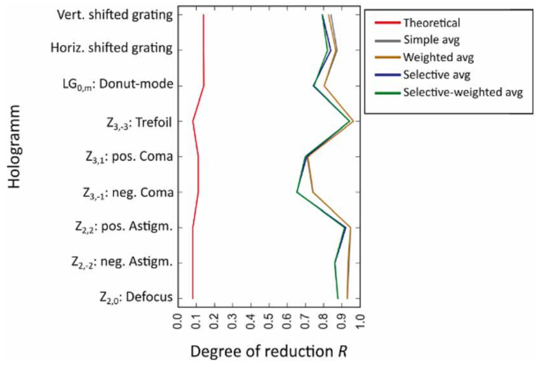

Fig. 3: *Measurement results for different wavefront deformation holograms and their speckle reduction.*

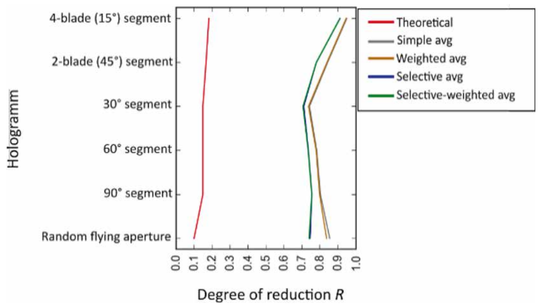

Fig. 4: *Result for holograms with angular spectrum variation in comparison to their reduction capability.*

Supported by: Baden-Württemberg Stiftung gGmbH
Project: „Intelligent optical sensor for 2D/3D surface measurements and inspection" (IOS23)
In cooperation with: IPVS, University of Stuttgart

References:

[1] Dorsch, R. G.; Häusler, G.; Herrmann, J. M. "Laser triangulation: fundamental uncertainty in distance measurement", Applied optics 33(7), 1306-1314 (1994).

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Characterization of homogenization components for next-generation CO_2 monitoring satellites

S. Amann, Q. Duong-Ederer, T. Haist, W. Osten

As part of the European Union's Copernicus program, a satellite is under development for spatial measurements of anthropogenic greenhouse gases in the atmosphere. The satellites instrument will use a pushbroom spectrometer to measure the sunlight reflected from the earth's surface spectrally and spatially. The distribution of the greenhouse gases within the air can be determined based on significant absorption lines. The requirements for such a measuring system are very high. An inaccuracy of current systems occurs with an inhomogeneous illumination of the spectrometer entrance slit. This appears with an inhomogeneously reflecting surface (e.g. transition from water to ground). Optical homogenizers in the entrance slit of the spectrometer can solve this problem and lead to better measurement results.

ITO, in collaboration with the European Space Agency (ESA), conducted a measurement campaign to investigate various aspects of the homogenizers. The devices consist of several square and rectangular fibers arranged side by side (along the slit) to retain the spatial information. An microscopic image is shown in fig. 1.

In a first step, we investigated the geometric properties of individual fibers and the entire arrays. For this purpose, microscopic images have been taken and analyzed using image processing. The results provide important information about the manufacturing tolerances of the devices.

The main measurements are about the light scrambling efficiency. Here, the fiber cores have been illuminated with inhomogeneous scenes under the conditions prevailing in the final system. The fiber output has then been investigated with a microscope setup (fig. 2). We have developed an algorithm to quantify the homogeneity of the near-field intensity distribution. The design of the pushbroom-spectrometer leads to the requirement to perform the measurements spatially incoherent and temporally coherent. This is achieved using a laser as light source (temporal coherent) and a rotating diffuser (reduces spatial coherence). One wavelength in the NIR and one in the SWIR spectral region have been investigated. The desired illumination scenes have been achieved by imaging a mask onto the fiber core. The mask is made of a chromium on glass plate processed in-house using photolithography. We put a lot of effort into the design of the test bench to achieve a homogeneous, diffraction limited, telecentric and interference free imaging system. The measurements show that fiber based homogenizers are well suited for use in a spectrometer. However, some problems may arise due to interference effects and gradients in the near-field energy distribution of the fiber output.

In further investigations, the depolarization properties of the fibers have been investigated. Depolarization might be another advantage of using fiber based devices in pushbroom-spectrometers, since unpolarized light is preferred. The measurements show that depolarization is mainly present for fibers with a length of more than 1 m.

Additionally, the focal ratio degradation has been determined. This effect leads to a broadening of the light cone. The far-field energy distribution of the light emitted by the fiber has been measured therefore. By plotting the emitted energy over the beam angle, we showed that the light leaving the fiber has a higher numerical aperture than the incident light.

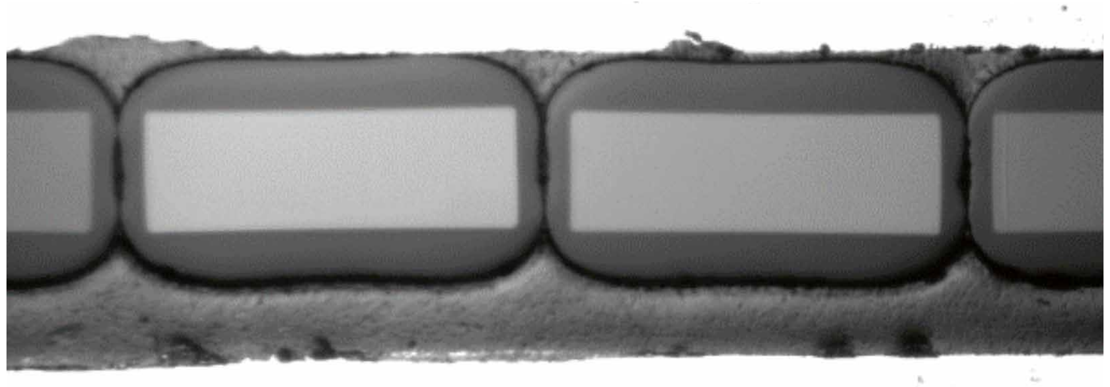

Fig. 1: *Microscopic image of a homogenizer device. The rectangular fiber cores are aligned in one line across the flight direction.*

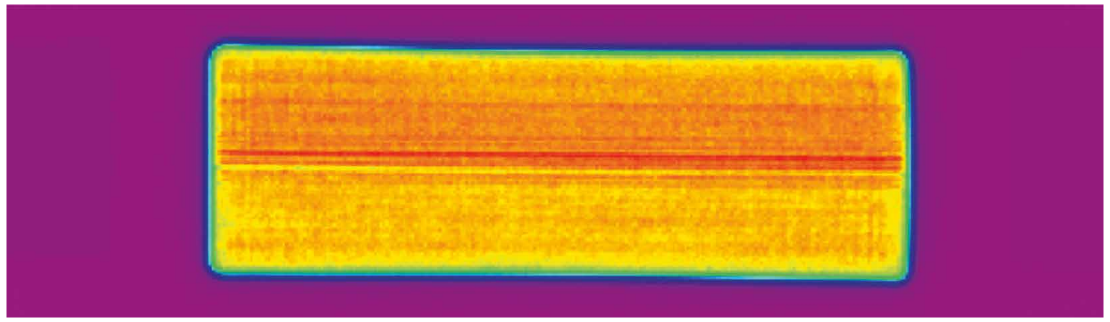

Fig. 2: *Example image of the near-field energy distribution (false color) of a half illuminated (vertical edge) fiber.*

Supported by: European Space Agency (ESA)

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[1] Sierk, B.; et al. "The CarbonSat candidate mission: imaging greenhouse gas concentrations from space", Proc. SPIE 9218, 2014.

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Supported by: Graduate School of Excellence advanced Manufacturing Engineering (GSaME), University of Stuttgart
Project: Single-Pixel Kamera mit Deep-ConvNet Signalverarbeitung für autonome Robotersysteme (F2-036)

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Project: Laser-basiertes 3D-Sensorsystem für das autonome Fahren unter schwierigen Wetter- und Sichtbedingungen ‚ClearView-3D' (95033117)
In cooperation with: Fraunhofer Institut für Physikalische Messtechnik, Freiburg
Institut für Informatik, Arbeitsgruppe Intelligente Autonome Systeme, Albert-Ludwigs-Universität, Freiburg

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Supported by: DFG German Science Foundation
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Supported by: DFG German Science Foundation
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Supported by: DFG German Science Foundation
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Machine Vision via Deep Learning

A. Birk, K. Frenner, W. Osten

The aim of many recent efforts in industrial automation is to enable machines and robots to work autonomously and cooperatively alongside one another. However, to do so, they need to be aware of their continuously changing surroundings at all times. This is why Machine Vision methods are of great importance for these automation tasks as they provide an accurate digital description of a given scene.

State-of-the-art technology that is capable of generating such a 3D representation of a machine's workspace requires an expensive hardware setup, consisting of multiple cameras with areal sensors and a powerful computing device to process the incoming data. It is important to note, however, that the data which is actually relevant to subsequent algorithms like path planning, is very limited in comparison. For many applications, it would suffice to know e.g. the location and size of all objects in the foreground.

This is where we see potential for improvement. Replacing the aforementioned system with generators for structured illumination and single pixel cameras, we employ a scene capturing technique that has gained significant attention in recent years [1] and enables us to vastly reduce the amount and size of necessary hardware and data generated. This system is able to capture the spatial information in the scene by projecting different light patterns, called pixel masks, onto the scene and measuring the intensity of the reflected light with a single pixel camera. The differences in the measured intensities then encode the spatial information about the objects in sight.

In contrast to other work in this area, we expressly avoid reconstructing an image of the scene from this data, but rather extract the relevant features of the real world objects right away. To do so, we utilize a deep neural network that directly returns data such as position, size, and orientation of objects. The setup as a whole is shown in fig. 1.

To further enhance the effectiveness of our approach, instead of choosing a static, pre-known set of illumination pixel masks, we are adapting them in the training process. To this end, similar to what is done in [2], we are modeling the process as an encoder-decoder-setup, where the structured illumination encodes the spatial information and the neural network decodes it again. This means specifically that the masks are being optimized along with the neural network, thus making sure they will turn out more specialized for the task than a generic set of masks, such as the Hadamard basis, would be. Our current simulation-based results show that this is indeed the case. For an impression of what the optimized masks look like, see fig. 2.

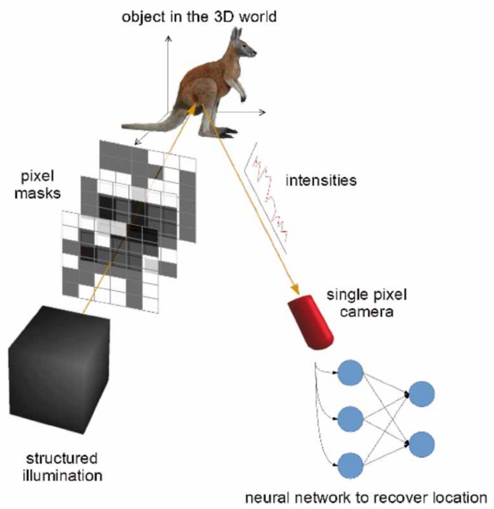

Fig. 1: *Basic setup for our approach to machine vision.*

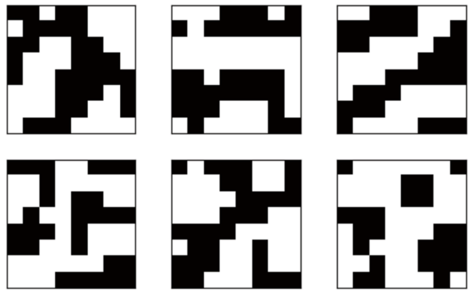

Fig. 2: *Examples for 8x8 px. illumination masks our network generates. The way each one divides the object space into different sections is visible.*

Supported by: Graduate School of Excellence advanced Manufacturing Engineering (GSaME), University of Stuttgart
Project: Single-Pixel Kamera mit Deep-ConvNet Signalverarbeitung für autonome Robotersysteme (F2-036)

References:

[1] Duarte, M. F.; Davenport, M. A.; et al. „Single-Pixel Imaging via Compressive Sampling", IEEE Signal Processing Mag., 83-91, Mar. 2008.

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Laser-Based 3D-Sensor-System for Autonomous Driving in Adverse Weather Conditions with Poor Visibility (ClearView3D)

C. M. Bett, K. Frenner, W. Osten

Automation is progressing steadily, especially in the automotive industry. Driver's assistance systems are nowadays state-of-the-art. For this purpose a bunch of different sensors are used. However, for autonomous driven cars though, data acquisition and fusion have to be improved considerably in order to generate real-time and robust scene detection.

Especially in harsh weather conditions (e.g. in rain, snow, fog) there does not yet exist a satisfactorily working sensor (combination) for distances in the length scale of 100 m. 'Clear-View-3D' shall close this gap by combining a Light Detection And Ranging (LiDAR)-System with a speckle-correlation sensor together with intelligent data processing.

From 2019 onward ITO will work together with Fraunhofer Institut für Physikalische Messtechnik (IPM) and Institut für Informatik (AIS) of the Albert-Ludwigs-University Freiburg to realize this sensor system. IPM has extensive knowledge of LiDAR-Systems [1] whereas AIS has been working for years in the exploration of unknown environment and precise navigation therein [2].

LiDAR-systems can measure the distance between objects very accurately. To interpret a complex scene though, more (optical) information is beneficial to robustly discriminate between different objects. Apart from the position of the objects, information about e.g. the angular size or polarisation could help to classify objects better. Therefore, we will develop a sensor which can measure the degree of coherence and/or the polarisation of the backscattered light. In stellar intensity interferometry, the degree of coherence directly leads to the angular size. For general imaging situations, this is not the case though. We therefore plan to resort to speckle correlation techniques (see fig. 1), as previous work carried out at ITO [3] indicate promising results.

In 2022, a proof-of-concept sensor shall operate on a vehicle to carry out field experiments.

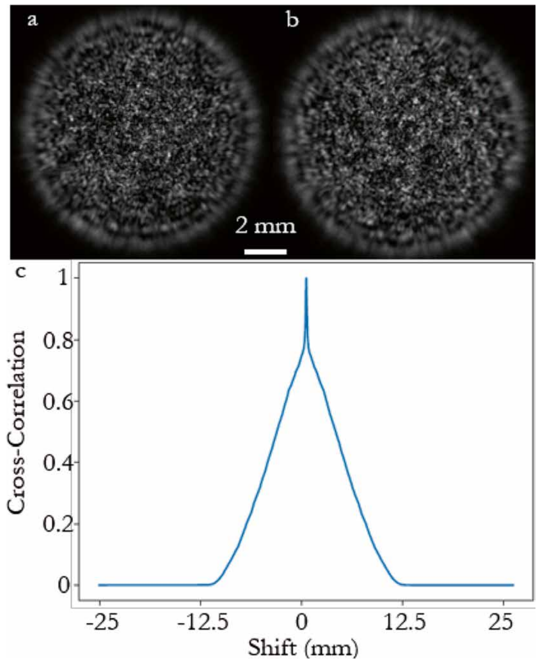

Fig. 1: *Simulated speckle pattern of a single mode fiber with NA 0.12 through a 256 mm thick medium with three million scattering particles (water drops). The fiber was positioned 30 mm in front of the scattering medium at $x = 0$ µm (a) and $x = 125$ µm (b). The cross-correlation of the two speckle pattern in x direction is given in c (x-cut). The shift in the recorded plane (44 mm behind fog) can be extracted to be -12 µm, which implies that the optical memory effect (see e.g. [3]) holds. Wavelength: 905 nm.*

Supported by: Baden-Württemberg-Stiftung
Project: Laser-basiertes 3D-Sensorsystem für das autonome Fahren unter schwierigen Wetter- und Sichtbedingungen ‚ClearView-3D' (95033117)
In cooperation with: Fraunhofer Institut für Physikalische Messtechnik, Freiburg; Institut für Informatik, Arbeitsgruppe Intelligente Autonome Systeme, Albert-Ludwigs-Universität, Freiburg

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[3] Singh, A.; Pedrini; G.; Osten, W.; et al. "Exploiting Scattering Media for Exploring 3D Objects" Light Science & Applications 6, 2017.

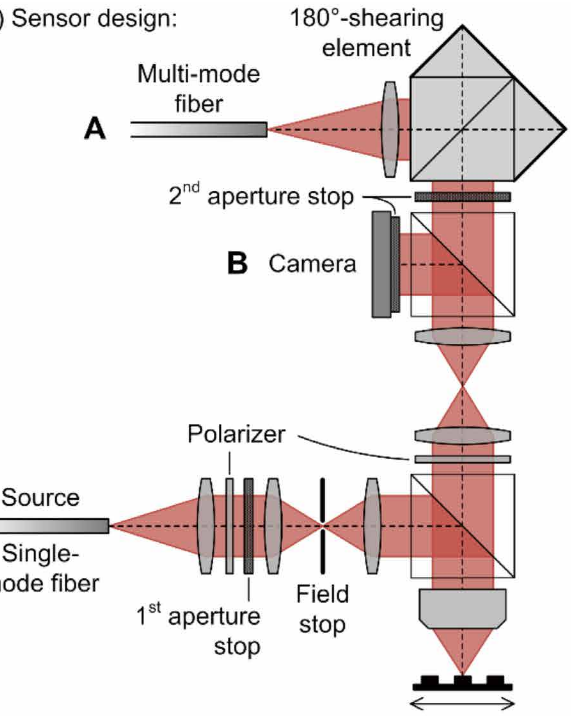
Optical sensor design for fast and process-robust wafer alignment on small diffraction gratings

M. L. Gödecke, C. M. Bett, L. Fu, K. Frenner, W. Osten

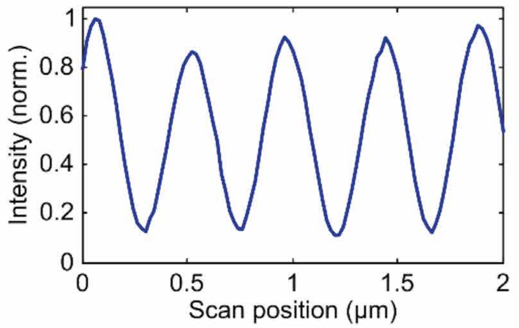
The state-of-the-art design of integrated circuits consist of dozens of individual layers stacked on top of each other. The accurate alignment of each layer with respect to underlying features is crucial for the final device performance. Typically, diffraction gratings are used to determine the wafer position interferometrically with sub-nanometer precision. Opposite higher diffraction orders are coherently superposed by a 180°-shearing element, generating a sinusoidal alignment signal whose phase encodes the grating-center position [1]; see also fig. 1 (a) and (b). Due to limited scribe space on the wafer, there is strong interest in aligning on smaller targets (only a few µm^2) with smaller pitches (down to 400 nm). For this purpose, high-NA off-axis illumination and a nearly diffraction-limited spot size on-wafer are required.

In several joint research projects with ASML, we designed, built up and tested an optical sensor which enables alignment on such marks. Fig. 1 (a) shows a schematic drawing of the sensor. Full-pupil illumination in combination with a dedicated aperture design creates a sufficiently small spot on the wafer. However, the illumination of extended pupil patches implies that the sensor is very sensitive towards aberrations. For the calibration, we implemented an additional beam-monitoring channel in the pupil plane, see fig. 1 (c). Straight-forward numerical post-processing allows for the calculation and compensation of the aberration-induced offsets. In the framework of a comprehensive tolerance analysis, the sensor performance was thoroughly validated.

(a) Sensor design:



(b) Alignment signal from channel A:



(c) Pupil image from channel B:

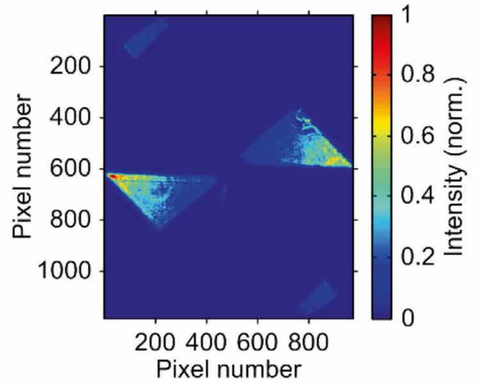


Fig. 1: *(a) Schematic drawing of the sensor design; (b) sinusoidal interference signal for the position determination; (c) intensity distribution in the pupil plane for the calibration of aberrations [2].*

Supported by: ASML Veldhoven
Projects: Wafer alignment on µDBO targets, parts 1 to 3
In cooperation with: ASML Veldhoven

References:

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GPU accelerated rigorous simulation with *MicroSim*

K. Frenner

For almost 20 years now, the software suite ***MicroSim*** has been used by ITO to carry out rigorous optical simulations at micro and nano scale. Launched in the late 90's as a simulation tool for interference microscopy of sub-lambda structures [1], it has been continuously evolving since that time. In addition to modern numerical techniques such as normal vector fields for convergence improvement of RCWA [2] or differential method for modeling curved 3D-structures, also field stitching and Kirchhoff-approximation methods for simulating large areas have found their way into our program package. Over time, ***MicroSim*** helped to solve a whole range of problems that occurred in research and collaborative projects with industry. Examples include simulation of confocal and white-light interference-microscopy, design of optical metamaterials, modeling alignment devices for semiconductor industry, defect detection, CD-metrology and line edge roughness metrology.

Not only because of the changing requirements of our projects, but also due to further development of hardware such as multicore and multiprocessor architectures, the program package had to be heavily adapted in the last 20 years. As a result of the associated performance improvements, it is now possible to simulate three-dimensional multilayer structures even in complex lighting situations. However, such models are still not satisfactorily fast to calculate.

In the past two years an attempt was made to improve this situation with the help of massively parallel GPU accelerator-cards. In a device like NVIDIA Tesla P100, more than 3500 SIMD-cores are available resulting in a peak performance of about 5 TFLOPs in double precision. Since this performance can be only achieved with relatively simple calculations such as matrix multiplications or inversions, it was decided to speed up the solver of the differential method in this way. That's reasonable, because there the numerical stiffness of the Maxwell equations implies that systems of ordinary differential equations must be solved implicitly. This either leads to inversion of large matrices or to iterative solving of linear systems of equations, which requires a lot of matrix multiplications.

We found that by using the GPU-card, the computational time of the accelerated differential method is significantly lower than the calculations with state-of-the-art RCWA especially for three-dimensional calculations with curved boundaries (e.g., microspheres). The advantage of the accelerated differential method is particularly clear when the boundaries of the nanostructures are vertical walls. Single-layer structures can be calculated within few seconds, whereas RCWA takes about 20 minutes. It can also be shown that for sufficiently well posed problems single precision data is sufficient. So it is possible to run such simulations on desktop machines equipped with graphics cards and CUDA support. Only recently such cards are provided with sufficient graphics memory (so called high-end gaming cards) so that the field size on the desktop compared to the server does not have to be limited.

As an example fig. 1 shows a simulation of the pupil image of a microsphere on a contact hole cross-grating. This model was calculated using 28 modes in 1.5 hours on a NVIDIA 1080Ti. The complexity of the example goes far beyond the possibilities of pure RCWA simulations.

