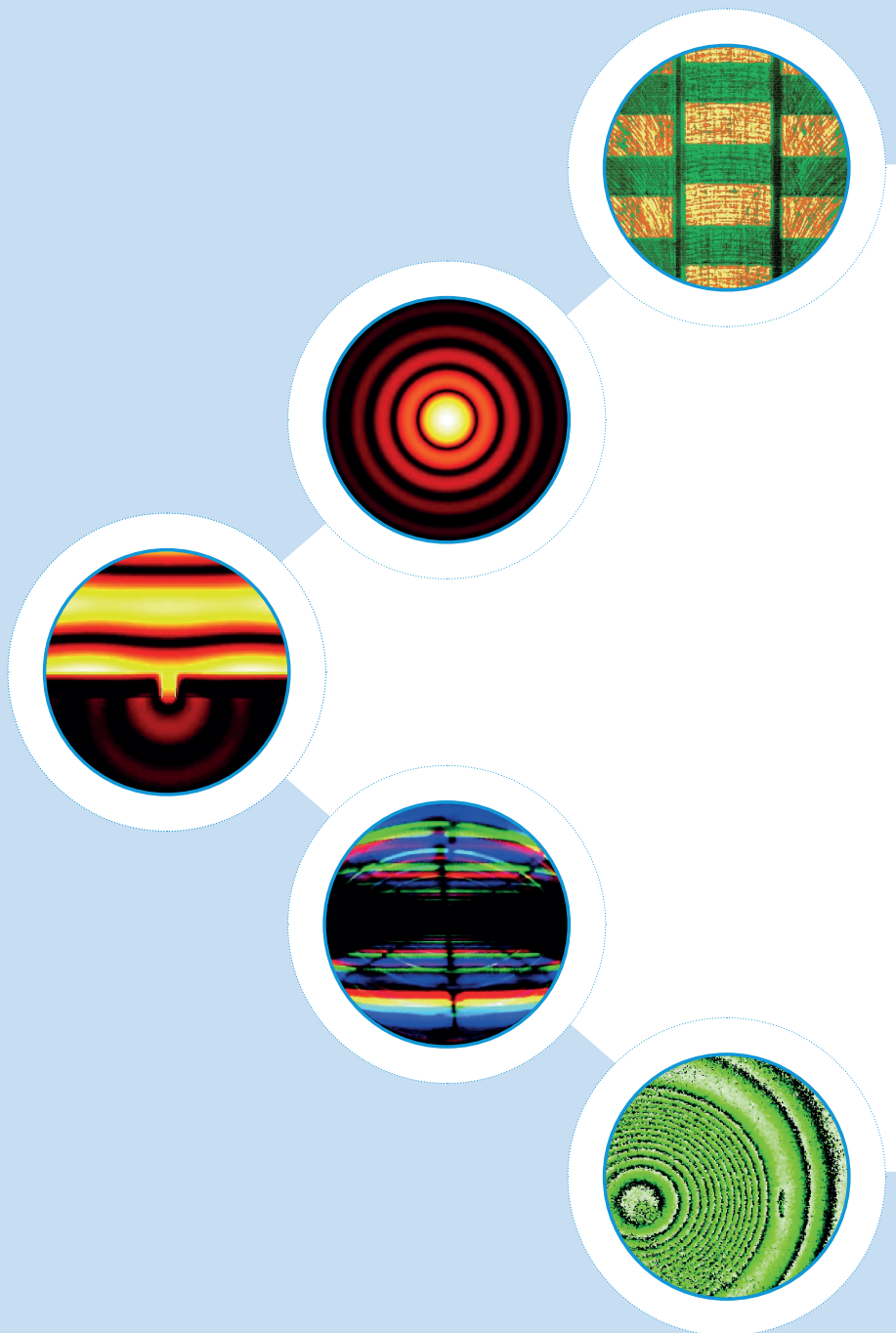


annual report
2023 – 2025

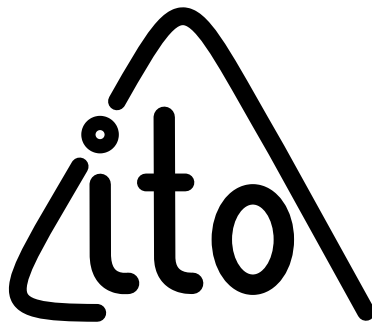
INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART



Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK UNIVERSITÄT STUTTGART

Prof. Dr.-Ing. Stephan Reichelt
Prof. Dr. Alois Herkommer



Pfaffenwaldring 9
D-70569 Stuttgart
Tel.: +49(0)711 685-66075
<https://www.ito.uni-stuttgart.de>

ANNUAL REPORT 2023 – 2025

Editorial



Dear colleagues, partners, and friends of ITO,

I am pleased to present this year's annual report, which offers an overview of the developments and activities at our institute.

Looking back on the past years at the Institute of Applied Optics (ITO) at the University of Stuttgart, it becomes clear that scientific progress is rarely linear. Rather, it is shaped by curiosity, collaboration, and the willingness to explore the boundaries of what is possible. Over the past three years, our community has further strengthened its impact in both fundamental and applied optical research, while at the same time reinforcing connections across disciplines, with industrial partners, and within international networks.

Applied optics and photonics are key drivers of innovation and economic growth. They make essential and diverse contributions to society by providing enabling technologies for many future-oriented as well as everyday applications. A particular highlight of the past year clearly reflected this role: ITO hosted the 126th Annual Meeting of the *Deutsche Gesellschaft für Angewandte Optik* (DGaO) in Stuttgart. The conference addressed current topics in applied optics through seven keynote lectures, more than 80 contributed talks, and 37 poster presentations, attracting a professional audience of over 200 participants. An extensive industrial exhibition offered opportunities for direct exchange with companies from the sector, while a parallel exhibition on optical phenomena invited visitors to explore and experiment. A detailed conference report can be found on the following pages. Selected contributions from the meeting will be published in a special issue of the journal *tm – Technisches Messen*.

ITO's mission remains firmly rooted in fundamental and applied optics – where basic scientific questions meet real-world challenges. Across our five research groups, activities ranged from the development of new surface and deformation measurement methods and hyperspectral imaging, to advances in high-resolution metrology and simulation techniques, the development of novel interferometric measurement approaches and fabrication methods for diffractive optics, as well as innovative 3D-printed micro-optics and coherent metrology and imaging techniques. The work of the junior research group led by Dr. A. Toulouse on endoscopic microfabrication, established in October 2025, illustrates the creative potential of ITO and reflects the vision of optical systems that may one day enable direct tissue reconstruction within the human body.

Another major milestone was the approval of the second funding phase of the DFG Research Training Group (RTG) "*Intraoperative Multisensory Tissue Differentiation in Oncology*". In this interdisciplinary program, researchers from the University of Stuttgart and the University of Tübingen collaborate to improve oncological interventions through novel sensor technologies. The first cohort of ITO doctoral researchers successfully completed their work in 2023 (see also the new overview of completed doctoral theses in the final pages of this report). The second cohort is nearing completion, and in spring of this year the final two doctoral candidates at ITO will continue to advance this exciting research area.

Alongside our research activities, we remain strongly committed to education and mentoring. Teaching at ITO provides a solid foundation in the field, spanning bachelor's and master's studies as well as structured doctoral programs, and prepares the next generation of scientists and engineers for an increasingly data-driven and technology-intensive world. With the introduction of an English-language master's program starting in autumn 2026, our study programs will increasingly address the interests of international students.

This year once again demonstrated that innovation does not emerge in isolation, but through sustained partnerships. Collaboration with national and international research institutions as well as industry continued to be a central pillar of our work, enabling us to address complex

challenges ranging from the micro- to the macro-scale. Our research outcomes continue to highlight the strength of open, interdisciplinary approaches supported by state-of-the-art simulation, design, and experimental capabilities.

Looking ahead to 2026 and beyond, we are guided by both continuity and change: continuity in our core strengths in optical metrology and system design, and change in the form of new questions arising from digitalization, artificial intelligence, and emerging imaging technologies. Our aim is not only to provide answers, but also to help shape how these questions are framed.

I would like to express my sincere thanks to everyone who contributes to the life of this institute – from researchers and administrative staff to students, alumni, and partners. Your commit-

ment, creativity, and collaboration are the true foundations of our success.

We hope you enjoy reading this annual report and find inspiration within its pages. We also wish to thank all our internal and external partners for their constructive and continued collaboration.

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Stephan Reichelt', with a stylized, flowing script.

Stephan Reichelt

Stuttgart, January 2026

Index

Institute structure

Team and structure	08
Studying optics.....	10
SPIE Student Chapter - University of Stuttgart	12
ITOM - Hands for AI	14
DGaO - 126th Annual Conference 2025	16
The research groups	18

Research projects

3D-Surface Metrology

Deformation monitoring of bridges	21
<i>T. Haist, S. Hartlieb, S. Reichelt</i>	
Holographic multipoints for Shack-Hartmann sensing	22
<i>Z. Wang, T. Haist, S. Hartlieb, A. Rüdinger, S. Reichelt</i>	
Programmable microscopy	23
<i>M. Tscherpel, T. Haist, S. Reichelt</i>	
Toward a 3D NIR microscopy and Raman spectroscopy instrument for astrogeological exploration	24
<i>C. Ryan, T. Haist, S. Reichelt</i>	
Programmable oblique structured light illumination for 3D metrology.....	25
<i>A. Fuhrmann, A. Gröger, K. Körner, A. Herkommer</i>	
Differential perspective.....	26
<i>T. Haist, A. Fauhalber, F. Lodholz, S. Reichelt</i>	
Differentiation of healthy and malignant breast tissue using hyperspectral imaging	27
<i>A. Rüdinger, T. Haist, S. Reichelt</i>	
Diffraction-based multispectral imaging	28
<i>T. Haist, R. Hahn, M. Tscherpel, N. Haile, M. Bäuerle, S. Reichelt</i>	
Calibration of spatial light modulators towards holographic displays	29
<i>M. Zimmermann, A. Brenner, T. Haist, S. Reichelt</i>	

Index

High Resolution Metrology and Simulation

Efficient deep learning neural networks for Mueller-matrix Fourier scatterometry at optical frequencies.....	31
<i>L. Fu, X. Wang, K. Frenner, S. Reichelt</i>	
Accelerated computation of 2D-periodic Green function using Ewald transformation and simplex interpolation	32
<i>L. Fu, K. Frenner, S. Reichelt</i>	
Fourier-optical simulation of a confocal intensity curve	33
<i>S. Wyss, L. Fu, S. Reichelt</i>	
Application of recurrent neural networks to accelerate ellipsometric measurements for monitoring battery manufacturing	34
<i>K. Frenner, X. Wang</i>	
YOLO-Sense: Improving warehouse safety with optical smart cameras	35
<i>T. Reif, A. Dawar, K. Frenner, S. Reichelt</i>	
Time-gated single pixel camera for compressed object detection through scattering media.....	36
<i>A. Birk, K. Frenner, S. Reichelt</i>	
Object detection through scattering media via dual-wavelength intensity interferometry.....	37
<i>C. M. Bett</i>	

Interferometry and Diffractive Optics

Absolute shape interferometry for aspheres and freeform surfaces	39
<i>A. Brenner, C. Schober, C. Pruß, A. Herkommer, S. Reichelt</i>	
Single-shot tilted wave interferometer	40
<i>C. Schober, C. Pruß, S. Reichelt</i>	
The Lilienthal 27 foot Schroeter primary metal mirror from 1793	41
<i>C. Pruß, W. Osten, A. Herkommer, C. Schober, K. Treptow, M. Wischert</i>	
Metrology of undeveloped 3D-printed structures using white light interferometry	42
<i>B. Bertschinger, C. Schober, C. Pruß, S. Reichelt</i>	
Robust light source characterization	43
<i>B. Bertschinger, C. Pruß, S. Reichelt</i>	
Nanopositioning and Nanomeasuring Machine NPMM-200.....	44
<i>A. Brenner, C. Schober, C. Pruß, S. Reichelt</i>	
Three dimensional scanning beam interference lithography	46
<i>K. Treptow, C. Pruß, T. Haist, S. Reichelt</i>	

Index

Interferometry and Diffractive Optics

Flexible alignment and calibration tool for scanning beam interference lithography systems	47
<i>K. Treptow, C. Pruß, T. Haist, S. Reichelt</i>	
Fabrication of diffractive elements	48
<i>K. Treptow, C. Pruß, T. Schoder, S. Reichelt</i>	
Diffractive axicons for quasi-achromatic, propagationinvariant tubular beams.....	49
<i>N. Sass, C. Pruß, S. Reichelt</i>	
Grating Reflectors Enabled laser Applications and Training (GREAT)	50
<i>A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt</i>	
Etching of thick optical elements.....	51
<i>A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt</i>	

Coherent Metrology

Lensless magneto-optical imaging.....	53
<i>G. Pedrini, S. Reichelt</i>	
Lensless imaging using the complex degree of coherence obtained by multiaperture interference	54
<i>G. Pedrini, S. Reichelt</i>	
Resolution enhancement in digital holography through speckle illumination.....	55
<i>A. Schiebelbein, G. Pedrini, S. Reichelt</i>	
Roughness measurement using spectral speckle correlation	56
<i>P. Laux, S. Reichelt</i>	
6-DoF speckle shift tracking sensor.....	57
<i>N. Borchers, T. Haist, S. Reichelt</i>	

3D-printed Microoptics and Simulation

Advances in wave-optical simulation methods for 3Dprinted micro-optics.....	59
<i>M. Wende, J. Drozella, A. Toulouse, A. Herkommer</i>	
Freeform micro-optics via two-photon polymerization	60
<i>C. Jimenez, A. Herkommer</i>	
3D-printing of luminescent microstructures.....	61
<i>V. Aslani, A. Herkommer, A. Toulouse</i>	
3D-printed immersion micro-optics enable new biophotonics and integrated photonics applications.....	62
<i>M. Wende, K. Doth, A. Toulouse</i>	

Index

Fringe projection elastography for tissue differentiation in oncology	63
<i>Ö. Atmaca, V. Aslani, T. Haist, A. Toulouse, A. Herkommer</i>	
Miniaturized, 3D-printed, holographic optical tweezers for particle trapping	64
<i>K. Doth, M. Wende, J. Drozella, T. Haist, A. Herkommer, A. Toulouse</i>	
Dual fiber probe with 3D-printed micro-lens for Brillouin microscopy	65
<i>J. Trapp, M. Wende, A. Herkommer, A. Toulouse</i>	
Towards endoscopic 3D bio-printing on the micro-scale	66
<i>A. Toulouse, M. Wende, A. Herkommer</i>	
Fabrication and characterization of a magnetic 3D-printed microactuator.....	67
<i>F. Rothermel, M. Wende, J. Drozella, A. Toulouse, A. Herkommer</i>	
3D-printed soft actuatable micro optics	68
<i>A. Toulouse, J. Grunewald, A. Herkommer</i>	
Low-cost optical demonstrators	69
<i>A. Herkommer</i>	

Publications & Kolloquium

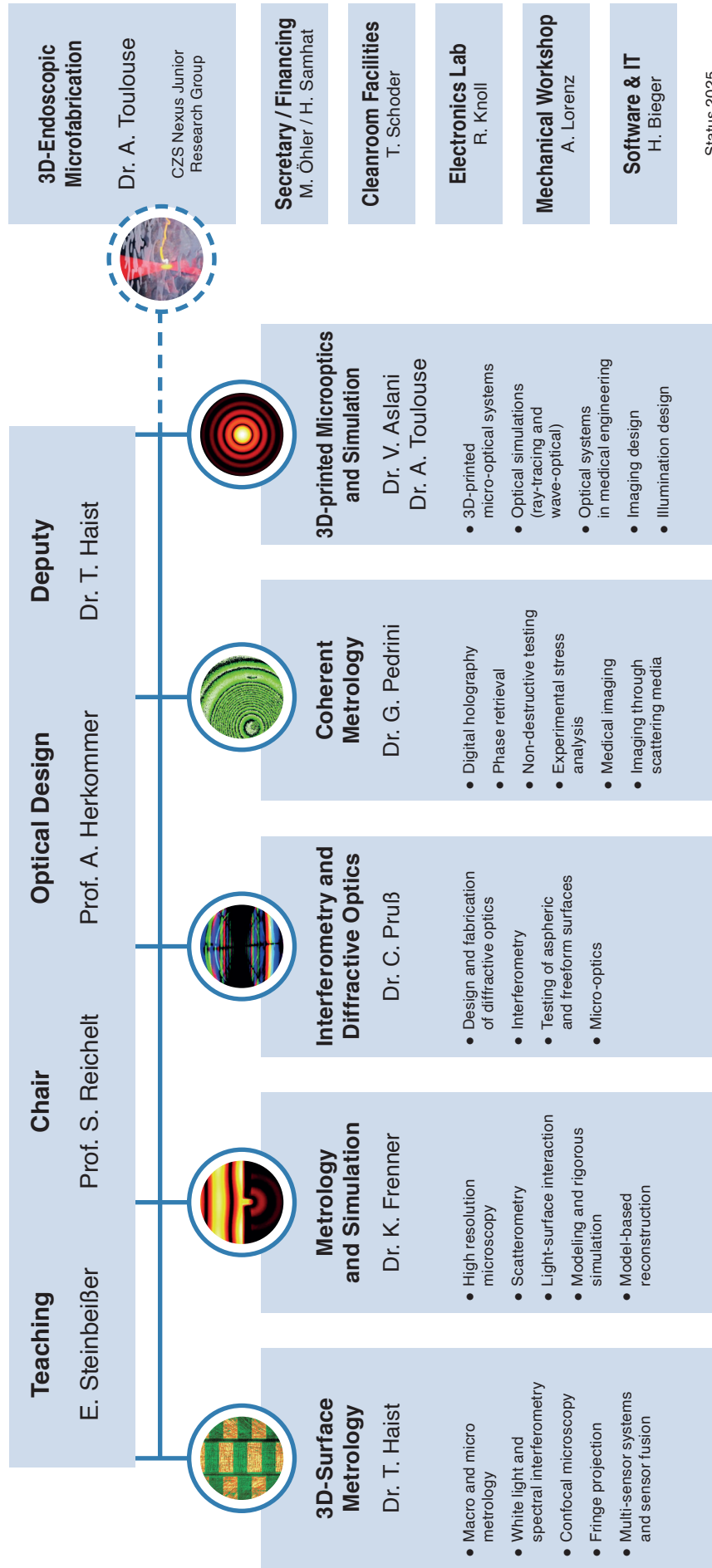
Invited lectures on international conferences	70
Awards	71
Membership of Editorial Boards	72
Reviewed papers.....	73
Reviewed papers and book chapter.....	76
Conference proceedings and journals	78
Patents	84
Doctoral Theses, Master & Bachelors Theses and Student Research Theses.....	87
Optik-Kolloquium 2023	98
Optik-Kolloquium 2024	99
Organized International Conferences / Impressum.....	100



A large part of the ITO Team in December 2025

Institute of Applied Optics / Institut für Technische Optik (ITO)

Structure and Team



Status 2025

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. S. Reichelt
Exercise: K. Doth, E. Steinbeißer
- **Optical Measurement Techniques and Procedures**
Lecture: Prof. Dr. S. Reichelt
Exercise: E. Steinbeißer, M. Zimmermann
- **Optical Information Processing**
Lecture: Prof. Dr. S. Reichelt
Exercise: Dr. K. Frenner
- **Fundamentals of Optics (only for B.Sc.)**
Lecture: Prof. Dr. A. Herkommer
Exercise: Dr. V. Aslani, J. Drozella
- **Optical Systems in Medical Engineering**
Lecture: Prof. Dr. A. Herkommer
Exercise: M. Wende, F. Fischer, V. Aslani
- **Development of Optical Systems**
Lecture: Prof. Dr. A. Herkommer
Exercise: Ö. Atmaca, A. Herkommer, J. Trapp
- **Optical Sensors for Autonomous Systems**
Lecture: Dr. T. Haist
Exercise: Dr. T. Haist

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

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

Additional studies:

- project work and thesis within our fields of research
(you will find a list of all student project works at the end of this annual report)
- practical course "Optic-Laboratory"
 - ⇒ holographic projection
 - ⇒ digital microscopy
 - ⇒ computer aided design of optical systems
 - ⇒ measurement of the spectral power distribution
 - ⇒ Köhler illumination
 - ⇒ 3D measurement with stereo vision
 - ⇒ Image recognition with artificial neural networks
- 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
 - ⇒ wavefront measurement
- common lab for mechanical engineering (APMB)

Activities of the Univ. Stuttgart SPIE Student Chapter

M. Zimmermann, M. Wende, J. Grunewald, C. Schober, J. Trapp, A. Savchenko, F. Fischer, C. Pruß

Since its founding in 2018, the Univ. Stuttgart SPIE Student Chapter continues to play an important role for optics-inclined students at the University of Stuttgart. As an officially recognized student group, the chapter brings together students of all levels, many from the ITO, including past and present officers. Our mission remains to strengthen the connections between students, the optics and photonics industry, and researchers in the field through scientific, professional, and social activities.

From 2023 to 2025, we continued to build upon our previous successes and expanded our activities both in scope and international collaboration.

In 2023, we offered an English course for our members to enhance their communication skills in academic and professional contexts. We attended the DGaO Ringvorlesung to get a glimpse into topics presented by research groups from across Germany. A highlight was the company visit to Q.ant, where we gained insights into quantum technology applications in industry, followed by a relaxed barbecue that encouraged informal exchange. Another remarkable event was our three-day Chapter Seminar in Salzburg, which included company visits to Sony DADC and MedPhoton. These visits provided valuable exposure to research and development practices in the fabrication of microstructures and computer tomography systems. During the Chapter Seminar, we again held a day of presentations under the motto "By students, for students." Here, participants were able to talk about their current research questions, and ample time was given for in-depth discussion of problems and solution ideas in small groups.

In 2024, we again participated in the DGaO Ringvorlesung series, continuing to promote scientific learning and exchange. Our main event, the Chapter Seminar, was held in Oberstaufen,

near the Swiss border. This three-day event combined the presentations "By students, for students" with company visits to SwissOptic and RhySearch, giving our members a close look at precision optics manufacturing and research infrastructure in Switzerland. Another highlight was our joint visit to TRUMPF, organized together with the Optica Stuttgart and SPIE/Optica Karlsruhe Chapters. The event fostered not only professional networking but also connections between chapters across southern Germany.