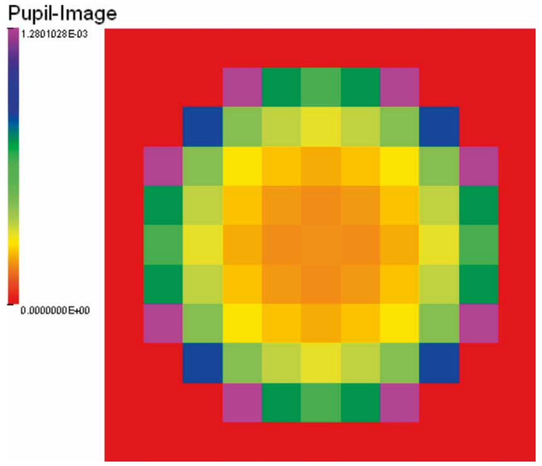

Fig. 1: *Simulation of the pupil image of a contact hole cross-grating with CD=100nm, p=500nm and λ=550 nm.*

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White-light Mueller-matrix scatterometry for the fast and robust characterization of periodic nanostructures

M. L. Gödecke, K. Frenner, W. Osten

Model-based optical scatterometry is the state-of-the-art optical inspection method for lithographically processed nanostructures. However, the quantitative characterization of structures with large parameter spaces often fails due to insufficient sensitivities and high cross-correlations. In order to improve the reconstruction process, it is essential to measure and evaluate as many information channels of the light field as possible, thus increasing the number of uncorrelated data sets.

In the framework of two preceding DFG-projects (Os 111/28-1 and -2), it was already demonstrated at ITO that the combination of conventional Fourier scatterometry and white-light interferometry improves the sensitivity, especially with respect to the height (or depth) of a sub-wavelength grating. Additionally, cross-correlations between different grating parameters are lowered significantly [1,2].

Polarization is another relevant information channel. In this project, we extend our white-light Fourier scatterometry by full Mueller-matrix polarimetry. Besides increasing the information content even further, this approach makes the complex refractive indices of the involved materials directly accessible. This is particularly important since the frequently used literature values may cause large errors in the reconstruction, even if they differ only slightly from the real values.

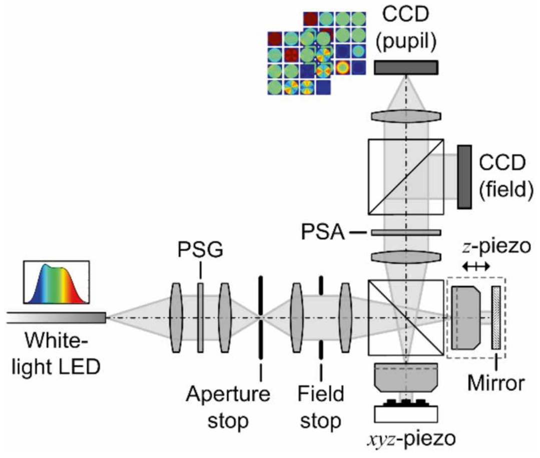

Fig. 1: *Schematic drawing of the experimental setup. PSG: polarization-state generator; PSA: polarization-state analyzer.*

Fig. 1 shows a schematic drawing of the experimental setup. Light from a broadband LED is coupled into the system via a multimode fiber. A Linnik-type interferometer with two high-NA, strain-free microscope objectives generates a typical white-light signal, which can be analyzed as is or post-processed by means of Fourier spectroscopy to separate the individual wavelengths. The polarization modulation occurs at the polarization-state generator (PSG) and analyzer (PSA). Each of these two modules consists of a linear polarizer; plus one phase modulator (half-wave plate or electro-optic/photoelastic modulator) in either the PSG or PSA. The minimum required number of measurements is determined by the choice of phase modulator: in case of the waveplate, at least four measurements are needed, whereas the variable retardance of the electro-optic or the photoelastic modulator reduces the number of measurements to only two. The intensity distribution is recorded in the angle-resolved pupil plane and the Mueller matrix is calculated in a numerical post-processing step.

A sensitivity analysis in the framework of a comprehensive simulation study revealed that the angle- and wavelength-resolved Mueller matrix by far outperforms other measurement configurations in case of multi-parameter variations. In addition to the geometrical parameters of the grating profile, we also assumed the refractive indices of the involved materials to be floating parameters in the reconstruction procedure. Fig. 2 shows some selected simulation results, obtained using state-of-the-art RCWA algorithms implemented in our in-house software package ITO MicroSim. The schematic drawing in (a) depicts the exemplary probed target: a dense silicon line grating covered by a native oxide layer. The design parameter values are stated in the figure caption. Except for the grating pitch, all parameters are allowed to vary slightly during the sensitivity analysis. Fig. 2 (b) shows the achieved 3σ-measurement uncertainty for the mid-cd as a function of the number of floating parameters. As expected, the measurement uncertainty increases when more parameters are varied simultaneously. The different colors stand for different scatterometric measurement configurations. For large parameter spaces, the Mueller-matrix approach achieves the overall lowest measurement uncertainty and is hence most qualified for handling complex structures. In addition, the Mueller matrix facilitates the reconstruction of target asymmetries or the analysis of isolated grating structures with critical dimensions as small as 10 nm (not shown here).

Clearly, the sensor calibration is one of the main challenges in this project. Within the remaining project duration, the focus lies on the experimental validation of the promising simulation results.

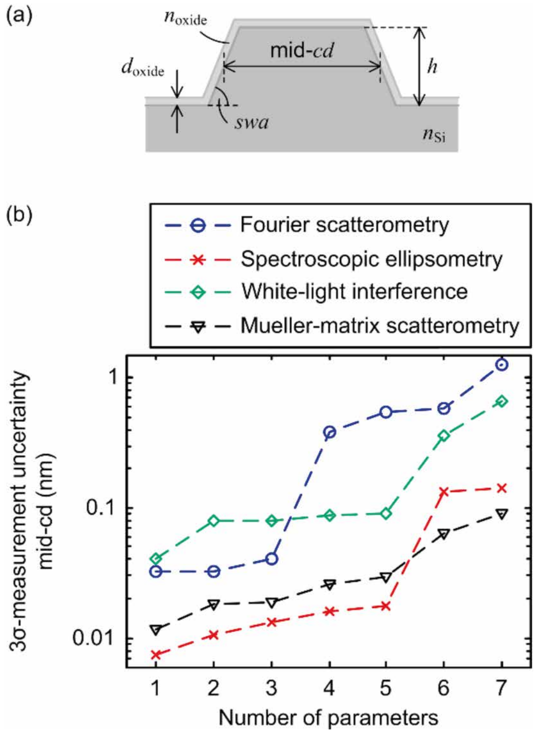

Fig. 2: *Selected simulation results. (a) Grating model: silicon line grating covered by a thin SiO_2-layer. The geometrical grating parameters are: pitch p=100 nm, critical dimension mid-cd=p/2, height h=100 nm, symmetric sidewall angles with swa=87°, and d_{oxide}=3 nm. The generally complex, wavelength-dependent refractive indices n_{Si} and n_{oxide} are taken from literature. (b) Measurement uncertainty of the mid-cd as a function of the number of parameters. We compare four different measurement configurations: Fourier scatterometry (averaging over propagation angles / pupil points), spectroscopic ellipsometry (wavelength averaging), white-light interference Fourier scatterometry, and Mueller-matrix scatterometry (full averaging plus polarization information). For large parameter numbers, the Mueller-matrix approach outperforms the others.*

Supported by: DFG German Science Foundation
Project: Schnelle Weißlicht-Müller-Matrix-Scatterometrie zur Charakterisierung von Nanostrukturen mit großem Parameterraum (OS 111/50-1)

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Improved cascaded DBR plasmonic superlens with shift-invariance for far-field imaging at visible wavelengths

H. Li, L. Fu, K. Frenner, W. Osten

To realize direct imaging with subwavelength resolution, we have designed and fabricated a novel cascaded plasmonic superlens for far-field observation [1, 2]. However, image distortion occurs when the object is shifted with respect to the corrugated lens surface due to near field interactions. In this report, we demonstrate a modified design to solve this problem [3]. The imaging capability of the superlens is validated both numerically and experimentally.

A cross-sectional schematic of current superlens is shown in fig. 1. The lens consists of two plasmonic slabs. One is a plasmonic cavity lens (PCL) for near-field coupling. To tune the performance wavelength to visible and to enhance the near-field transmission, a Bragg distributed reflector (DBR) structure is integrated to the PCL around the lens center, forming additional lateral cavities for sur-face waves. The other one is a planar plasmonic lens (PPL) for phase compensation and thus for image magnification.

Numerical calculations were performed using an in-house developed software package Microsim (results are not shown here [4]). A pair of slits in a chromium layer located 70 nm beneath the superlens was used as an object. With an object size of 200 nm, which is defined as the distance between the two slit centers, a resolvable far-field image projected by the superlens with a magnification factor of 2.6 is obtained at the wavelength of 640 nm [3]. To explore the shift invariance of the object against the superlens, we further calculated far-field intensity distributions by shifting the DBR-PCL structure with respect to the optical axis. No obvious influence from a lateral position shift up to 550 nm can be observed at the image plane, which numerically verifies the shift invariance of the lens.

The superlens was then fabricated on the top of the pair-slit object with a size of 200 nm via FIB-milling and film deposition processes. The imaging property of the cascaded superlens was measured using a conventional microscope with an NA of 1.3. The object was illuminated by a collimated laser beam at $\lambda = 640$ nm. The image in the far field was captured by a CCD camera. The measured results are shown in Figs. 2 (a-c) for a relative lateral position shift of 200, 350 and 550 nm, respectively. It can be seen that the image in all of the three cases are resolvable. The intensity distributions drawn from the measured image along the red lines are further compared in fig. 2 (d). The images show similar size and contrast, indicating that the alignment problem has been solved.

In summary, we have designed a novel cascaded plasmonic superlens for far-field imaging at visible wavelengths. A lateral resolution of 200 nm at the wavelength of 640 nm was demonstrated both numerically and experimentally. Compared to our previous design reported in [2], the imaging performance of current approach is improved in terms of shift invariance between the object and the lens due to the modified design at the lens center. Our structure can be further extended for 2D imaging when circular gratings are used for the two slabs.

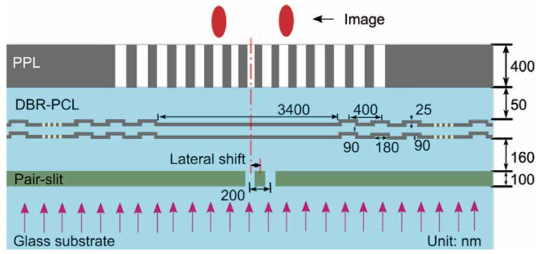

Fig. 1: *Schematic of a DBR plasmonic superlens.*

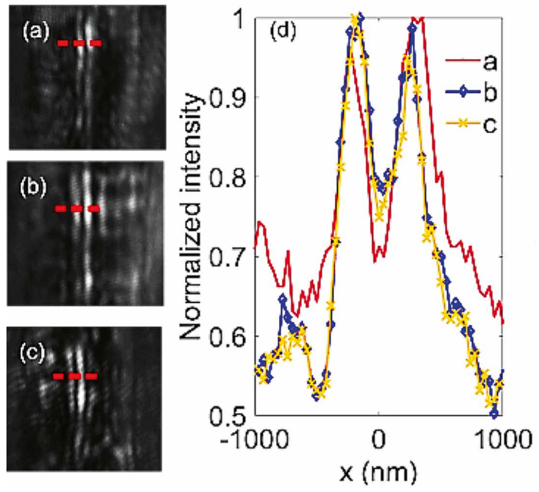

Fig. 2: *CCD images of a pair-slit object with different lateral position shifts: (a) 200 nm, (b) 350 nm and (c) 550 nm. (d) Normalized intensity distribution alone the red dashed lines in (a-c).*

Supported by: China Scholarship Council (CSC) and DFG through the project OS111/40-2

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Treatment of singular integrals on higher order quadrilateral elements via direct evaluation method for a speckle simulator using surface integral equation method

L. Fu, K. Frenner, W. Osten

Galerkin surface integral equation (SIE) formulations have been widely used to solve Maxwell's equations for exploring light matter interactions with high precision. We have implemented the Galerkin SIE formulation according to Poggio, Miller, Chang, Harrington, and Wu (PMCHWT) using higher order ten-edge quadrilateral elements aimed for simulating speckles from large area rough surfaces of any material at optical frequencies using Fortran 90 [1]. To solve the unknown surface fields represented by the element edges, calculation of matrix elements with four-dimensional integrations containing kernels of Green's function and gradient Green's function is involved. Besides many advantages of the method, difficulties of weak and strong singularities arise with the integrations when two elements are nearby or overlapping. Particularly, when metallic surfaces at optical frequencies are to be considered, singularities should be treated more carefully. For a calculation with high precision, a mesh size between λ/10 and λ/20 is normally demanded. Thus, a huge number of unknowns have to be solved for a large surface (e.g., 1×1 mm²), and therefore, possible efficient integration algorithms should be applied since they need normally more integration points. In our previous implementation, strong singularities for two overlapping elements were treated by singularity extraction based on Taylor expansion [1]. For the case of elements with corner or edge overlap, normal integration with more integration points were used. To improve computation efficiency, in this report the cases with corner and edge overlaps are treated by a direct integration method (DIM) [2], by which several coordinate transformations and integration reordering are performed to cancel the denominator in the Green's function up to an order of R^2. Therefore, the weak or strong singularities are treated simultaneously.

For the 4D integration, Legendre Gauss quadrature rule with identical number N of integration points for each dimension was used. To explore the convergence rate, relative error referring to the result with $N = 30$ (the same value within machine precision was obtained by both DIM and normal integration methods) is defined as

$$\varepsilon = \frac{\left\|\mathrm{I} - \mathrm{I}_{\mathrm{ref}}\right\|_2}{\left\|\mathrm{I}_{\mathrm{ref}}\right\|_2},$$

where $\|\cdot\|_2$ is the 2-norm. Three typical integrations of I_A, I_B and I_C containing both weak and strong singular terms are studied and their convergence rates are shown in fig. 1.

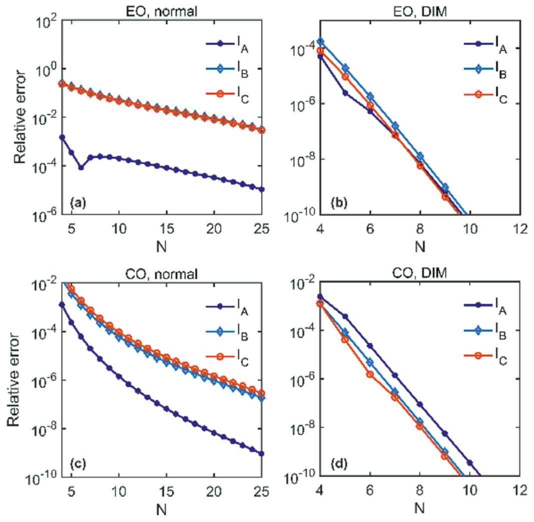

Fig. 1: *Relative integration error for the elements with edge overlap by normal integration method (a) and by DIM (b). Integration error for the elements with corner overlap (c) by normal method and (d) by DIM.*

From Figs. 1(a) and (b) we see that to obtain an accuracy around 10^{-3}, in the case of edge overlap (EO), $N = 27$ has to be taken by normal integration, while $N = 4$ is enough by DIM. The benefit of using DIM for this case is enormous. On a personal computer with 3.4 GHz CPU and 32 GB RAM, the computing time for the former case was around 2.21 s, while for the latter it was around 0.03 s, which is 69 times faster. Nevertheless, its benefit for the case of corner overlap (CO) is not so obvious when the same accuracy is considered. As we can see from Figs. 1(c) and (d), to achieve the same accuracy, $N = 6$ has to be taken for the normal integration, while $N = 4$ for DIM. Although less integration points were used by DIM, it is slower than by normal integration due to coordinate transformations and subdomain integrations. Therefore, in this report normal integration was used for the case of corner overlap.

With this, we study near and far fields scattered by plasmonic spheres to validate our implementation and to optimize the computing time. First, near fields scattered from a silver sphere with a radius of 200 nm illuminated by a plane wave at a wavelength of 550 nm ($\varepsilon_r = -12.94 - i0.43$) with E-field along the x-axis and propagation along the z-direction was calculated by the SIE method. The sphere was meshed with 672 eight-node quadrilateral elements (a mesh size of ~λ/20) with 4032 independent unknown edges. The x-component of the E-field intensity in the xz-plane is plotted in fig. 2(a) and fig. 2(b) shows the result from the Mie-calculation. We see that the near-field patterns from the two methods agree with each other very well. Plotting the fields along the x-axis and z-axis as shown in fig. 2(c) we can compare the results directly. The intensity in the shadow range of the sphere (right-hand side) has a relative larger deviation from the Mie-calculation. Taking the results from Mie-calculation as reference, relative errors demonstrate that the difference along the x-direction at $z = 0$ is around 1 %, while larger error arises in the near field regime of the sphere along the z-direction at $x = 0$. This is due to the intrinsic problem of the PMCHWT formulation due to plasmonic resonances, which can be improved by other kinds of formulations [3].

To further validate the implementation, far-field bistatic radar cross-section (RCS) for a gold nano-sphere ($\varepsilon_r = -8.0 - i1.66$) with a radius of 200 nm was calculated in the far field for comparison with the result from litera-

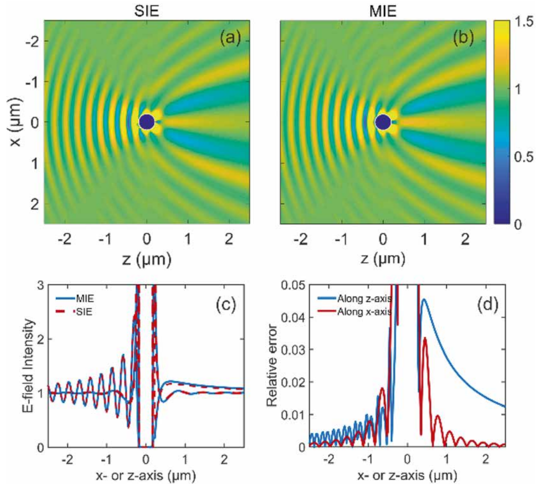

Fig. 2: *Near E-fields of a silver sphere at the wavelength of 550 nm. Intensity in the xz-plane from (a) SIE calculation and (b) Mie-calculation. Field intensities along the z- and x-directions at x = 0 and z = 0, respectively from the plots in (a) and (b). (d) Relative errors of the two SIE curves in (c) with respect to those from Mie-calculation.*

ture [3]. The sphere was also still illuminated by the plane wave at λ = 550 nm, at which gold sphere is more approaching its plasmonic resonance. The calculated bistatic RCS from the SIE formulation is compared with the result from the Mie calculation in fig. 3. Again, very good agreements are obtained in both parallel (ϕ = 0°) and normal (ϕ = 90°) scattering planes, validating our implementation further.

Because computation time is a great concern for our speckle simulator, the time consumed for the calculation on a server (2× Xeon E5-2627, 3.5 GHz) with 12 threads and OMP algorithm is summarized in Table I. With 672 elements and 4034 unkowns, 41 seconds was used for matrix calculation, while 9 seconds for solving the linear equation using LU decomposition. With 2688 elements and 16128 unknowns, a computation cost between $O(N^2)$ and $O(N^3)$ is shown for both calculations. Furthermore, more time in the latter case is consumed to solve the linear system. When a large area problem with more than $10^6 \sim 10^8$ unknowns is under consideration, the computation cost with current implementation is not yet acceptable, not to mention the memory requirement. Therefore, we will further implement fast multiple method and multilevel fast-multiple method to speed up. The computation cost via these algorithms can be reduced from $O(N^3)$ to O(NlogN) [4].

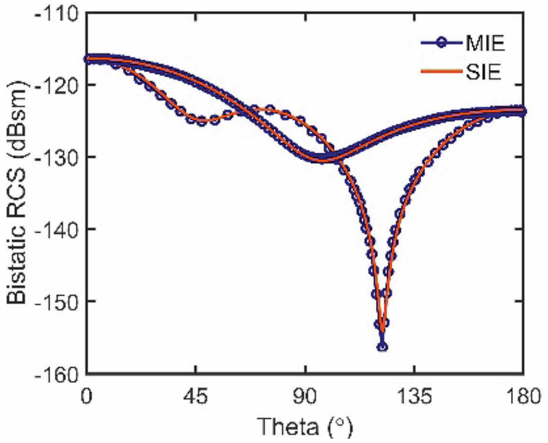

Fig. 3: *Far field bistatic radar cross section of a gold sphere by SIE method and Mie calculation in two orthogonal scattering planes.*

Number of elements (edges)	***Matrix (s)***	***LU (s)***
672 (4034)	*40.95*	*9.103*
2688 (16128)	*322.213*	*402.0*

Table I: *Time consumed by matrix calculation and LU-decomposition*

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 (OS111/51-1)

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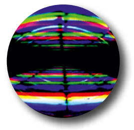
Interferometry and Diffractive Optics



Fizeau-type Tilted Wave Interferometry

R. Beißwanger, C. Schober, C. Pruß, W. Osten

Today's optic industry benefit from various improvements in manufacturing technology of optical components. Processing of non-spherical optics is now state of the art and of high relevance. Current optics designs rely heavily on those elements, since the small form factors and high performance of actual designs would be impossible with traditional spherical optics designs.

Tilted Wave Interferometry (TWI) is a flexible, very fast and accurate measurement technology, which keeps pace with the demands of modern fabrication of aspheres and freeform surfaces [1]-[3]. Without any null compensator like CGH, movement of the specimen during measurement and setup time between measurements, the TWI measures surface deviations full field and with high lateral resolution. Together with the high measurement speed of typically less than 30 sec per measurement, a close integration into the fabrication chain is possible.

Over the last 12 years, the state of the art TWI was developed in Mach Zehnder configuration (see fig. 1). A TWI in common path configuration (fig. 2) has several benefits over the state of the art configuration (see below), but leads in combination with the TWI specific illumination scheme to challenges with multiple-beam interferences. We have solved these issues [6], developed the TWI in common path Fizeau configuration and demonstrated full functionality. One of our solutions consists of a new illumination design with four sets of illumination patterns, that each generate their own reference wave.

In common path configuration, the reference beam and the measurement beam travel the same optical path inside the interferometer. This leads to a self-compensation effect, since disturbances, which occur in the common path, affects the measurement and reference beams in the same way. Static disturbances, like errors in interferometer optics, are suppressed to a high degree in the interferogram. As a consequence, tolerances of interferometer components in the common path can be relaxed. Temporal effects like air turbulence and vibrations are also effectively suppressed, resulting in relaxed environmental conditions and eases the operation in production areas.

Extensive Monte Carlo simulations show improvements in static disturbances, like errors on optical interferometer components. An example is shown in fig. 3 (a) and (b), where a disturbance on the collimation lens of height 0,7 wavelengths is placed in the interferometer models.

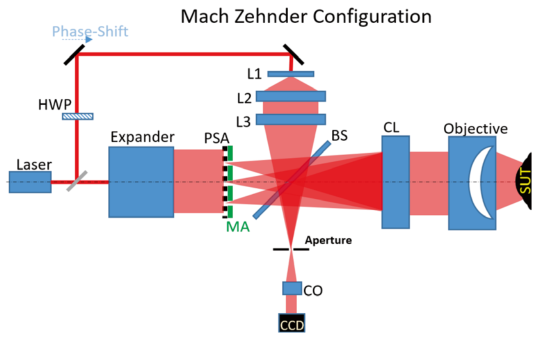


Fig. 1: *TWI in Mach Zehnder configuration. HWP: Half Waveplate, PAS: Point Source array, MA: Mask Array, L1, L2, L3: Optics for reference arm, BS: Beam Splitter, CL: Collimation lens, CO: Camera Optic, CCD: Camera, SUT: Surface under test.*

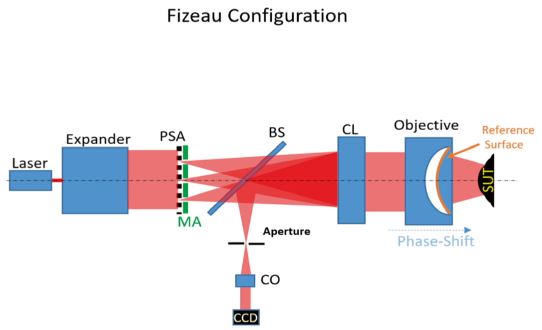


Fig. 2: *TWI in common path Fizeau configuration (see fig. 1 for denomination).*

A simulation of a measurement shows that the reconstruction error of the common path approach can be one order of magnitude lower than the state of the art Mach Zehnder configuration.