In 2025, we upheld our participation in the DGaO Ringvorlesung while expanding our engagement with external researchers. We hosted two visiting scientists for inspiring talks: Prof. Gijs van Soest from Erasmus MC, Rotterdam, Netherlands, who shared his insights into catheter-based imaging with light and ultrasound, and Dr. Michelangelo Masini, head of Zeiss corporate R&D, who gave an engaging presentation about Innovation at Zeiss, talking about robotic technology in modern neurosurgery. We rounded off the year with a company visit to Nanoscribe and the Zeiss Innovation Hub close to Karlsruhe, where we learned about the newest features of cutting-edge two-photon lithography and its applications in micro-fabrication.

Through these activities, our chapter continued to foster a strong professional network, promote student development, and strengthen ties with industry and academia alike. We look forward to further expanding our initiatives and collaborations in the years to come.

Supported by: SPIE – The International Society for Optics and Photonics

SPIE. **STUDENT**
CHAPTER
UNIVERSITY
OF STUTTGART



Fig. 1 Visit of Sony DADC during our Chapter Seminar in 2023.



Fig. 2 Visit of SwissOptic during our Chapter Seminar 2024.



Fig. 3 Lectures of the visiting scientists Prof. Gijs van Soest (left) and Dr. Michelangelo Masini (right) in 2025.

Hands for AI – a roadmap for the optical metrology software ITOM

B. Bertschinger, C. Pruß

ITOM is an open-source software developed at the Institute of Applied Optics (ITO) of the University of Stuttgart. It is specifically designed for the control of measurement systems, laboratory automation, and data evaluation. The core functionalities are structured into the following areas [1],[2]:

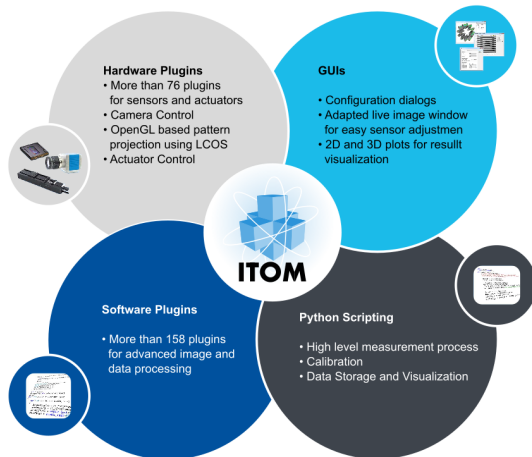


Fig. 1 Overview of the functionalities of the scientific development environment for metrological applications ITOM.

1. Hardware Control & Plug-and-Play Integration

Modular plugin system: Hardware components such as cameras, actuators (motors), light sources, and I/O devices are integrated via external libraries.

Unified interfaces: Standardized interfaces allow hardware plugins (e.g. different camera models) to be exchanged without modifying the script code.

Broad manufacturer support: All major camera manufacturers as well as a wide range of actuators and A/D converters are supported.

2. Development Environment & Scripting

Embedded Python: ITOM uses Python 3 as its scripting language and provides a powerful IDE with syntax highlighting, auto-completion, and debugging features.

Scientific libraries: Packages such as NumPy, SciPy, and Matplotlib are integrated by default.

Real-time image processing: Integration of OpenCV enables high-performance real-time processing of image data.

3. Data Visualization & Analysis

Interactive plots: Support for visualizing data in 1D, 2D, 2.5D, and 3D.

Specialized libraries: Direct integration with the Point Cloud Library (PCL) for processing 3D point clouds.

Optical simulation: Functions for ray tracing and optical simulations are included.

4. Graphical User Interfaces (GUI Design)

WYSIWYG editor: The integrated Qt Designer allows the creation of professional graphical user interfaces for measurement workflows.

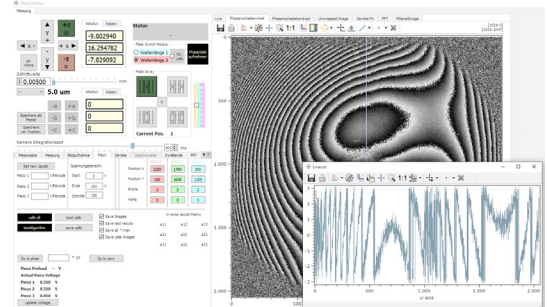


Fig. 2 Example of a graphical user interface using ITOM for measurement data acquisition via camera and additional actuators.

Dynamic customization: Dialogs and windows can be modified at runtime to adapt to specific experiments or laboratory set-ups.

5. Open Source & Platform Independence

Availability: The software is licensed under the GNU LGPL and can therefore be used free of charge, including for commercial purposes.

Platforms: itom runs on Windows, Linux, macOS, and even on the Raspberry Pi. ITOM combines the advantages of programming environments such as MATLAB with the hardware flexibility of LabVIEW in a free, Python-based environment.

Over the past three years, the ITOM developers have placed a strong emphasis on improving accessibility for developers. This effort involved a comprehensive refactoring of the CMake build system, a restructuring of the project architecture into well-defined submodules, and a cleaner handling of external dependencies. Libraries such as Qt, PCL, and OpenCV are now integrated as self-building source code via CMake external projects, rather than being treated solely as binary packages.

The overarching goal of these changes is to make the build process more robust, transparent, and consistent across all supported platforms. These objectives will be fully realized with the upcoming release of ITOM v5.0. This represents a significant milestone for the project and establishes a solid foundation for future development, even as the broader technical landscape continues to evolve rapidly. Large Language Models (LLMs) have developed into a core foundational technology in research and industry since the breakthrough of the transformer architecture in 2017 and the scaling of pretrained language models [3], with applications ranging from chatbots and programming assistance to scientific text analysis. Since the widespread introduction of ChatGPT at the end of 2022, their adoption has increased dramatically, as reflected in the large number of new models (e.g., the GPT family, LLaMA, PaLM), domain-specific variants, and their deployment in numerous production systems [4]. The advent of AI has transformed how we interact with and develop software. AI models are now widely used across applied scientific fields and increasingly support the software development process itself. For the dissemination and use of ITOM, this offers both benefits and considerations. Assisted programming with AI, also known as “vibe coding”, is a highly beneficial approach, especially for less experienced programmers. It enhances accessibility to programming languages and the broader field of informatics. A key factor for its success is a well-established training dataset for the AI models. ITOM already provides extensive documentation and can compete with established scientific development environments such as LabView or MATLAB. Since ITOM is hosted on GitHub, this documentation is fully accessible and can serve as a valuable resource for AI training. In

addition, forums, user comments, and error reports offer rich supplementary material for model learning.

While ITOM has room to expand its dedicated AI knowledge base, the existing resources already provide a solid foundation. Strengthening this training base offers a clear opportunity to enhance AI-assisted programming. Currently, secondary training sources for ITOM are somewhat limited, which can constrain AI systems in providing fully reliable suggestions. Addressing this gap will allow ITOM to offer even more robust AI support, further attracting and empowering developers and ensuring its competitiveness with other AI-enhanced development environments. Hence, we propose adapting an existing open-source, code-focused large language model, such as StarCoder, and retraining it specifically for ITOM. This AI assistant would support code development in a manner similar to Microsoft CoPilot in Visual Studio, enhancing productivity and accessibility for developers.

This AI support should be designed so that developers' questions and the AI's responses are reviewed and evaluated by the development team. These interactions can then serve as a valuable secondary source for documentation. In this way, we not only provide enhanced support to our existing user base but also create high-quality training data for future AI systems, gradually building a self-supporting AI-assisted developer environment tailored to ITOM.

In cooperation with: The ITOM open source community.

References

- [1] M. Gronle, W. Lyda, M. Wilke, C. Kohler, and W. Osten, "itom: an open source metrology, automation, and data evaluation software," *Appl. Opt.* **53**, 2974-2982 (2014).
- [2] Gronle, M., Kohler, C., Wilke, M., Lyda, W., Bieger, H., Osten, W., "itom - An Open Source Measurement, Automation and Evaluation Software Suite", in: *Fringe 2013*, 957-964 (2013)
- [3] Minaee et al.: "Large Language Models: A Survey", arXiv:2402.06196.
- [4] Zhao et al.: "A Survey of Large Language Models", arXiv:2303.18223

DGaO's 126th Annual Conference 2025 held in Stuttgart

C. Pruß

The DGaO conference serves as a platform for scientific exchange within the community, supporting the DGaO's mission of fostering applied optics and collaborative advancement of the field. In 2025, ITO had the privilege to host this conference at the University of Stuttgart. From June 10-14th, more than 200 scientists gathered to **discuss recent topics in optics**, covering a broad spectrum ranging from optical metrology to optical design and manufacturing technology for optical components and systems. Seven keynote lectures and more than 80 presentations were given on stage, 37 at the poster. A panel discussion moderated by Dr. Ulrike Böhm (Carl Zeiss AG) on career prospects in optics and photonics attracted a large fraction of the younger scientists.



Fig. 1 Industry exhibition during conference breaks.

The accompanying **industry exhibition** provided opportunities for personal exchange with companies from the sector, while another exhibition showcased optical phenomena.

The **core scientific topics** were reflected in the keynote lectures. Prof. Dr. Reichelt opened with research on single-shot measurement methods for analyzing dynamic processes. Prof. Dr. Herbert Gross addressed simulation and tolerancing of optical systems with freeform surfaces. Prof. Dr. Colin Sheppard (UNSW Sydney) presented innovative approaches to improving resolution in confocal microscopy through detector

arrays. Simon Hartel (Landshut University) demonstrated geometric algebra applications for system optimization in light sectioning systems. Dr. Florian Dötzer (TU Ilmenau) discussed camera-based interferometric systems for picometer-range vibration measurements. Dr. Stefan Risse (Fraunhofer IOF) presented advances in production and characterization of metal optics with freeform surfaces, demonstrating nanometer precision in large optical components. Dr. Vladimir Mitev (Carl Zeiss SMT GmbH) explained how ZEISS mirrors with picometer-range precision requirements enable state-of-the-art microchip production for EUV lithography, supporting Moore's Law continuation.

A special highlight was the **Fraunhofer lecture** given by Dr. Peter de Groot, long-time Chief Scientist and Research Director at Zygo Corporation and SPIE President for 2025. During the conference banquet, he reflected in a professionally excellent and entertaining manner on his innovative contributions to optical metrology with the title "Did I invent that? Reflections on creativity and innovation in optics."



Fig. 2 Fraunhofer lecture given by Dr. Peter de Groot.

The DGaO honored outstanding scientific work with the **Young Scientist Award**. Andreas Brenner received the award for his master's thesis "Calibration of light modulators with physically interpretable neural networks." The prize for the best doctoral thesis went to Dr. Simon Amann for his dissertation "Novel concepts for the realization of a miniaturized computed tomogra-

phy imaging spectrometer." DGaO President Ricarda Kafka and Prof. Dr. Steffen Reichel, head of the prize committee, presented the certificates.



Fig. 3 DGaO Young Scientist Award.

The conference featured an engaging **social program and networking**. Angelika Schmid

(Werner Sobek AG) explained the architecture and structural engineering challenges of the new Stuttgart Central Train Station at the welcome evening. A city excursion provided insights into Stuttgart's culture and history, concluding in a beer garden.



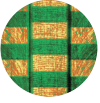
Fig. 4 The conference's success was the result of many helping hands of a highly motivated ITO team.

In cooperation with: Deutsche Gesellschaft für angewandte Optik e.V.



Fig. 5 Participants of the conference.

The research groups



3D-Surface Metrology

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

Current research activities are:

- 3D-measurement applying fringe projection and deflectometry (macroscopic and microscopic)
- adaptive techniques using spatial light modulators
- confocal microscopy
- white light interferometry
- hyperspectral imaging
- sensor fusion and data interpretation strategies

Contact: haist@ito.uni-stuttgart.de



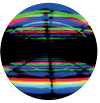
High Resolution Metrology and Simulation

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

Contact: frenner@ito.uni-stuttgart.de



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

Contact: pruss@ito.uni-stuttgart.de



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

Contact: pedrini@ito.uni-stuttgart.de



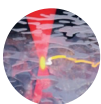
3D-printed Microoptics and Simulation

In our research group we focus on the development of novel tools for simulation and optimization, and the design of innovative complex optical systems for industrial or medical purposes. A strong focus lies on the realization of novel micro-optical systems fabricated via two-photon-polymerization. The classical optical design of imaging and illumination systems, as well as ray-based and wave-optical system simulations remain core competencies and research fields of our group.

Research areas include:

- design, simulation and manufacturing of 3D-printed micro-optical systems
- optical simulations (ray-tracing and wave-optical)
- optical systems in medical engineering
- imaging design
- illumination design
- phase space methods in optical design and simulation

Contact: aslani@ito.uni-stuttgart.de, toulouse@ito.uni-stuttgart.de, herkommer@ito.uni-stuttgart.de



3D-Endoscopic Microfabrication

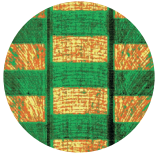
This Nexus Junior Research Group, funded by the Carl-Zeiss-Stiftung, focuses on novel optical methods for endoscopic 3D-bioprinting. The group will evaluate which methods of single- and multi-photon polymerization are best-suited for fiber integration and biomedical applications, aiming for, fast, safe and robust tissue regeneration.

Research areas include:

- methods for fiber-based 3D printing
- endoscopic bioprinting
- 3D-printed microoptics for endoscopy

Contact: toulouse@ito.uni-stuttgart.de

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
- hyperspectral imaging
- sensor fusion and data interpretation strategies

Contact: haist@ito.uni-stuttgart.de

Deformation monitoring of bridges

T. Haist, S. Hartlieb, S. Reichelt

In the Sonderforschungsbereich 1244 of the DFG, research on adaptive buildings is performed. For the control of such adaptive buildings it is necessary to measure the state of the building in a continuous (24/7) and fast way. Accuracies in the mm range are to be achieved even for very large structures.

Camera-based systems are very promising candidates for such measurements because measurement rates in the range of 100 Hz with low latencies can be achieved in a very cost effective way.

Unfortunately, the typically achieved accuracies for such image-based measurements are in the range of 1:10,000 (1D) of the measurement field. For a 100 m bridge this translates to an accuracy of 1 cm.

Two methods based on diffractive optical elements have been developed and applied to improve accuracy: the multipoint method and the holographic wide-angle method. Both methods use active light emitters (typically LEDs) mounted at the structure to be monitored (see Fig. 1).

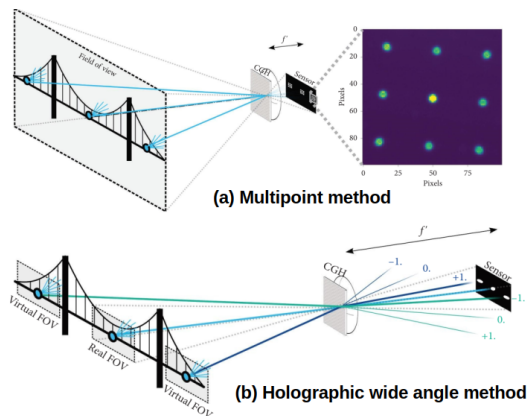


Fig. 1 Two hologram-based approaches for rapid deformation measurement in bridges.

The multipoint method replicates the image of each LED. Averaging position measurements across multiple copies of the LED image effectively reduces noise and discretization errors.

The holographic wide angle method achieves a long focal length while covering a wide angle. Again, a diffractive optical element is used to achieve this.

Both methods considerably improve the accuracies compared to a straight-forward standard

imaging approach [1].

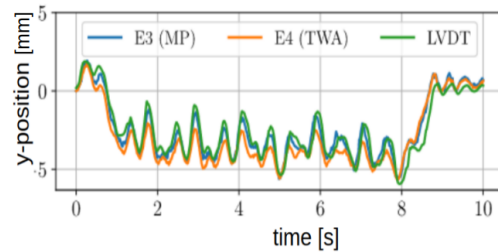


Fig. 2 The two hologram-based methods for the fast deformation measurement of bridges. Deformation at one point (E4) during passage of a train.

We used the methods for the measurement of a typical high-speed railway bridge in the north of Germany. The bridge has a length of 65.5 m and a resonant frequency of 2.7 Hz. We compared the measurements with a direct mechanical contact measurement using linear variable differential transformers (LVDTs), offering both a high measurement rate and high accuracy.

It turned out that the three different applied measurement methods are in very good agreement. The measurement uncertainties of the deformations are in the range of 30 μm at distances between 34 and 50 meters [1].

Supported by: This work was supported by the DFG.

Project: SFB1244

References

- [1] S. Hartlieb, A. Zeller, T. Haist, A. Reichardt, C. Tarín Sauer, and S. Reichelt, "Advanced Imaging-Based Metrology for Precise Deformation Monitoring: Railway Bridge Case Study," *Structural Control and Health Monitoring* **2025**(1), 5603393 (2025).

Holographic multipoints for Shack-Hartmann sensing

Z. Wang, T. Haist, S. Hartlieb, A. Rüdinger, S. Reichelt

Shack-Hartmann sensors (SHS) offer a simple way of measuring wavefronts. Typically very good light efficiencies and high speeds of operation can be achieved. However, for the standard SHS there is a trade-off with respect to measurement accuracy and dynamic range. Both of these measures can be improved by using the multipoint technique.

To this end each subaperture or microlens of the conventional SHS is replaced by a hologram (Fig. 1) that leads to subaperture-specific spot pattern (Fig. 2). The lens term of the conventional microlens is not incorporated into the hologram because of three reasons. First, the space-bandwidth product of the hologram can be decreased and manufacturing becomes easier. Second, the zeroth as well as negative diffraction orders will not lead to problems and third, the size of the measurement aperture can be decoupled from the image sensor size.

This last point is especially important for the realization of low-cost SH sensors because in conventional SHS a large wavefront leads to a large image (and expensive) image sensor.

The holograms have been optimized using direct binary search and fabricated as binary elements. This leads to point symmetric patterns which are advantageous for the multipoint technique (errors will be canceled by the symmetric counterpart).

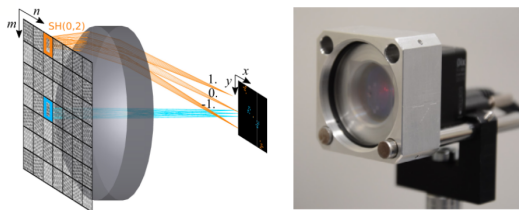


Fig. 1 Principle of the sensor and photo of the realized prototype.

The unique spot pattern of each subaperture can be located using correlation, no matter where it is located on the image sensor. As a result, the dynamic range of this sensor is large compared to the conventional SHS where each spot is not allowed to cross the border of the subaperture.

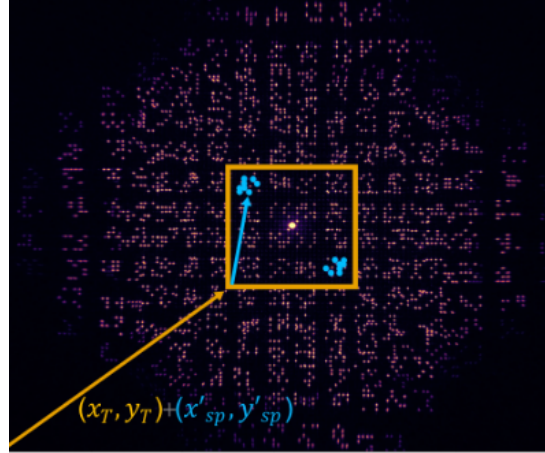


Fig. 2 Spot pattern on the image sensor.

Apart from that we now have multiple spots to measure the position. Discretization and noise induced errors are averaged and — therefore — reduced. It can however happen that spots of different patterns might overlap. In this case it is necessary to detect these overlaps and not evaluate the spots at these problematic positions [1]. Based on the shifts for each subaperture one can easily reconstruct the corresponding Zernike aberration coefficients for the incoming wavefront.

For a standard image sensor we achieved accuracies of about $\lambda/50$ RMS for a dynamic range of more than $\pm 8^\circ$ and a measurement aperture of 20×20 mm [1]. The parameters can be easily adapted to other sensor specifications. In addition, the spatial extension of the wavefront is decoupled from the image sensor size. This allows laterally extended wavefronts to be measured in a cost-effective manner.

A disadvantage of this principle is that the incoming light is divided among multiple spots on the image sensor. Consequently, the sensor is not well suited for low-light applications (e.g., astronomy).

References

- [1] S. Hartlieb, Z. Wang, A. Rüdinger, T. Haist, and S. Reichelt, "Large dynamic range Shack-Hartmann wavefront sensor based on holographic multipoint generation and pattern correlation," *Optical Engineering* **63**(2), 024107–024107 (2024).

Programmable microscopy

M. Tscherpel, T. Haist, S. Reichelt

In the ZIM project adapt.MICRO we developed a microscope technology that makes it possible to combine many different microscopy methods in one piece of hardware.

The core elements are active spatial light modulators, which are integrated at three distinct positions along the beam path: twice in the illumination path and once in the imaging path. This makes it possible to change the optical properties or the beam path of the microscope purely via software. As a result, different methods can be changed very quickly and without optomechanical adjustment of the microscope. This reduces the number of microscope systems required for different analyses and increases the information density of individual analyses by allowing methods to be easily combined.

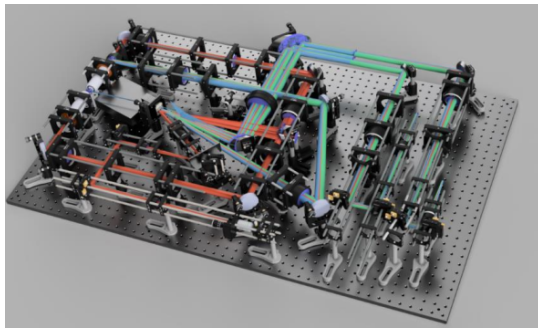


Fig. 1 Sketch of the setup.