The expected improvements in temporal stability are confirmed by our lab implementation of the new TWI approach. First measurements show agreements with other measurement technologies, for example with the NPMM.

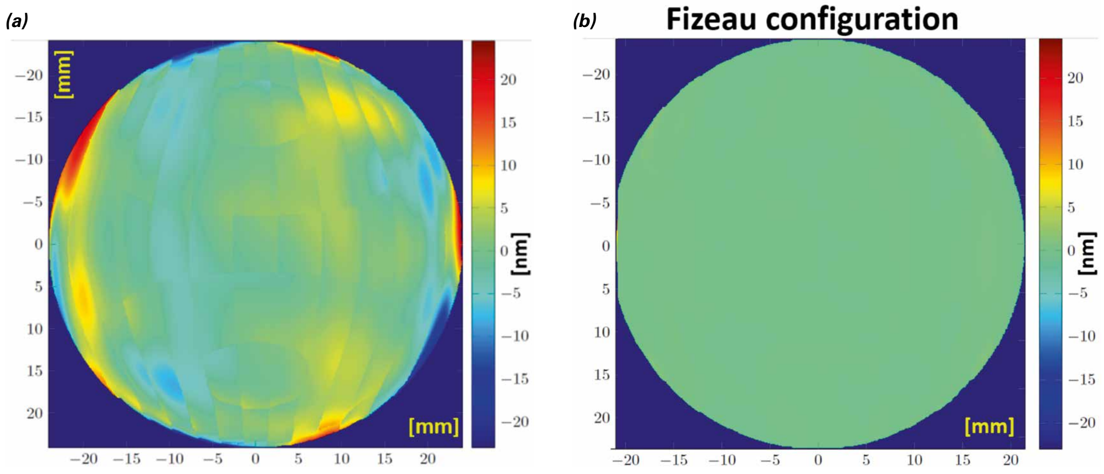


Fig. 3: *Reconstruction error of a freeform specimen (FFA5) with a disturbed interferometer model, resulting from a simulation of the state of the art Mach Zehnder interferometer (a) and the new common path TWI (b), that shows an improvement of up to one order of magnitude.*

In cooperation with: Mahr GmbH

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Tilted Wave Interferometry for efficient measurement of large convex surfaces

A. Harsch, C. Pruß, W. Osten

Interferometers are common tools for measuring large surfaces – if they are concave and spherical. Problems arise if large aspheres and freeforms have to be measured. For their investigation it is necessary to make use of stitching methods. There, the specimen is divided into a mesh of overlapping subapertures, which are small enough to be measured in a single shot. An exemplary asphere with a diameter of 140 mm is shown in fig. 1, with a possible mesh of subapertures (measured with a TWI, diameter of subapertures 48 mm, 40 % overlapping) skteched in fig. 2. To keep measurement time and computation time small, the aim is always to have as few subapertures as possible. The analysis of an off-axis subaperture (highlighted in fig. 2 and depicted in fig. 3) of this exemplary asphere shows that the local deviation from the best fit sphere mainly consits of coma and astigmatism. For conventional Fizeau interferometers without any compensation, such a shape would lead to high fringe densities. This leads to decreasing sizes of the measurable area and thereby resulting in a siginficant increase of required subapertures. In contrast, the Tilted Wave Interferometer with its freeform capability is able to compensate those deviations without any additional optics. Therefore, it is possible to acquire larger subapertures compared to null interferometers. In this example, a reduction of more than 90 % is achieved.

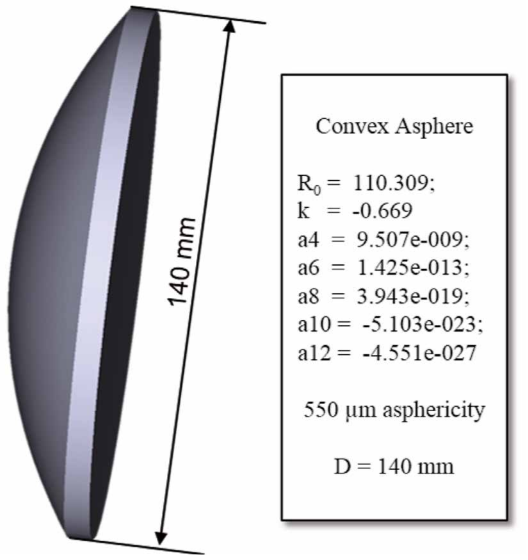

Fig. 1: *Example of a large convex asphere. A possible mesh of subapertures is shown in fig. 2.*

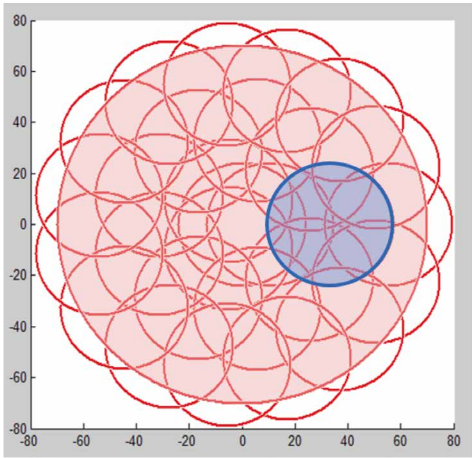

Fig. 2: *Mesh of subapertures for the convex asphere shown in fig. 1. The deviation from the Best Fit Sphere of the blue subaperture is seen in fig. 3.*

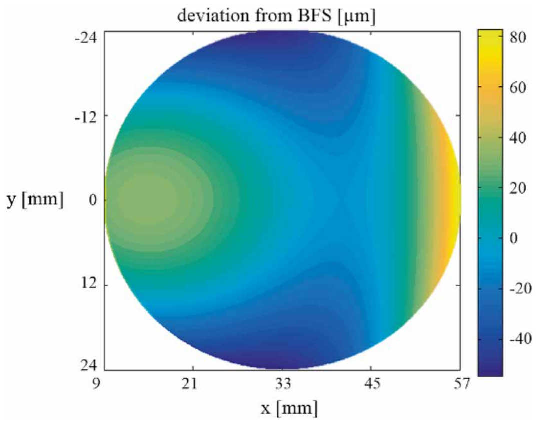

Fig. 3: *Deviation from the best fit sphere of the blue subaperture of fig. 2.*

Supported by: AiF within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on an enactment of the German Parliament via the Forschungsvereinigung Feinmechanik, Optik und Medizintechnik e.V. FOM in the project TWI-Stitch: Kombination von Subaperturen zur hochgenauen Vermessung asphärischer Flächen unter Verwendung eines speziell angepassten Tilted Wave Interferometers.
Project: IGF Vorhaben 18592 N.
In cooperation with: Technische Hochschule Deggendorf and Mahr GmbH.

References:

[1] Harsch, A.; et al. "Tilted Wave Interferometry for testing large surfaces", Proc. SPIE 10829, 2018.

Optimization of tilted wave interferometer calibration using statistical methods

A. Harsch, A. Parvizi, J. Schindler, R. Beisswanger, C. Pruß, W. Osten

The Tilted Wave Interferometer (TWI) is a fast and flexible tool for asphere and freeform metrology. Since the TWI is based on a non-null setup, a 2-dimensional calibration with OPD correction values for each pixel is not appropriate. Instead, a 4-dimensional calibration is used, to also cover field dependencies of the systematic instrument error [1]. A black box approach that describes the OPLs through the interferometer with the help of polynomials allows calibrating all possible ray paths through the system. It is the task of the calibration to determine the polynomial coefficients Q_{ij} and P_{kl} such that the black box polynomials return the same aberration response as the real interferometer does. In the project "AutoCalib", new methods for the optimization of the calibration and measuring algorithms are investigated [2]. During the calibration procedure, calibration spheres are measured at multiple positions within the testing space. To assess the performance of the calibration process of the TWI, Monte Carlo Simulations are used. Their results show whether a chosen set of calibration positions will lead to a successful calibration. To get statistically relevant data, a computation time of at least 24 hours is necessary, which slows down the optimization process very much.

A new assessment tool was developed that analyses the variation matrix A and therefore reduces computation time and consequentially development time significantly. The mentioned variation matrix A is used for solving the inverse problem which arises during the calibration. It contains the changes of the nominal optical path lengths at incremental changes of the polynomials coefficients. The solution of the inverse problem represents the terms, with which the coefficients have to be corrected. If we would know the precision and accuracy of these correction terms, the solution could be judged easily. Since the true values are unknown, a least square estimation is carried out. The covariance of this estimated correction term is dependent only on the variation matrix A and therefore can be evaluated without data acquisiton or simulation.

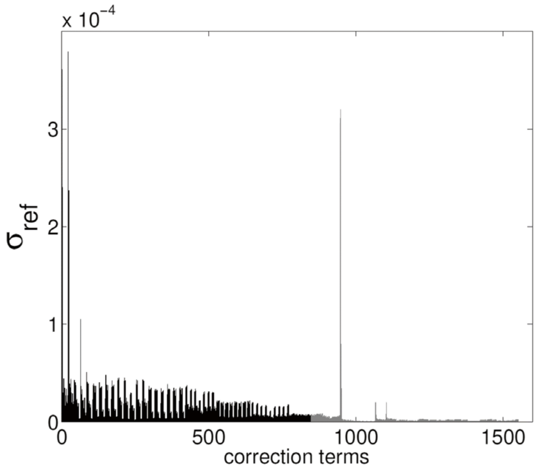

Fig. 1: *Standard deviation of the correction terms corresponding to Q (black) and P (grey) for a reference configuration*

Supported by: DFG German Science Foundation
Project: Ein selbst-kalibrierendes Verfahren zur Vermessung von Asphären und Freiformflächen
(OS 111/45-1)

References:

[1] Baer, G; Schindler, J.; Pruß, C.; Siepmann, J.; Osten, W. "Calibration of a non-null test interferometer for the measurement of aspheres and free-form surfaces.", Opt Express. 2014; 22(25):31200.

[2] Schindler, J.; Pruß, C.; Osten, W. "Simultaneous removal of nonrotationally symmetric errors in tilted-wave-interferometry", Optical Engineering, 2019.

Positioning errors in precision freeform surface measurements

A. Harsch, C. Pruß, W. Osten

Virtual experiments are a powerful way to investigate complex measurement systems and to analyze the influence of parameters. For the assessment of the Tilted Wave Interferometer virtually measured phase data of realistic setups are generated using raytracing of a virtually misaligned measurement setup probing a virtual sample. The resulting phase data of the virtual measurements are evaluated with the regular algorithms. By comparing the obtained result with the known shape of the virtual sample, the performance can be assessed. This approach has been successfully used in the determination of optimal calibration configurations [1] for the TWI.

For the investigation of effects on the measurement results, multiple parameters have to be taken into account: The form of the surface itself, as well as the surface error, the surface's nominal position and orientation within the testing space as well as misalignment in all six degrees of freedom and last, camera noise. The principle is shown in fig. 1.

A set of experiments was defined, consisting of three types of surfaces (an asphere, a toroidal surface and a specific metrological freeform known as "Two Radii" specimen) with three different error types added each. The positioning was realised with misalignments of up tp 10 μm per axial direction and rotational errors up to 0.35 mrad.

An analysis of the reconstruction error shows that misalignments in x and y direction as well as rotational errors can be handled well. Only a misalignment along the z axis causes larger errors. The consequence of this result is to introduce additional absolute knowledge about the specimen's position. One possible implementation is to measure the distance between cat's eye position and the adjusted measurement position. This can be realized by white light interferometry or a distance measuring interferometer.

The simulations revealed another relevant aspect of freeform metrology: the ambiguity between surface error and misalignment. For spheres, one cannot differentiate between a lateral misalignment and a surface error containing tilt. For freeforms the characteristics are more manifold. For instance in the case of the investigated toroidal surface, the ambiguity exists for astigmatism and the rotation around the z axis.

Consequently, without additional fiducials, misalignment uncertainty translates to shape uncertainty. To avoid misinterpretation, the shapes of the specimen have to be carefully analysed to know in advance the position/shape ambiguity of the specific specimen.

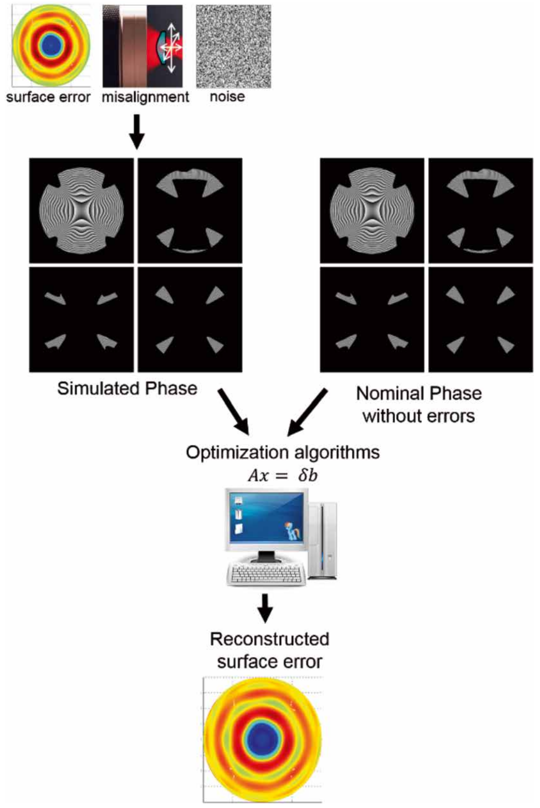

Fig. 1: *Scheme of virtual experiments.*

Supported by: The EMPIR initiative is co-founded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
Project: EMPIR project 15SIB01 FreeFORM
In cooperation with: PTB

References:

[1] Baer, G. "Ein Beitrag zur Kalibrierung von Nicht-Null-Interferometern zur Vermessung von Asphären und Freiformflächen", Universität Stuttgart, 2016.

[2] Harsch, A.; Pruß, C.; Baer, G. and Osten, W.: "Monte Carlo Simulations – a tool to assess complex measurement systems", Proc. SPIE 11171, Sixth European Seminar on Precision Optics Manufacturing, 111710C (28 June 2019); https://doi.org/10.1117/12.2526799.

In-process metrology for additive manufactured optics

F. Rothermel, C. Pruß, A. Herkommer

Many additive manufacturing technologies struggle with the task of printing optics, as the surfaces are too rough due to the layer-by-layer process and therefore require post-processing. A recently developed inkjet method called "Printoptical Technology®" however solves this issue. There, droplets of an acrylic, PMMA-like polymer flows on the surface, forming a new layer, which is then cured with UV-light afterwards. In this way, extremely smooth surfaces (RMS < 2 nm) can be achieved.

A remaining problem is the lack of shape quality that prohibits the printing of imaging optical elements that are comparable e.g. to injection-molded components. This results from deviations that occur throughout the manufacturing process and are not controllable, yet. Therefore, a metrology system is required, which measures those deviations in process and gives feedback for the printer. The implementation of the metrology system in the printer environment is shown in fig. 1.

This measurement task is challenging, since the in-process implementation comes with rough conditions: High speed measurement of the specimen that moves with 1 m/s and dealing with backside reflections as well as a large FOV of 180 mm and high lateral (~50 μm) and vertical (~λ/10) resolution. An approach that fulfills these requirements is a grazing-incidence interferometer with diffractive elements for beam splitting and recombination, shown in fig. 2. There, light from a collimated light source is diffracted by a first diffraction grating into 0th and 1st order, i.e. object and reference beam. They are reflected by a reference mirror and the specimen respectively and recombined through a second diffraction grating.

The interference pattern is imaged onto a tilted camera sensor in order to achieve full resolution across the entire FOV.

This arrangement shows several advantages. The large incidence angle results in a large FOV, while the optical components can be standard sized, with exception of the reference mirror. The symmetric setup also allows for the use of broadband light sources like LEDs to suppress negative influences by backside reflections. A fast data acquisition can be achieved through usage of line scan cameras and short exposure times.

First measurements on a moving USAF-Target were conducted that demonstrate the functionality of the setup (see fig. 3). The measurement is achieved by scanning the specimen with consecutive pixel lines and introducing a phase shift by tilting the reference mirror. A current topic of investigation are phase fluctuations during the scanning process, which are currently a limiting factor for the method.

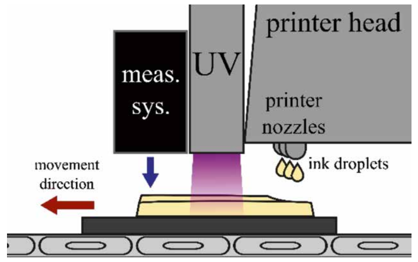

Fig. 1: *Schematic implementation of an arbitrary measurement system in the printer environment.*

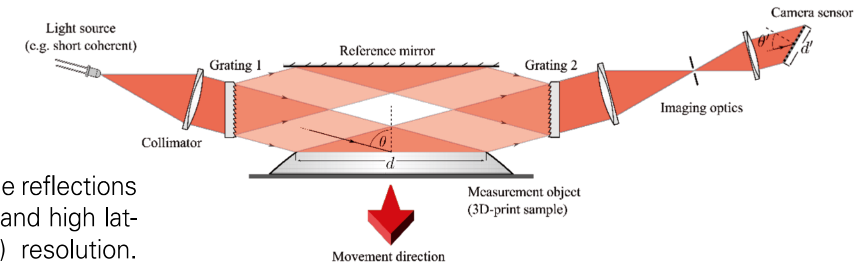

Fig. 2: *Schematic of the diffractive grazing-incidence interferometer. The arrow indicates the movement axis of the specimen, which is perpendicular to the elongated field of view of the interferometer.*

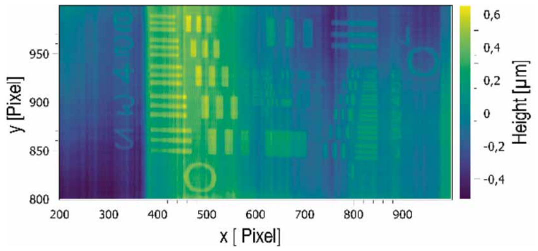

Fig. 3: *Scanned measurement of USAF-Target.*

In cooperation with: Institute of Photonics, University of Joensuu – We thank for providing measurement samples.

References:

[1] Rothermel, F.; Pruß, C.; Herkommer, A. "In-Prozess Messtechnik für 3D-gedruckte Optiken (Conference Presentation)", presented at 119. Jahrestagung der DGaO, Aalen, 2018.

Nanometer reproducibility on decimeter scales – the NPMM200 as basis for new reference measurements

C. Pruß, A. Gröger, S. Hartlieb, K. Frenner, W. Osten

In December 2018 we reached a major milestone for our metrology equipment: The nanometrology and nanopositioning machine NPMM200, a unique research device funded by the German Research Association (DFG) passed the acceptance tests and was handed over from the Technical University of Ilmenau to ITO. TU Ilmenau has designed, built and put into operation a machine that is dedicated to nanometer-precise and nanometer-accurate positioning over a large measurement volume of 200 x 200 x 25 mm^3. Table 1 shows some specifications of the machine. The NPMM200 is equipped with a flexible sensor platform (see fig. 1) that can accommodate optical topography sensors, atomic force sensors or any other sensor or system within the size (decimeter scale) and weight specifications (several kg).

A series of acceptance tests showed the performance of the system. Fig. 2 illustrates the positioning precision on the example of 1 nanometer steps in 3D-space. The high positioning performance is achieved in the whole measurement volume. Height measurements are a way to show the performance of absolute accuracy at least along one axis, since there exist calibrated height normals. A measurement exists of a scan along a specified path, covering the bottom, top and bottom level again. The difference between the upper and lower level is the height. A series of measurements on a 4 mm calibrated height standard from PTB has shown the remarkable precision of less than 80 picometers. This is comparable to measuring the television tower of Stuttgart with a repeatability of less than the size of a red blood cell.

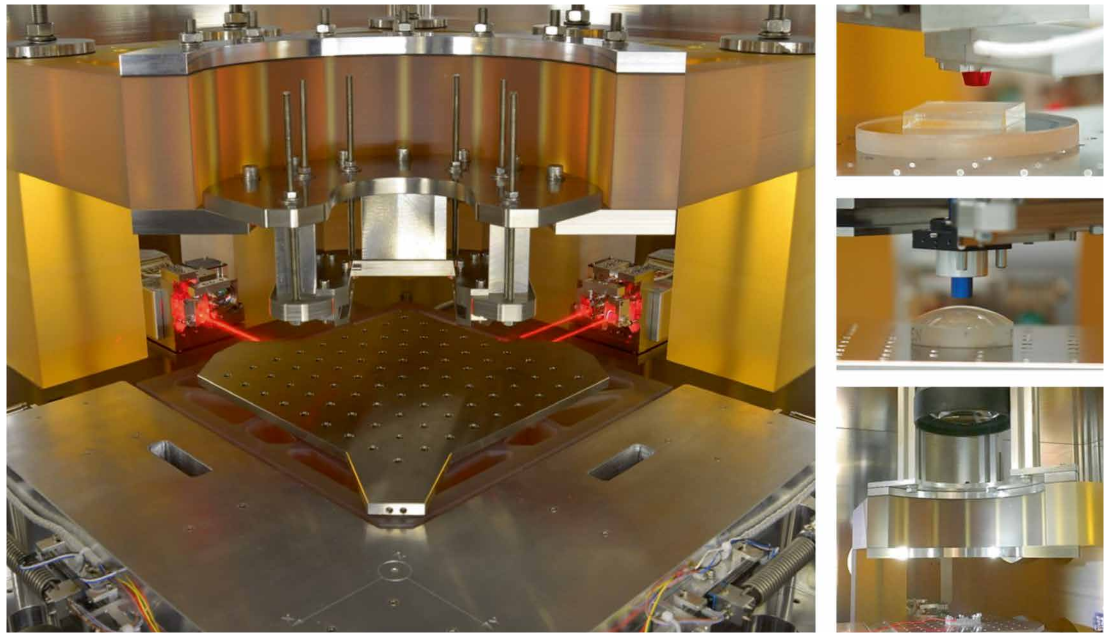

Fig. 1: *The heart of the NPMM200 is the metrological frame. It holds the sensors and the interferometers that monitor the position of the sample stage. Sensor examples are shown on the right: top: focus sensor for height measurements, middle: chromatic confocal sensor, bottom: large telecentric lens instead of sensor. In this configuration the distortion of the telecentric lens is calibrated.*

Specifications of the NPMM200

Positioning volume	**200 mm x 200 mm x 25 mm**
Max. mass of test sample	**6,35 kg (incl. 3,85 kg carrier plate)**
Precision position metrology	**< 0,08 nm**
Max. scan-speed	**30 mm/s**
Positioning reproducibility	**< 4 nm**
Positioning uncertainty 3D	**30 nm (2 sigma)**
Measurement conditions	**Technical vacuum or ambient pressure**
Max. sensor weight	**35 kg (including mechanical holder)**

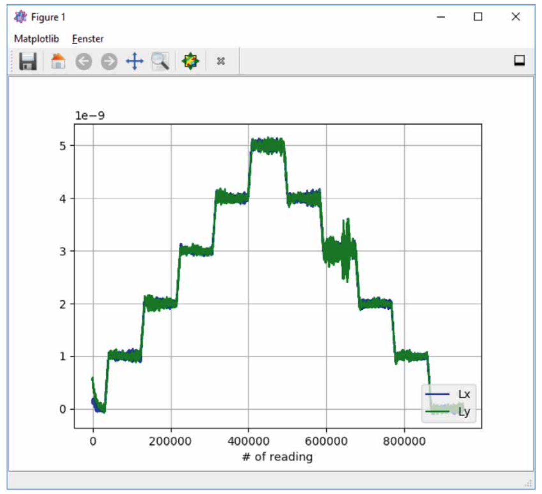

Fig. 2: *Nanometer steps of the sample stage in x- and y-direction.*

Supported by: DFG, project Os111/44-1.
In cooperation with: TU Ilmenau

Diffractive optics fabrication

M. Dombrowski, T. Schoder, C. Pruß, W. Osten

Diffractive optical elements (DOE) are thin (typically micrometer-range) phase modulating elements that operate by means of interference and diffraction. This allows functionalities not possible with conventional refractive optics. Therefore they became a valuable tool in optical design and for metrology applications.