The system is meant as an experimental platform (see Fig. 1) enabling the study of different microscopic imaging modalities. Among these methods are

- hyperspectral imaging (by switchable illumination, see Fig. 2),
- fringe projection profilometry (see Fig. 3),
- stereo vision,
- phase contrast imaging (different methods),
- phase retrieval,
- bright and dark field illumination,
- extended depth of field, and
- simplified confocal microscopy.

The work has been done in close cooperation with Dr. Lingel from EurA AG. Two experimental setups — one at ITO and one at EurA — have been realized.

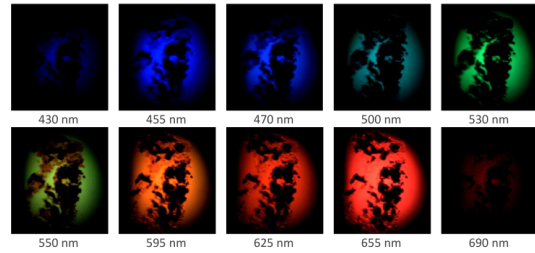


Fig. 2 Hyperspectral imaging.

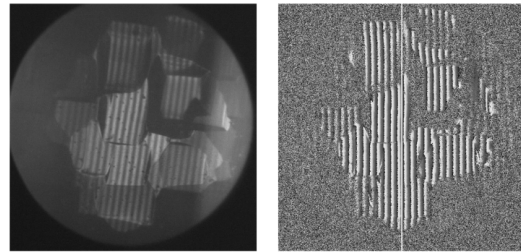


Fig. 3 Fringe projection profilometry.

For confocal imaging, different defocus phase maps are encoded on the SLM in the Fourier plane while a spot pattern is projected (see Fig. 4). For measurement of a mirror a standard deviation of the height of 350 nm has been achieved (using a numerical aperture of 0.55).

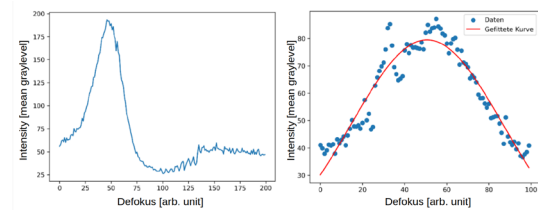


Fig. 4 Confocal signal with defocus, left: overall, right: central area with Gaussian fit for improved accuracy.

Supported by: BMWI.

Project: adapt.MICRO, FKZ: KK5481401SY2.

In cooperation with: EurA AG, Ellwangen (Dr. C. Lingel)

Toward a 3D NIR microscopy and Raman spectroscopy instrument for astrogeological exploration

C. Ryan, T. Haist, S. Reichelt

Rover-based space exploration allows for in-situ investigation of astrological material. Imaging and laser spectroscopic techniques in combination are established in these challenging environments. With added depth information, astrogeologists have more information to work with. Topography measurement techniques have been compared with respect to rover- and inline laser spectrometer requirements [1]. We now develop a space-suitable, inline fringe projector as a step towards a combined Near Infrared and Raman Analysis 3D microscope (NIRA 3D), enabling highly resolved 3D multispectral and chemical maps of extra-terrestrial geology.

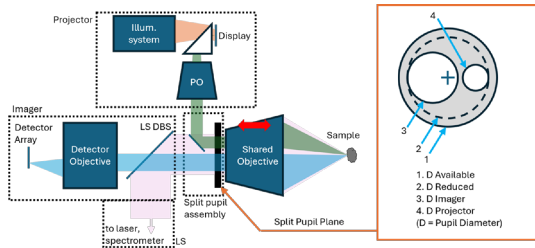


Fig. 1 Left: Optical architecture of NIRA 3D showing integration of projector, imager, laser spectrometer and a shared objective with a dichroic beam splitter (DBS) and split pupil assembly. Right: Division-of-aperture scheme at shared objective exit pupil plane.

Light from a prototype, space-worthy “pico-projector” is injected via dichroic beam splitters and division-of-aperture of the shared objective, whose usable exit pupil diameter is reduced by the need for focusing translations. The projector design is based entirely on off-the-shelf optics and consists of a projection objective, a DMD-based display, and illumination via a NIR-LED with a dual-MLA-based homogenizer.

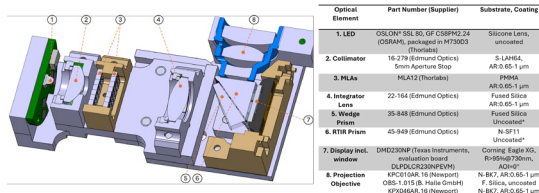


Fig. 2 Pico-projector design and commercial optics parts list.

The volume contribution of the pico-projector is much smaller than that of the context imager.

Trade-offs between radiometry and required volume envelope indicate a shared objective lens. MLA and DMD properties must be carefully chosen in coordination for an optimized design. Aperture splitting causes asymmetric aberrations, which vary with the autofocus position, in particular distortion and astigmatism are affected. Miniaturization of the optics decreases sensitivity to thermal focal shifts and improves thermal homogeneity but requires more care in optomechanical design to avoid stress buildups.

The figure below shows the as-built projector during alignment characterization testing. Estimates of MTF from measurements approach the design values, illumination efficiency and straylight are still being optimized.

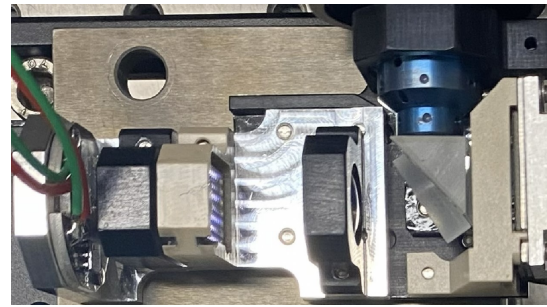


Fig. 3 Photo of projector during alignment characterization testing.

After calibration, the pico-projector and fully system 3D performance will be measured and measurements of astrogeological analogues will be assessed. The technology readiness level (TRL) of the pico-projector will be increased by space environment testing in a thermal-vacuum chamber.

Supported by: This work is funded by the German Aerospace Center (DLR).

In cooperation with: German Aerospace Center, Institute for Space Research

References

- [1] C. Ryan, T. Haist, G. Laskin, S. Schröder, and S. Reichelt, “Technology Selection for In-line Topography Measurement with Rover-Borne Laser Spectrometers,” *Sensors* **24**(9) (2024). URL <https://www.mdpi.com/1424-8220/24/9/2872>.

Programmable oblique structured light illumination for 3D metrology

A. Fuhrmann, A. Gröger, K. Körner, A. Herkommer

The ProMakroS project, a collaboration between AuriEga GmbH and the Institute of Applied Optics, focused on the development of a programmable oblique illumination system for structured light projection that enables high-precision 3D metrology. The main objective was to generate computer-controlled illumination patterns and project them into the object plane under well-defined optical conditions, enabling accurate surface reconstruction from recorded images. Figure 1 shows the final prototype system.

The key technological advantage and novelty is the oblique projection of digitally generated patterns via a standard digital projector combined with a cost-efficient imaging setup. The projected image is first formed in an intermediate image plane, which is re-imaged via a telecentric system into the measurement plane while obeying the Scheimpflug condition to ensure sharp imaging across the field. To enhance the overall transmission of the system, a static micro-mirror array (blazed grating) is placed in the intermediate image plane. This microstructure, specifically designed at ITO and fabricated using ultraprecision manufacturing techniques, efficiently redirects the incident light bundle to subsequent telecentric relay optics.

A low-cost replication process for this static micro-mirror array was developed and successfully implemented within the project. This represents an important result, enabling the cost-efficient fabrication of otherwise complex optical microstructures. Downstream of the illumination path, a telecentric imaging system equipped with a digital camera captures the structured patterns reflected from the surface of the object. A dedicated computational pipeline in ITOM [3] reconstructs the projected pattern, performs phase evaluation, and calculates a dense 3D point cloud of the measured object (Fig. 2).

During the integration system test phase, it became evident that the existing central-perspective imaging configuration of the camera caused significant challenges in calibration. As a result, the camera path was redesigned to be fully telecentric as well.

The project is planned to be commercialized with the industrial partner. The innovative system design principle for illumination and metrology led to two granted patents [1, 2].

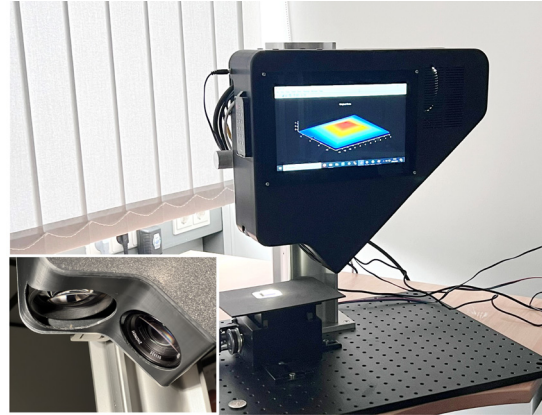


Fig. 1 Full 3D-metrology system, based on oblique structured light projection. The inset shows details of the imaging and illumination port.

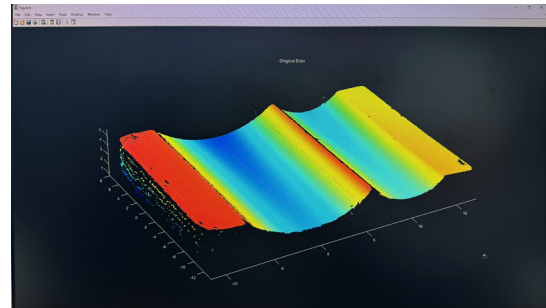


Fig. 2 Measurement result of a test part.

Supported by: This work was supported by AiF Projekt GmbH, Projektträger des BMWK.

Project: ProMakroS - KK5051803

In cooperation with: AuriEga GmbH

References

- [1] A. Fuhrmann, K. Körner; DE-Patent (2024): Programmierbare Schräglichtquelle zur Musterprojektion auf ein Objekt für Bildverarbeitung und 3D-Messtechnik, insbesondere auch mittels Triangulation; DE102023001730A1
- [2] A. Fuhrmann, K. Körner; DE-Patent (2025): Anordnung und Verfahren zur Beleuchtung, insbesondere auch für die Makro-Fotografie, für Bewegtbild-Aufnahmen im Nahbereich oder für Inspektionen; DE102023004572B3
- [3] ITO provides an open-source metrology library ITOM at: <https://github.com/itom-project>

Differential perspective

T. Haist, A. Fauhalber, F. Lodholz, S. Reichelt

Perspective is a simple, yet powerful method for estimating distances to objects. If the real-life size of an extended object is known, the distance to the object can be easily computed after measuring the image-size of the object. Compared to triangulation, the “triangle” used for the underlying geometry is different (base of triangle at the object). Therefore using perspective, a small sensor can measure distances. But only to extended objects, whereas in the more often used triangulation setup a laterally extended sensor measures the distance to points (see Fig. 1).

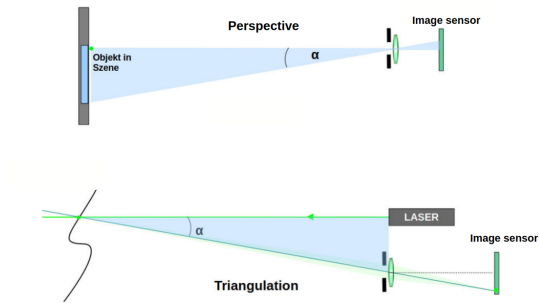


Fig. 1 Triangles used for measurement in triangulation and perspective. For perspective the base of the triangle is the object, whereas for triangulation it is the sensor.

If the real-life size of the object is not known, the distance can still be measured using two axially separated measurements (see Fig. 2). This can be achieved optically (e.g. using two cameras) or by employing two consecutive image recordings done from two distances.

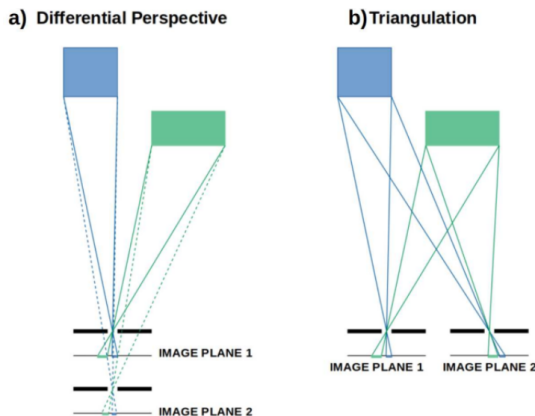


Fig. 2 In differential perspective the separation of the two cameras (or two recordings) are axially separated.

Figure 3 shows such an application where two camera exposures of a camera on a vehicle are performed. The temporal separation Δt leads

directly to a spatial separation and if the camera/vehicle speed is known (which is typically the case) the spatial separation, of course, can be easily computed. During evaluation, first the objects of interest in the images are detected and segmented. Then, the image sizes of these objects are computed. Based on these image sizes the distance to an unknown object can be computed [1].

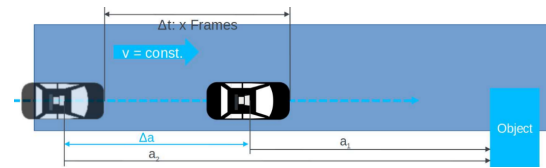


Fig. 3 Instead of two cameras, one moving camera can be employed, e.g. a camera mounted on a car.

Figure 4 shows one exemplary set of measurements that have been recorded on a car using just one camera [1]. The results show that quite accurate distance measurements even at large distances can be easily achieved. However one has to emphasize that these results have been obtained for non-moving objects (traffic signs, license plates). For (fast) moving objects the speed of these objects have to be estimated or errors are to be taken into account.

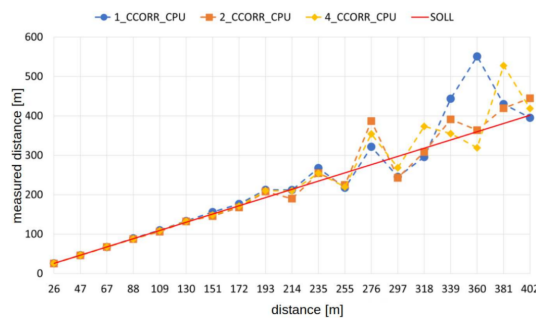


Fig. 4 Distances measured on a moving car using one camera.

Supported by: This work was supported by the Baden-Württemberg Stiftung

Project: See3D

References

- [1] T. Haist, F. Lodholz, A. Faulhaber, and S. Reichelt, “Differential perspective as a non-expensive distance sensing principle,” in *Proc. SPIE: Automated Visual Inspection and Machine Vision V*, vol. 12623, pp. 91–99 (SPIE, 2023).

Differentiation of healthy and malignant breast tissue using hyperspectral imaging

A. Rüdinger, T. Haist, S. Reichelt

Within the multimodal breast cancer therapy concept, the resection of the tumor is one common method. To ensure the complete resection, while preserving healthy tissue, determination of the tumor margins is necessary. For this purpose, in a first step a hyperspectral reference measurement system was developed, to measure the tissue spectra of healthy and malignant *ex-vivo* tissue samples. The system measures the tissue spectra within a large spectral range (450 - 1450 nm) with a good spectral and spatial resolution [1]. Figure 1 shows the measurement setup installed at the University Hospital Tübingen, enabling tissue measurement immediately after resection.

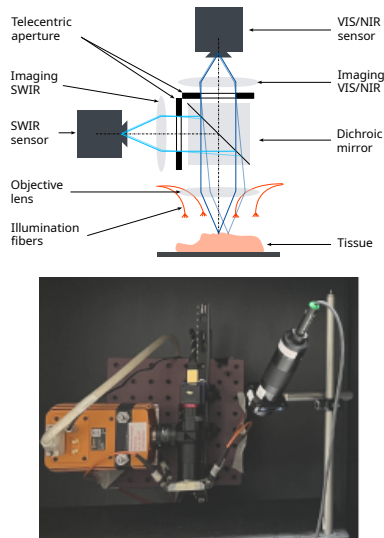


Fig. 1 Schema and photo of the hyperspectral reference measurement system.

After preprocessing the hyperspectral cubes, the measurement images were overlaid with histological ground truth data, to label the pixel spectra accordingly. To minimize the influence of tissue type margins as well as uncertainties in the histological overlay, only smaller regions of interest (ROI) are evaluated instead of the entire measurement image. It was shown, that characteristic spectral differences in the mean spectra of healthy and malignant tissue of one patient, could also be reproduced for the mean spectra of all 19 patients of the study, making it possible to differentiate between healthy and altered tissue [2, 3].

Preliminary classification results demonstrate effective differentiation, including the adap-

tion of models pretrained on ROI data to full measurement images (see Fig. 2).

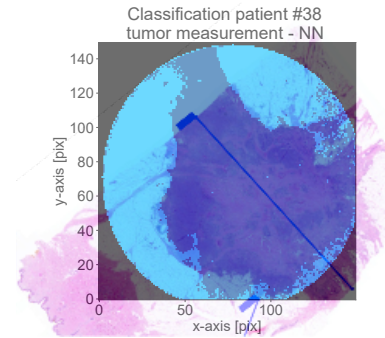


Fig. 2 Overlay of histological section of tumor area of patient #38 with the prediction of a fully connected neural network. Dark blue indicates predicted tumor pixel and light blue predicted healthy tissue.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: Research Training Group 2543: Intra-operative Multisensory Tissue Differentiation in Oncology (project ID 40947457, subproject A2)

In cooperation with: University Hospital Tübingen

References

- [1] A. Rüdinger, T. Haist, and S. Reichelt, "Hyperspectral measurement system for characterization of healthy and malignant tissue spectra," in *DGaO Proceedings*, p. P19 (DGaO - The German Branch of the European Optical Society, 2024). URL https://www.dgao-proceedings.de/download/125/125_p19.pdf.
- [2] A. Rüdinger, O. Atmaca, V. Bahlinger, E. Weisser, S. Matovina, A. Rohner, A. Strauß, V. Aslani, S. Thiele, A. Toulouse, T. Haist, A. Staebler, S. Brucker, F. Fend, A. Herkommer, and S. Reichelt, "Bimodal tissue differentiation using hyperspectral imaging and elastographic Fourier transform profilometry," *Light: Advanced Manufacturing* **6**(0), 1. URL <http://dx.doi.org/10.37188/lam.2025.073>.
- [3] A. Rüdinger, V. Bahlinger, A. Rohner, A. Staebler, T. Haist, S. Brucker, F. Fend, , and S. Reichelt, "Spektrale Analyse von malignem und gesundem Gewebe basierend auf hyperspektralen Bild-daten," in *DGaO Proceedings*, B10. URL https://www.dgao-proceedings.de/download/126/126_b10.pdf.

Diffraction-based multispectral imaging

T. Haist, R. Hahn, M. Tscherpel, N. Haile, M. Bäuerle, S. Reichelt

A new, cost-effective method for multispectral single-shot imaging has been developed and patented at ITO (EP 4184136 C0). It is based on imaging the scene onto a diffractive optical element (DOE) that transmits wavelengths relevant to the task [1, 2]. This eliminates the need for complex mosaic filter array fabrication.

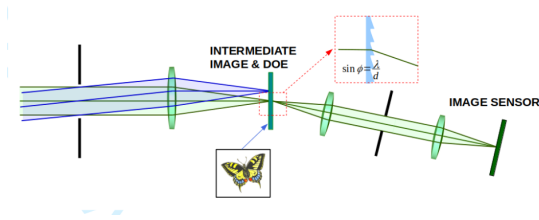


Fig. 1 Principle of the multispectral imaging using diffraction.

The camera can be individually adapted by changing the grating structures. The selection of any spatial-spectral patterns for a specific application is possible. The spatial resolution and the spectral resolution is coupled by an uncertainty relation where the limit is given by the fabrication of the DOE. Because of this and because of light efficiency, typically, quite broad spectral bands are employed.

If two image sensors are used it is possible to obtain a high spatial resolution grayscale image based on the zeroth diffraction order in combination with a multispectral image (see Fig. 2).

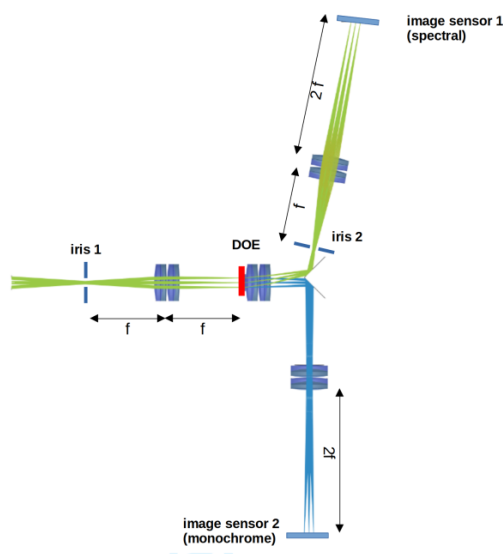


Fig. 2 Extension by using also the zeroth diffraction order and two image sensors.

We see potential areas of application in the fields of agriculture and food, environmental monitoring, medical imaging, remote sensing, security, and defense.

As part of the project, various prototypes have been generated and investigated (see Fig. 3) in order to subsequently find suitable industrial partners for the methodology.

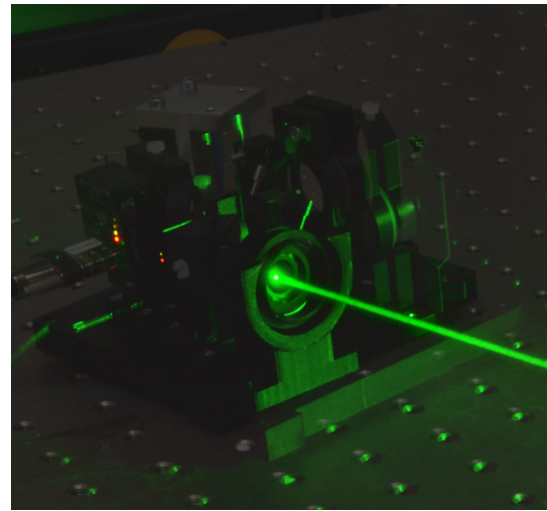


Fig. 3 A prototype for pulse detection.

Supported by: This work was supported by the University of Stuttgart.

Project: WTT Haist

References

- [1] R. Hahn, J. Görres, T. Haist, W. Osten, and S. Reichelt, "Novel snapshot hyperspectral imager based on diffractive elements," in *Optical Sensing and Detection VII*, vol. 12139, pp. 145–156 (SPIE, 2022).
- [2] T. Haist, R. Hahn, and S. Reichelt, "Diffraction-based dual path multispectral imaging," *tm-Technisches Messen* **90**(7-8), 418–424 (2023).

Calibration of spatial light modulators towards holographic displays

M. Zimmermann, A. Brenner, T. Haist, S. Reichelt

The hardware for three-dimensional holographic displays typically relies on phase-only spatial light modulators (SLMs), which are also widely used in laser material processing as well as in optical tweezers for biological and quantum experiments.

Since SLMs exploit the wave properties of light, form deviations in the optical system on the order of the wavelength strongly affect the quality of the desired wavefront. To enhance holographic displays, we adapted the camera-in-the-loop (CITL) calibration procedure, achieving a calibration that enables the experimental demonstration of far-field holograms without speckle in the target area and with a high agreement between calculated and recorded results.

Camera-in-the-loop calibration was introduced by Peng et al. to improve image quality in holographic near-eye displays [1]. It enables a full characterization of an optical system instead of calibrating its components separately and aligning them afterward. A physically interpretable neural network models the optical path based on Fourier optics principles. The system setup is shown in Fig. 1. During calibration, several holograms are computed, and the corresponding intensities are recorded. The neural network is trained with these data and iteratively refined until convergence.

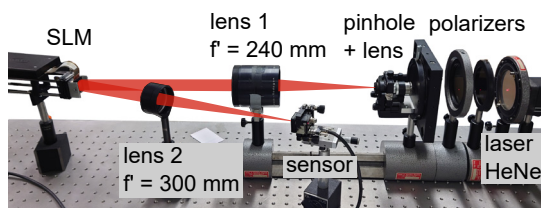


Fig. 1 Experimental setup. The SLM is illuminated with collimated light from a HeNe-laser and the monochrome sensor records the far field intensity.

Holograms are optimized using a stochastic gradient descent algorithm. To suppress speckle, the standard mean-squared-error loss is extended to include phase singularity information. Speckles arise from phase discontinuities and can be reduced by phase smoothing. The resulting optimization yields holograms with significantly improved uniformity in the target region. Figure 2 shows the recorded far-field intensities when the hologram is computed without and with calibration.

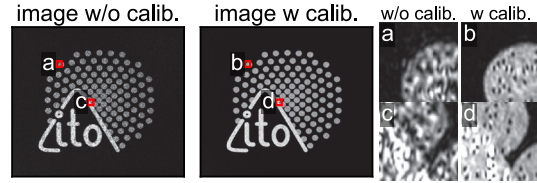


Fig. 2 Comparison of the recorded far-field intensity on the sensor without and with calibration.

Figure 3 compares the recorded and simulated far-field intensities when the speckles are suppressed. Most phase singularities are successfully removed, leading to a uniform intensity distribution. Images (c) and (d) show a remaining speckle pair, which could be removed by further iterations. The CITL calibration enables precise system modeling and serves as a foundation for experimental speckle suppression using phase smoothing. This confirms the high accuracy of the calibration approach [2].

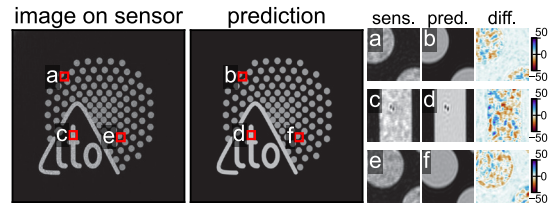


Fig. 3 Comparison of the recorded far-field intensity on the sensor with the predicted far-field intensity as calculated by the stochastic gradient descent algorithm with speckle suppression.

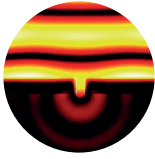
The precise calibration of optical systems with SLMs forms the foundation for upcoming holographic displays. Our ongoing work focuses on applying this method to larger display prototypes at the ITO.

Supported by: This work was in part supported by Vector Stiftung.

References

- [1] Y. Peng, S. Choi, N. Padmanaban, and G. Wetzstein, "Neural Holography with Camera-in-the-Loop Training," *ACM Trans. Graph.* **39**(6). URL <https://dl.acm.org/doi/10.1145/3414685.3417802>.
- [2] M. Zimmermann, A. Brenner, T. Haist, and S. Reichelt, "Improved Far-Field Holograms Using Spatial Light Modulators and Camera-in-the-Loop Optimization," *Opt. Eng.* **64**(09). URL <https://doi.org/10.1117/1.0E.64.9.094102>.

High Resolution Metrology and Simulation



The objective of the group is the analysis and the implementation of new principles for the 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

Contact: frenner@ito.uni-stuttgart.de

Efficient deep learning neural networks for Mueller-matrix Fourier scatterometry at optical frequencies

L. Fu, X. Wang, K. Frenner, S. Reichelt

Manufacturing computer chips involves nanometer-sized patterns on silicon wafers. Ensuring the accuracy of these features is critical to the performance and reliability of the final product, making optical scatterometry essential for quality control. However, traditional scatterometry methods, such as iterative fitting and library search, are challenged by their slow speed and enormous data requirements. To overcome these limitations, we explored a deep learning neural network, which can powerfully learn complex data relationships.

In this report, we demonstrate the high potential of a ResNet 18 deep learning network for this task. Training data consisting of simulated Fourier-plane Mueller matrices with all diffraction orders were generated using the RCWA method. The structure investigated is a periodic silicon grating with a pitch of 500 nm, a height around 100 nm covered by a thin layer of 3 nm SiO₂. It is illuminated by a light of 405 nm. Six structural parameters were varied: critical dimension (CD), grating height (H), side wall angle left (SWA_L) and right (SWA_R), top rounding (R_T) and bottom rounding (R_B) [1].

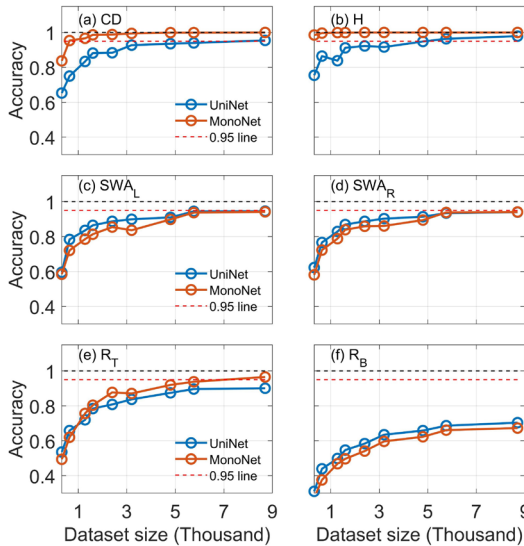


Fig. 1 Performance comparison of UniNet and MonoNet in terms of prediction accuracy versus dataset size (thousand) for the six parameters: (a) CD, (b) H, (c) SWA_L, (d) SWA_R, (e) R_T and (f) R_B.

Two distinct training strategies were compared: UniNet which uses a single network to predict the six parameters simultaneously; MonoNet which uses six separate networks to predict one

parameter at a time. Performances in terms of accuracy as a function of the dataset size are presented in Fig. 1. For parameters CD and H, MonoNet achieves extremely high accuracy with a small dataset size of 640. In contrast, UniNet requires a dataset size of 6,500 to achieve the same accuracy when the six parameters are predicted simultaneously. In general, MonoNet outperforms UniNet for parameters CD, H, and R_T. The two methods are comparable for SWA_L and SWA_R at larger dataset sizes, and MonoNet shows lower precision only for R_B.

The performance discrepancy between the two methods can be attributed to the multicollinearity effect [2]. In UniNet, all output parameters share a single feature representation within the network, which leads to gradient interference and can ultimately degrade the model's performance. In contrast, MonoNet trains the network for only one parameter at a time, effectively eliminating this GI. Consequently, MonoNet's performance is constrained only by the physical uncertainty inherent to the task. Our previous studies have already demonstrated a strong correlation between MonoNet's performance and parameter uncertainty [1]. These results provide valuable insights for developing more reliable and accurate measurement techniques, even in the presence of real-world imperfections.

Supported by: This work was supported by the German Research Foundation (DFG)

Project: Deep learning based computational imaging and optical metrology (FR3383/2-1)

In cooperation with: College of Physics and Optoelectronic Engineering at Shenzhen University, China; Shanghai Institute of Optics and Fine Mechanics, China

References

- [1] L. Fu, X. Wang, K. Frenner, and S. Reichelt, "Efficient deep-learning ResNet architectures for Mueller-matrix Fourier scatterometry," in *Modeling Aspects in Optical Metrology X*, B. Bodermann and K. Frenner, eds., p. 1356807, International Society for Optics and Photonics (SPIE). URL <https://doi.org/10.1117/12.3066282>.
- [2] J. Y.-L. Chan, S. M. H. Leow, K. T. Bea, W. K. Cheng, S. W. Phoong, Z.-W. Hong, and Y.-L. Chen, "Mitigating the Multicollinearity Problem and Its Machine Learning Approach: A Review," *Mathematics* **10**(8) (2022).

Accelerated computation of 2D-periodic Green function using Ewald transformation and simplex interpolation

L. Fu, K. Frenner, S. Reichelt

Efficient simulation of light scattering from doubly periodic nanostructures in layered media is essential for optical scatterometry, which is widely used in semiconductor manufacturing. For this purpose, we employ a surface integral equation (SIE) method to solve Maxwell's equations [1]. The feasibility of the SIE method for 2D-periodic structures strongly depends on the efficient evaluation of the 2D quasi-periodic Green's function (PGF) and its gradient (GPGF) [2], which can be accelerated using Ewald representation [2]. However, direct Ewald summation remains computationally expensive. Further speed-up can be achieved by tabulating PGF and GPGF in the unit cell and reconstructed via interpolation.

In this report, we demonstrate the computation of 2D quasi-periodic PGFs and their gradients using the Ewald representation combined with 2nd-order 3D simplex interpolation [3]. Interpolation is performed on the regularized PGF/GPGF in the reference unit cell. The final values for field points outside the cell are recovered by adding the removed singular terms and applying the appropriate phase factor.

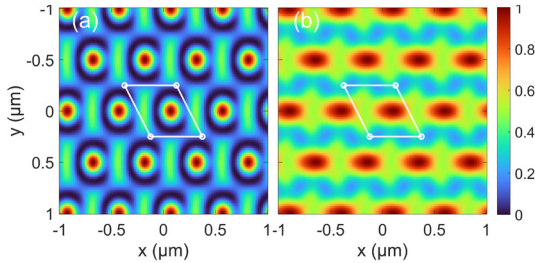


Fig. 1 Normalized intensity of interpolated 2D PGF in (a) and GPGF in (b) with $n = 1.5$ at $\theta = 10^\circ$.

The algorithms were implemented in FORTRAN 90 and tested for field points $\mathbf{R}(x, y, z)$ with $(x, y) \in [-1.0, 1.0] \mu\text{m}$ at $z = 0.75\lambda$, where $\lambda = 500 \text{ nm}$. The lattice consists of primitive vectors $\mathbf{a}_1 = [0.5, 0.0, 0.0] \mu\text{m}$ and $\mathbf{a}_2 = [0.25, 0.5, 0.0] \mu\text{m}$. Fig. 1 shows the normalized intensities of interpolated PGF and GPGF for a refractive index $n = 1.5$ at an incident angle of $\theta = 10^\circ$. The grid spacing for tabulation is 10 nm. 128 sampling points are taken along both x - and y -directions, respectively. The white parallelograms indicate the position of the reference unit cell. Interpolation achieves an RMS error of 2.04×10^{-4} for PGF and 7.77×10^{-4} for GPGF relative to direct Ewald evaluation ($m, n \in$

$[-9, 9]$), while the runtime is reduced from 14.0 s to 0.62 s, an improvement factor of more than 20.

To validate the method for complex refractive indices, we repeated the calculation for $n = 3.95 - i0.03$ at $\theta = 30^\circ$ (Fig. 2). The RMS errors are 3.8×10^{-3} (PGF) and 2.1×10^{-3} (GPGF), respectively. Direct Ewald evaluation requires 21 s, whereas interpolation needs only 0.73 s, an improvement factor of almost 30.

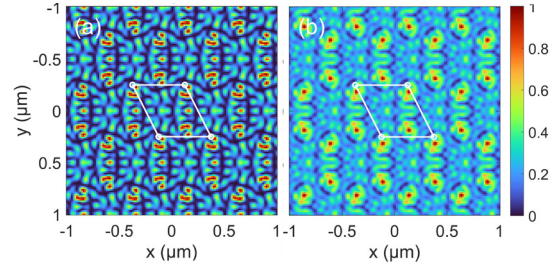


Fig. 2 Normalized intensity of interpolated PGF in (a) and GPGF in (b) with $n = 3.95 - i0.03$ at $\theta = 30^\circ$.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: Entwicklung und Verifizierung eines effizienten Simulationswerkzeugs für elektrisch große, doppelt periodische 3D-Nanostrukturen in geschichteten Medien für die optische Mueller-Matrix-Fourier-Scatterometrie (ScatteroSim, RE5039/1-1).

References

- [1] L. Fu, M. Daiber-Huppert, K. Frenner, and W. Osten, "Simulation of realistic speckle fields by using surface integral equation and multi-level fast multipole method," *Optics and Lasers in Engineering* **162**(3), 107438 (2023). URL <https://doi.org/10.1016/j.optlaseng.2022.107438>.
- [2] P. Jorna, V. Lancellotti, and M. C. van Beurden, "Computational Aspects of 2D-Quasi-Periodic-Green-Function Computations for Scattering by Dielectric Objects via Surface Integral Equations," *Progress In Electromagnetics Research B* **63**, 49–66 (2015).
- [3] F. T. Celepcikay, D. R. Wilton, D. R. Jackson, and W. A. Johnson, "Interpolation of Ewald-accelerated periodic Green's function representations for homogeneous or layered media," *IEEE Transactions on Antennas and Propagation* pp. 2517–2525 (2017).

Fourier-optical simulation of a confocal intensity curve

S. Wyss, L. Fu, S. Reichelt

Confocal microscopy is a well-established technique for three-dimensional surface topography measurements in production metrology and scientific research, because it is fast, contactless and offers high resolution. To identify and reduce systematic measurement errors, reliable modeling of the instrument is required. Currently, no rigorous and complete confocal microscope model is available. To address this gap, we have developed a microscope model based on the boundary-element method (BEM), which numerically solves the Maxwell equations for the light-surface interactions. The BEM implementation is carried out using SpeckleSim, a software recently developed at the Institute of Technical Optics (ITO) [1]. The imaging process of the microscope is implemented using Fourier optics, with the amplitude transfer function (ATF) filtering only the scattered light, that falls within the numerical aperture of the objective.

As a first test object for the microscope model, a one-dimensional rectangular line grating is used. The line grating, made of silicon, has a nominal grating period of $20\text{ }\mu\text{m}$ and a nominal height of 90 nm . To save computation time during the simulation, only the smallest symmetric part of the grating line is simulated, which is a single step. For the z -scanning, a small region of approximately $\pm 0.5\text{ }\mu\text{m}$ is selected symmetrically around the plane of the step surface at $z = 0\text{ }\mu\text{m}$, ensuring that it reliably contains the confocal peak. To further reduce computing time while still covering a larger scanning range, the simulated z -scanning is nonlinear. About 13 scanning points were identified as an optimal compromise between effort and accuracy. The x -scan is performed in 33 equidistant steps from $-5\text{ }\mu\text{m}$ to $5\text{ }\mu\text{m}$. Consequently, a few hundred xz -positions are generated, and for each position a full simulation with the confocal model is carried out for both TM- and TE-polarized illumination.

The average of the results with TM- and TE-polarized illumination, corresponding to unpolarized illumination, is used for the surface reconstruction. For each x -position, the maximum intensity of the z -scan is determined, and the corresponding z -value at this maximum defines the height. To locate the maximum, the intensity data are fitted with two model functions - a Gaussian curve and a cubic polynomial (see Fig.1) - and compared using two criteria.

The first criterion is the Bayesian information criterion (BIC) [2], which relates the residual sum

of squares to the number of free model parameters, allowing comparison of models with different degrees of freedom and prevent over- or under-fitting. The model with the lowest BIC value is preferred. The BIC is calculated for all x -positions and is consistently smaller for the Gaussian fit.

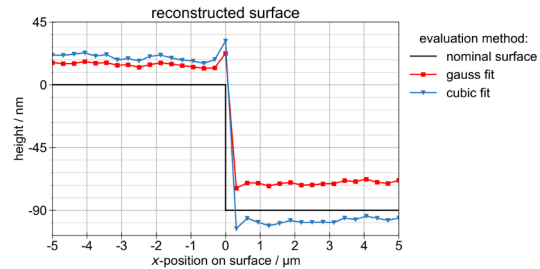


Fig. 1 Reconstruction of the surface from simulated confocal profiles with two different fitting algorithms, with a Gaussian and with a cubic polynomial fit.

The second criterion is the comparison with the nominal surface. On the upper plateau of the step, the Gaussian-fit reconstruction is closer to the nominal value, whereas on the lower plateau, the cubic polynomial fit is nearer to the nominal value (see Fig.1). Nevertheless, the Gaussian fit reproduces the true step height more accurately.

The microscope model is currently being refined by reducing the z -scan range to a narrower interval symmetrically around the confocal peak and by using uniform step sizes. In addition, simulated results are being compared with experimental measurements. Further details of the microscope model are described in [3].

In cooperation with: Physikalisch-Technische Bundesanstalt, Braunschweig (B.Bodermann, S.Gao)

References

- [1] L. Fu, M. Daiber-Huppert, K. Frenner, and W. Osten, "Simulation of Realistic Speckle Fields by Using Surface Integral Equation and Fast Multipole Method," *SSRN Electronic Journal* **162** (2022).
- [2] G. Schwarz, "Estimating the Dimension of a Model," *The Annals of Statistics* **6**(2) (1978).
- [3] S. Wyss, M. Wurm, B. Bodermann, S. Gao, L. Fu, and S. Reichelt, "Comparison of two fit algorithms to find the maximum of a simulated confocal intensity curve," in *Modeling Aspects in Optical Metrology X*, vol. 13568, International Society for Optics and Photonics (SPIE, 2025).

Application of recurrent neural networks to accelerate ellipsometric measurements for monitoring battery manufacturing

K. Frenner, X. Wang

In the global race to perfect the production of high-performance batteries, a critical bottleneck remains: the ability to monitor and control the manufacturing process in real-time. Our pioneering project "OpticalRNN" has made significant strides in overcoming this hurdle, successfully demonstrating an innovative method that combines artificial intelligence with advanced optical metrology to dramatically accelerate quality control for battery components.

Ellipsometry is a well-established, highly precise optical technique used to characterize thin films by measuring the change in polarization of light as it reflects off a surface. This allows for the determination of properties like layer thickness and refractive index. However, traditional ellipsometry is model-based and often too slow for the rapid, in-situ (real-time) monitoring required in a high-volume battery production line.

The core of the project was the development of a sophisticated recurrent neural network (RNN) based on an encoder-decoder architecture. The goal was to train this network to deconstruct complex ellipsometric measurement signals, specifically the parameters ψ and δ taken at various angles of incidence, into their most meaningful components, thereby allowing for the instantaneous identification of material properties.

Initial tests were conducted on two different layer systems: silicon dioxide on silicon (SiO_2/Si), a standard in semiconductor technology, and a lithium manganese oxide on platinum (LMO/Pt) structure, which serves as a simplified model for a lithium-ion battery electrode.

The results were promising (Figure 1). The Flexible-Encoder proved highly effective at reconstructing the measurement signals, demonstrating its ability to learn and replicate the complex optical responses. However, when it came to the direct determination of layer thickness and refractive index, the Fixed-Encoder initially showed a higher degree of accuracy. The project highlighted that while the fundamental goal of signal decomposition was achieved, further optimization of the neural network is needed for the Flexible-Encoder to match the performance of its conventional counterpart in parameter reconstruction.

In parallel with the development of the neural network, the project also involved detailed analysis of the surfaces of battery anodes and cathodes using White Light Interferometry (WLI) and Ellipso-Height Topometry (EHT). These measurements revealed the rough and complex topography of the electrodes (Figure 2), underscoring the necessity of combining EHT measurements with spectroscopic data and AI-powered evaluation. This combined approach is essential for reliably determining crucial material properties such as porosity and grain size, which are directly linked to battery performance and lifespan.

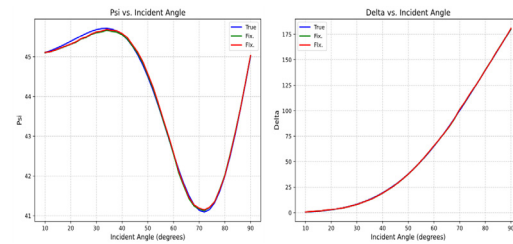


Fig. 1 Reconstruction results of our 'Fixed' and 'Flexible Encoder' are almost identical and show only a small deviation from the 'Ground Truth'.

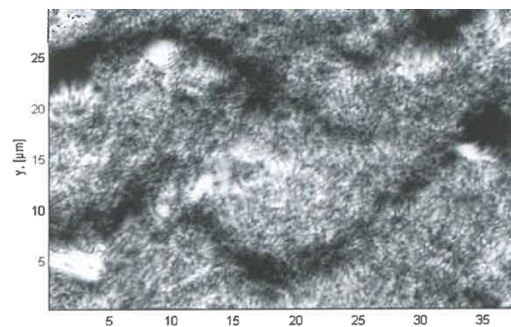


Fig. 2 Surface topography in grayscale, where lighter areas represent higher regions and darker areas represent lower regions.

Supported by: This work was supported by ICM InnovationsCampus.

Project: BUP46 - OpticalRNN

In cooperation with: Prof. Dr. K. Leonhardt, Ditzingen.