At ITO there is a long tradition of design and fabrication of DOE, for our own research work as well as for scientific and industrial partners. The fabrication is mainly based on laser direct writing on specialized equipment, capable of processing also large precision substrates with a thickness of 20 mm and a diameter of 200 mm. On our circular laser writing systems (CLWS) for photolithography we can manufacture high resolution binary and multi-level diffractive structures. The flexible high precision tools work in polar coordinates, comparable to a DVD writer. In 2009 we developed a CLWS machine that is capable to write on rotation symmetric curved substrates. It offers the advantage of a high, continuous scanning speed and facilitated fabrication of rotationally symmetric structures.

Structures are written directly into photoresist. The resulting microstructures are then either used directly (e.g. for prototyping or for mastering) or are transferred into the substrate using a dry etching process (reactive ion etching RIE, typically into fused silica substrates).

Application examples for our diffractive elements are hyperchromatic refractive/diffractive hybrid lenses (fig. 1) for Chromatic Confocal Coherence Tomography (CCCT) [1], polarization selecting elements for high power lasers in the kW-class (fig. 2) [2] and large imaging DOE as part of telecentric lenses (fig. 3). Further application examples are:

- Beam shaping elements
- DOE for optical sensors
- Custom made diffractive and refractive micro-lens arrays
- Custom phase structures
- Phase contrast plates
- Calibration targets

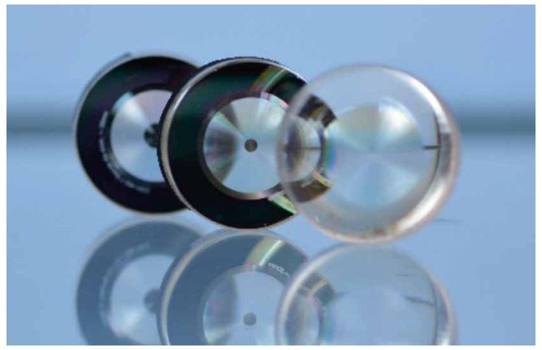

Fig. 1: *Hybrid lens for CCCT. Blazed diffractive surface on plano-concave lens and integrated stray light apertures.*

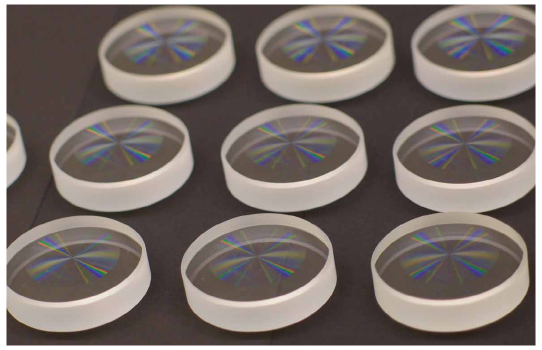

Fig. 2: *Grating Waveguide Output Couplers designed for intra-cavity polarization selection in radially polarized thin disk lasers.*

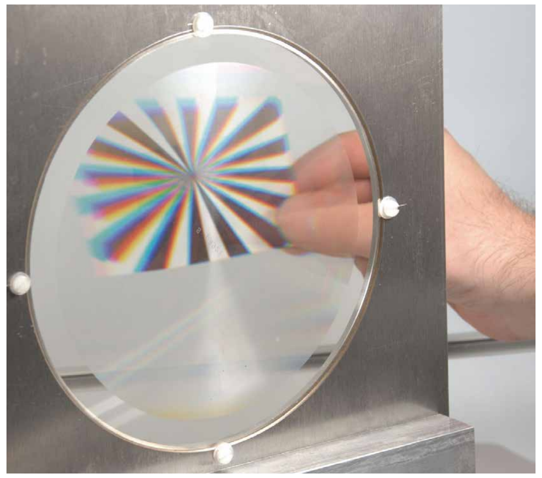

Fig. 3: *Demonstrator of the diffractive front element for a large FOV telecentric objective lens.*

References:

[1] Boettcher, T.; Gronle, M.; Osten, W. "Multi-layer topography measurement using a new hybrid single-shot technique: Chromatic Confocal Coherence Tomography (CCCT)", Opt. Express 25, 10204-10213 (2017).

[2] Dietrich, T.; Rumpel, M.; Beirow, F.; Mateo, C. M.; Pruß, C.; Osten, W.; Abdou Ahmed, M. and Graf, T. "Thin-disk oscillator delivering radially polarized beams with up to 980 W of CW output power," Opt. Lett. 43, 1371-1374 (2018).

Sub-lambda grating structures for kW-class radially polarized laser beams

C. M. Mateo, M. Dombrowski, L. Fu, C. Pruß, T. Dietrich, T. Graf, M. Abdou Ahmed, W. Osten

New ways and concepts to form the polarization state of laser beams have gained high interest recently. This is especially true for high power lasers, since it allows to access new efficient methods for material processing such as welding, cutting or drilling. With radially or tangentially polarized beams, laser material processes can achieve higher quality, reduce fabrication time and save energy. It has been shown previously, that sub-lambda dielectric grating structures are well suited to form laser beams with tailored polarization.

Within the SubWell project, we studied conceptual novel sub-lambda dielectric grating designs and cost-effective fabrication processes. The goal was to provide components suitable for thin disk lasers with kW-class output power. Three designs were provided by our partners from IFSW ("Institut für Strahlwerkzeuge"). In two designs, the sub-lambda grating components operate as part of the laser resonator: One component replaces the resonator end mirror, the other the output coupler mirror. The end mirror design is a grating waveguide mirror (GWM), i.e. a broadband intra-cavity grating mirror that shows a reduced reflectivity for the undesired polarization state. This is achieved with the help of sub-λ axicon grating structures (period 580 nm). The second component, a grating waveguide output coupler (GWOC, period ~700 nm), shows the desired reflectivity of about 96 % only for the desired radial polarization, but much higher transmission values for the undesired azimuthal polarization, which efficiently damps the undesired laser mode. The third design is intended to convert the polarization outside the resonator from linear to the desired radial polarization state.

At ITO, the laser lithography and plasma etching processes to produce the sub-lambda grating structures were developed. GWM and GWOC recipes and process chains were developed for SiO_2 and Ta_2O_5. Scanning Beam Interference Lithography (SBIL) produced the most efficient structures for this purpose. For SBIL, a small (few 10 µm) interference pattern is generated and stepped in radial direction over the rotating substrate. This results in radial gratings with no pixellation artefacts. The fabricated elements were tested and integrated at IFSW into high power disc lasers. Fig. 1 shows schematic experimental setup and intensity output. With the fabricated GWM we reached an output power up to 980 W with a degree of polarization of >95 % and optical efficiency of 53 % [1].

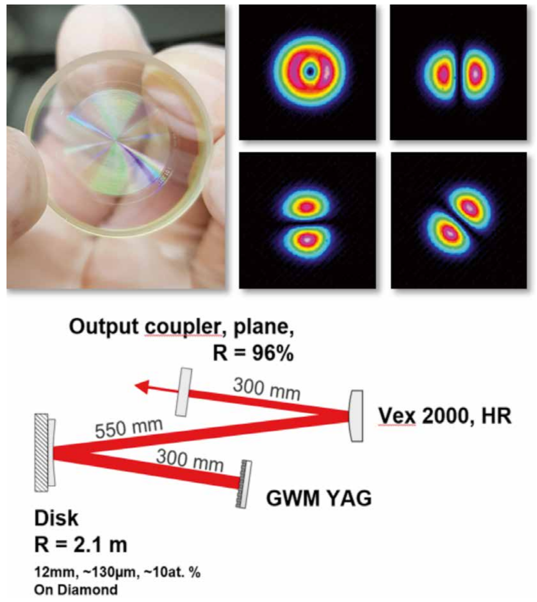

Fig. 1: *a) Photo of a GWM. b) Far-field intensity distribution for a GWM of the laser beam and the resulting intensity distribution when the beam was transmitted through a rotating polarization analyzer. c) schematic experimental setup for GWM demonstrator.*

Supported by: AiF, project SUBWELL
In cooperation with: IFSW, University of Stuttgart, within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on an enactment of the German Parliament.

References:

[1] Dietrich, T.; Rumpel, M.; Beirow, F.; Mateo, C. M.; Pruß, C.; Osten, W.; Abdou Ahmed, M. and Graf, T. "Thin-disk oscillator delivering radially polarized beams with up to 980 W of CW output power," Opt. Lett. 43, 1371-1374 (2018).

Resist characterization for developer free lithography processes

R. Hahn, M. Dombrowski, 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.

To solve this problem, within the joint project "PhotoEnco" a new manufacturing strategy is investigated. The goal is in-situ manufacturing that allows to manufacture the encoder discs in a fully integrated state. This eliminates one of the cost-intensive production steps, manual centering of the code disk. The in-situ manufacturing requires that no wet-chemical structuring process can be used, since this would damage the electronic components.

Therefore new resists with thermal bleachable dye based on a polymer matrix have been produced by the project partner Allresist. The dye degenerates at elevated temperatures. The idea is to locally heat up the coating with a writing laser, thus bleaching the dye, allowing to generate encoder structures in the coating. The advantage of this process compared to ablation processes (e.g. local ablation of a chromium layer) is that the thermal bleaching process does not remove any particles from the coating that could damage the electronics of the encoder.

In systematic characterization procedures, the achievable contrast and the maximal transmission were measured as a function of wavelength, coating parameters and coating type. Fig. 2 shows exemplary results of a resist that has been processed on a hotplate. By measuring the spectral resolved transmission before and after the bleaching the resist is characterized. The results of the sample resist in fig. 2 show a maximum contrast of over 0.85 and a maximum transmission in the bleached state of over 90 % at 620 nm for thick layers. Those values are close to the ones obtained by chrome based encoder discs. In the next steps these results will be used to further optimize the resists to obtain a material with a good process window for laser bleaching. As of now, the bleaching speed still needs to be increased.

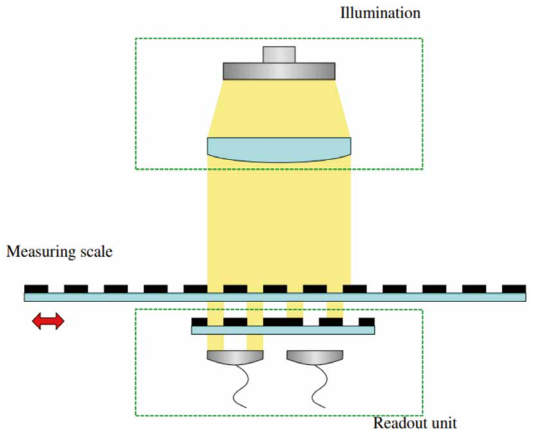

Fig. 1: *Schematic drawing of a rotary encoder.*

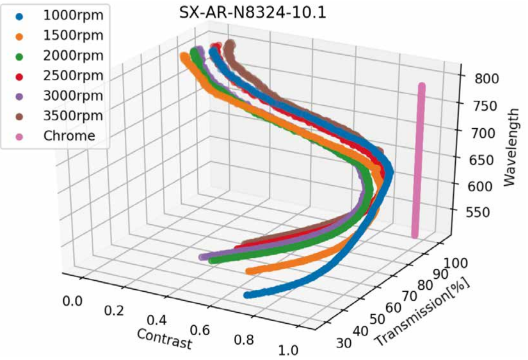

Fig. 2: *Transmission and contrast of a thermal bleachable resist.*

Supported by: BMBF (13N10854)
Project: "PhotoEnco – Photonisch strukturiebare Werkstoffe und photonische Prozesse für die individualisierte Herstellung von Encodermaßverkörperungen und deren Abtastperipherien"
In cooperation with: SICK AG, Allresist, Acsys, STVision.

New process chain for encapsulated diffractive lenses

M. Dombrowski, S. Thiele, M. Röder, C. Pruß, A. Zimmermann, W. Osten

Diffractive optical elements (DOE) are important tools for optical designers due to their ability to generate arbitrary, complex wave fronts compensating chromatic and spherical aberrations or creating specific features like multiplexing or arbitrary beam shaping, e.g. for computational imaging. For the successful application, precise fabrication of high-resolution binary and multi-level diffractive structures is the key. Typically, photolithography is used to fabricate these elements, which is often limited to flat substrate geometries. For cost effective mass production a master structure is replicated using injection moulding, hot embossing, roll-to-roll fabrication and others.

Extending flat diffractive elements to threedimensional curved elements can significantly reduce packaging space by combining refractive and diffractive properties in one element. In the recently finished AiF project HOLEOS, a process chain was successfully developed that allows manufacturing of low-cost curved DOE [1]. It involves master fabrication on a curved glass substrate and an injection compression moulding step for replication (fig. 1). However, it has shown that the master generation process based on a glass master is challenging in terms of mechanical tolerances. Therefore, an optimised new process chain will be developed in the new AiF-project Redolis 3D.

Basis for the replication insert fabrication is a metal substrate generated by ultra-precision machining (UPM) that includes all necessary mechanical alignment and reference featuers. A laser lithography process on this substrate using laser-direct writing (LDW) is the next step in our process chain [2]. LDW offers significant advantages for the process due to its resolution and flexibility. It overcomes shortcomings of ultra-precision diamond turning regarding structure size, shapes and orientation. The resulting photoresist master will be used to create a stamper using Ni electroplating. By means of injection compression moulding, we will transfer the curved DOE into a thermoplastic transparent material.

The targeted system design we target in this project encapsulates the DOE and thus protects the microstructures. The goal is to demonstrate two different applications: A zero optical power element working in the near infrared and an objective where the DOE corrects chromatic aberrations for visible light.

Fig. 1: *Zero-refractive lens using injection compression molding for replication*

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 Ministry of Economic Affairs and Energy based on an enactment of the German Parliament.

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[1] Thiele, S.; et al.: "3D laser direct-writing for injection compression molding of diffractive-refractive elements", ITO Annual Report 2015/2016.

[2] Häfner, M.; Reichle, R.; Pruß, C.; Osten, W. "Laser direct writing of high resolution structures on curved substrates: evaluation of the writing precision", Fringe Proc. 2009, pp. 772 ff.

Coherent Metrology

Residual stress evaluation of ceramic coating under industrial conditions by laser ablation and digital holography 74

Supported by: DFG German Science Foundation
Project: Ermittlung von Eigenspannungen in beschichteten Oberflächen (OS 111/37-1).
In cooperation with: IFKB, Universität Stuttgart, Prof. R. Gadow and IMW, Universität Stuttgart, Prof. S. Schmauder

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Supported by: International Thermonuclear Experimental Reactor (ITER)

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Supported by: DFG German Science Foundation
Project: Die materielle Veränderung von Kunst durch Transporte (OS 111/34-2)
In cooperation with: Staatliche Akademie der Bildenden Künste Stuttgart, Prof. Christoph Krekel

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Project: „Optische Echtzeit-3D-Datenerfassung bei erschwerten Sichtbedingungen
für die Anwendung im Straßenverkehr"(ODESSA)
In cooperation with: Institut für Lasertechnologien in der Medizin und Meßtechnik an der Universität Ulm (ILM)

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Supported by: European Commission, H2020-TWINN-2015 HOLO project (687328)

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

G. Pedrini, I. Alekseenko, 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.

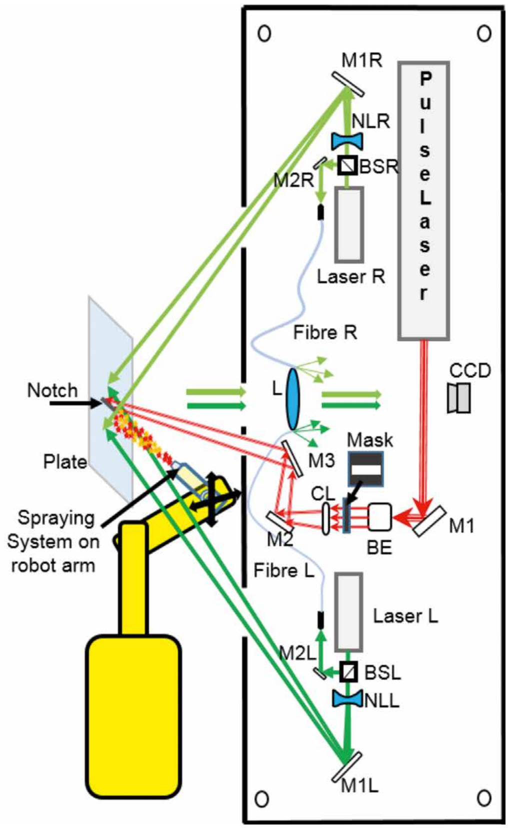

Fig. 1: *Set-up for laser machining and displacement measurement.*

We propose an approach (see fig. 1) 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. 2(a). In fig. 2(b) we may see the system during the coating process. 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.

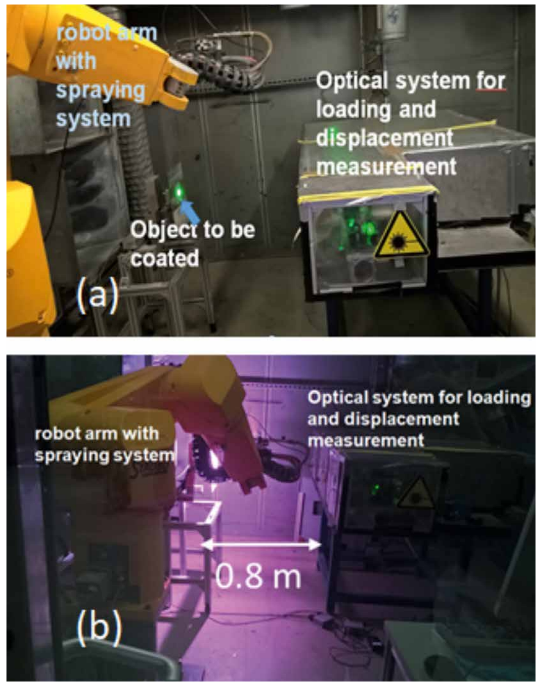

Fig. 2: *Coating system mounted on a robot arm and optical system (a). System during the coating process (b)*

Fig. 3 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 140 µm. It would be necessary to increase the width of the notch in order to achieve depths of 200 µm or more.

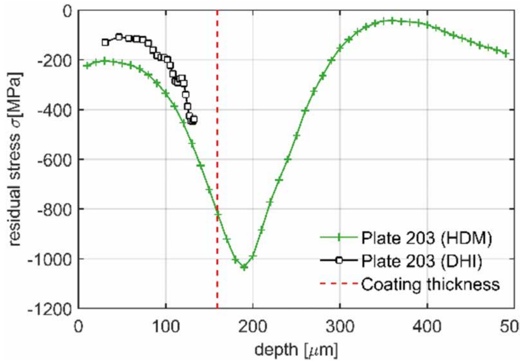

Fig. 3: *Residual stresses inside a coating measured by the micro hole drilling method (HDM) and laser ablation combined with digital holographic interferometry (DHI) The coating thickness for this plate is approximately 160 µm (dashed vertical line).*

Supported by: DFG German Science Foundation
Project: Ermittlung von Eigenspannungen in beschichteten Oberflächen (OS 111/37-1).
In cooperation with: IFKB, Universität Stuttgart, Prof. R. Gadow and IMW, Universität Stuttgart, Prof. S. Schmauder.

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

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

The International Thermonuclear Experimental Reactor (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 divertors that endure high rates of erosion and deposition, each of a size of 10 x 30 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.

The setup sketched in fig. 2 was used for long distance (23 m) shape measurements in an environment where the vibration was not isolated. Two tunable lasers having high wavelength stability have been used for the experiments. Two acousto optical modulators (AOM_1 and AOM_2) are used as shutters for producing two sequential light pulses having different wavelength.

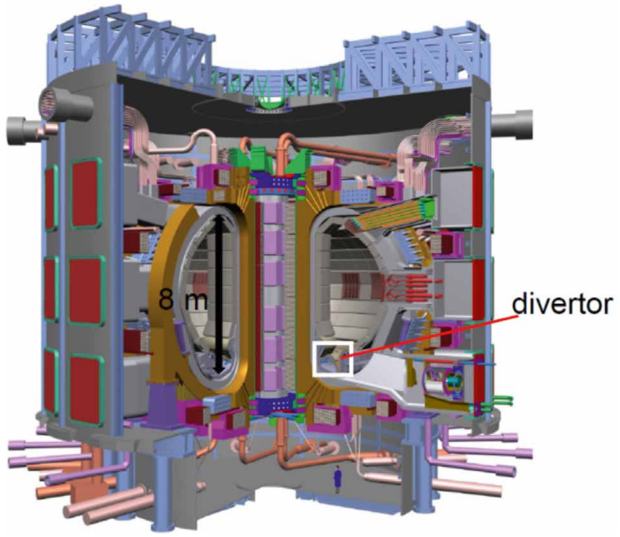

Fig. 1: *CAD model of the Tokamak (https://de.wikipedia.org/wiki/ITER).*

The beams transmitted by the two AOMs are combined by the beamsplitter BS producing two reference and two beams for illuminating the object located in the corridor on a simple table at distance of 23 m from the measuring system. A diverging lens (NL) is used to spread the illumination beam. Some of the light is scattered by the object in the observation direction, where a positive lens (L) forms an image of the object on a CCD sensor. In order to image the object with enough resolution it is necessary to use a lens (L in fig. 3) having large aperture and long focal length. We choose for the experiment a doublet having focal length 2000 mm and a diameter of 250 mm.