YOLO-Sense: Improving warehouse safety with optical smart cameras

T. Reif, A. Dawar, K. Frenner, S. Reichelt

With the rapid development of computer vision, object detection has become a key technology for warehouse safety and Industry 4.0 applications. Among current state-of-the-art algorithms, YOLOv6 stands out for its balance between accuracy and real-time capability. To significantly enhance safety in warehouse environments, the system was optimized through targeted finetuning using domain-specific image data and potential hazardous scenarios. However, as standard models operate on a single-frame basis, they exhibit weaknesses in dynamic scenes involving motion blur or occlusions. To address these limitations, we present an architecture that integrates temporal information via an LSTM network to enhance robustness. The system is further augmented by a purely camera-based distance measurement to objects and personnel, aimed at preventing collisions and maximizing occupational safety.

Temporal Modeling and Feature Fusion. To enhance robustness against dynamic interference such as occlusions and motion blur, the YOLOv6 architecture was extended by a temporal feature fusion mechanism. The system integrates an LSTM (Long Short-Term Memory) network that analyzes object trajectories across consecutive frames and predictively maps the object state in the form of Gaussian heatmaps. These serve as spatial priors within the feature pyramids of the backbone, with an adaptive fusion module dynamically regulating the weighting of temporal information based on its entropy and confidence. A mask weighting mechanism suppresses the accumulation of prediction errors and stabilizes the localization of both stationary and moving objects. Evaluation on an industrial dataset ($n = 9,699$) demonstrates significantly higher precision and stability of regression values under noise compared to the baseline [1].

Domain-specific Finetuning. To optimize the detection performance of the YOLOv6 system for the specific requirements of an industrial warehouse environment, a targeted finetuning of the network parameters was conducted. For this purpose, a specialized dataset was utilized, which reflects a high variance of typical warehouse scenarios and specifically addresses critical edge cases. By integrating image data showing personnel in unconventional postures, under extreme levels of occlusion, or in direct interaction with industrial trucks, the model's sensi-

tivity to potential hazardous situations was significantly increased. This domain-specific adaptation reduces the rate of false-negative detections in complex work areas and ensures that object detection provides a reliable basis for accident prevention even under challenging conditions, such as adverse lighting in high-bay warehouses.

Distance measurement methods. To ensure precise spatial localization, two complementary methods were implemented: First, binocular stereo triangulation, which calculates depth via disparity between two synchronized camera channels for high precision in safety-critical areas. Second, monocular depth estimation, where a neural network generates a metrically calibrated depth map from a single image (see Fig. 1). This dual approach enables reliable collision avoidance and spatial orientation, even in system-configurations without redundant sensors.

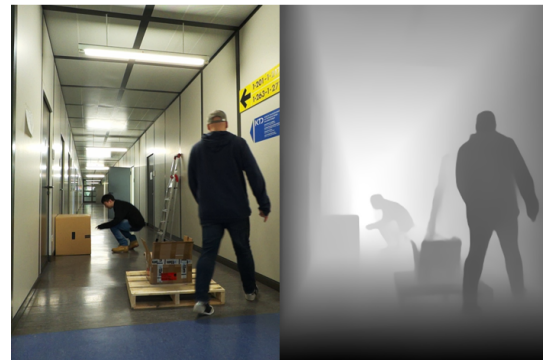


Fig. 1 Comparison of a camera image from a warehouse-like environment (left) and the corresponding monocular generated depth map (right).

Supported by: This work was supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK)

Project: YOLO-Sense (KK5051807RG4)

In cooperation with: tbm hightech control GmbH, T & O Electronic Solutions GmbH

References

- [1] X. Zuo, "Ein Zeitbasiertes Objekterkennungs-Framework durch die Kombination von LSTM-Vorhersage und YOLOv6-Detektion," Masterarbeit, Institut für Technische Optik, Universität Stuttgart (2025).

Time-gated single pixel camera for compressed object detection through scattering media

A. Birk, K. Frenner, S. Reichelt

Optical detection of shapes and objects in sub-optimal conditions has been an area of active research for decades, its relevance growing as automation increases. The main challenges arise mainly in the discrimination of environmental disturbances such as fog, dust, snow, floating debris etc. It is relevant in machine vision tasks such as fault detection, process supervision as well as robot and vehicle guidance.

For the present project, we built an initial demonstrator that is based on the principles of compressed sensing and ultra-fast detection – a concept we call the time gated single pixel camera (TGSPC) [1]. Its fundamental principle is that of the single pixel camera [2].

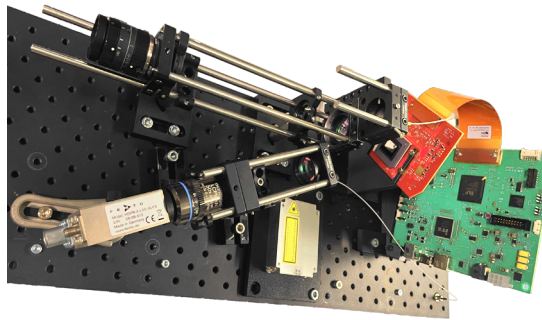


Fig. 1 Optical assembly with light source, collector optics, DMD for masking, detector.

The TGSPC is, by its design, able to effectively filter out most unwanted environmental influences, such as fog in the air between the setup and the object. It achieves this through actively separating and ultimately discriminating information from different regions of depth in the object space. We aimed to implement it using off-the-shelf components and a simple optical setup, shown in Fig. 1, in a transportable and eye-safe demonstrator. From back to front, the most important components are

Photodetector. We use a single InGaAs photodetector with a sampling rate of 2 GHz. Thus, we achieve a time resolved light intensity measurement fast enough to be able to differentiate between light path lengths, giving us depth resolution akin to classic time-of-flight measurements. The major disadvantage is that we lose all lateral resolution, which we need to regain by other means described below.

Digital Micromirror Device (DMD). We use a DMD to structure the backscattered light from the scene before detection. Specifically, the DMD allows us to display arbitrary dark-light masks which shadow parts of the scene while letting others pass. Compressed sensing algorithms are then used to reconstruct an image of the scene by combining different mask patterns and their respective measured light intensities. The DMD achieves pattern rates of about 10 kHz. Since a usable image can be reconstructed using a few hundred masks (exact figure varies with resolution and specific algorithm), video-level frame rates of >10 Hz are possible.

Light source. The setup requires a short-pulsed light source with high intensity, and to keep the demonstrator eye-safe when put into appropriate housing. We therefore opted to use an NIR laser source ($\lambda = 1550$ nm), which allows eye-safe operation at significantly higher power than in the visible range.

We presented the demonstrator at Hannover Messe 2024 and collected valuable feedback on the concept.

Proposed future expansions include more sophisticated, AI-based data processing and introducing a second, symmetric detector arm.

Supported by: The authors would like to thank the Ministry of Science, Research and Arts of the Federal State of Baden-Württemberg for the financial support of the projects within the InnovationCampus Future Mobility (ICM).

Project: Time Gated Single Pixel Camera (BUP31)

References

- [1] C. M. Bett, M. Daiber-Huppert, K. Frenner, and W. Osten, "Time-gated-single-pixel-camera: a promising sensor for robust object detection in adverse weather conditions for autonomously driven vehicles," in *Fifteenth International Conference on Machine Vision (ICMV 2022)*, W. Osten, D. P. Nikolaev, and J. J. Zhou, eds., vol. 12701, p. 1270107, International Society for Optics and Photonics (SPIE, 2023).
- [2] M. F. Duarte, M. A. Davenport, D. Takhar, J. N. Laska, T. Sun, K. F. Kelly, and R. G. Baraniuk, "Single-Pixel Imaging via Compressive Sampling," *25*(2), 83–91.

Object detection through scattering media via dual-wavelength intensity interferometry

C. M. Bett

In this project, a speckle-based method for detecting macroscopic objects through extended scattering media is investigated, a critical challenge for autonomous systems operating in adverse environments like mines, underwater, or heavy weather.

Unlike traditional ballistic filtering, which discards scattered light, this approach – termed dual-wavelength intensity interferometry – utilizes all detected photons by exploiting the "memory effect" [1]. This principle suggests that an optical transfer function remains invariant under small changes in illumination. By correlating speckle patterns generated at two distinct wavelengths, the medium's influence can be compensated for and the object's diffraction pattern at the synthetic difference wavelength can be reconstructed.

My theoretical derivation shows that the wavelength cross-correlation function behaves analogously to the free-space transfer function in the difference wavelength multiplied by the mean angular spectrum function of the scattering process – even for extended multiply scattering media. Experimental validation using double and multiple slits confirmed this, demonstrating that macroscopic objects in the millimeter range can be detected through scattering media up to 20 cm long, see Fig.1 [2].

The detection sensitivity of this method is inherently tied to the number of averaged speckles, with the signal-to-noise ratio following $\text{SNR} \propto \sqrt{N_{\text{speckles}}}$. By leveraging modern camera sensors to capture thousands of speckles simultaneously, we can detect signals that nominally fall outside the standard memory effect range.

Furthermore, I demonstrated that temporal averaging in dynamic media or the use of structured illumination can enhance resolution and signal clarity, even allowing detection beyond the calculated resolution limit via Moiré effects.

Although initially focused on static transmission, real-time imaging is possible by simultaneous dual-wavelength illumination, paving the way for the detection of dynamic objects in rapidly changing industrial or natural environments.

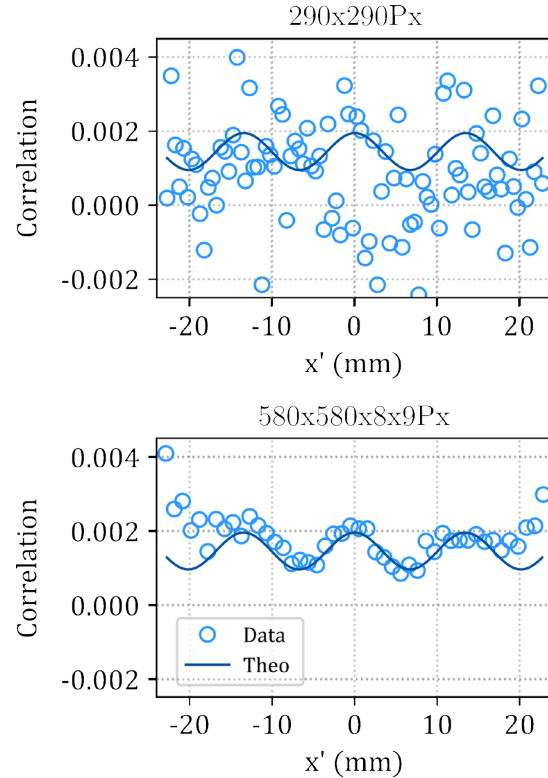


Fig. 1 Reconstructed cosine signal for a double slit object embedded between a total of ten ground glass diffusers (slit distance 20 mm, total medium length 200 mm) for two different numbers of averaged pixels.

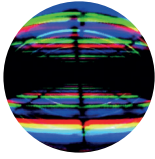
Supported by: This work was supported by the Ministry of Science, Research and Arts Baden-Württemberg as well as the University of Stuttgart within the framework of Research Seed Capital.

Project: Nutze die kleine Ordnung im Chaos: Eine neue Messmethode zur Sicht durch ausgedehnte opake Medien

References

- [1] S. Feng, C. Kane, P. A. Lee, and A. D. Stone, "Correlations and fluctuations of coherent wave transmission through disordered media," *Physical review letters* **61**(7), 834–837 (1988).
- [2] C. M. Bett and W. Osten, "Illumination is all it takes: on the detection of objects embedded in scattering media via multi-wavelength speckle correlation," in *Unconventional Imaging, Sensing, and Adaptive Optics 2024*, Jean J. Dolne, Santasri R. Bose-Pillai, and Matthew Kalensky, eds., vol. 13149, p. 131491A (SPIE, 2024).

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

Contact: pruss@ito.uni-stuttgart.de

Absolute shape interferometry for aspheres and freeform surfaces

A. Brenner, C. Schober, C. Pruß, A. Herkommer, S. Reichelt

Tilted Wave Interferometry (TWI), which was invented at ITO, is a flexible approach for areal measurements of aspheres and freeform surfaces. In the project Absoform, TWI in Fizeau configuration [1] is extended to operate at two wavelengths. The synthetic wavelength

$$\lambda_{\text{syn}} = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|}, \quad (1)$$

extends the unambiguity range to several ten micrometers. By combining the multi-wavelength approach with tilted wave interferometry, we aim to determine the position of the surface under test (SUT) relative to its nominal position unambiguously.

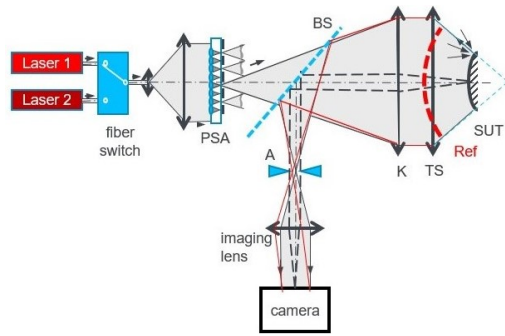


Fig. 1 Schematic of a multi-wavelength TWI of Fizeau type [2].

The principle of the setup is shown in Fig 1. A microlens array, illuminated by either Laser 1 or Laser 2, creates a static point source array (PSA) whose light is collimated and directed through the transmission sphere (TS) to illuminate the surface under test (SUT) under different angles. Four reference waves are generated at the beam splitting Fizeau surface (Ref) by the

four point sources closest to the optical axis. The returning light is then reflected by the beam splitter (BS) toward the camera and filtered at the interferometer aperture (A).

Figure 2 shows phase measurements of a surface under test illuminated with two different wavelengths. The strong deviation of the returning test wavefront from the reference wavefront leads to interferograms with high fringe densities. In the example shown, four different sources of the PSA generate four interferogram patches. From two phase maps recorded at wavelengths λ_1 and λ_2 , the synthetic wavelength λ_{syn} can be generated by subtracting the phase maps of the original wavelengths. This results in a reduced fringe density and higher unambiguity range.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: AbsoForm 496703792

In cooperation with: Physikalisch Technische Bundesanstalt (PTB)

References

- [1] C. Schober, R. Beisswanger, A. Gronle, C. Pruss, and W. Osten, "Tilted Wave Fizeau Interferometer for flexible and robust asphere and freeform testing," *Light: Advanced Manufacturing* **3**(4), 1 (2022).
- [2] C. Pruß, P. Rothenberger, A. Brenner, C. Schober, G. Scholz, I. Fortmeier, and A. Herkommer, "Absolute position information to reduce uncertainty in flexible asphere and freeform metrology," in *Twelfth European Seminar on Precision Optics Manufacturing*, G. Fütterer, C. Wünsche, H. Thieß, A. Haberl, and O. W. Föhnle, eds., p. 8 (SPIE, 2025).

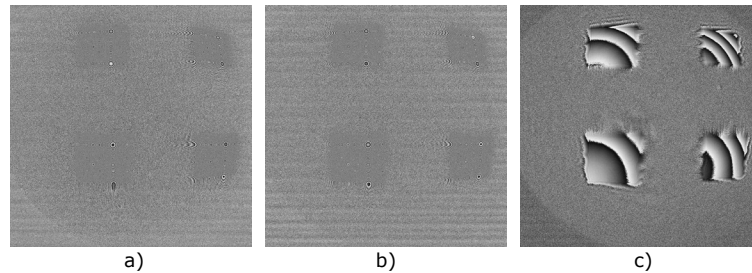


Fig. 2 Measurement for single mask position: (a) Phase map at λ_1 ; (b) Phase map at λ_2 ; (c) Phase map at synthetic wavelength λ_{syn} (Research Thesis Peter Rothenberger).

Single-shot tilted wave interferometer

C. Schober, C. Pruß, S. Reichelt

Freeform and aspheric surfaces are important building blocks to reach the requirements of today's optics products. A key aspect of current research and production of these optical surfaces is the measurement capability. A technique for fast and flexible measurements of such surfaces is tilted wave interferometry (TWI). It uses a special scheme of off-axis point sources to illuminate the system under test with light waves under different angles to compensate the local deviation from a spherical surface. In the current realization of the system, the measurement time is about 30 seconds. In this time, 20 interferograms are captured and subsequently evaluated.

In our research project "Single-shot tilted wave interferometer", we are bringing this measurement technique into a new measurement time regime. Using a special sensor that captures the intensity, spectral information and the polarization state of the incident light, it is possible to reduce the entire measurement to a single captured camera image, thus reducing the measurement time of the system to the range of less than 1 ms [1].

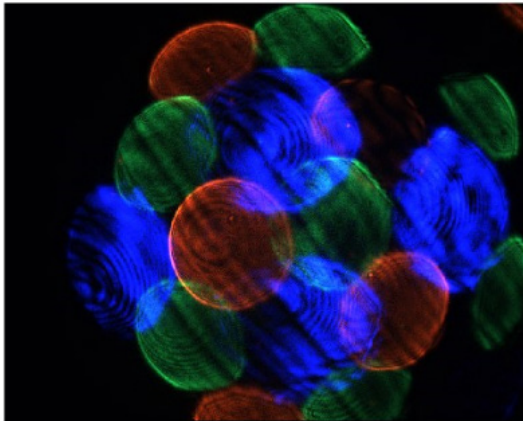


Fig. 1 Color camera image of the test wavefront for the measurement of a sphere in non-null condition. The patches are separated and there is no neighboring patch formed by light of a point source of the same wavelength [2].

The demonstrator setup, uses three lasers, at 633 nm, 532 nm and 459 nm, respectively. It is designed with an special illumination unit with an evenly spaced hexagonal array of point sources, where no pair of neighboring point sources are emitting at the same wavelength [3, 4]. With the demonstrator setup a sphere is measured in a non-null-condition to show how the complete shape information of a strong asphere can be recorded by a single camera image with illumi-

nation times of less then one millisecond [2]. The color camera image of the test wavefront is shown in Fig. 1. The 2π -phase images in the four color channels measured with the polarizing phase-shift method are shown in Fig. 2.

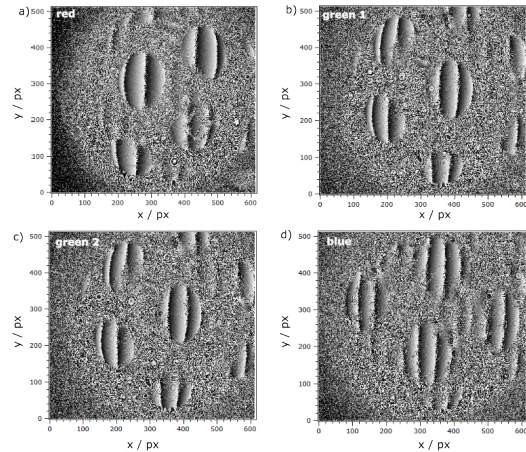


Fig. 2 Captured 2π -phase images by polarizing phase-shifting for the different color channels of the camera of a sphere measured in non-null condition. For better visibility, a reference phase was subtracted to form a virtual null test and then the SUT was moved away from the optical axis, which leads to tilt fringes occurring [2].

Supported by: This work was supported by University of Stuttgart, Wissenstransferförderung.

References

- [1] C. Pruss and C. Schober, *Einzelbild-Tilted Wave Interferometer* (Institut für Technische Optik, Universität Stuttgart, Patent: DPMA-AZ: 10 2020 130 841, 2022).
- [2] C. Schober, C. Pruß, A. Herkommer, and S. Reichelt, "Ultimate measurement speed for flexible asphere and freeform metrology: TWISS (invited-paper)," in *Optical Instrument Science, Technology, and Applications III*, vol. 13024, p. 1302402, International Society for Optics and Photonics (SPIE, 2024).
- [3] C. Schober, L. Lausmann, K. Treptow, C. Pruss, and S. Reichelt, "Neue Designmöglichkeiten durch Zweiphotonenlithographie für ein RGB-Interferometer-Beleuchtungsmodul," in *DGaO-Proceedings (ISSN: 1614-8436)* (2023).
- [4] C. Schober, L. Lausmann, K. Treptow, C. Pruss, and S. Reichelt, "Complex illumination system for fast interferometric measurements," *EPJ Web Conf.* **287** (2023).

The Lilienthal 27 foot Schroeter primary metal mirror from 1793

C. Pruß, W. Osten, A. Herkommer, C. Schober, K. Treptow, M. Wischert

The roots of modern astronomy instrumentation date back to famous names like Galileo Galilei (1564-1641) and Johannes Kepler (1571-1630) and their lens telescope designs, which were in 1688 complemented by Isaac Newton (1642-1726) with his reflective, mirror-based design. A lesser known chapter of telescope history was written in the little village Lilienthal near Bremen, Germany, where Johann Hieronymus Schroeter (1745-1816) built some of the finest instruments of his time, among them the impressive 27 foot giant telescope [1].



Fig. 1 Original Schroeter 27 foot primary mirror. Photo: CP

Schroeter together with Johann Gottlieb Friedrich Schrader, professor at the University of Kiel, and Harm Gefken, Schroeter's gardener, came up with a new method of making metallic mirrors from a copper-tin-arsenic alloy that exhibited high reflectivity and color fidelity that did not fade, in contrast to other metal mirrors of the time such as the ones produced by Friedrich Wilhelm Herschel (1738-1822). In June 2024 we had the chance to measure the original mirror (see Fig. 1) with an aperture of 50,8 cm and a radius of curvature of nominally 16,5 m. We assessed the form error and radius of curvature of the nominally spherical surface in a null test setup. The phase was evaluated using single frame polarization phase shifting, averaging over typically 500 frames to average out the effects of air turbulences. Figure 2 shows the test setup based on a polarization camera.

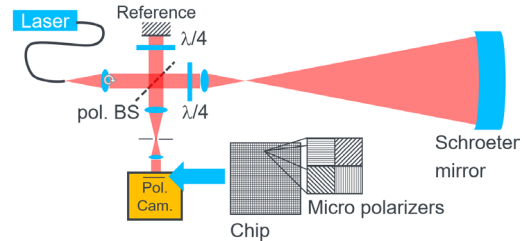


Fig. 2 Principle setup of the Twyman-Green interferometer used to test the mirror.

The surface shape (see Fig. 3 shows a noticeable astigmatism. The origin of it and whether it has been present during Schroeter's observations is subject of current investigations.

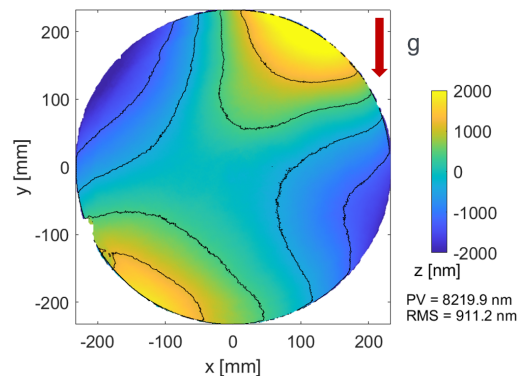


Fig. 3 Principle setup of the Twyman-Green interferometer used to test the mirror.

Supported by: DLR (The German Aerospace Research and Technology Centre)

Project: 50RO2312

In cooperation with: TELESCOPIUM-Lilienthal gemeinnützige Stiftungsgesellschaft mbH, Lilienthal and Deutsches Museum, München. We sincerely thank H.-J. Leue (TELESCOPIUM) as well as C. Sicka and S. Griebach (Dt. Museum).

References

- [1] W. Osten, C. Pruss, A. Herkommer, C. Schober, K. Treptow, M. Wischert, H.J. Leue, "The reconstruction, testing, and improvement of a historical giant astronomical telescope," in *Ultra-High-Definition Imaging Systems VIII*, S. Miyata, T. Yatagai, Y. Koike, eds., vol. 13389, p. 1338902, International Society for Optics and Photonics (SPIE, 2025). URL <https://doi.org/10.1117/12.3040884>.

Metrology of undeveloped 3D-printed structures using white light interferometry

B. Bertschinger, C. Schober, C. Pruß, S. Reichelt

In medical diagnostics, there is a high demand for sensor technology that works in the smallest of spaces and openings and offers as many functionalities as possible at the same time. In recent years, it has been demonstrated that two-photon lithography is a completely new manufacturing approach that enables unprecedented flexibility in the production of optical microsystems, including mechanical functionalities on a micrometer scale. The Integrated3DPrint project consortium is investigating how multifunctional, highly integrated optical sensors for medical technology can be manufactured cost-effectively and in large quantities, reliably and with consistent quality, independently of manual process steps.

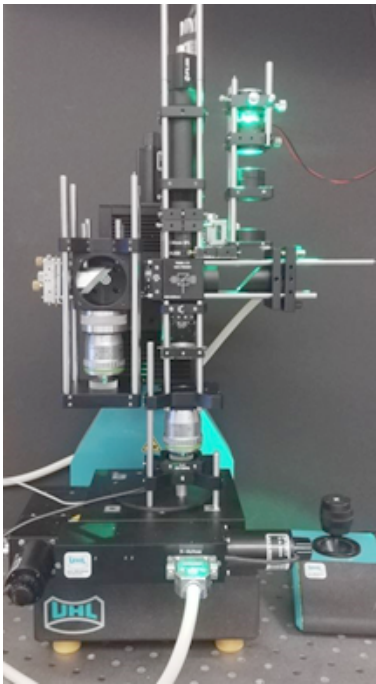


Fig. 1 White light interferometric laboratory setup designed to measure undeveloped 3D printed microsystems.

ITO's subproject focuses on production-oriented shape measurement technology for 3D-printed microsystems. The aim of the subproject is to control printing in the undeveloped state. This will allow iterative corrections with short cycle times. The method is based on areal white light interferometry in combination with model-based evaluation algorithms. Here, polarization based phase shifting is investigated to speed up the metrology process.

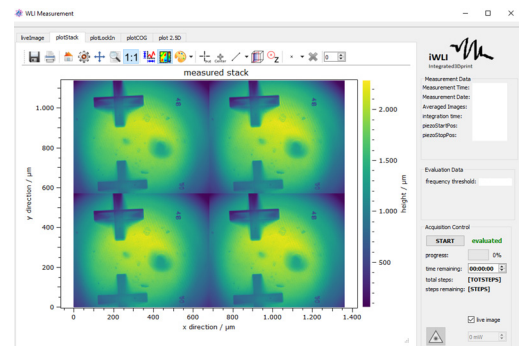


Fig. 2 Evaluation of the raw signal using the institute's open-source software ITOM.

Polarization based phase shifting is realized using a polarization sensitive sensor that utilizes a micropolarizer array to detect polarization in one camera frame with a high lateral resolution. Figure 2 shows an example of a measurement signal, where the four quadrants indicate four different polarization directions. First measurement results on mirror surfaces indicate good reproducibilities for height measurements in the range of 8 nm.

Project: Integrated3DPrint, FKZ 13N16874

In cooperation with: Printoptix GmbH, PolyDiagnost, Nanoscribe GmbH & Co. KG, SMP GmbH, 4PI University of Stuttgart

Robust light source characterization

B. Bertschinger, C. Pruß, S. Reichelt

Interferometry relies on coherence. At the same time, coherent stray light is an important limitation, therefore the coherence properties of light sources in interferometry are chosen to match the target application. The choice of light sources is large, ranging from short coherence sources like thermal light sources, light emitting diodes (LEDs), spectral lamps such as Mercury lamps, often combined with band pass filters, superluminescence diodes to lasers such as the well established long coherence Helium-Neon frequency-stabilized gas laser. Experimentally, they can be characterized based on their intensity, spectral properties and temporal stability. However, drifts of characterization setups can be a limiting factor. In this work we developed a setup that offers different measurement channels and multiplexing approaches. The objective is to compare the performance of light

sources by coupling them into different measurement channels that measure the same object. Thus drift effects can be largely eliminated.

The principle of the setup is shown in Fig 1. The setup combines a so-called light engine with what we call the repro engine. They are coupled using 4- f relay telescopes. The light engine is fed by up to three light sources that can be compared (Source 1-3). Their beams are combined using polarization and dichroitic beamsplitters. A Helium-Neon laser operating at 633 nm is coupled into the light engine to help aligning the setup. The repro engine basically is an interferometric in-line setup with an optical path difference compensation cavity. The resulting interfering wavefronts are imaged onto a camera. The setup allows spatial or temporal multiplexing using chopper wheels.

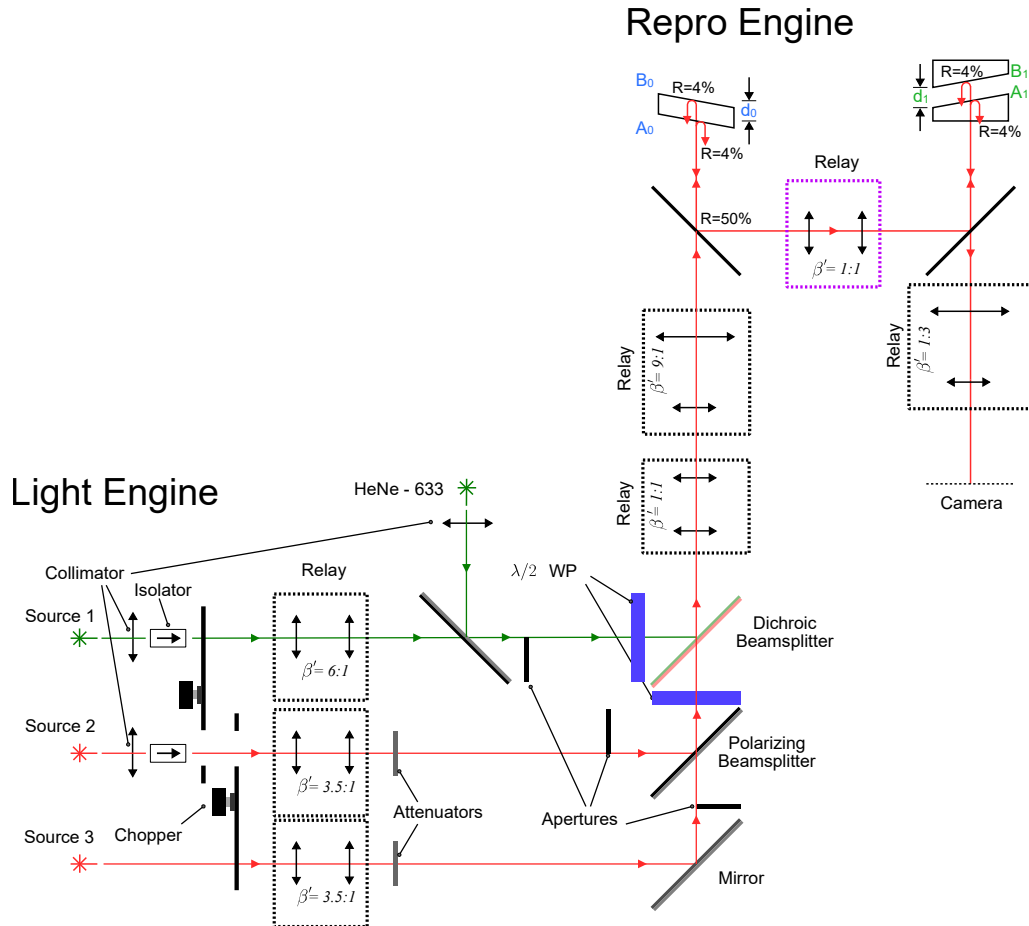


Fig. 1 Layout of the setup to investigate light sources with different coherence properties.

Nanopositioning and Nanomeasuring Machine NPMM-200

A. Brenner, C. Schober, C. Pruß, S. Reichelt

Since 2018, the Institute of Applied Optics (ITO) is operating a dedicated Nano Center that consolidates the institute's research activities on nanometer-accurate surface topography characterization and the fabrication of nanostructures. The core of this center is the Nanopositioning and Nanomeasuring Machine NPMM-200 [1]. This unique system was developed at TU Ilmenau within a DFG transfer project and built according to ITO's specifications for ultra-high-resolution positioning and measurement tasks in large volumes. The machine enables the positioning of a platform within a working space of $200 \times 200 \times 25 \text{ mm}^3$ with a resolution of 20 pm. To stabilize the measurements against environmental influences of temperature, pressure and humidity, the machine is contained within a vacuum chamber. The drives of the machine are temperature controlled with an active cooling system. The open vacuum chamber is shown in Fig. 1.



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

For the realization of this resolution six interferometers measure the movement of a mirror-corner like sample carrier. The interferometers are fixed in a measurement frame made of ZERODUR glass ceramic (see Fig. 2). The specific arrangement of the interferometer axes and the minimization of angular deviations of the platform throughout the entire working volume reduce the Abbe error, resulting in exceptional 3D positioning performance.

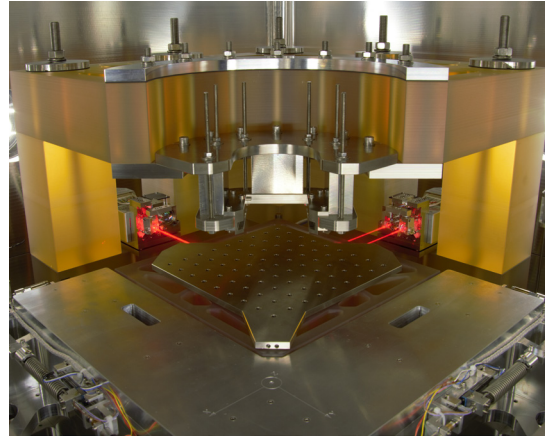


Fig. 2 Metrological frame of the NPMM-200. Interferometers for x, y -movement and z -rotation, platform and the flexible sensor mount are visible.

On the metrological frame different types of sensors or other equipment can easily be attached. This is the basis for the flexible use of the machine. Application areas range from form (e.g. asphere and freeform surfaces or height calibration standards) and deformation measurements to sensor calibration and interference lithography [2]. Standard sensors are a laser focus sensor or a chromatic confocal sensor for steeper gradients.

Figure 3 illustrates the evaluation of the measurement data at three probing points using the laser focus sensor in closed-loop control mode. At each point, the system records the sensor signals over a fixed measurement duration, sampled at 4166.665 Hz.

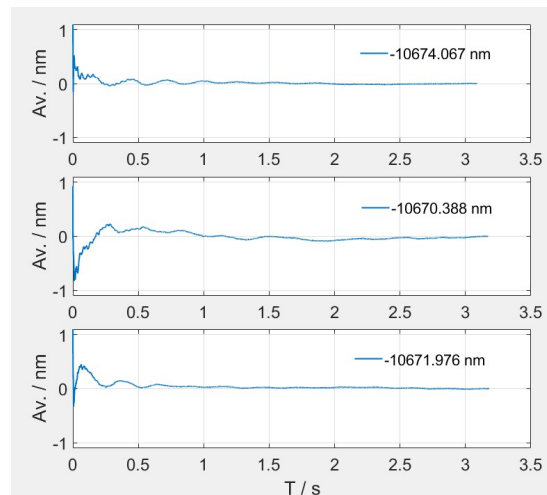


Fig. 3 Running mean Av of the measured height z at three probing points in closed-loop control.

The measured height value z is obtained from the combination of the interferometer position in the z -direction and the signal of the laser focus sensor. In the diagrams, the values plotted over time represent the running mean of z , computed from the beginning of the stationary interval up to each time step. When the probe approaches the surface, a transient settling phase occurs during which the closed-loop controller establishes stable contact. If the probing and closed-loop stabilization are successful, the running mean converges rapidly to a constant value, indicating a stable and reliable height measurement.

In 2023, measurements were carried together with colleagues from the Technical University of Ilmenau, Institute of Process Measurement and Sensor Technology. Using the NPMM-200 a novel absolute surface determination method was implemented that relies on spatial gradients, i.e. the local slope vectors obtained from two sequential measurements of a test mirror placed at two equidistantly shifted positions while a reference mirror remains fixed. Using a least-squares reconstruction, the surface over a $192\text{ mm} \times 192\text{ mm}$ area matches a conventional measurement with a root-mean-square deviation of 5.3 nm. Simulations show that small rotational errors of the test mirror around the shift axes dominate the reconstruction error, whereas translational errors are negligible. These rotational contributions are mitigated by a high-precision shift stage and an additional boundary condition in the reconstruction algorithm. Future work will address residual errors in the corner regions and explore larger sub-aperture constraints to improve stability [3].

Since 2025, a new chromatic confocal sensor has been in operation, designed for the precise measurement of contours with steep gradients (Fig. 4). With a working distance of 10 mm and a measurement range of $\pm 0.3\text{ mm}$, it delivers high precision of a few nanometers even on sharply inclined surfaces, making it ideal for inspecting complex geometries.

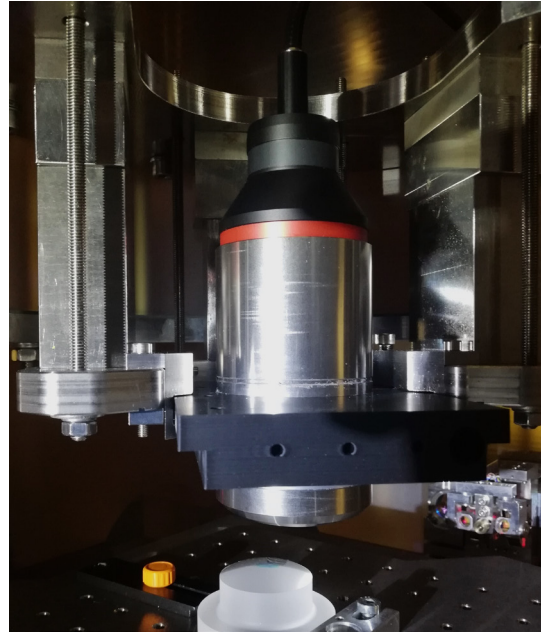


Fig. 4 Keyence chromatic confocal sensor positioned in the sensor mount of the NPMM-200.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: 267094782

References

- [1] G. Jäger, E. Manske, T. Hausotte, A. Müller, and F. Balzer, "Nanopositioning and nanomeasuring machine NPMM-200—a new powerful tool for large-range micro- and nanotechnology," *Surface Topography: Metrology and Properties* **4**(3), 034004 (2016).
- [2] C. Schober, C. Pruss, A. Herkommer, and W. Osten, "The NPMM-200: large area high resolution for freeform surface measurement," in *Seventh European Seminar on Precision Optics Manufacturing*, A. Haberl, G. Fütterer, O. W. Fähnle, and R. Rascher, eds., pp. 40–46 (SPIE, 2020).
- [3] S. J. F. Calderón, R. Mastlylo, C. Schober, C. Pruss, I. Ortlepp, G. Straube, and E. Manske, "Absolute determination of a large mirror surface from spatial gradients using a coordinate measuring machine," in *Applied Optical Metrology V*, E. Novak and C. C. Wilcox, eds., vol. 12672, p. 1267205, International Society for Optics and Photonics (SPIE, 2023). URL <https://doi.org/10.1117/12.2675734>.

Three dimensional scanning beam interference lithography

K. Treptow, C. Pruß, T. Haist, S. Reichelt

Laser lithography is a proven means to fabricate micro- and nanostructured surfaces. Especially for applications in optics design and optical metrology, the positioning accuracy of the structures is crucial. For these applications, typical structures are periodic grating or quasi-periodic grating-like structures, where the line density varies slowly compared to the line width. The known lithography systems differ in terms of production speed, structure shape and the dimension and shape of the substrate. With the DFG-project "3D-SBIL" we build a flexible interference lithography system with high accuracy fabrication in combination with the nano positioning and measuring machine "NPM-200". Together with the Institute of System Dynamics at the University of Stuttgart and the Institute of Process Measurements and Sensor Technology at the TU Ilmenau we cover all essential tasks to build the new system.

For high-precision positioning, the NPM-200 [1] is used as the substrate holder. With this stage it is possible to move the substrate in the single digit nanometer range. However, it will be a challenge to minimize all disturbing effects during the scanning patterning process.

The requirements are defined as follows: The new system should structure linear gratings with variable periods in the range of 300 nm structure size. In addition, the orientation should be able to rotate during the patterning process. The maximum patterning speed should be 30 mm/s and the position accuracy needs to be around 10 nm. At an advanced state the system might be able to structure non-planar surfaces with gradients up to 5° to fabricate hybrid optics with refractive and diffractive characteristics.

The experimental setup is shown in Fig. 1. The writing beam with a wavelength of 405 nm will be separated at the first linear grating G_1 in $\pm$ first order. At the second grating G_2 the beams are parallelized. The microscope objective lens MO focuses both beams in the substrate plane such that they generate an illumination pattern. The gratings G_1 and G_2 can be rotated around the optical axis by angle $\delta\gamma$. The head can be shifted by δx and δy relatively to MO. With an enhanced vectorial measurement uncertainty model [2], the mechanical setup was realized (see Fig. 2).

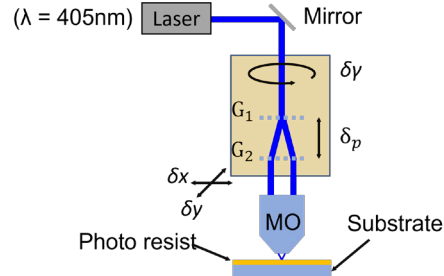


Fig. 1 Optical scheme of the new writing head.

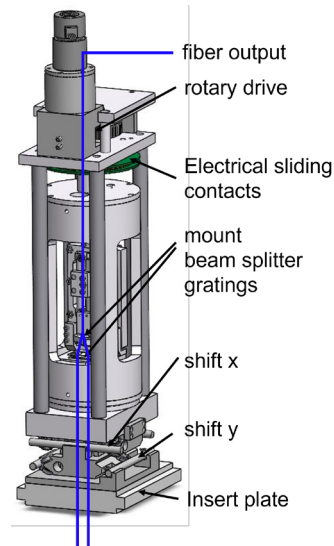


Fig. 2 Mechanical setup of the writing head.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: SBIL 3D, grant no. 465642714.

In cooperation with: ISYS University of Stuttgart and IPMS Technical University of Ilmenau

References

- [1] G. Jäger, E. Manske, T. Hausotte, A. Müller, and F. Balzer, "Nanopositioning and nanomeasuring machine NPM-200—a new powerful tool for large-range micro- and nanotechnology," *Surface Topography: Metrology and Properties* **4**(3), 034004 (2016). URL <https://dx.doi.org/10.1088/2051-672X/4/3/034004>.
- [2] I. Ortlepp, S. Eisele, K. Treptow, J. Rühle, C. Pruß, T. Haist, S. Reichelt, O. Sawodny, E. Manske, and T. Kissinger, "Enhanced Vectorial Measurement Uncertainty Model," *Metrology* **5**(2) (2025). URL <https://www.mdpi.com/2673-8244/5/2/19>.

Flexible alignment and calibration tool for scanning beam interference lithography systems

K. Treptow, C. Pruß, T. Haist, S. Reichelt

Scanning beam interference lithography is an effective approach to realize large gratings with high positioning fidelity. The grating is formed by a small patch of two interfering beamlets that is scanned across the substrate. The quality of the resulting grating depends on the quality of the fringes within the interfering beamlets and their alignment relative to the scan path. As a new measurement approach for the quantitative evaluation of the fringe system in scanning beam interference lithography systems, a fringe observation system (FrObSy) was developed.

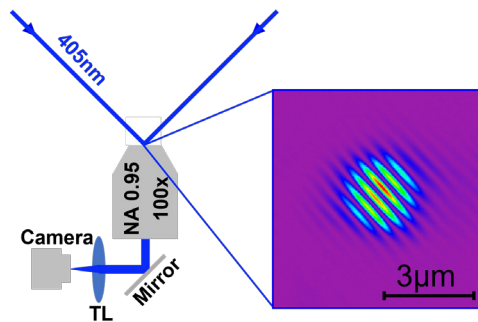


Fig. 1 Principal sketch of the fringe observation system. The writing spot can be observed in the focal plane of the two interfering beams.

It consists of a compact microscope (see Fig. 1, left) that is positioned on the scanning stage, in our case the nanopositioning and measuring machine NPM-200 [1]. It directly images the fringe pattern onto a camera, and therefore provides a means to directly observe the energy distribution the photo resist layer would be exposed to. Quantification of the fringe motion observed during scanning is performed using the carrier-frequency method [2].

FrObSy enables a variety of new alignment and calibration procedures that would otherwise require exposure tests, thereby facilitating system characterization:

- (1) The skew between the two interfering beams can be observed and optimized to maximize the contrast of the illumination pattern (see Fig. 1, right).
- (2) The orientation of the fringes with respect to the axes of the NPM-200 can be determined using the observation system, allowing precise alignment of the interference pattern.
- (3) The fringe period can be quantified by observing the fringe motion while displacing the

NPM axis perpendicular to the fringes.