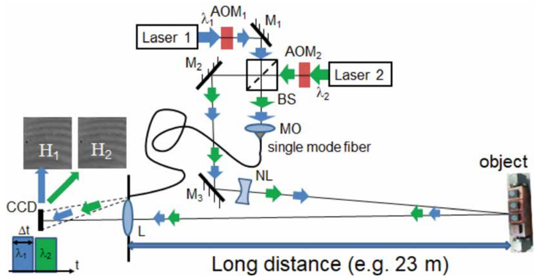

Fig. 2: *Arrangement for fast sequential recording of two holograms with two wavelengths.*

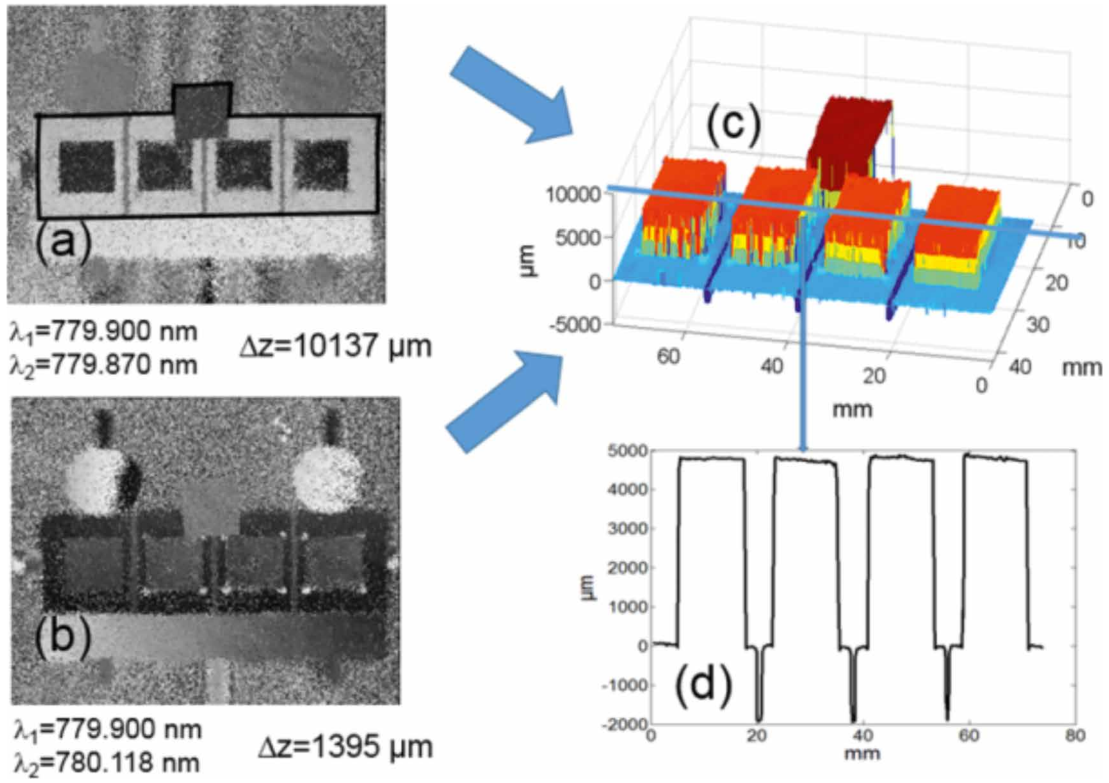

Fig. 3: *Shape reconstruction (c) of the tungsten sample from two phase maps (a), (b) obtained from holograms recorded at the wavelengths: 779.900 nm, 779.870 nm and 779.900 nm, 780.118 nm, respectively. Profile along a line (d).*

The results obtained with the dual wavelength technique strongly depends on the roughness of the sample. In order to investigate if the technique will be suitable for shape measurements inside the reactor a sample with tungsten monoblocks each having a size 12 x12 x 5 mm³ was used. The monoblocks have been exposed to very intense heat fluxes in an electron beam facility to study how tungsten behaves under ITER-relevant conditions. The object was located on a table at a distance of 23 from the imaging lens. The results of the shape reconstruction are shown in fig. 3. The exposure time for recording the two holograms was (2 x 300 µs). Fig. 3(a), (b) show two phase maps obtained from holograms recorded at the wavelengths 779.900 nm, 779.870 nm and 779.900 nm, 780.118 nm, respectively. The figures show the intersection of the object surface with equidistant planes Δz spaced by 10.13 mm (a) and 1.39 mm (b). By combining the coarse information without uncertainty (Δz = 10.13 mm is larger compared with depth of the sample which for the investigated area marked in fig. 3(a) is approximately 8 mm) with the more accurate but with uncertainty information contained in the phase map shown in fig. 3(b), we are able to retrieve the shape of the object (see fig. 3(c)) and its profile along a line (see fig. 3(d)). We did not know the exact shape of the sample and thus we were not able to estimate the accuracy of the measurement. In order to do this, it would be necessary to measure the sample with another method (optical or mechanical).

Supported by: International Thermonuclear Experimental Reactor (ITER).

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

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FEM-Modeling of shearographic phase maps for the defect detection on artwork

D. Buchta, G. Pedrini, W. Osten

The preservation of artwork is an important as well as a challenging task for conservators. In recent times, the increase of museum loan services and the associated increasing number of transports makes this task even more challenging. Especially hidden defects like delaminations or woodworm tunnels in wooden panel paintings are difficult to detect.

While tactile methods are rather unsuitable for the application on artworks, optical techniques provide the possibility of non-destructive testing. Among others shearography has proven its suitability for the detection of sub-surface defects [1]. The typical shearographic setup, shown in fig. 1, consists of an expanded laser beam, a Michelson interferometer, a camera and a loading device. Due to a slightly tilted mirror a self-reference is generated, which makes the setup very robust. The comparison of two states (before and after loading) gives information about the surface displacement induced by the loading and so about underlying damages. The main problem of this technique is the solution of the inverse problem. The measurement only gives information of the surface deformation induced by sub-surface defects and not of the defects itself. To get access to this information, we use FEM-simulations, which generate a displacement-map and calculate afterwards the expected phase maps [2]. By adding multiplicative noise we achieve very realistic simulation results. With this method we create a look-up table for defects with different types, size and depth. As depicted in fig. 2, simulations and measurement matches very well. Because the signal strongly depends on the depth of the defect, a good estimation of the defect depth is possible by analyzing the signal strength. To take other defect parameters into account the matching of the look- up table and the measurement is done by a subtraction of simulated and measured phase maps. The look-up table entry, for which this difference becomes minimal, contains then the information about type, size and depth of the measured defect.

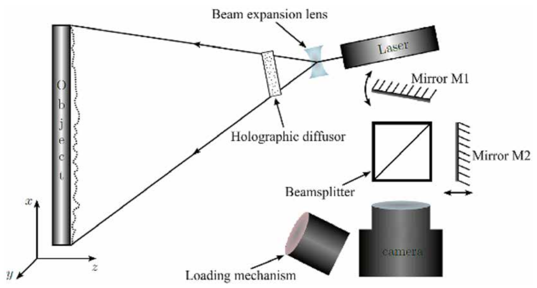

Fig. 1: *Shearographic setup.*

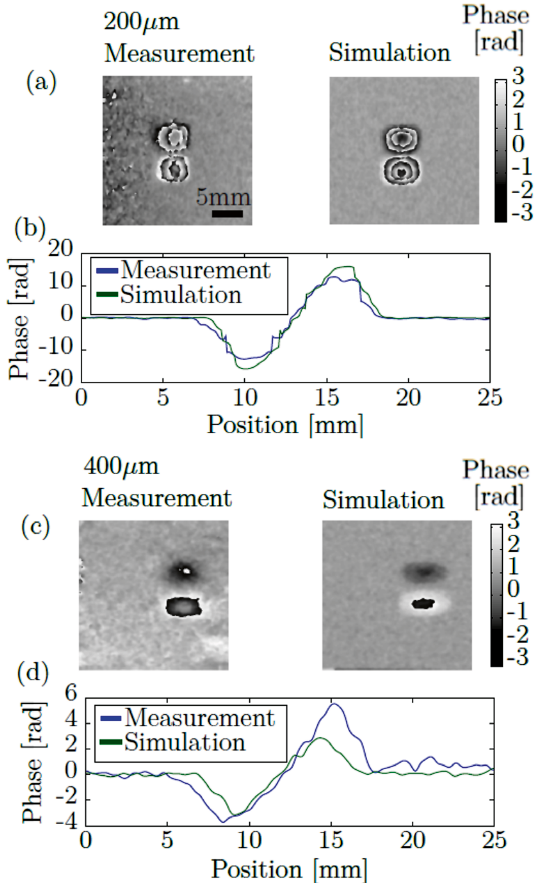

Fig. 2: *Comparison of measurement and simulation for delaminations (10 x 10 mm²). (a) phase maps 200 μm depth. (b) profile lines 200 μm depth (demodulated). (c) phase maps 400 μm depth. (d) profile lines 400 μm depth (demodulated).*

Supported by: DFG German Science Foundation
Project: Die materielle Veränderung von Kunst durch Transporte (OS 111/34-2)
In cooperation with: Staatliche Akademie der Bildenden Künste Stuttgart, Prof. Christoph Krekel

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Deconvolution 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. 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 spatial-incoherently 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), see fig. 1).

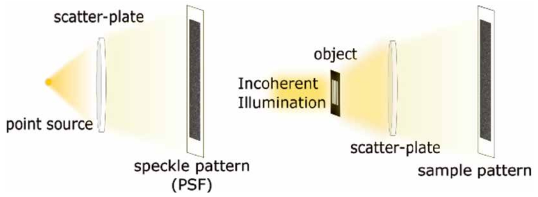

Fig. 1: *Setup: the speckle pattern of a previously recorded point source is cross-correlated with the pattern generated by a spatial-incoherently illuminated sample.*

With our scatter-plate microscope, we achieve diffraction limited resolution (fig. 3 a) [1]. By applying methods of deconvolution we were able to improve the image quality further and achieved a resolution even below 1μm, which is below the diffraction limit determined by the numerical aperture. Deconvolution is based on the knowledge about the transfer function of an imaging system. In the case of the scatter-plate microscope, this transfer function turns out to be the autocorrelation of the recorded point spread function. We found both inverse filter deconvolution approaches (like e.g. the Wiener filter) and iterative deconvolution algorithms suitable for application in scatter-plate microscopy [2–4]. The best results were achieved with the iterative Gold-algorithm and the iterative Jansson-van-Cittert-algorithm (see fig. 2 c) and d) and fig. 3 b).

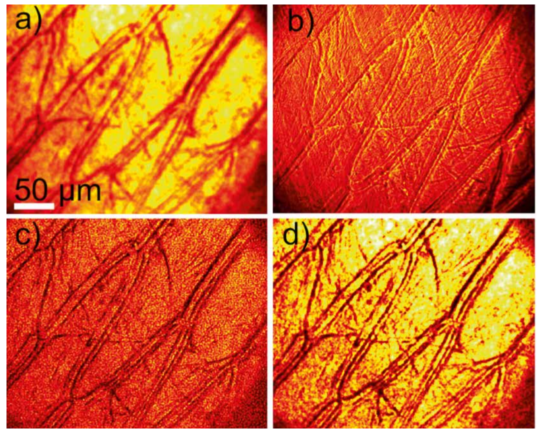

Fig. 2: *Onion cells. a) Scatter-plate microscope, b) conventional microscope objective, c) scatter-plate microscope with Gold deconvolution algorithm c) scatter-plate microscope with Jansson-van Cittert deconvolution algorithm.*

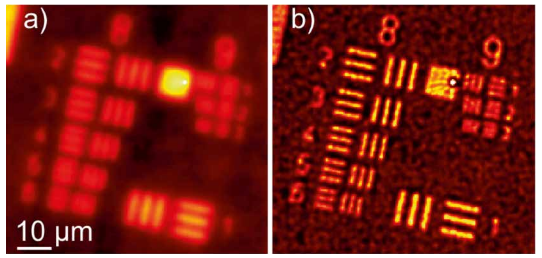

Fig. 3: *USAF test target. a) Scatter-plate microscope, b) scatter-plate microscope with Gold-deconvolution algorithm.*

Supported by: DFG German Science Foundation
Project: High-resolution microscopy using a scattering layer (OS 111/49-1)

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Real-time 3D data acquisition in difficult visibility conditions for road traffic applications

A. Gröger, G. Pedrini, D. Claus, W. Osten

Modern driver assistance systems and, in particular, autonomous driving require the 3D detection of the traffic situation in real time under different weather or visibility conditions. In particular, extreme conditions such as fog, heavy rain or snowfall can greatly affect or even prevent the visibility of pedestrian or objects such as cars or street signs.

The technique proposed for acquiring three-dimensional environmental data corresponds to a macroscopic implementation of the optical coherence tomography (OCT) known from medical technology. Signal detection is based on interferometric principles. The finite coherence length of the light source is exploited, which causes an interference signal to be detected only from a certain depth range. Due to the interference with a reference wave, the light coming from the object is amplified compared to the non-interfering light. This allows the light scattered by fog, snow, smoke or rain to separate from the relevant signal reflected from the object. As in OCT, objects are detected at different distances by varying the reference arm. For the traffic application, a depth range 100,000 times greater than conventional OCT techniques is scanned so that objects can be detected up to a distance of 100 meters.

The increased depth resolution in combination with digital image processing should enable the system to detect and recognize objects, such as pedestrians, animals, cars, and even their movement speeds.

Provided is an active illumination with a pulsed infrared laser. This is designed so that other road users can neither be endangered nor disturbed by the radiation. It should be possible to develop the method compact and robust enough to allow autonomous driving. The development of an operational prototype towards the end of the project period is targeted.

Fig. 1 shows schematically the planned system. The light source used is a pulsed laser with a wavelength of 1064 nm. This wave length is well suited because it is invisible to the human eye, but can still be detected by CCD or CMOS sensors. In the first simulations it was already established that light of this wavelength penetrates very well through fog. The pulse duration is approximately Δt = 6 ns. This corresponds to a light path of 1.8 m (speed of light x Δt). By using appropriate optics and lenses the beam is widened. In future applications, other lasers that emit at slightly shorter wavelengths (900–950 nm) may be used. In this wavelength range, the detectors show a higher sensitivity.

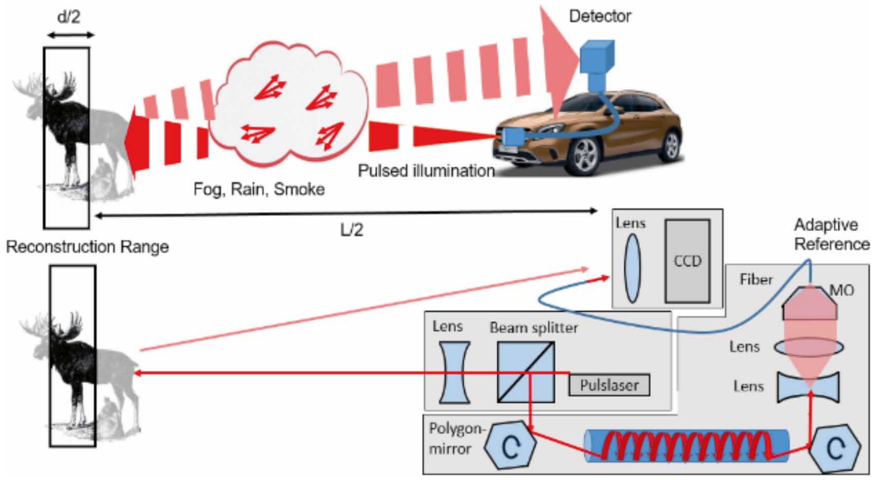

***Fig. 1:** Set-up of the planned system.*

Supported by: Baden-Württemberg Stiftung gGmbH
Project: „Optische Echtzeit-3D-Datenerfassung bei erschwerten Sichtbedingungen für die Anwendung im Straßenverkehr"(ODESSA)
In cooperation with: Institut für Lasertechnologien in der Medizin und Meßtechnik an der Universität Ulm (ILM)

Computational Imaging & Metrology

G. Pedrini, G. Situ, X. Peng, W. Osten

The project "Sino-German Cooperation Group on Computational Imaging and Metrology" aims at further deepening the research cooperation between the College of Optoelectronics Engineering (COE) at the Shenzhen University, the Shanghai Institute of Optics and Fine Mechanics (SIOM) and ITO.

Optical sensing, imaging and metrology systems are central to many fields of science and are ubiquitous across a variety of domains including industry, medicine, defense, commerce, art, and personal recreation. Recovering a full description of a wave from limited intensity measurements remains a central problem in optics. There is continuous motivation to create smaller, lower cost, and more capable optoelectronic systems. This pressure drives a high rate of innovation, with many of the novel systems frequently relying on a high level of synergy between the optical measurement–hardware design and signal processing–computational optical sensing and imaging (COSI).

Major themes investigated in this project are:

1. Measuring projections or transforms of the underlying signal to avoid the limitations of conventional approaches such as in synthetic aperture imaging, which avoids the resolution limit associated with the size of the physical receiver aperture, or holography and correlography methods that entirely eliminate the lens system.
2. Use of a priori knowledge regarding signal properties to achieve improved sensing performance and enable novel sensing methods, such as in the recent developments in compressed sensing.
3. Efficient methods for obtaining information about higher-dimensional optical fields, for example, 3D/4D and light-field sensing.
4. Advanced signal recovery methods for inferring the underlying signal from measurements acquired in complicated transform domains.
5. Quantitative phase imaging (quantitative phase imaging, digital holography, fringe projection profilometry, 4D light field, optical security, etc) fall the category of computational imaging. Optical waves oscillate too fast for detectors to measure anything but time-averaged intensities. This is unfortunate since the phase can reveal important information about the object. When the light is partially coherent, a complete description of the phase requires knowledge about the statistical correlations for each pair of points in space. Recovery of the correlation function is a much more challenging problem.

In all these cases, direct incorporation of signal processing into the system design is required to reconstruct the image or embedded signal in a form and dimensionality that best conveys the information of interest to an observer. High rates of advancement in source, detector, and computational technology are combining to rapidly advance the field of COSI.

The anticipated added-values of the project include the training of young scientists with higher level research, creating international impact on the research of computational imaging and metrology. The research outcomes will be of significance in a broad range of potential applications such as industry, medicine, security, cultural heritage, entertainment, to name just a few.

***Fig. 1:** The opening ceremony of the Sino-German cooperation group on the morning of July 20th, 2018 in Shenzhen.*

Supported by: Sino-German Centre (GZ 1391)

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High resolution digital holographic microscopy applied to surface topography of DOE

V. Cazac, A. Meshalkin, E. Achimova, V. Abaskin, I. Shevkunov,
V. Katkovnik, , D. Claus, G. Pedrini

Advanced nanotechnologies and nanophysics use chalcogenide glasses (ChG) as basic components in engineering of diffractive optical elements (DOE). The optical properties of ChG films, such as absorption coefficient and refractive index, can be changed by light or e-beam exposure. The direct formation of micro and nano-relief on the ChG surface is achieved by polarized coherent radiation. From the application point of view, the phenomena is useful for the production of a variety of high-performance diffractive optical elements (DOE) without any additional/wet development.

The surface relief of the gratings is a main feature determining the quality of DOEs. Due to the high resolution required, the profile and surface of the gratings are conventionally measured via Atomic Force Microscopy (AFM). AFM is a precise technology giving detailed images of samples surface, but the field of view is restricted. In addition, due to the nature of AFM probes, usually it is not possible to measure steep gradients or overhanging structures. AFM is a scanning method, which is time consuming, and requires a complicated software to obtain the sample shape.

Digital holographic microscopy (DHM) is inherently full-field and seems a suitable non-contact approach, which partially overcomes the difficulties imposed by AFM. Fig. 1 shows a comparison between topography and cross-section of gratings measured by digital holography and AFM. For the evaluation of the off-axis holograms with efficient noise suppression an iterative technique (Sparse Phase and Amplitude Reconstruction, SPAR) was used. This algorithm is based on the sparse modeling of the object amplitude and phase. The sparsity hypothesis assumes that there are functions (atoms) such that both the phase and amplitude can be well approximated by series of small number of these functions. From fig. 1 we may see that digital holography combined with the SPAR reconstruction algorithm can be successfully used as an alternative for the phase reconstruction of surface relief gratings and it shows only small difference from the ideal AFM cross-sections.

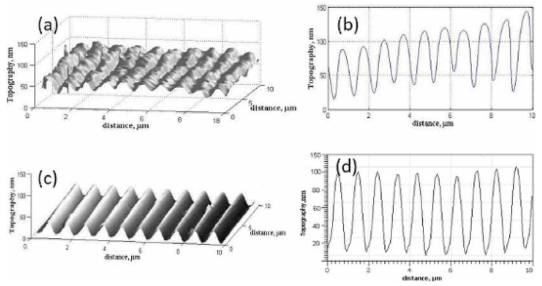

Fig. 1: *3D topography maps and cross-section, of a grating formed on NML As2S3-Se measured by digital holography (a,b) and AFM (c,d).*

Supported by: European Commission,
H2020-TWINN-2015 HOLO project (687328)

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Optical Design and Simulation

Review: Optical Design and Simulation at ITO

A. Herkommer

In 2019 it will be eight years, since the professorship and research group “Optical Design and Simulation” has been established at ITO. A good moment for looking backward, forward, and maybe highlight some recent advances and projects. However, first I need to thank all the supporting companies (and people behind) for this initiative: The companies Trumpf, Polytec, Sick, Leica Microsystems, Karl Storz and Berliner Glas have made this research group possible and I am very grateful for their funding, their cooperation and their advice over the past years.

So what is new in 2017/2018? It is mainly two projects, which turned out to be quite successful and will probably be in the focus within the next years. Those two projects are targeting for different extremes: Our activity in 3D-printing of optical micro-systems is striving for excellence in research, as the method is able to produce optical systems which are not being able to be produced by any other technology. It is amazing to explore possibilities to miniaturize full optical systems, design, 3D-print and qualify them in one day. The vivid cooperation with our partners at 4th Physics Institute in Stuttgart and Nanoscribe turns out to be a very fruitful basis for novel systems and applications. Within the project we were able to win the 2nd best paper award (Simon Thiele) at Photonics Europe and the best student paper and 3rd best design contribution at Photonics West (Andrea Toulouse). As this technology is not only fascinating us, we had the chance to present our research in 2019 at the famous Hannover trade fair and at the Lindau Nobel Laureate Meeting [1], both with the help of Baden-Württemberg-International. It was a great experience to present our research to Nobel-prize winners.

Fig. 1: Two Nobel-prize winners (Ted Hänsch and William Mörner) fascinated by ITO-printed optics, presented by Andrea Toulouse (picture: ITO)

As the project is so successful, we will procure our own Nanoscribe-system in 2019. It will allow us to further explore in complex imaging, illumination and metrology systems in the size of 10 µm–2 mm.

The other main project is not targeting for Nobel-prize winners, but for “Public Sciences”. With our BMBF-project BaKaRoS[2], we have successfully developed an optical kit, which enables makers, students or school kids to build up several optical experiments and create photonic ideas of their own. The opto-mechanics is based on our partner fischertechnik, which allows easy and accurate construction. With the other partner Fraunhofer IAO we have extensively used this kit to provide workshops for all levels of expertise, from school kids up to industry partners. As the photonic kit proved to be very useful for educating optics and also to create prototypes, we will try to continue this activity via another BMBF-project and as a tool at ITO for educating optics.

Fig. 2: The optical kit BaKaRoS, used by in a workshop for kids (picture: ITO).

Both projects “Printoptics” and “BaKaRoS” are not only a great source of funding, research and networking, but both of them are also supporting other activities in optical design: Printed surfaces are one way to explore freeform surfaces, and BaKaRoS allows us to aim for more holistic designs, integrating camera and image processing into the design process.

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[2] https://www.bakaros.de/

3D printed freeform micro-optics: Complex designs with diameters from 100 µm to 1.5 mm

S. Thiele, S. Ristok, A. Toulouse, J. Drozella, H. Giessen,
A. Herkommer

Femtosecond direct laser writing is a well published fabrication method for freeform micro-optics of high complexity [1]. Examples of multi-lens systems directly printed onto imaging sensors, miniature concentrator optics for light emitting diodes, beam shaping at the tip of optical fibers or achromatic compound lenses could be demonstrated in collaboration with the 4th Physics Institute.

Typical lateral dimensions of these components are in the range of few hundreds of micrometers, which, thanks to small apertures, enables components with small wavefront errors. However, in order to fully exploit the commercial potential of this technology, the fabrication of highly precise structures on the millimeter scale is highly desirable.

Our recent experiments demonstrate that complex lenses, e.g. hybrid refractive-diffractive aspheres can be directly printed with diameters of >2 mm without the necessity of stitching. A root mean square (RMS) surface roughness of less than 20 nm was measured for these lenses. In order to determine shape deviations, an aspheric lens with a diameter of 1.5 mm was fabricated. The initial peak-to-valley shape deviations of ~10 µm could be reduced to values of below 1 µm over the whole aperture through iterative improvements.

One of the most challenging aspects of high printing volumes is an increased writing time. Thanks to special trajectory planning, initial fabrication times of ~40h for a lens with 1.5 mm in diameter could be reduced to less than 2h. Potential for further improvements has been identified.