(4) The tilt of the interference pattern can be calibrated using the aerial images to achieve precise focusing and alignment (Fig. 2).

(5) Finally, the scanning and stitching process can be observed to quantify positioning errors (Fig. 3) of the exposure pattern before the actual exposure in the photoresist.

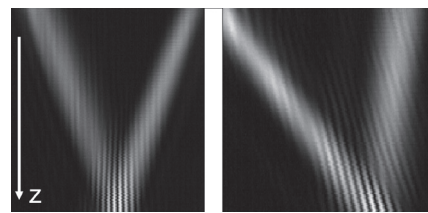


Fig. 2 z -scans of the writing spot to calibrate the tilt.

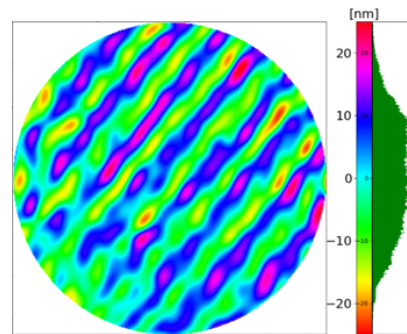


Fig. 3 Positioning error of the writing pattern during a scan and stitch process.

Supported by: This work was supported by the German Research Foundation (DFG).

Project: SBIL 3D, grant no. HA 3490/4-1.

In cooperation with: ISYS Universität Stuttgart, IPMS Universität Ilmenau

References

- [1] G. Jäger, E. Manske, T. Hausotte, A. Müller, and F. Balzer, "Nanopositioning and nanomeasuring machine NPM-200—a new powerful tool for large-range micro- and nanotechnology," *Surface Topography: Metrology and Properties* **4**(3), 034004 (2016). URL <https://dx.doi.org/10.1088/2051-672X/4/3/034004>.
- [2] M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," *J. Opt. Soc.* **72** (1982).

Fabrication of diffractive elements

K. Treptow, C. Pruß, T. Schoder, S. Reichelt

Diffractive optical elements (DOEs) constitute essential components in optical design and metrology applications. They are typically thin, phase-modulating structures with lateral dimensions on the (sub-) micrometer scale whose operation is governed by interference and diffraction phenomena. Consequently, their functional behavior differs fundamentally from that of conventional refractive optical elements.

At ITO, a dedicated cleanroom infrastructure is available, featuring a wide range of fabrication tools and metrology systems with a focus on diffractive optical elements. DOE fabrication is primarily carried out using laser direct writing at a wavelength of 405 nm on specialized equipment that can process large, high-precision substrates with thicknesses up to 20 mm and diameters up to 200 mm. The circular laser writing system (CLWS) facilitates the production of high-resolution binary and gray-scale structures in polar coordinates, operating on a principle similar to that of conventional optical disc writers. All fabrication steps are monitored using appropriate metrology, among them atomic force microscopy (AFM), scanning electron microscopy (SEM), confocal and white light interference microscopy as well as other interferometers. Metrology is essential to iteratively optimize of the process.

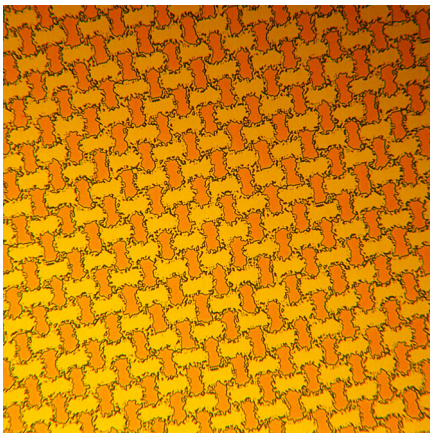


Fig. 1 Replicated multipoint structures for use in a stereo vibration detection system.

Structures are directly written into photoresist and developed. The resulting resist microstructures can be transferred into the substrate using dry etching processes (reactive ion etching RIE, typically into fused silica substrates or other dielectric materials) to obtain robust structures with high transmission also in the ultravio-

let range if required by the application. Alternatively, resist patterns can be used to pattern hard masks (e.g. chromium). The hard mask can be used as etching mask for RIE to achieve high aspect ratios. Small-scale production of identical diffractive elements can be realized using mask lithography, for example for prototype sensor systems. In Fig. 1, a replicated multipoint element [1] is shown, which was produced by a mask lithography process. Figure 2 shows the master substrate with a chromium mask.

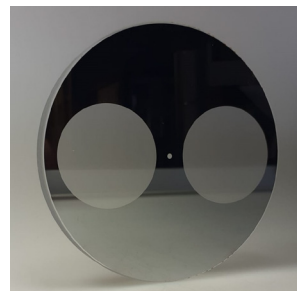


Fig. 2 Lithography mask with two circular structured areas.

The diffractive master was fabricated using the CLWS. Its structures are transferred into a photo resist layer using contact lithography at 405 nm, with the master substrate and the photo resist covered substrates in direct physical contact. The structure was replicated multiple times. DOEs offer almost unlimited design freedom that allows new measurement approaches. An example is the DOE shown in Fig. 3 that is used to realize differential perspective. Here, the multipoint method is employed to determine object-to-sensor distances with higher accuracy. Consequently, the diffractive structure becomes more complex.

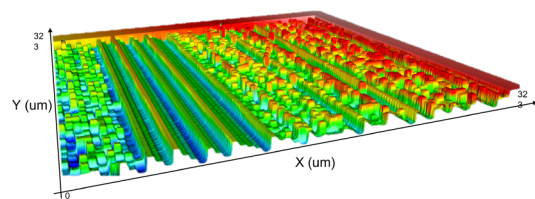


Fig. 3 Multipoint structure combined with features to generate differential perspective measurements.

References

- [1] S. Hartlieb et al., "Advanced Imaging-Based Metrology for Precise Deformation Monitoring: Railway Bridge Case Study," Structural Control and Health Monitoring (5603393) (2025).

Diffractive axicons for quasi-achromatic, propagation-invariant tubular beams

N. Sass, C. Pruß, S. Reichelt

Ring-shaped light fields are important in applications that require uniform material interaction, optical trapping, or low-loss atomic guiding. These applications demand beam profiles that remain stable even under varying environmental conditions. In particular, practical systems must tolerate temperature-induced wavelength shifts, mechanical drifts, and deviations from ideal beam collimation. The optical system presented here (see Fig. 1) is designed to meet these requirements. It is based on a purely diffractive arrangement of two axicons with identical grating periods.

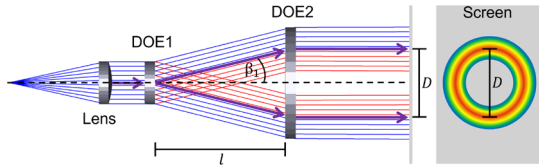


Fig. 1 Setup for generating a quasi-achromatic, propagation-invariant tubular beam using two diffractive axicons.

The configuration transforms an incident Gaussian beam into a ring-shaped light field with a propagation-invariant diameter. The diameter is determined solely by the grating period p , the wavelength λ , and the axial separation l between the two diffractive elements,

$$D = 2l \tan \left[\arcsin \left(\frac{\lambda}{p} \right) \right]. \quad (1)$$

Once these parameters are fixed, the ring diameter remains constant over long propagation distances.

The first diffractive element is implemented as a two-level binary axicon, which ensures symmetric diffraction into the ± 1 diffraction orders and generates a truly tubular intensity distribution. The second axicon redirects the divergent ring segments such that their chief rays propagate parallel to the optical axis, thereby fixing the ring diameter.

A central property of the proposed design is its low sensitivity to the collimation state and waist position of the incoming beam. As a result, the ring diameter remains unchanged even

when the input beam is slightly focused or defocused. This behavior directly translates into robustness against temperature variations and mechanical instabilities, which typically shift the beam waist position in practical setups. In contrast, conventional refractive axicon-based systems exhibit pronounced diameter changes under comparable perturbations. Numerical investigations were performed using geometrical ray tracing and scalar wave-optical simulations. Two-dimensional simulations were applied to analyze the full propagation behavior of the ring-shaped intensity distribution and to assess the limitations of simplified one-dimensional models. The simulations were used to study the influence of system parameters, in particular the phase offset of the binary axicon, on the resulting beam structure. Experimental measurements were conducted to verify the numerical results. The measured intensity distributions and propagation characteristics show good agreement with the simulations. The experiments confirm that the ring diameter remains stable over extended propagation distances and is only weakly affected by wavelength variations and changes in the input beam conditions. A detailed analysis of the diffraction-order interference mechanism in the Fourier plane and the full axial propagation behavior of the tubular beam is presented in the references [1, 2].

Supported by: This work was supported by the Hilti Family Foundation.

In cooperation with: RhySearch in Buchs and HILTI in Liechtenstein

References

- [1] N. Sass, C. Pruss, O. Krieglsteiner, D. Schachtler, K. Treptow and S. Reichelt, "Diffractive axicons for quasi-achromatic, propagation-invariant tubular beams," *Optics Express* **34**(2), 3087–3105 (2026).
- [2] N. Sass, C. Pruss, O. Krieglsteiner, D. Schachtler, K. Treptow and S. Reichelt, "Tubular light beam with propagation-invariant diameter based on diffractive axicons," *tm – Technisches Messen* (2026). DOI: 10.1515/teme-2025-0142.

Grating Reflectors Enabled laser Applications and Training (GREAT)

A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt

The international training network (ITN) GREAT finished in January 2024. As a part of the HORIZON 2020 program supported by the Marie Skłodowska-Curie Action, it brought together a consortium of 16 scientific institutions and private sector partners from 4 countries: Germany, France, Finland and the United Kingdom. Fifteen early stage researchers were trained on topics of design, fabrication, and implementation of grating waveguide structures (GWS) in high-power laser systems.

GWS is a combination of planar waveguide and a diffraction grating. It relies on resonance effects to achieve up to 100% of diffraction efficiency with high wavelength and polarization selectivity. GWS can be used as a pulse compression gratings (PCG), for spectral stabilization and wavelength multiplexing, as well as for the generation of laser beams with axially-symmetric polarizations.

Based on designs provided by the project partner IFSW (Institut für Strahlwerkzeuge, University of Stuttgart) we fabricated circular GWS with the help of scanning beam interference lithography (SBIL) working in polar coordinates and subsequent plasma etching. Such elements, used as grating waveguide output couplers (GWOC) or end-mirrors (GWM) can be used for generation radially polarized beams directly out of laser cavity [1]. Figure 1 shows a photo of a fabricated GWM based on a $\text{HfO}_2/\text{SiO}_2$ mirror. The grating profile measured by atomic force microscopy (AFM) is shown in Fig. 2.



Fig. 1 Photo of a fabricated grating waveguide mirror.

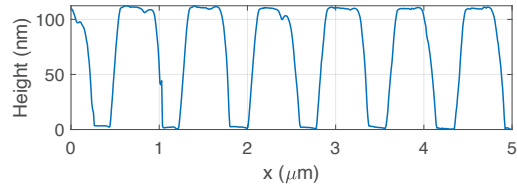


Fig. 2 AFM measurement of a GWM grating profile etched into HfO_2 .

Other investigated material systems are based on Niobium. We fabricated $\text{Nb}_2\text{O}_5/\text{SiO}_2$ GWOCs that were subsequently characterized at IFSW under sub-picosecond laser radiation [2]. It was observed that laser-induced damage threshold (LIDT) of the fabricated GWOC is close to the performance of the unstructured output coupler.

Supported by: European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813159.

Project: ITN GREAT.

In cooperation with: 16 academic and scientific partners from France, United Kingdom, Finland and Germany. Coordinated by Dr. Marwan Abdou Ahmed (IFSW, University of Stuttgart)

References

- [1] D. Didychenko, et al. "Generation of a radially polarized beam in a polycrystalline ceramic $\text{Yb}:\text{Lu}_2\text{O}_3$ thin-disk laser." *Appl. Phys. B* **129**(146) (2023).
- [2] D. Didychenko, F. Li, A. Savchenko, et al. "Analysis of laser-induced damage threshold of circular grating waveguide structures exposed to sub-picosecond laser radiation centered at a wavelength of 1030 nm." *Appl. Phys. B* **131**(39) (2025).

Etching of thick optical elements

A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt

Optical components for high-power laser systems, such as pulse compression (PCG) and polarization-control gratings, can be several millimeters thick. They are typically fabricated on dielectric substrate using a combination of lithography process and etching, which transfers a patterned mask into the material. While effects of plasma parameters on etching rates were mostly studied on Si wafers with oxide coatings, little is known how thickness of a dielectric substrate affects etching results. We investigated this dependence both theoretically and experimentally [1].

A plasma sheath region that forms between the dielectric substrate and the plasma, was simulated by the combination a one-dimensional fluid model and an equivalent electric circuit (EEC) for inductively coupled plasma (ICP) etching system. We find that the sheath potential, and therefore the ion energy, decreases for thicker dielectric samples, following a power-law dependence on the sample capacitance. We also observe (Fig.1) that, while ion energy increases with ICP power for Si wafer, the trend is reversed for thicker dielectric samples and can drop below the energy threshold required to sustain etching. We developed a semi-empirical model to predict the etch rate by combining chemical and physical contributions based on simulation results.

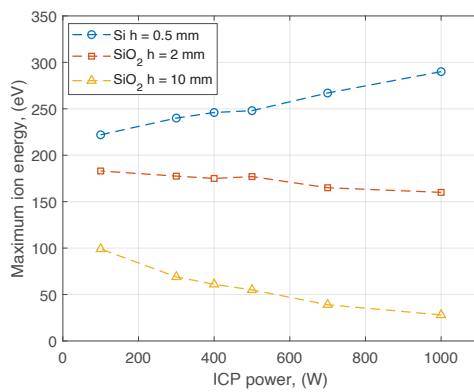


Fig. 1 Maximum ion energy vs ICP power for different samples.

We performed a set of etching experiments on fused silica samples with thickness 2, 5, and

10 mm over a range of ICP powers. Experimentally obtained etching rates and their simulated counterparts are shown in Fig. 2. A linear fit with R^2 of 0.86...0.97 indicates a good predictive performance of the developed model. Both experimental and simulated results show complete etching suppression at 1000 W of ICP power for the 10 mm sample.

Practically, these results show that sample thickness must be considered during development of the etching process. Neglecting this parameter can lead to incorrect estimates of ion energy and, therefore, inaccurate predictions of etch rates.

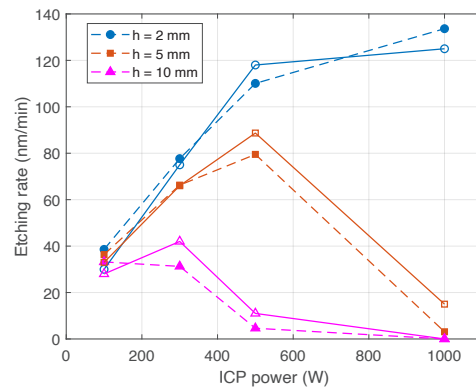


Fig. 2 Experimental etching rates (solid lines) and result of model (dashed line) vs ICP power. Plots are for samples with thickness $h = 2$ mm (circles), $h = 5$ mm (squares), and $h = 10$ mm (triangles).

Supported by: the German Federal Ministry for Economic Affairs and Energy by resolution of the German Federal Parliament, project KuHLGit. The etching equipment was funded by the German Science Foundation DFG, project 54555282.

References

- [1] A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt, "Effect of sample thickness on etching rate: Simulations and experiments," *J. Eur. Opt. Society-Rapid Publ.* **21**(52) (2025).

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

Contact: pedrini@ito.uni-stuttgart.de

Lensless magneto-optical imaging

G. Pedrini, S. Reichelt

Resolving magnetic microstructures is the key to understanding both fundamental magnetic phenomena and global magnetic behavior. It allows bridging the internal atomistic order of ferri- or ferromagnetic states and the final functionality of a magnetic material or device. Magneto-optical methods, which utilize polarized light and an imaging microscope objective allow to visualize the interaction of polarized light with the magnetization state of the sample in reflection through the magneto-optical Kerr effect or in transmission through the accordant Faraday effect, present the most prominent and widespread techniques for investigating magnetic microstructures. We have shown (see Ref. [1]), that lensless optical microscopy allows the measurement of magnetic contrast. The setup used for the investigation is shown in Fig. 1. The linearly polarized light of a He-Ne laser is transmitted through the sample (doped Yttrium-Iron Garnet film with perpendicular magnetic anisotropy grown on a transparent Gadolinium-Gallium Garnet substrate), an aperture of 500 μm diameter, an analyzer, and diffraction patterns at selected positions behind the sample are recorded (e.g. 40 diffraction patterns spaced by 0.1 mm). Figure 2a displays conventional lens-based magneto-optical images of the garnet sample (zoom from the 500 μm diameter FoV defined by the pinhole). The analyzer was in the crossed position with respect to a polarizer angle of 0° and the images were taken at polarizer angles of -5° , 0° and $+5^\circ$. Figure 2b and c summarize the reconstructed intensity and phase of the lensless magneto-optical imaging approach. As in the conventional case (Fig. 2a), one clearly identifies the two polar domain orientations in the intensity channel if the polarizer is set away from the crossed orientation, and upon inverting the polarizer position the contrast inverts. Also in the fully crossed position (0°), the intensity image corresponds to that of the conventional, lens-based image. In addition to providing the intensity, the lensless approach now also allows reconstructing the phase shift of the polarized light interacting with the domains of opposite out-of-plane polarity. We observe a clear phase contrast for oppositely magnetized domains in agreement with an imaginary part of the Faraday component, which furthermore inverts, when changing the polarizer angle from -5° to $+5^\circ$. Of especial significance is the phase image at the fully crossed polarizer setting (central image in Fig. 2c), which in contrast to the intensity images, now directly presents the domain pattern like a regular polar Faraday image. This is in full ac-

cordance with the 180° phase shift between the two oppositely oriented Faraday components of identical amplitudes which pass the fully crossed analyzer. In total, the lensless approach not only results in the identical contrast mechanism for the intensity channel as standard Faraday (or Kerr) microscopy, it also leads to a clear domain contrast in the phase channel for polarizer setting close to and including the crossed orientation. This will e.g. offer advantages for imaging magnetic materials with predominantly phase-shifted Faraday (or Kerr) components.

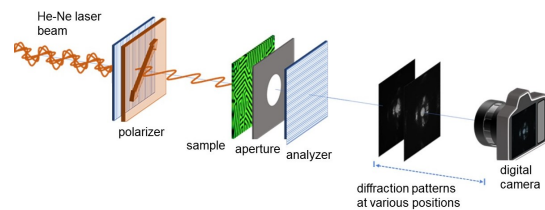


Fig. 1 Schematics of multiplane setup for lensless magneto-optical imaging.

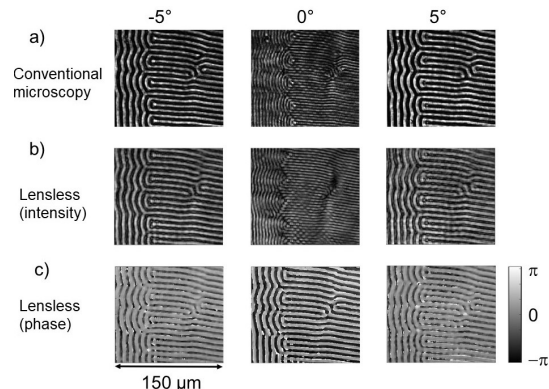


Fig. 2 Magneto-optical investigation with linearly polarized light and analyzer. a) Magneto-optical image of the garnet sample recorded by conventional lens-based microscopy. b) Intensity and c) phase reconstructed from measured diffraction patterns in the lensless-setup.

In cooperation with: Leibniz Institute for Solid State and Materials Research, Dresden, (V. Neu, I. Soldatov, R. Schäfer)

References

- [1] V. Neu, G. Pedrini, I. Soldatov, S. Reichelt, and R. Schäfer, "Lensless magneto-optical imaging," *Scientific Reports* **15**(1), 28277 (2025). URL <https://doi.org/10.1038/s41598-025-10005-1>.

Lensless imaging using the complex degree of coherence obtained by multiaperture interference

G. Pedrini, S. Reichelt

The van Cittert-Zernike theorem states that the Fourier transform of the intensity distribution function of a distant, incoherent source is equal to the complex degree of coherence. The complex degree of coherence $j(P_1, P_2)$ at the points P_1, P_2 located at a certain distance from the distant source can be determined experimentally by using the two pinholes Young experiment (see Fig. 1), where the phase and amplitude are calculated by processing the pattern obtained by the interference between the light transmitted through the pinholes located at P_1 and P_2 . For obtaining image reconstructions using the van Cittert-Zernike theorem, the complex degree of coherence has to be measured at many pinholes distances. We proposed a method for measuring $j(\Delta X, \Delta Y)$ in one shot by using a mask with many apertures, located symmetrically around the center O' [1]. The main idea is to locate such mask at a certain distance from the light source and record with a pixelated detector behind the mask the interference produced by the light arising from the apertures. Figure 2(a) shows the experimental setup used for the verification of the method. The sample used is the "U" mask (0.7 mm x 1 mm) illuminated with light arising from a LED emitting at the central wavelength of 625 nm and having 25 nm bandwidth. The distance between the sample and the mask containing the slits was 650 mm. We designed a mask (see Fig. 2(c)) with apertures symmetrically located around the center. Each single slit has a size of 100 μm x 20 μm . The distance between the slit pairs increases radially by 50 μm from one slit pair to the next one. Figure 2(d) shows one part of the interference pattern recorded with a CMOS camera located 30 mm behind the mask. Figure 2(e) shows the calculated amplitude $|j(\Delta X, \Delta Y)|$ for some points. Our mask had only 480 double slits thus only 480 values of $j(\Delta X, \Delta Y)$ were measured (the value for the second half plane are obtained by complex conjugation), thus the total points that used for the reconstruction is 2 x 480=960. By applying a Fourier transform to the sparse measured samples $j(\Delta X, \Delta Y)$ we can retrieve an image of the object. The reconstruction in Fig. 2(f) has small size but by zooming in we see the reconstructed U character (Fig. 2(g)). The reconstruction is done only on few pixels (15 x 20), by zero padding $j(\Delta X, \Delta Y)$ before Fourier transforming we are able to reconstruct

the sample on more pixels (see Fig. 2(h)).