An overview of the results is displayed in fig. 1 which compares two smaller doublet lens systems with results from the newly established writing mode for millimeter sized lenses. The 3D surface profile shows a close resemblance to the design and reveals a smooth and non-distorted shape. All lenses show that the quality is sufficient for imaging applications.

In order to improve the commercial viability of this technology, productivity will be increased. Furthermore, the performance of embedded diffractive structures can be improved by reducing rounding effects at the zone boundaries. We aim to achieve this through specific changes to the direct laser writing process. As a next step, the demonstrated single surfaces will be combined to monolithic assembly-free lens stacks of multiple components. We aim to achieve distortion-free imaging with megapixel resolution combined with high image contrast thanks to integrated absorptive structures [2].

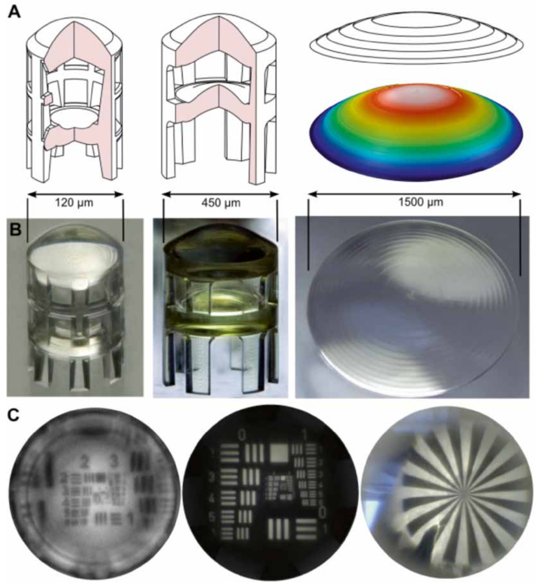

*Fig. 1: **A**, CAD models of doublet designs and a hybrid refractive-diffractive singlet lens with a diameter of 1.5 mm including its surface measurement. **B**, White light microscope images of the fabricated results. **C**, Obtained images through the different lenses from B.*

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Projects: “Printoptics” (BMBF 13N14096) and “Opterial” (BW-Stiftung).
In cooperation with: 4th Physics Institute.

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[1] Malinauskas, M.; et al. “Ultrafast laser nanostructuring of photopolymers: A decade of advances”, Physics Reports 533 (2013).

[2] Toulouse, A.; et al. “Alignment-free integration of apertures and nontransparent hulls into 3D-printed micro-optics”, Optics Letters 43, 5283-5286 (2018).

Aperture fabrication process for 3D-printed micro-optics

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

The fabrication of high-quality imaging micro-optics via femtosecond direct laser writing is state of the art [1]. The images formed by these lenses, however, often lack contrast since both lenses and lens mounts are fabricated of the same transparent photopolymer. Stray light can therefore penetrate into the system along unwanted paths and consequently degrade the image contrast. In order to improve imaging quality, we present a super-fine inkjet process as an easy-to-use and self-assembling approach to augment 3D-printed micro-optics with well-defined apertures and non-transparent hulls.

Our imaging 3D-printed micro-optics have typical dimensions in the order of 100–500 µm. The lens mounts and apertures are designed with a thickness of 10–30 µm and comprise a system of microchannels, which is printed simultaneously with the lens. In a second step, the microchannel system is filled with a metallic nanoparticle ink in the super-fine inkjet printer. Here, a thin needle with a tip width of single micrometers is aligned to a port of the microchannel (see fig. 1). The needle incorporates an electrode and as an electric field pulse is applied, the ink is extruded from the needle in volumes as small as 0.1 fl to 10 pl. The ink is then guided through the pre-defined microchannel system via microcapillary forces and the created absorbing structures are thus perfectly aligned to the lens system.

The world's first 3D-printed micropinhole camera highlights the importance of non-transparent structures for micro-optics (see fig. 2). While the image of a fully transparent micropinhole camera is dominated by stray light, image formation is evident for a micropinhole camera with aperture and shielding black hull fabricated by our super-fine inkjet process.

This super-fine inkjet process is applicable for a multitude of 3D-printed micro-optical systems. In excess of mere contrast improvement, apertures can be created to add functionality e.g. for telecentricity or spatial filtering. Furthermore, the realization of smooth reflective films for mirrors and catadioptric designs is conceivable. The process can also be employed to fill cavities with functionalized liquids such as liquid crystals or magnetic particle fluids.

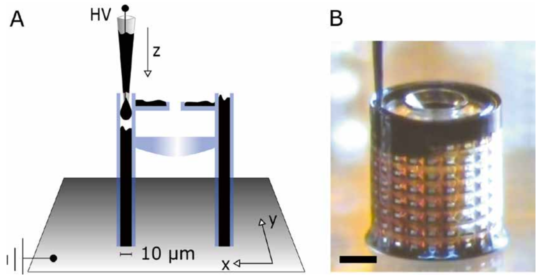

Fig. 1: *__A__, Scheme of the super-fine inkjet process. __B__, 3D-printed micro-lens during the inkjet process of its hull. Scale bar: 150 µm. [2]*

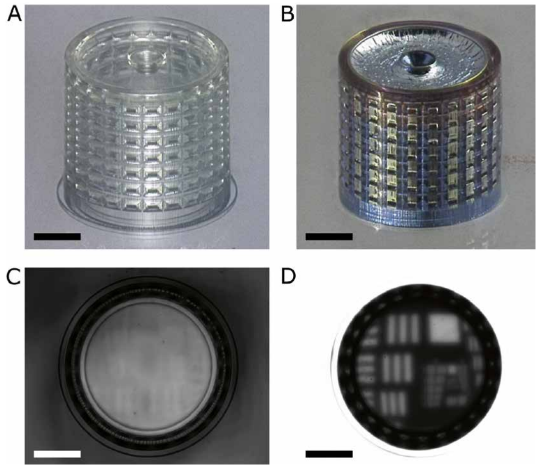

Fig. 2: *__A__, Fully transparent 3D-printed micropinhole camera. __B__, micropinhole camera with aperture and non-transparent hull. __C__ and __D__, images of a USAF 1951 resolution test chart in the image planes of the micropinhole cameras above, respectively. Scale bars: 100 µm. [2]*

Supported by: Bundesministerium für Bildung und Forschung, Baden-Württemberg Stiftung, European Research Council
Projects: Printoptics, Printfunction, Opterial, ComplexPlas
In cooperation with: 4th Physics Institute and Research Center SCoPE, University of Stuttgart.

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[1] Gissibl, T.; Thiele, S.; Herkommer, A.; and Giessen, H. "Two-photon direct laser writing of ultracompact multi-lens objectives". Nature Photonics, 10(8), 2016.

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

Bionic approach for the design of a virtual reality headset

A. Toulouse, S. Thiele, A. Herkommer

Virtual reality (VR) has been highlighted as one of the emerging technologies in the Gartner Hype Cycle for several years. In 2016, it left the Disillusionment Valley and has been on the Slope of Enlightenment since. Remaining issues are the enormous eye box, the vergence-accomodation conflict and reaching the foveal angular resolution of the human eye.

In order to address these deficiencies we present a bionic approach for the design of a VR headset which is visualized in fig. 1. The basic idea is to image the pupil of the human eye to the pupil of a bionic copy, the "display eye" (see fig. 2). The "display eye" has similar characteristics and abilities as the real eye, namely rotation, focus variation, and (foveated) display resolution. In detail, this means that the movement of the real eye is tracked and the display eye performs a synchronized counter-rotation to keep the foveal spot at the center of the display eye. Thus, the eye box is effectively reduced for the display system and only the central imaging system has to cover it completely. Furthermore, the display consists of a high resolution microdisplay at the center and can have additional low resolution peripheral displays. The pixel density thus mimics the cone cell density of the real eye and allows us to reach the acuity limit at the fovea in terms of pixel density. Finally, the "display eye" has a well-defined pupil position, which is ideal for the implementation of a varifocal lens to shift the virtual image of the display to finite distances and thus force our real eye to refocus which solves the vergence-accomodation conflict.

The basic concept has been transferred into an actual optical design (see fig. 3). This design covers a full field of view of 70° and diffraction limited performance at the foveal spot for up to 15° eye rotation. Here, 30 px/° (20/20 vision) can be reached with a commercially available 20 mm 2k microdisplay only, compared to necessary 4k microdisplays in conventional designs.

The presented optical design is a proof of concept that does not yet contain a varifocal lens or cover the desired 210° horizontal total field of perception of the moved eye [2]. However, it is highly extendable and meets all requirements to include a varifocal lens or additional peripheral displays without limiting resolution at the fovea (further designs available in ref. [1]).

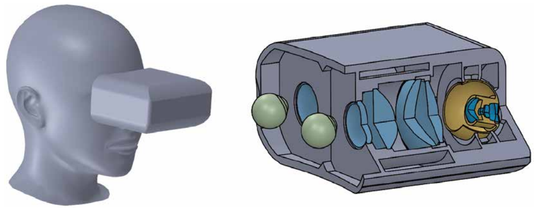


Fig. 1: *Visualization of the bionic VR system implemented into a headset. [1]*

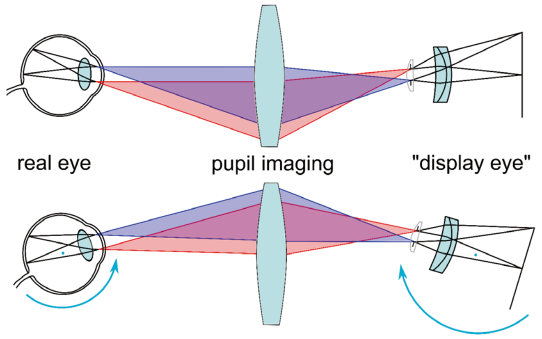


Fig. 2: *Basic concept of the display system. A central lens images the pupil of the real eye to the pupil of its bionic copy, the "display eye". As the real eye rotates, the "display eye" counter-rotates synchronously and thus keeps the foveal spot at the center of the display. [1]*

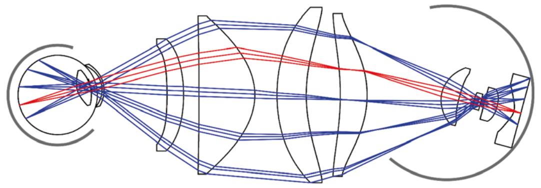


Fig. 3: *Monochromatic optical design of the bionic VR system. The pupil imager consists of four aspherical lenses to cover 70° full field of view on a 20 mm 2k microdisplay with 30 px/° angular resolution. The field, which originates from the center of the display system, stays at the foveal spot when the eye is rotated (red, here 15° rotation). [1]*

Supported by: Research center SCoPE of the University of Stuttgart.

References:

[1] Toulouse, A.; Thiele, S.; and Herkommer, A. "Virtual reality headset using a gaze-synchronized display system". Proc. SPIE 11040, 2019.

[2] Singer, W.; Hillenbrand, M.; and Münz, H. "Tackling the challenges of fully immersive head-mounted AR devices". Proc. SPIE 10590, 2017.

Fast and comfortable GPU-accelerated wave-optical simulation of 3D-printed freeform microlens systems

J. Drozella, S. Thiele, A. Herkommer

Advances in 3D-printing technology lead to the availability of highly complex free-form optical systems on a scale up to 2 mm. While geometrical imaging errors scale with the system size, the wave-description of optical electromagnetic fields does not. Therefore, wave-optical effects have to be considered in the development of small-scale optics, as they can dominate imaging performance of geometrically optimized microlens systems.

Wave-optical simulation can be performed using rigorous calculation toolboxes like FDTD or FEM, which try to solve Maxwell's equations for electromagnetic fields with as little approximation as possible. These calculations come with large requirements to calculation hardware and time as well as user proficiency, particularly for 3-dimensional calculation, and are usually only reasonably applicable to very small systems of sizes to about 100 µm.

In order to allow for a faster and more comfortable wave-optical simulation of micro systems, we adapted the approach of the Wave Propagation Method [1], which is based on the scalar Helmholtz-equation.

Provided as a plugin algorithm for the Institutes open source software ITOM it allows for the simulation of a number of different inputs without the need for extensive preparation. Zemax models can directly be imported for wave-optical simulation. Changes to the systems can easily be made, even allowing for the replacement of surfaces with topologies from measurements.

Simulation results can be analyzed in multiple ways. Using a cross-section of the electric field propagation along a center plane of the system (see fig. 1), a good overview and estimation of the optical performance can be achieved. Freely selectable planes perpendicular to the optical axis allow an analysis concerning spot diameters or imaging performance. All output data is available as ITOM dataObject-matrices and can be processed using internally provided routines, Python libraries, or exported to third-party tools. This way, points of highest intensity, extraction of representative curves, or image analysis can be performed.

Advantages of using wave-optical approaches as an addition to common ray-tracing tools like Zemax can especially be found in the ability to model diffractive elements as volumes, instead of thin phase-elements (fig. 2). Additionally, a wave-optical simulation is able to display multiple diffraction orders simultaneously.

The implementation is focused both on speed of calculation, combining computing power of CPUs and GPUs, as well as comfortable usability, while maintaining numerical accuracy and memory requirements appropriate to regular desktop PCs.

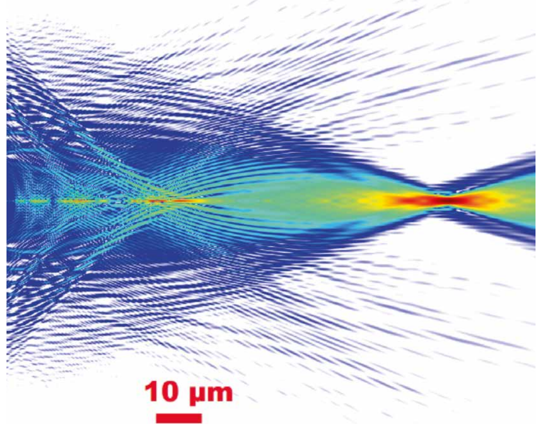


Fig. 1: *Center-cross-section of logarithmic intensity distribution resulting from a diffractive structure on the end of a monomode fiber used for optical trapping. Multiple diffraction orders are visible.*

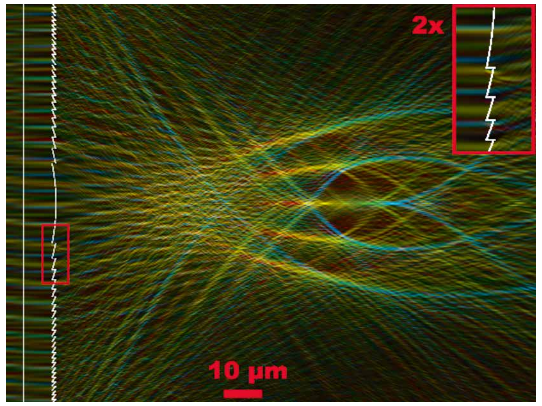


Fig. 2: *RGB-representation of a DOE-singlet-lens simulated in 3D for 5 angles of incidence and 10 wavelengths. Overlaid lens outlines in white.*

Supported by:
BMBF-Project: Printoptics BW-Stiftung
Project: Opterial

References:

[1] Schmidt, S. et al. "Wave-optical modeling beyond the thin-element-approximation." Optics Express 24 (26), pp. 30188–30200, 2016.

Development of a low-cost 3D microscope

C. Reichert, F. Würtenberger, A. Herkommer

Using digital 3D microscopy, magnified three-dimensional images of small objects can be created and surface structures can be examined and measured without contact. This makes them an ideal component for industrial and medical applications.

For the 3D reconstruction, images from different planes of an object are taken with the microscope. The 3D image of the object can then be reconstructed from the recorded image stack. The corresponding depth is for each image determined by means of a sharpness calculation and a depth map is created (see figure 1). This depth map can then be displayed graphically in a 3D image, but also as STL model or as a color-coded image.

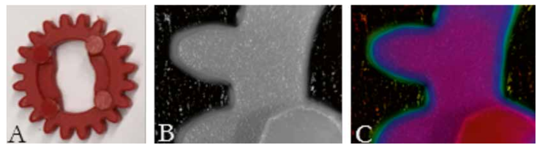


Fig. 1: ***A****: fischertechnik gear,* ***B****: Depth of field image,* ***C****: Height map coded in the colors.*

As part of the research project BaKaRoS (www.bakaros.de) to develop optical systems that can be easily replicated in schools, the 3D microscope shown in fig. 2 was developed, including recording and reconstruction software. To build the 3D microscope we used inexpensive materials like a webcam, fischertechnik building blocks and lenses (focal length 40 mm) that are used in education areas. The material costs of the built 3d microscope are approximately 70 euro.

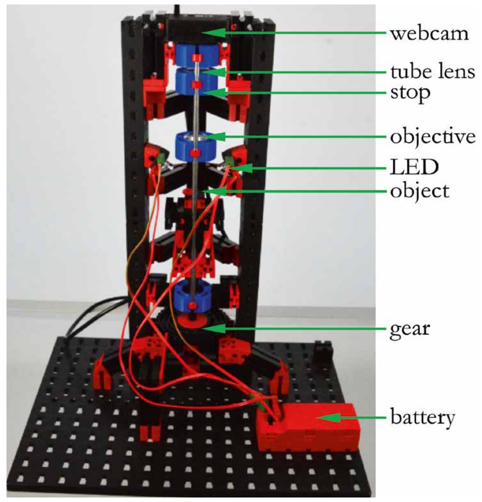


Fig. 2: *Structure of the 3D Microscope.*

In the microscope shown here, the object is moved through the focal plane using a height-adjustable microscope slide. The height adjustment is done with a screw that can be moved in a defined way using the gearwheel. A further rotation of the gear wheel around one tooth, corresponds to a change in height of about 75 micrometers. To generate the image stack, the user must rotate the gear wheel by hand and take an image for every position of the object.

As with all digital microscopes, the imaging system of the microscope consists of an objective lens and a tube lens. A diaphragm is mounted below the tube lens at the focal point of the objective lens on the image side. This is intended to ensure that the system is telecentric on the object side and thus the image position or magnification remains constant even with small displacements of the object. Since the images are superimposed in a stack for the reconstruction, it is essential for an exact reconstruction that the object does not move in the image field or at least hardly moves at all. The optic design of the 3D microscope is shown in fig. 3.

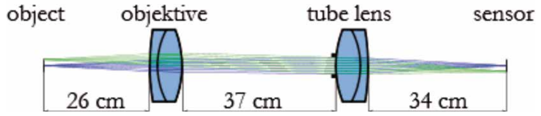
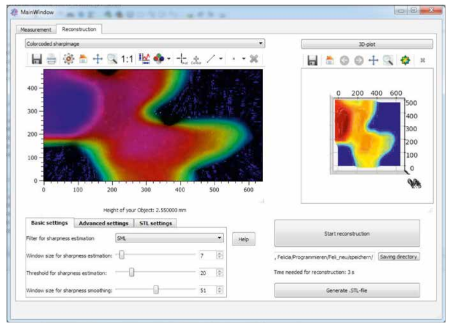


Fig. 3: *Optic design of the 3D microscope.*

The recording and reconstruction algorithm were written in the freely available measurement and evaluation software "ITOM" and summarized in a GUI (see figure 4) with instructions. The user can select different camera parameters and filters (e.g. min_max_range or 7x7 sobel) and export the 3d image as STL file.



Height of your Object: 2.550000 mm

Filter for sharpness estimation: SML

Window size for sharpness estimation: 7

Threshold for sharpness estimation: 20

Window size for sharpness smoothing: 51

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Time needed for reconstruction: 3 s

Fig. 4: *GUI of the 3d microscope.*

Supported by: BMBF initiative "Open Photonics" ('BaKaRoS'). FKZ 13N14168.

Holistic optimization of optical systems

C. Reichert, R. Kumar, T. Gruhonjic, A. Herkommer

The functional components (camera, imaging system, image processing software) of an optical system are currently often simulated and optimized separately. For example, commercially available optical design programs such as Zemax or Code V do not offer a standard way of incorporating the characteristics of the sensor or image processing processes into the merit function. However, these components can have a decisive influence on the quality of the image and should be considered when developing the optical system. For example, within a digital optical system, certain aberrations such as color aberrations or distortion can be corrected by image processing. These aberrations should therefore only play a reduced role in the design of the optical system.

The research deals with an approach of holistic optimization for optics in one open software environment. We focus on (i) develop an open optic design software from scratch, (ii) a multi-objective approach that considers not only the image quality, but also the post image processing, (iii) broad exploration of the holistic design space to get the best possible trade-off solutions. The final software is open source available to all, and everyone can contribute to improve it in future. In the software post processing of the image is an integral part of the optimization of the optical system.

We have developed our own optimization algorithm GLOW (Genetic Local Optimization Winner) in C++ for the design of complex optical systems. For this purpose, the evolutionary genetic algorithm was combined with a local optimizer (see fig. 1). With the help of the genetic algorithm, the optimizer is able to determine a good result without getting stuck in a local optimum. After an abort criterion the genetic optimizer switches to the local mode and optimizes the system until another abort criterion is reached. In order to verify the performance of the optimizer, the same systems were optimized under the same conditions with Zemax. The results were then statistically evaluated and compared. It has been proven that the GLOW Optimizer is able to successfully optimize simple and complex optical systems and find several different solutions for a given problem.

For the image simulation we first calculate the position of the exit pupil. Second, we trace rays along the optical system to calculate the optical path difference (OPD) map at the exit pupil. We do an interpolation to find PSFs at all the field points. After that we convolve the 2D object with the 4D PSF matrix to get the simulated image. The comparison with the image simulation of Zemax shows, that our algorithm works (see fig 2).

To do the holistic optimization we have to include the postprocessing of the simulated image in the GLOW optimization (see fig. 3). We calculate a value V to compare the post processed image with the original object and put that in the merit function. In summary, the holistic approach and software allows an optimization for overall simpler but powerful optical systems.

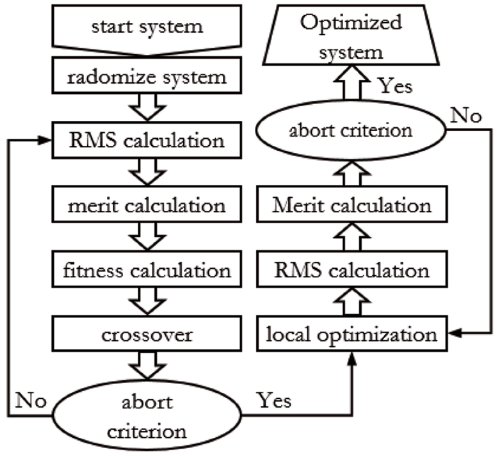

Fig. 1: *Functionality of the GLOW optimizer.*

Fig. 2: *Results of image simulation.* ***A****: with our algorithm,* ***B****: with Zemax.*

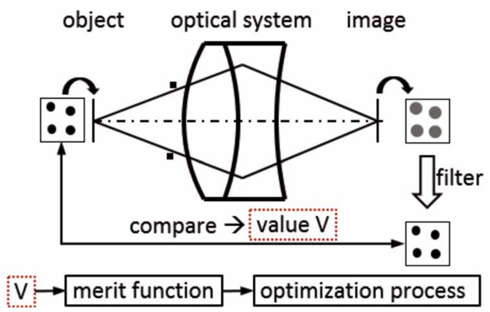

Fig. 3: *Process flow of optimization.*

Supported by: BMBF initiative "Open Photonics" ('BaKaRoS'). FKZ 13N14168

Design of illumination systems for extended sources

D. Rausch, A. Herkommer

Illumination design usually requires the collection of a large solid angle of radiation from the light source. However, it is known that for example high NA conic reflectors in combination with extended light sources result in a non-uniform irradiance profile. Reason behind is that many illumination elements are based on the assumption of non-physical point sources. However realistic light sources are exhibiting a finite area or volume, which together with the large angular emission characteristics correspond to a noticeable etendue. This needs to be considered during illumination design.

We propose an illumination design method based on the analysis of phase space transformations, which includes the source extension from the very beginning. Illustration and evaluation of the local mapping of the source to the target radiance distribution in phase space allows a more profound understanding of the underlying effects and limitations and in consequence an appropriate optical design concept for correction of the uniformity at the target.

Figure 1 shows an example of an ideal conic reflector, which will perfectly image a point source to the secondary focus. However if a uniform extended source is used, the resulting radiance distribution is non-homogeneous. This can be easily understood form an analysis of the corresponding phase-space transformation, which illustrate the transformation of ray-angels (u) and positions (x) from source to target. The system reveals an non-linear distortion of phase space, corresponding to a varying angle-dependent magnification.

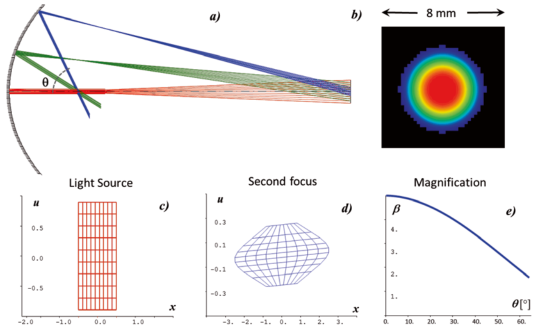

Fig. 1: *a) ray-tracing of an extended source for various angles b) irradiance at the second focus for a uniform circular source; c) phase space of the source; d) mapped phase space on the second focus; e) magnification versus source object angle.*

Once the optical effect is understood the skilled illumination designer can deterministically develop solutions, respectively correction elements. In the above example we need an optical element, which can change the magnification without changing the location of the secondary focus. An appropriate correction element can be realized by a thick lens, as shown in fig. 2. The front and back surface of the thick lens must be highly aspheric, or in the general case a freeform lens, since the lens provides a telescopic effect, drastically changing in order to compensate the effect of the varying magnification.

The example proves that an analysis of the radiance transformation properties of illuminations elements and systems can provide deterministic recipies for the improvement of illumination systems.

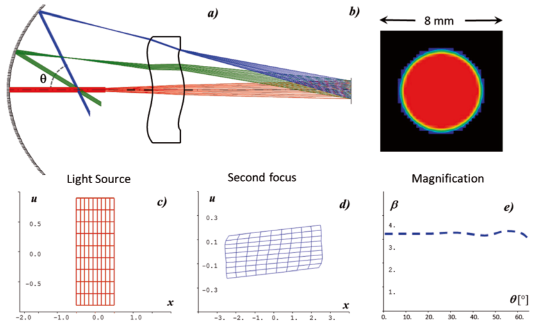

Fig. 2: *Similar analysis as presented in fig. 1, but including a thick aspheric correction lens, which provides a varying telescopic effect to compensate the magnification change from the ellipse.*

Supported by: the Research Center SCoPE, University of Stuttgart.

References:

[1] Rausch, D.; Rommel, M.; Herkommer, A. and Talpur, T. "Illumination design for extended sources based on phase space mapping". Optical Engineering, 56(6), 065103 (2017).

[2] Rausch, D. and Herkommer, A., "Design of a freeform uniformity corrector lens for extended sources in elliptical reflectors" . Accepted for publication in JPhys Photonics (2019).

Matrix-based Aberration Calculus of Freeform Optical Systems

B. Chen, A. Herkommer

Since the early days of optics the classical shape of an optical surface used to be spherical or at least rotational symmetric, mainly because for this shape accurate manufacturing methods have been available. Today's optics manufacturing capabilities allow freeform surfaces, which offer the optical designer additional degrees of freedom to achieve good imaging properties, especially in compact folded geometries. However, visualization and calculation of aberrations for non-rotational symmetric systems is complex.

We have developed a simple method for calculation of surface resolved aberrations in freeform systems. In this method we employ the 4d-phase space representation of the optical system and analyze the local transformations of the ray positions and angels. Extraction of the linear system behavior and comparison to real ray-tracing behavior allows a general visualization of aberration generation and aberration propagation in freeform systems. Also mathematically the individual surface aberration contributions can be calculated.

An example is illustrated for the freeform prism system as shown in fig. 1, which is employed in many AR/VR applications. Based on a reference ray we can define a series of "dummy" planes into any ray-tracer to analyze the ray-propagation in the 4d-phase space (x,y,u,v).

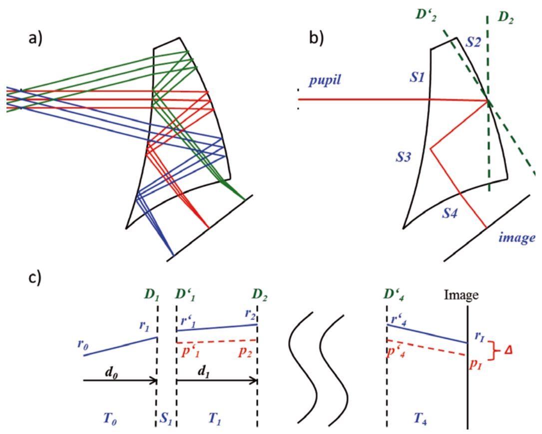

Fig. 1: *Illustration of a patented freeform prism (a) and corresponding location of auxiliary reference planes (b), leading to an unfolded auxiliary system of a sequence of dummy surfaces (c).*

For every ray we can record the real ray-tracing behavior before (r) and after (r') each dummy surface. We can furthermore compare the behavior to the paraxial ray-tracing along the reference ray, which is described by a number of paraxial matrixes S and T, respectively the sequence M. This propagation in the 2d-phase space (x,u) is illustrated in fig. 2 .

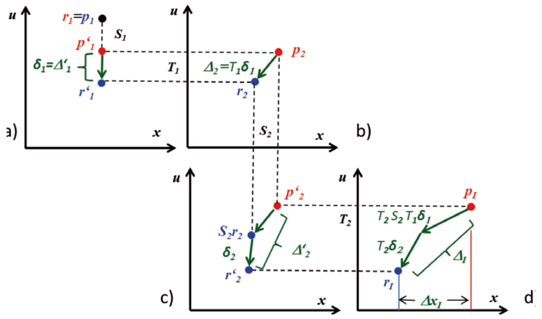

Fig. 2: *Illustration of aberration propagation in phase space, where a) to b) represents the free propagation to surface S2, b) to c) illustrates the action of surface S2, and c) to d) resembles propagation to the image.*

By employing some simple matrix mathematics, we were able to show that the exact aberration contribution at the image Δ, of each surface for every ray including all orders can be calculated, via:

$$\Delta^{i}_{I} = \mathbf{M}_{I,i}(\mathbf{r}'_{i} - \mathbf{S}_{i}\mathbf{r}_{i})$$

Here M corresponds to the paraxial propagation matrix form surface I to the image, and r and r' are ray data.

The method is carried out in the general 4d-phasespace and is not limited to any assumptions about symmetry or surface shape. In summary it allows for exact aberration calculation in freeform systems.

Supported by: the Research Center SCoPE, University of Stuttgart.

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[1] Herkommer, A. "Phase-Space Representations of Freeform Optical Systems." Optical Encyclopedia (2018): 205-215.

[2] Chen, B. and Herkommer, A. "Generalized Aldis theorem for calculating aberration contributions in freeform systems" Optics express, 24(23), 26999-27008 (2016).

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Exploiting the whole Information Content of the Light Field: Approaches & Limitations

Applied Optics and Photonics China - AOPC 2017, Beijing, China, June 2017

W. Osten

Exploiting the whole Information Content of the Light Field: The Role of Polarization and of the Angular Spectrum

Conress Physics Society of the Philippines, Cebu, Philippines, June 2017

T. Haist

Using spatial light modulators

SLM -Tutorial at the New SPIE Digital Optical Technologies conference, Munich, Germany, June 2017

W. Osten

Exploiting the whole information content of the Light Field: The role of Coherence and Time of Flight

9th International Conference on Information Optics and Photonics – CIOP 2017, Harbin, China, July 2017

A. Herkommer

Surface Resolved Aberration Contributions in Freeform Optical Systems

IODC, OF&T Congress, Denver, USA, July 2017

S. Thiele, S. Ristok, K. Arzenbacher, H. Giessen, A. Herkommer

Complex Micro-Optics by Femtosecond Direct Laser Writing

IODC, OF&T Congress, Denver, USA, July 2017

W. Osten

Exploiting the whole Information Content of the Light Field: Approaches & Limitations

MediNano, Amalfi, Italy, September 2017

W. Osten

Taking advantage of the whole information content of the light field: Approaches and Limitations

59 IWK Symposium, Ilmenau, Germany, September 2017

W. Osten

Taking advantage of the whole information content of the light field: Approaches and Limitations

Holography Symposium, Kaliningrad, Russia, October 2017

W. Osten

Exploiting the whole information content of the light field: Approaches and Limitations

Phase2Phase Conference Delft, Netherlands, October 2017

W. Osten

Exploiting the whole information content of the light field: Approaches and Limitations

3D Nordost, Berlin, Germany, December 2017

Invited lectures on international conferences

2018

W. Osten

Shaping the light for the investigation of depth-extended scattering media

BIOS 2018, Photonics West, San Francisco, January 2018

S. Thiele, A. Toulouse, S. Ristok, K. Weber, M. Schmid, H. Giessen, A. Herkommer

Complex freeform micro-optics by femtosecond laser direct writing

SPIE Photonics West 2018 – LASE, San Francisco, USA, January 2018

W. Osten

How to drive an Optical Measurement System to outstanding Performance

OPTO 2018, San Francisco, February 2018

W. Osten

Some unconventional ways to use a scattering media for optical Imaging

Photonics Europe 2018, Strasbourg, France, April 2018

W. Osten

How to design an Optical Measurement System with outstanding Performance

icOPEN, Shanghai, China, May 2018

W. Osten

Optical Metrology – Tutorial

euspen 18th International Conference and Exhibition, Hannover, Germany, June 2018

W. Osten

Exploiting the whole information content of the light field: Challenges, Approaches and Limitations

JDCB – Joint Japan-German Workshop, Berlin, Germany, June 2018

W. Osten

New approaches for the investigation of depth-extended scattering media

Light Conference, Changchun, China, July 2018

W. Osten

Optical Metrology: The long and unstoppable way to become an outstanding measuring tool

Speckle 2018, Janow Podlaski, Poland, September 2018

S. Thiele, P. Geser, A. Toulouse, S. Ristok, H. Giessen, A. Herkommer

Printed freeform micro-optical systems

EOSAM 2018, Delft, Netherlands, October 2018

W. Osten

Machine Vision: Improving the Information content of Image Data by Exploitation of the full Information Capacity of the Light Field

ICMV 2018, Munich, Germany, November 2018

W. Osten

Digitale Transformation – Herausforderung und Chancen für die Optische Messtechnik

WLT-Spectaris Workshop, Berlin, Germany, November 2018

W. Osten

Holografie – ein Verfahren jenseits der stereoskopischen Bildgebung

Campus Innovation 2018, Hamburg, Germany, November 2018

W. Osten

Different Approaches for Resolution Enhancement in Optical Micro and Nano Metrology

11th ODF, Hiroshima, Japan, November 2018

A. Herkommer

Printed optics – changing the rules in optical system design

Photonik-Forum Baden-Württemberg, Stuttgart, Germany, November 2018

Editorial work

Banerjee, P.; Osten, W.; Picart, P.; Cao,L.; Nehmetalla, G. (Eds.):

Digital Holography and 3D Imaging: Joint feature issue in Applied Optics and Journal of the Optical Society of America B

Applied Optics, Vol. 56 (May 2017), Doc. ID 292363

Lehmann, P.; Osten, W.; Albertazzi, A. (Eds.):

Optical Measurement Systems for Industrial Inspection X

Proc. SPIE Vol. 10329, Bellingham 2017

Gorecki, C.; Asundi, A.; Osten, W. (Eds.):

Optical Micro- and Nanometrology in Microsystems Technology VII

Proc. SPIE Vol. 10678, Bellingham 2018

Osten, W., Tornari, V.:

Methods for the non- and minimally invasive evaluation of works of art

Strain: Vol. 54., No. 3, 2018 and Strain: Vol. 55 No. 2, 2019

Herkommer, A., Duerr, F.

Interdisciplinary Simulation

Advanced Optical Technologies No. 2, 2019

Awards

2017 – June 2019

G. Baer:

Winner of the „Prize for special scientific achievements“ of the „Vereinigung von Freunden der Universität Stuttgart“ for his dissertation “Ein Beitrag zur Kalibrierung von Nicht-Null-Interferometern zur Vermessung von Asphären und Freiformflächen”, 2017

S. Thiele, A. Herkommer:

Winner of the first price “Ideenwettbewerb 3D-Druck der Baden-Württemberg Stiftung” at the „Forschungstag 2017“

W. Osten:

Honorary Doctor Degree Dr.-Ing. E.H. of the University of Technology Ilmenau, Germany, 2017

C. Pruss, G. Baer, J. Schindler, W. Osten:

Rudolf Kingslake Medal and Prize of The International Society for Optics and Photonics SPIE, 2018

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“.

W. Osten: Board Member

W. Osten

Elected Member of the Board of Directors of the SPIE for 2015-2017

W. Osten

Member of the Advisory Board of the Dept. “Mechanical Engineering” of the Worcester Polytechnic Institute, Worcester, USA

W. Osten

Member of the Advisory Board of the “Centre for Optical and Laser Engineering” in the School of Mechanical and Aerospace Engineering at the Nanyang Technological University, Singapore

W. Osten

Member of EAC - The European Advisory Committee of SPIE

W. Osten

Member of the Supervisory Board of the Hahn-Schickard-Gesellschaft, Baden-Württemberg

W. Osten

Member of the Advisory Board of the Kiepenheuer Institute for Solar Physics, Freiburg

W. Osten

Head of the Advisory Board of the Centre for Sensor Systems ZESS, Siegen

W. Osten

Member of the Scientific Advisory Board of the Res. Community for Precison Mechanics, Optics and Medical Engineering FOM, Berlin

W. Osten

Member of the Advisory Board of The Hannover Center for Optical Technologies HOT, Hannover

W. Osten

Member of the Steering Comm. of the Congress “Laser – World of Photonics” in Munich, biennial international congress

W. Osten

Member of the VDI/VDE – GMA Advisory Board FB 8 “Optische Technologien”

W. Osten

Member of the International Program Committees of numerous International Scientific Conferences

Membership of Editorial Boards

W. Osten

Co-Editor of the Journal
“Applied Physics B: Lasers and Optics”

W. Osten

Member of the Editorial board of the Nature Journal “Light: Science & Applications”

W. Osten

Member of the Editorial board of
“Chinese Optics Letters”

W. Osten

Member of the Editorial board of the Journal “Strain”

W. Osten

Member of the Editorial board of the Journal “Optics and Lasers in Engineering”

W. Osten

European Editor of the Journal
“Holography and Speckle”

W. Osten

Member of the Editorial board of the Journal “Opto-Mechatronics”

W. Osten

Member of the Editorial board of the Journal “Optica Applicata”

W. Osten

Member of the Editorial board/Topical Editor of the Journal “3D Research”

W. Osten

Associate Editor of the Journal
“IEEE Transactions on Industrial Informatics”

A. Herkommer

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

Reviewed Papers

2017

Banerjee, P.; Osten, W.; Picart, P.; Cao, L.; Nehmetallah, G.

Digital Holography and 3D Imaging: introduction to the joint feature issue in Applied Optics and Journal of the Optical Society of America B

Applied Optics 56 (2017) 13 pp. DH1-DH4

Banerjee, P.; Osten, W.; Picart, P.; Cao, L.; Nehmetallah, G.

Digital Holography and 3D Imaging: introduction to the joint feature issue in Applied Optics and Journal of the Optical Society of America B

Journal of the Optical Society of America B –
Optical Physics 34 (2017) 5 pp. DH1-DH4

Bilski, B.; Frenner, K.; Osten, W.

Effective CD: a contribution toward the consideration of line edge roughness in the scatterometric critical dimension metrology

J. Micro/Nanolith. MEMS MOEMS 16 (2017) 2 pp. 024002

Bielke, A.; Pruss, C.; Osten, W.

Design of a variable diffractive zoom lens for interferometric purposes

Optical Engineering 56 (2017) 1 pp. 014104

Boettcher, T.; Gronle, M.; Osten, W.

Multi-layer topography measurement using a new hybrid single-shot technique: Chromatic Confocal Coherence Tomography (CCCT)

Optics Express 25 (2017) 9 pp. 10204-10213

Chen, B.; Herkommer, A.

Alternate optical designs for head-mounted displays with a wide field of view

Applied Optics 56 (2017) 4 pp. 901-906

Claus, D.; Pedrini, G.; Osten, W.

Iterative phase retrieval based on variable wavefront curvature

Applied Optics 56 (2017) 13 pp. F134-F137

Claus, D.; Reichert, C.; Herkommer, A.

Focus and perspective adaptive digital surgical microscope: optomechanical design and experimental implementation

Journal of Biomedical Optics 22 (2017) 5 pp. 056007

Claus, D.; Mlikota, M.; Geibel, J.; Reichenbach, T.; Pedrini, G.; Mischinger, J.; Schmauder, S.; Osten, W.

Large-field-of-view optical elastography using digital image correlation for biological soft tissue investigation

Journal of Medical Imaging 4 (2017) 1 pp. 014505

Eckerle, M.; Beirow, F.; Dietrich, T.; Schaal, F.; Pruss, C.; Osten, W.; Aubry, N.; Perrier, M.; Didierjean, J.; Délen, X.; Balembois, F.; Georges, P.; Abdou Ahmed, M.; Graf, T.

High-power single-stage single-crystal Yb:YAG fiber amplifier for radially polarized ultrashort laser pulses

Applied Physics B (2017) pp. 123:139

Fischbach, S.; Schlehahn, A.; Thoma, A.; Srocka, N.; Gissibl, T.; Ristok, S.; Thiele, S.; Kaganskiy, A.; Strittmatter, A.; Heindel, T.; Rodt, S.; Herkommer, A.; Giessen, H.; Reitzenstein, S.

Single Quantum Dot with Microlens and 3D-Printed Micro-objective as Integrated Bright Single-Photon Source

ACS Photonics 4 (6) (2017) pp. 1327–1332

Frank, B.; Kahl, P.; Podbiel, D.; Spektor, G.; Orenstein, M.; Fu, L.; Weiss, T.; Horn-von Hoegen, M.; Davis, T. J.; Frank-J. zu Heringdorf, M.; Giessen, H.

Short-range surface plasmonics: Localized electron emission dynamics from a 60-nm spot on an atomically flat single-crystalline gold surface

Science Advances 3 (2017) 7 pp. e1700721

Gharbi, S.; Pang, H.; Lingel, C.; Haist, T.; Osten, W.

Reduction of chromatic dispersion using multiple carrier frequency patterns in SLM-based microscopy

Applied Optics 56 (2017) 23 pp. 6688-6693

Hahn, R.; Krauter, J.; Koerner, K.; Gronle, M.; Osten, W.

Single-shot low coherence pointwise measuring interferometer with potential for in-line inspection

Measurement Science and Technology 28 (2017) 2 pp. 025009

Liu, J.; Claus, D.; Xu, T.; Kessner, T.; Herkommer, A.; Osten, W.

Light field endoscopy and its parametric description

Optics Letters 42 (2017) 9 pp. 1804-1807

Narayanamurthy, C.S.; Pedrini, G.; Osten, W.

Digital holographic photoelasticity

Applied Optics 56 (2017) 13 pp. F213 - F217

Osten, W.

Digital Holography

In: Encyclopedia of Modern Optics II, Vol. 4, 2017, pp. 139-150
doi:10.1016/B978-0-12-803581-8.09618-1,

Pruss, C.; Baer, G.B.; Schindler, J.; Osten, W.

Measuring aspheres quickly: tilted wave interferometry

Optical Engineering 56 (2017) 11 pp. 111713

Rausch, D.; Rommel, M.; Herkommer, A.

Illumination design for extended sources based on phase space mapping

Optical Engineering 56 (2017) 6 pp. 065103

Schmidt, S.; Thiele, S.; Herkommer, A.; Tunnermann, A.; Gross, H.

Rotationally symmetric formulation of the wave propagation method-application to the straylight analysis of diffractive lenses

Optics Letters 42 (2017) 8 pp. 1612-1615

Singh, A.K.; Pedrini, G.; Takeda, M.; Osten, W.

Scatter-plate microscope for lensless microscopy with diffraction limited resolution

Scientific report 7 (2017) pp. 10687

Singh, A.K.; Pedrini, G.; Osten, W.; Takeda, M.;

Diffraction-Limited Microscopy with a Simple Scatter Plate

Optics and Photonics News (Dez. 2017)

Singh, A.K.; Naik, D.N.; Pedrini, G.; Takeda, M.; Osten, W.

Exploiting scattering media for exploring 3D objects

Light Science & Applications 6 (2017) pp. e16219

Thiele, S.; Arzenbacher, K.;Gissibl, T.; Giessen, H.; Herkommer, A.

3D-printed eagle eye: Compound microlens system for foveated imaging

Science Advances 3 (2017) 2 pp. e1602655

Weber, K.; Hutt, F.; Thiele, S.; Gissibl, T.; Herkommer, A.; Giessen, H.

Single mode fiber based delivery of OAM light by 3D direct laser writing

Optics Express 25 (2017) 17 pp. 19672-19679

Yang, H.; Haist, T.; Gronle, M.; Osten, W.

Simulation of microscopic metal surfaces based on measured microgeometry

Simulation mikroskopischer Metalloberflächen unter Verwendung von gemessenen Mikrogeometrien

tm – Technisches Messen (2017) ISSN (Online) 2196-7113, ISSN (Print) 0171-8096

Zhou, M.; Singh, A.K.; Pedrini, G.; Osten, W.; Min, J.; Yao, B.

Speckle-correlation imaging through scattering media with hybrid bispectrum-iteration algorithm

Optical Engineering 56 (2017) 12 pp. 123102

Reviewed Papers

2018

Achimova, E.; Abaskin, V.; Claus, D.; Pedrini, G.; Shevkunov, I.; Katkovnik, V.

Noise minimized high resolution digital holographic microscopy applied to surface topography

Computer Optics 42 (2018) 2 pp. 267-272

Buchta, D.; Serbes, H.; Claus, D.; Pedrini, G.; Osten, W.

Soft tissue elastography via shearing interferometry

Journal of Medical Imaging 5 (2018) 4 pp. 046001

Buchta, D.; Heinemann, C.; Pedrini, G.; Krekel, C.; Osten, W.

Combination of FEM simulations and shearography for defect detection on artwork

Strain 54 (2018) 3 pp. e12269

Cai, Z.; Liu, X.; Chen, Z.; Tang, Q.; Gao B.Z.; Pedrini, G.; Osten, W.; Peng, X.

Light-field-based absolute phase unwrapping

Optics Letters 43 (2018) 23 pp. 5717-5720

Cazac, V.; Meshalkin, A.; Achimova, E.; Abashkin, V.; Katkovnik, V.; Shevkunov, I.; Claus, D.; Pedrini, G.

Surface relief and refractive index gratings patterned in chalcogenide glasses and studied by off-axis digital holography

Applied Optics 57 (2018) 3 pp. 507-513

Claus, D.; Pedrini, G.; Buchta, D.; Osten, W.

Accuracy enhanced and synthetic wavelength adjustable optical metrology via spectrally resolved digital holography

Journal of the optical society of America A-Optics image science and vision 35 (2018) 4 pp. 546-552

Dietrich, T.; Rumpel, M.; Beirow, F.; Mateo, C.; Pruss, C.; Osten, W.

Thin-disk oscillator delivering radially polarized beams with up to 980 W of CW output power

Optics Letters 43 (2018) 6 pp. 1371-1374

Li, H.; Fu, L.; Frenner, K.; Osten, W.

Cascaded plasmonic superlens for far-field imaging with magnification at visible wavelength

Optics Express 26 (2018) 8 pp. 10888-10897

Li, H.; Fu, L.; Frenner, K.; Osten, W.

Cascaded DBR plasmonic cavity lens for far-field subwavelength imaging at a visible wavelength

Optics Express 26 (2018) 15 pp. 19574-19582

Keck, A.; Sawodny, O.; Gronle, M.; Haist, T.; Osten, W.

Model-Based Compensation of Dynamic Errors in Measuring Machines and Machine Tools

IEEE/ASME Transactions on Mechatronics, 23 (2018) 5 pp. 2252-2262

Krauter, J.; Osten, W.

Nondestructive surface profiling of hidden MEMS using an infrared low-coherence interferometric microscope

Surface topography-metrology and properties 6 (2018) 1 pp. 015005

Schaal, F.; Rutloh, M.; Weidenfeld, S.; Stumpe, J.; Michler, P.; Pruss, C.; Osten, W.

Optically addressed modulator for tunable spatial polarization control

Optics Express 26 (2018) 21 pp. 28119-28130

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

Alignment-free integration of apertures and nontransparent hulls into 3D-printed micro-optics

Optics Letters 43 (2018) 21 pp. 5283-5286

Zhou, M.; Singh, A.K.; Pedrini, G.; Osten, W.; Min, J.; Yao, B.

Tunable output-frequency filter algorithm for imaging through scattering media under LED illumination

Optics Communications 410 (2018) pp. 160-163

Conference proceedings and journals

2017

Bielke, A.; Pruss, C.; Osten, W.

Streulichtreduzierung bei einem variablen Interferometer-Objektiv mit zwei diffraktiven Elementen

Proc. DGaO 118. Tagung (2017) B 29

Bilski, B.; Frenner, K.; Osten, W.

Effective–CD: a contribution toward the consideration of line edge roughness in the scatterometric critical dimension metrology

J. Micro/Nanolith. MEMS MOEMS 16 (2017) 2, Nr. 024002

Boettcher, T.; Gronle, M.; Osten, W.

Single-shot multilayer measurement by chromatic confocal coherence tomography

Proc. of SPIE (2017) Vol. 10329-18

Buchta, D.; Claus, D.; Pedrini, G.; Osten, W.

Depth-resolved Hyperspectral Digital Holography

Digital Holography and Three-Dimensional Imaging, OSA Technical Digest (online) Optical Society of America (2017) paper W4A.3.

Buchta, D.; Heinemann, C.; Pedrini, G.; Krekel, C.; Osten, W.
(invited paper)

Lock-in-shearography for the detection of transport-induced damages on artwork

Proc. of SPIE (2017) Vol. 10331-15

Cassarly, W.; Rehn, H.; Herkommer, A.

IODC 2017 illumination design problem: the centennial illuminator

Proc. of SPIE (2017) Vol. 10590-03

Claus, D.; Boettcher, T.; Osten, W.

Hybrid optical design for a wide field chromatic confocal scanning interferometer

Proc. DGaO 118. Tagung (2017) B 35

Chen, B.; Herkommer, A.

Comparison of different designs of head mounted displays with large field of view

Proc. of SPIE (2017) Vol. 10335-5

Claus, D.; Mlikota, M.; Geibel, J.; Reichenbach, T.; Pedrini, G.; Mischinger, J.; Schmauder, S.; Osten, W.

Large-field-of-view optical elastography using digital image correlation for biological soft tissue investigation

J. Med. Imag. 4 (2017) 1 Nr. 014505

Claus, D.; Pedrini, G.; Buchta, D.; Osten, W.

Spectrally resolved digital holography using a white light LED

Proc. of SPIE (2017) Vol. 10335-1H

Dietrich, T.; Rumpel, M.; Fu, L.; Pruss, C.; Osten, W.; Abdou Ahmed, M.; Graf, T.

CW thin-disk laser emitting kW-class beams with radial polarization

Proc. of IEEE: European Conference on Lasers and Electro-Optics and European Quantum Electronics Conference, Optical Society of America (2017) paper CA_2_1

Giessen, H.; Thiele, S.; Ristok, S.; Herkommer, A.

Microstructured Optics by 3D Printing

Proc. of IEEE: European Conference on Lasers and Electro-Optics and European Quantum Electronics Conference, Optical Society of America (2017) paper CE_6_1

Gödecke, M. L.; Peterhänsel, S.; Buchta, D.; Frenner, K.; Osten, W.

Detection of grating asymmetries by phase-structured illumination

Proc. of SPIE (2017) Vol. 104490C

Krauter, J.; Boettcher, T.; Gronle, M.; Osten, W.

Low-coherence Interferometry for Industrial Applications

Proc. of AMA, Nuremberg, Germany (2017) B5.4

Krauter, J.; Gronle, M.; Osten, W.

Optical inspection of hidden MEMS structures

Proc. of SPIE (2017) Vol. 10329-39

Li, H.; Fu, L.; Frenner, K.; Osten, W.

Nanofabrication results of a novel cascaded plasmonic superlens: lessons learned

Proc. of SPIE (2017) Vol. 10330-36

Pruss, C.; Mateo, C.-M.; Schwanke, O.; Fu, L.; Dietrich, T. ; Rumpel, M.; Abdou Ahmed, M.; Graf, T.; Osten, W.

Sub-lambda Polarisationsformer für Hochleistungslaser

Proc. DGaO 118. Tagung (2017) P 11

Schindler, J.; Pruss, C.; Osten, W.

Increasing the accuracy of tilted-wave-interferometry by elimination of systematic errors

Proc. of SPIE (2017) Vol. 10329-3

Weidmann, P.; Pedrini, G.; Martinez-Garcia, V.; Wenzelburger, M.; Killinger, A.; Schmauder, S.; Gadow, R.; Osten, W.

Evaluation of Residual Stress Determinations Conducted with Laser Ablation and Optical Displacement Measurement

Proc. of ICRS-10 (2017) Vol. 2, pp. 323-328

Yang, H.; Haist, T.; Gronle, M.; Osten, W.

Simulated BRDF based on measured surface topography of metal

Proc. of SPIE (2017) Vol. 10334-4

Conference proceedings and journals

2018

Baer, G.

Object-oriented optical design

Proc. DGaO 119. Tagung (2018) B21

Baumgartner, A.; Amann, S.; Müller, C.; Herkommer, A.; Dressel, M.; Fella, S.

Infrared reflectance factor of various asphalts

Proc. of SPIE (2018) Vol. 10783-1X

Beisswanger, R.; Pruss, C.; Osten, W.

Interferometrische Radienbestimmung unter nicht konstanten Umgebungsbedingungen

Proc. DGaO 119. Tagung (2018) P7

Boettcher, T.; Osten, W.

From topography to refractive index: Flexible multi modal measurements by fusion of chromatic-confocal and spectral interferometric schemes

Proc. of AMA (2018) Vol. 85, pp. 471-477

Boettcher, T.; Claus, D.; Osten, W.

Towards Full-Field Chromatic Confocal Microscopy

Proc. of OPAL (2018) pp. 115-117

Chen, B.; Thiele, S.; Xu, M.; Herkommer, A.

Micro objectives with extremely large field of view

Proc. of SPIE (2018) Vol. 10690-16

Claus, D.; Pedrini, G.

Ptychography: quantitative phase imaging with incoherent imaging properties

Proc. of SPIE (2018) Vol. 10677-1E

Claus, D.; Pedrini, G.; Boettcher, T.; Taphanel, M.; Osten, W.; Hibst, R.

Development of a realistic wave propagation-based chromatic confocal microscopy model

Proc. of SPIE (2018) Vol. 10677-OC

Drozella, J.; Frenner, K.; Osten, W.

GPU-accelerated simulation of the super-resolution capabilities of dielectric microspheres using the Differential Method

Proc. of SPIE (2018) Vol. 10678-ON

Faulhaber, A.; Haberl, S.; Haist, T.; Gronle, M.; Baroud, Y.; Osten, W.; Simon, S.

Dynamic holography for speckle noise reduction in hybrid measurement system

Proc. of SPIE (2018) Vol. 10744-OJ

Haberl, A.; Harsch, A.; Fütterer, G.; Liebl, J.; Pruss, C.; Rascher, R.; Osten, W.

Model based error separation of power spectral density artefacts in wavefront measurement

Proc. of SPIE (2018) Vol. 10749-OT

Hahn, R.; Krauter, J.; Körner, K.; Osten, W.

Robuster kurzkohärenter Single-Shot-Sensor

Proc. DGaO 119. Tagung (2018) A14

Harsch, A.; Pruss, C.; Haberl, A.; Osten, W.

Tilted wave interferometry for testing large surfaces

Proc. of SPIE (2018) Vol. 10829-08

Hartung, A.; Thiele, S.; Drozella, J.; Giessen, H.; Herkommer, A.

Schwärzen von 3D-gedruckten Mikrooptiken mittels Inkjet-Verfahren

Proc. DGaO 119. Tagung (2018) A4

Herkommer, A.; Thiele, S.

Design und Herstellung von 3D-gedruckten mikrooptischen Systemen mittels 2-Photonen Polymerisation

Proc. DGaO 119. Tagung (2018) A2

Krauter, J.; Osten, W.

Inspection of hidden MEMS by an infrared low-coherence interferometric microscope

Proc. of SPIE (2018) Vol. 10749-11

Krauter, J.; Osten, W.

Optische Inspektion verkapselter MEMS

Proc. DGaO 119. Tagung (2018) A13

Li, H.; Fu, L.; Frenner, K.; Osten, W.

A cascaded plasmonic superlens for far-field imaging with magnification at visible wavelength

Proc. DGaO 119. Tagung (2018) B32

Lotz, S.; Reichert, C.; Haist, T.; Herkommer, A.

„BaKaRoS" – ein Baukastensystem für einen niederschwelligen Zugang zur technischen Optik

Proc. DGaO 119. Tagung (2018) P20

Ludwig, S.; Singh, A.K.; Pedrini, G.; Osten, W.

Scatter-plate microscope: improved image acquisition

Proc. of SPIE (2018) Vol. 10677-17

Osten, W.

Optical metrology: the long and unstoppable way to become an outstanding measuring tool

Proc. of SPIE (2018) Vol. 10834-02

Osten, W.; Frenner, K.; Pedrini, G.; Singh, A.K.; Schindler, J.; Takeda, M.

Shaping the light for the investigation of depth-extended scattering media

Proc. of SPIE (2018) Vol. 10503-18

Osten, W.; Haist, T.; Manske, E.

How to drive an optical measurement system to outstanding performance

Proc. of SPIE (2018) Vol. 10557-0Q

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

Digital holography for erosion monitoring inside the ITER Tokamak

Proc. of SPIE (2018) Vol. 10677-22

Pruss, C.; Osten, W.

Asphären- und Freiformflächenmesstechnik: Herausforderungen im Spannungsfeld zwischen Flexibilität und Kalibrierung

Proc. DGaO 119. Tagung (2018) H4

Reichert, C.; Würtenberger, F.; Hinderer, V.; Haist, T.; Herkommer, A.

Erfassung menschlicher Vitalparameter mithilfe optischer Messtechnik

Proc. DGaO 119. Tagung (2018) B6

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

Surface polarization scattering generated from a birefringent material with rough surface

Proc. of SPIE (2018) Vol. 10694-OJ

Rothermel, F.; Pruss, C.; Herkommer, A.; Osten, W.

In-Prozess Messtechnik für 3D-gedruckte Optiken

Proc. DGaO 119. Tagung (2018) A3

Thiele, S.; Geser, P.; Giessen, H.; Herkommer, A.

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Chen, Bo

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Talpur, Taimoor

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Schau, Philipp

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Kraus, Niclas

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Guo, Chenchen

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Beutler,Steffen

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Knipl, Christian Adam

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Kircher, Raphael

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Drozella, Johannes

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Niemeyer, Arvid

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Träger, Nick-André

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Rieger, Simone

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Rothermel, Florian

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Grupp, Barbara

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Birk, Alexander

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Ramos, Scarlett

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Erlenwein, Caroline

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01/2018

Kustermann, Anja

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01/2018

Gröger, Alexander

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Hartstern, Maike Janine

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Schätzle, Oliver

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02/2018

Weder, Karl Julius

Auslegung und Design eines Mikroskopobjektives unter technologischen und wirtschaftlichen Betrachtungen

03/2018

Rzhanova, Kseniia

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Richter, Kurt

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04/2018

Koschig, Maximilian

Diffraktive Strahlformung für die optimierte Bearbeitung transparenter Materialien

04/2018

Keller, Dominik

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Pang, Hao

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04/2018

Ulmer, Marc

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05/2018

Schober, Christian

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05/2018

Hermanutz, Lena Sophie

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06/2018

Landeck Elisa

Erweiterung des gestalterischen Spielraums von Leuchten durch Integration von fluoreszierenden Elementen

08/2018

Zhu, Danxuan

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09/2018

Chen, Karin Jia-Yin

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Pink, Karsten

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09/2018

Dilger, Pablo

Entwicklung von Bildverarbeitungsalgorithmen zur Fluidbestimmung in einem Lab-on-a-Chip System

10/2018

Bantle, Viola

Entwicklung einer Smartphone-basierten sonografischen Messmethode zur Bewertung des patellofemoralen Schmerzsyndroms

10/2018

Badawi, Daniel

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11/2018

Graf, Andreas

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11/2018

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Hokenmaier, Lukas

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Wagenknecht, Hannah

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Thomas, Marie Franziska

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08/2017

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Dashchenko, Andey

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Hinderer, Verena

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12/2017

Krauss, Marla

Entwicklung eines Miniatur-Lichtblattmikroskops

03/2018

Busch, Valentin

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Stark, Jonas

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Volland, Alina

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Canga, Aybuke-Bihter

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Scheibe, Annin

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Ramos, Scarlett

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Kokkinidou, Despoina

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05/2017

Hartlieb, Simon

Konzeptionierung, Simulation und Realisierung eines Tilted Wave Interferometers nach dem Fizeau-Prinzip

05/2017

Zhang, Zhen

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Qi, Liting

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Schwegler, Tobias

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Hutter, Marco

Verbesserung und Weiterentwicklung eines neuartigen Single-Shot Weißlichtinterferometers

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Kaufmann, Sven

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Wiedmann, Anne

Tiefenscannende 3D Mikroskopie

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Zimmermann, Felix

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10/2017

Schönegg, Lisa

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11/2017

Chang, Li Wen

Holografische Messung von Schwingungen und Verformungen; Holographic measurement of vibrations and deformations

12/2017

Munz, Christoph

Simulationsstudie zur Messung von fluoreszierenden Objekten in streuenden Medien mit einer Single-Pixel-Kamera

12/2017

Mayer, Juliane

Anwendung von Mikrolinsen-Arrays zur Fehlsichtigkeitskorrektur

12/2017

Serbes, Hüseyin

Aufbau eines flächigen CCSI-Sensors

04/2018

Fitz, Stephanie

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04/2018

Buchholz, Thomas

Simulation und Integration einer Lasertriangulation mit Messung der Speckle-Rauschreduzierung durch Multipointverfahren

04/2018

Kocak, Burak

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04/2018

Awadni, Aymen

Untersuchung von Anregungstechniken für die Lock-In Shearography

05/2018

Guo, Yifeng

Stitching mit Iterative Closest Point für optische Topographiesensoren

05/2018

Hoppe, Konstantin

LED-basierte Entfernungsbestimmung mittels Stereo Vision

07/2018

Landeck, Elisa

Erweiterung des gestalterischen Spielraums von Leuchten durch Integration von fluoreszierenden Elementen

08/2018

Said, Ramedani

Herstellung von Mikrolinsenarrays mittels eines Super Inkjet-Druckers

08/2018

Maier, Felix

Konzeption und Konstruktion eines anzeigenden Laserscanners mit Hilfe von diffraktiver Optik

08/2018

Bruch, Jessica

Optische Simulationen anhand eines CAD-Augenmodells

10/2018

Bienert, Florian

Design und Optimierung einer Gitterwellenleiterstruktur mithilfe eines evolutionären Algorithmus zur Polarisationswandlung von linearer zu radialer Strahlung von High-Power-Lasern

11/2018

Jung, Chris

Ansätze zur magnetischen Aktuierung 3D-gedruckter Mikrooptiken mit Hilfe von Ferrofluiden.

11/2018

HoloMet 2017

Future Challenges to Optical Imaging and Measurement Technologies in Times of Digital Transition

Wolfgang Osten, Erich Steinbeißer

The HoloMet workshops are an irregular series of events where international experts meet to discuss the latest developments in the field of optical metrology.

Four workshops have taken place so far:

- Berlin/Germany 2000 [1],
- Balatonfüred/Hungary 2001 [2],
- Balatonfüred/Hungary 2010 [3], and
- Utsunomiya/Japan 2012.

The 2017 workshop was organized by the Institute of Applied Optics in Stuttgart from September 24th to September 26th in coincidence with the 32nd ITO Optics Colloquium (see next page).

The chosen overall theme was a response to the digitization hype that has now spread to all sectors of public, scientific, economic and political life. With this event was attempted to systematize the current challenges in the field of optical technologies as well as to address the corresponding research needs.

Eight challenges were selected:

1. The continuously decreasing feature sizes while simultaneous increase in field sizes: **The high dynamic range challenge**,
2. The growing role of precision: **The Localization and Positioning Challenge**,
3. The increasing complexity of functional surfaces: **The surface design challenge**,
4. New materials drive innovation: **The material challenge**,
5. New Additive Manufacturing Technologies allow efficient fabrication technologies and new products: **The Fabrication/Additive Manufacturing Challenge**,
6. The Digital Transition: **The Challenge of Unlimited Networking**,
7. The mining and evaluation of multi-variate data for the generation of reliable and confiding results: **The Big Data Challenge**,
8. New business models are coming up: **The Paradigm Shift Challenge**.

Some information about the topics can be found in [4]. More than 60 participants representing 16 countries joined that workshop. A photo taken from the conference dinner at the castle Hohenbeilstein is shown in fig. 1.

Fig. 1: *Participants of the 2017 HoloMet Workshop at the castle Hohenbeilstein*

This meeting of many international experts was also a welcome opportunity to award the new HoloKnight. Prof. Guohai Situ from the Shanghai Institute of Optics and Fine Mechanics was given the accolade by Sir Peter of Middlefield and named as Sir Guohai of Shanghai, see fig. 2. This title is awarded to only one recognized expert per year by the international order of the HoloKnights.

The order of HoloKnights took also the opportunity to recognize the outstanding contributions of Eugene Arthurs, former CEO of the SPIE, with the title of an Honorary Member of the HoloKnight Order, see, fig. 3.

Another outstanding event was the presentation of the 2017 Hans-Steinbichler-Award for Outstanding Contributions in Optical Metrology to Prof. Gerd Jäger from the Technische Universität Ilmenau for his contributions to high-precision optical metrology. The award is donated every 4 years by the son of Hans Steinbichler, Marcus Steinbichler. The 2017 award honors especially Prof. Jägers achievements for the design, implementation and application of the Nano-Positioning and -Measuring Machine NPMM 200, see fig. 4.

Fig. 2: *Sir Peter of Middlefield congratulates Sir Guohai of Shanghai for being accepted in the order of the HoloKnights*

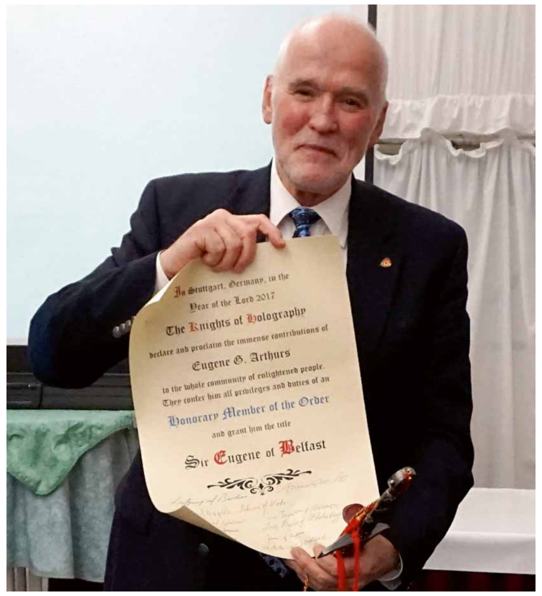

Fig. 3: *Eugene Arthurs knighted as Sir Eugene of Belfast*

Fig. 4: *Prof. Gerd Jäger honored with the 2017 Hans-Steinbichler-Award*

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Optik-Kolloquium 2017

Optics for Medical and Nano Technologies

am 27. September 2017, Teilnehmer: ca. 200

Welcome Address and Introduction
Prof. Dr. Wolfgang Osten
ITO, Universität Stuttgart

Speckle, Scattering and Imaging
Prof. Dr. Chris Dainty
National University of Ireland, Galway, Ireland

Applications of Digital Holography with the Principle of Inverse Scattering
Prof. Dr. YongKeun Park
Department of Physics, KAIST, Korea

Opto-Biology: As the Biological Matter Can Cooperate to Microscopy
Dr. Pietro Ferraro
CNR-ISASI – Institute of Applied Sciences & Intelligent Systems, Naples, Italy

Lithography Optics Continues to Enable Moore's Law
Winfried Kaiser
Carl Zeiss SMT GmbH, Oberkochen, Germany

An Overview of Metrology and Control Challenges in Semiconductor Lithography
Dr. Stefan Keij
ASML Veldhoven, The Netherlands

New Ways for High Precision Testing of Large Optical Components under Harsh Environmental Conditions
Prof. Dr. James C. Wyant
Optical Science Center, University of Arizona, Tucson, USA

The Light Years Ahead: How Today's Promising Augmented and Virtual Reality Markets Help Shape New Optics Frontiers
Dr. Bernard Kress
Microsoft Corporation, Mountain View, USA

The Nanopositioning and Nanomeasuring Machine NPMM-200: Sub-Nanometer Resolution and Highest Accuracy in Extended Macroscopic Working Areas
Prof. Dr. Eberhard Manske
Technische Universität Ilmenau, Germany

Bestowal of the 2017 Hans-Steinbichler-Award for Outstanding Contributions to Optical Metrology
Laudation: Prof. Dr. Ichirou Yamaguchi
2013 Awardee
Presentation: Dr. Marcus Steinbichler
Neubeuern, Germany
Laureate: Prof. Dr. Gerd Jäger
Technische Universität Ilmenau, Germany (emeritus)

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

2017 – 2018

W. Osten

SPIE Congress Optical Metrology 2017

June 26 – 29, 2017, Munich, Germany

W. Osten

SPIE Conference "Optical Measurement Systems for Industrial Inspection X"

June 26 – 29, 2017, Munich, Germany

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SPIE Conference
"Digital Optical Technologies"

June 26 – 29, 2017, Munich, Germany

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HoloMet 2017: Future Challenges to Optical Imaging and Measurement Technologies in Times of Digital Transition

September 24 – 27, 2017, Stuttgart, Germany

A.Herkommer

SPIE – Photonics Europe
3D Printed Optics and Additive Photonic Manufacturing

April 22 – 26, 2018, Strasbourg, France

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SPIE Conference
"Optical Micro- and Nanometrology VII"

April 25 – 26, 2018, Brussels, Belgium

A.Herkommer

EOS-conference on Freeform Optics for Illumination, Augmented Reality and Virtual Reality

October 8 – 12, 2018, Delft, Netherlands

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