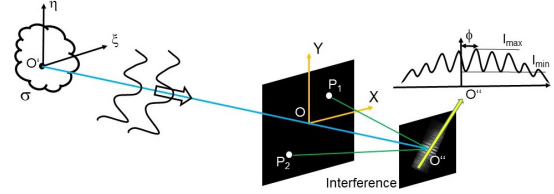


Fig. 1 Setup for measuring the complex degree of coherence.

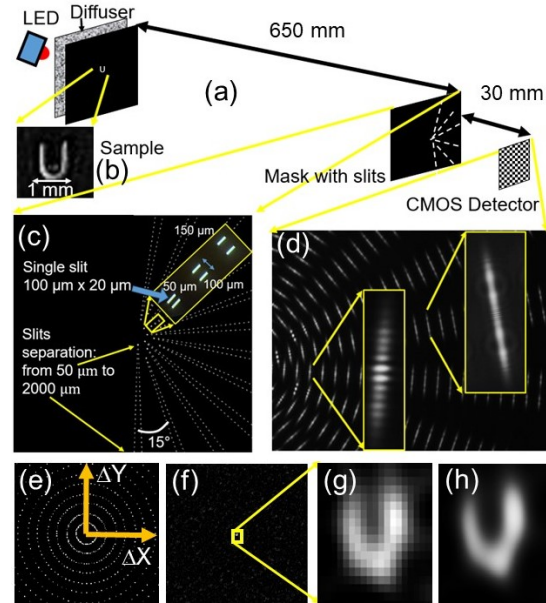


Fig. 2 Experimental verification of the proposed method. (a) Experimental setup; (b) sample, (c) mask with slits; (d) interference patterns recorded behind the mask; (e) some measured points of $j(\Delta X, \Delta Y)$; (f) reconstruction of the intensity of the sample; (g) enlarged reconstruction; (h) reconstruction obtained by zero padding.

In cooperation with: State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing China

References

- [1] G. Pedrini, R. Li, L. Cao, and S. Reichelt, "Lensless imaging in one shot using the complex degree of coherence obtained by multiaperture interferences," *Opt. Lett.* **49**(3), 718–721 (2024). URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-49-3-718>.

Resolution enhancement in digital holography through speckle illumination

A. Schiebelbein, G. Pedrini, S. Reichelt

Digital Holography (DH) is a coherent imaging technique that captures both amplitude and phase, enabling nanometer-scale height resolution and numerical propagation to different depths [1, 2]. This versatility supports applications ranging from 3D measurements and non-destructive testing to lensless, aberration-free imaging. Despite these advantages, DH remains a niche technology. One major limitation arises from its coherent transfer function, which restricts the transmission of high spatial frequencies. As a result, coherent imaging exhibits lower lateral resolution compared to incoherent imaging, as illustrated in Fig. 1 [3].

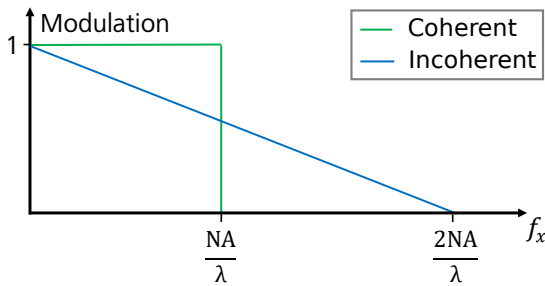


Fig. 1 Comparison of coherent and incoherent transfer functions. The incoherent transfer function can transmit frequencies up to a cutoff of $2NA/\lambda$, which is twice as high as that of the coherent transfer function (NA/λ).

To overcome this limitation, multiple decorrelated speckle illuminations can be employed to introduce angular diversity in the illumination. This effectively enhances the achievable resolution compared to conventional coherent imaging. Although this approach slightly reduces height contrast, a clear improvement in lateral resolution can be observed (see Fig. 2). Unlike methods where the diffuser is continuously moved and the coherence is destroyed, the approach presented here preserves coherence, maintaining full numerical control of the complex electric field. However, this benefit comes at a cost: the method requires calibration measurements of the speckle illumination, followed by computationally intensive deconvolution and averaging across multiple decorrelated speckle configurations. Consequently, while this strat-

egy limits real-time acquisition, it serves as a powerful tool in microscopy, enhancing resolution without the need to increase the numerical aperture. For a more detailed discussion of this work, see the proceeding in [4].

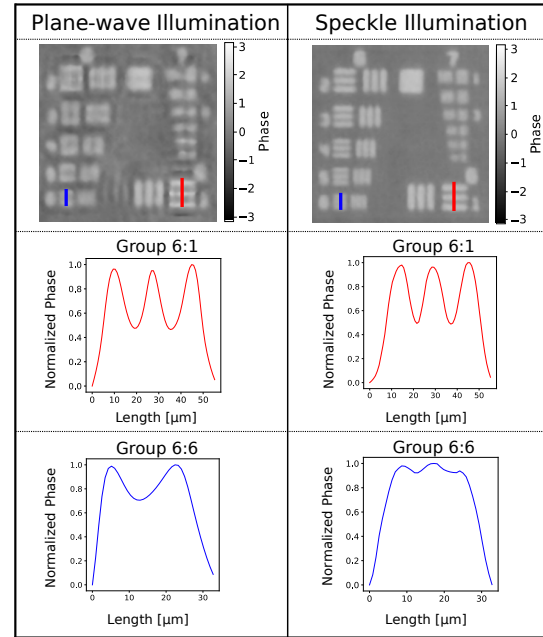


Fig. 2 Comparison between speckle and plane-wave illumination on a USAF test target. Speckle illumination significantly enhances lateral resolution from group 6:1 to group 6:6.

In cooperation with: Carl Zeiss AG (T. Schmitt-Manderbach, D. Bublitz, D. Seidel)

References

- [1] P.-A. Blanche, *Optical holography: Materials, theory and applications*, chap. 5 (Elsevier, 2019).
- [2] T. Kreis, *Handbook of holographic interferometry: optical and digital methods* (John Wiley & Sons, 2006).
- [3] J. W. Goodman, *Introduction to Fourier Optics*, chap. 6 (Roberts and Company publishers, 2005).
- [4] A. Schiebelbein et al., "Resolution Enhancement in Digital Holography through Adaptive Speckle Illumination," (DGaO Proceedings, 2025).

Roughness measurement using spectral speckle correlation

P. Laux, S. Reichelt

Surface roughness characterization is critical for quality assurance in manufacturing. The aim of this work is to enable inline measurement of surface roughness for fast-moving metal sheets, where conventional measurement techniques struggle. In Fig.1, speckle patterns captured from the same surface are shown for (a) a static sample and (b) a sample moving in the x -direction.

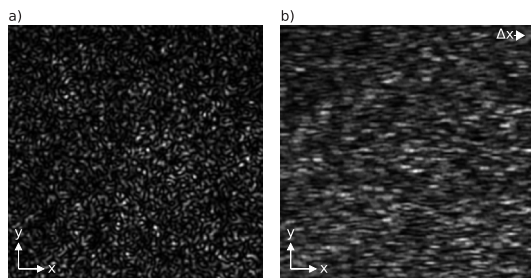


Fig. 1 Subjective speckle from the same surface: (a) static, (b) moving in the x -direction.

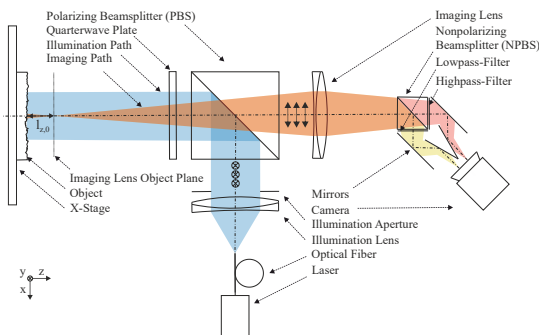


Fig. 2 Experimental setup for simultaneous imaging at different wavelengths. The speckle patterns are imaged side-by-side on the camera sensor. Here, 640 nm and 660 nm are used.

The spectral speckle correlation (SSC) method leverages laser speckle patterns recorded at multiple wavelengths to quantitatively determine surface-roughness parameters [1]. When coherent light illuminates a rough surface, it produces a characteristic speckle pattern whose properties correlate directly with the surface roughness. By capturing speckle images at different wavelengths and computing their cross-correlation, we establish a quantitative relationship between speckle decorrelation and surface roughness [2].

With the setup shown in Fig.2, we illuminate and acquire both wavelengths simultaneously to

enable high-speed measurements and reduce disturbances. The wavelengths are combined using a fiber combiner. A polarizing beam splitter together with a quarter-wave plate provides on-axis illumination. The beams are then separated with a nonpolarizing beam splitter and filters, forming two images side-by-side on the camera. Additionally, Gaussian filtering in the Fourier domain is applied to separate surface texture from speckle prior to correlation.

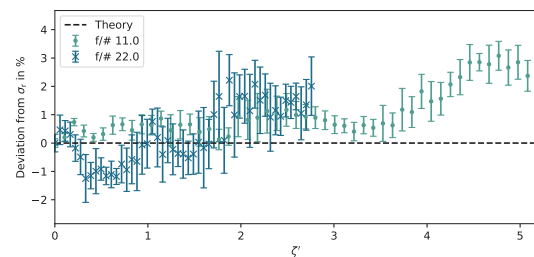


Fig. 3 Measured roughness, normalized to the static roughness.

Figure3 shows the deviation of the normalized roughness as a function of the dimensionless parameter ζ' , which quantifies the speckle travel during the exposure.

This approach yields accurate roughness estimates even when the sheet traverses multiple speckle grains during exposure. Extrapolation to $\zeta' = 2$ with the setup of Fig.2 and 500 mW sources suggests suitability for continuous, in-line quality control at typical line speeds (about 16.5 m min^{-1}).

In cooperation with: Fraunhofer Institute for Physical Measurement Techniques IPM, Freiburg (A. Schiller, A. Bertz, D. Carl)

References

- [1] P. Laux, A. Schiller, A. Bertz, D. Carl, and S. Reichelt, "Large area roughness measurements using spectral speckle correlation," *Opt. Eng.* 64(7) 074101 (2025), URL <https://doi.org/10.1117/1.OE.64.7.074101>.
- [2] P. Laux, A. Schiller, C. Bett, A. Bertz, D. Carl, and S. Reichelt, "Large area roughness measurements using spectral speckle correlation," *Opt. Express* 33, 48575-48590 (2025), URL <https://doi.org/10.1364/OE.578858>.

6-DoF speckle shift tracking sensor

N. Borchers, T. Haist, S. Reichelt

Six-degree-of-freedom (6-DoF) pose measurements, encompassing simultaneous position (XYZ) and orientation (UVW) tracking, are essential in precision manufacturing. Robots offer high repeatability, but their single-shot accuracy diminishes under heavy loads, posing challenges in various applications.

To provide a solution for this challenge, a 6-DoF sensor based on speckle shift measurements was simulated and set-up in the lab [1]. The sensor observes the speckle pattern generated when light scatters off an optically rough surface. This speckle pattern shifts when the target surface moves. By capturing the speckle shifts at multiple image sensor positions, as shown in Fig. 1, the sensor can distinguish between the different translations and rotations, enabling precise pose measurements.

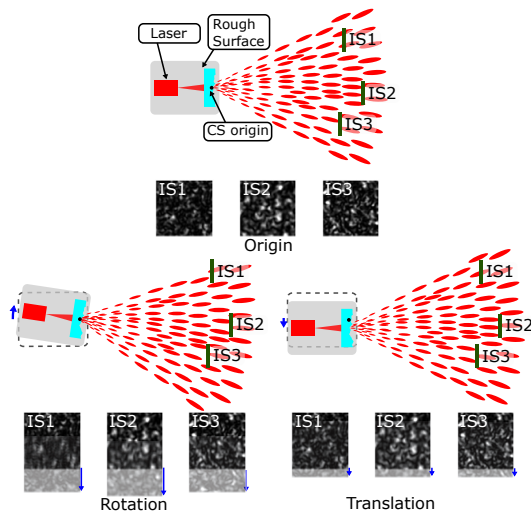


Fig. 1 General principle of the speckle tracking sensor: Different surface movements cause different speckle shifts, here shown for lateral translations.

The relationship between speckle shifts and pose shifts of the target is then encoded into the sensitivity matrix S , enabling precise and fast calculations of relative of 6-DoF movements. The sensor, as shown in Fig. 2, includes a laser illuminating the target (diffuser) and three image sensors capturing the speckle pattern. The system requires a stable laser wavelength and geometry to ensure accurate measurements.

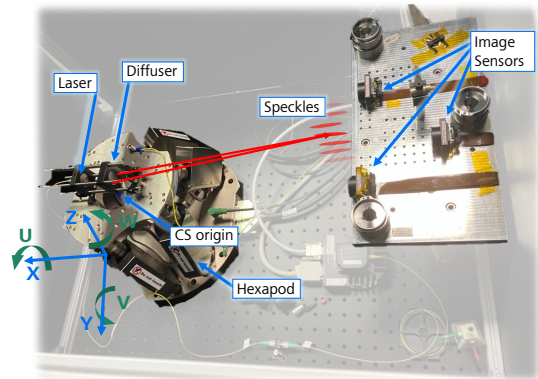


Fig. 2 Speckle tracking sensor setup: Left: Target platform on hexapod, the shown coordinate system is shifted for better visibility, Right: Camera platform.

The sensor's accuracy was verified through experiments with a lateral movement, a rotation and a combination of all 6-DoF. For lateral movements in Y , as shown in Fig. 2, from $-1.2\mu\text{m}$ to $1.2\mu\text{m}$, the system achieved a trueness below $2.2\mu\text{m}$ for translations and below $5.1\mu\text{rad}$ for rotations, with a precision below $1.5\mu\text{m}$ for translations and below $5\mu\text{rad}$ for rotations. For random 6-DoF movements a precision below $2\mu\text{m}$ for translations and $7\mu\text{rad}$ for rotations, with a trueness of $1.5\mu\text{m}$ and $5.2\mu\text{rad}$ was shown.

In comparison to other technologies used for 6-DoF measurements several differences become apparent. CMM's offer high accuracy but are limited by their physical size and speed. Stereo photogrammetry provides good lateral accuracy but is less effective for axial measurements. Laser tracers offer high precision but require multiple sensors for full 6-DoF measurements. Speckle shift tracking excels at cost-efficiency and its capability in measuring tip/tilt rotations, while maintaining competitive accuracy for other degrees of freedom.

In cooperation with: Carl Zeiss AG

References

- [1] N. Borchers, U. Vogl, C. Glasenapp, T. Haist, S. Reichelt, "Speckle shift tracking sensor for high accuracy 6-DoF pose measurements", *tm - Technisches Messen*, 2026. URL <https://doi.org/10.1515/teme-2025-0130>.

3D-printed Microoptics and Simulation



In our research group we focus on the development of novel tools for simulation and optimization, and the design of innovative complex optical systems for industrial or medical purposes. A strong focus lies on the realization of novel micro-optical systems fabricated via two-photon-polymerization. The classical optical design of imaging and illumination systems, as well as ray-based and wave-optical system simulations remain core competencies and research fields of our group.

Research areas include:

- design, simulation and manufacturing of 3D-printed micro-optical systems
- optical simulations (ray-tracing and wave-optical)
- optical systems in medical engineering
- imaging design
- illumination design
- phase space methods in optical design and simulation

Contact: aslani@ito.uni-stuttgart.de, toulouse@ito.uni-stuttgart.de,
herkommer@ito.uni-stuttgart.de

Advances in wave-optical simulation methods for 3D-printed micro-optics

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

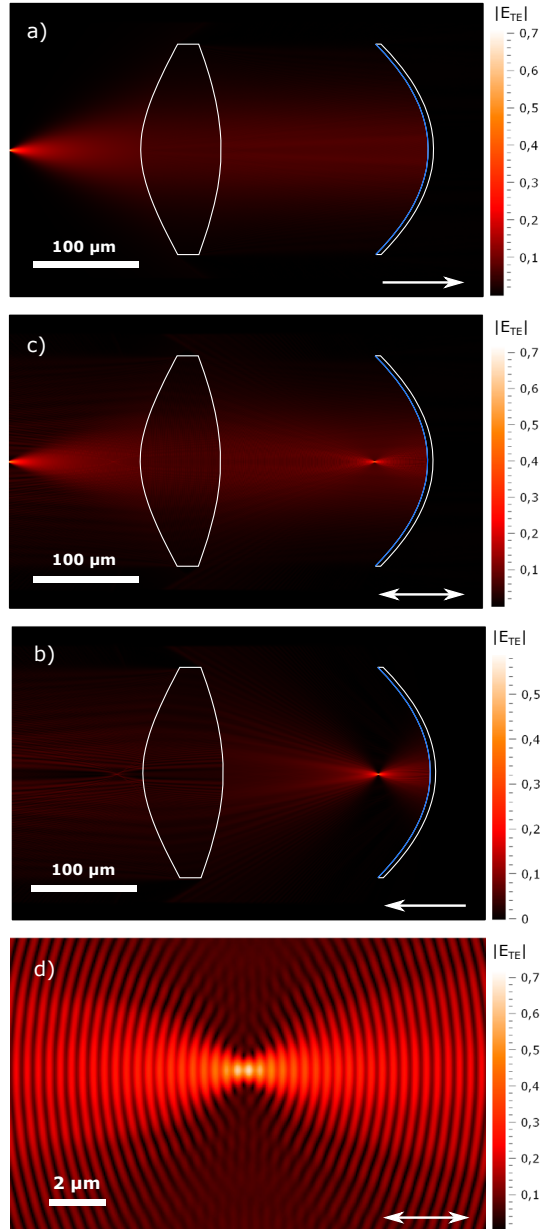


Fig. 1 The new BWPM allows the simulation of a catadioptric micro optical system, comprising a transparent lens and a silver-coated focusing mirror. a) Forward propagating electric field. b) Backward propagating electric field. c) Total electric field. d) Focal region of the parabolic mirror as simulated in c), showing the interference of forward- and backward propagating fields.

Additive manufacturing offers unprecedented possibilities to produce micro-optics, with almost arbitrarily complex surface shapes. Appropriately fast and accurate simulation methods are necessary to predict and optimize the optical system performance, to allow to fully exploit the flexible production capabilities of 3D-printing.

The Wave Propagation Method (WPM) has proven to be well suited to study 3D-printed micro-systems due to its swift calculation speed and high accuracy; so far, however, it was restricted to scalar electromagnetic fields and forwards-only propagating light. This prohibited the comprehensive simulation and optimization of polarization-sensitive and reflective micro-optics.

We have overcome these limitations with the new Bidirectional Wave Propagation Method (BWPM) [1]. It allows the simulation of polarized and back-reflected light, sufficiently fast for practical application on 3D-printed micro-optics. The BWPM opens up unprecedented avenues to study catadioptric micro-optics, and allows in-depth studies of back-reflection-sensitive imaging systems such as OCT-endomicroscopes [2], and optical sensors on fiber-tips [3].

Supported by: Carl Zeiss Stiftung (Endo-Print3D); University of Stuttgart (RiSC).

References

- [1] M. Wende, J. Drozella, and A. M. Herkommer, "Fast bidirectional vector wave propagation method showcased on targeted noise reduction in imaging fiber bundles using 3D-printed micro optics," *Optics Express* **31**(18), 28874–28890 (2023).
- [2] M. Wende, J. Drozella, A. Toulouse, and A. M. Herkommer, "Fast vector wave optical simulation methods for application on 3D-printed micro optics," in *Laser 3D Manufacturing XI*, vol. 12876, pp. 143–157 (SPIE, 2024).
- [3] M. Wende, J. Drozella, A. Toulouse, and A. M. Herkommer, "Fast vector wave optical simulation methods for application on 3D-printed microoptics," *Journal of Optical Microsystems* **4**(2), 024501–024501 (2024).

Freeform micro-optics via two-photon polymerization

C. Jimenez, A. Herkommer

Freeform micro-optical components are central to the next generation of compact optical systems, enabling precise control over light propagation in ways that conventional optics cannot achieve. To this end, Generated Jacobian Equations (GJEs) based inverse designs represent an interesting alternative to the realization of such freeform based micro-optical systems. However, such a design strategy has not been explored in combination with two-photon polymerization (2PP) based micro-fabrication technologies. By combining the best from both fields, the potential for creating novel micro-optical elements tailored for specific optical transformations is highlighted.

Our implementation relies on the work presented in [1] for which an iterative algorithm is used to obtain freeform optical surfaces via the use of a GJE. Such a design algorithm exploits the relationship between a generating function G and its unique inverse H , also referred to as a Hamilton's characteristic function. As in [1] we rely on an angular characteristic formulation to our problem, for which the source and target coordinates are both expressed in terms of stereographic values.

As a test target irradiance distribution, a modulated cosine-squared function, given by $\cos(\frac{2\pi x_t}{\beta})^2$ has been chosen. In this case, x_t denotes the x cartesian coordinates at the target plane and β the desired fringe periodicity. The obtained freeform lens design, which is shown in Fig. 1 (b) was subsequently fabricated by means of a commercially available 2PP system (Photonic Professional GT2 with a 25x Zeiss objective). The lens was fabricated directly on top of an AlGaInP visible laser diode (LD) with a central emission wavelength at 650 nm. These LDs consist of an emission surface protected by a window glass with a thickness of 400 μm , for which a schematic representation of the modeled system is presented in Fig. 1(a).

The fabricated freeform surface was characterized using a white-light interferometer (WLI, Zygo, Nexview NX2) for which the recorded intensity map is presented in Fig. 2 (a). Following, the irradiance distribution generated by this freeform lens was recorded with a CMOS camera in close proximity to the LD sample, for which the obtained irradiance map is presented in Fig. 2 (b). These results were presented during the European Optical Society annual meeting 2025 [2] and are also used in the DFG graduate school GRK 2642: Towards Graduate Ex-

perts in Photonic Quantum Technologies, where freeform surfaces are used for coupling of quantum light sources to fibers [3].

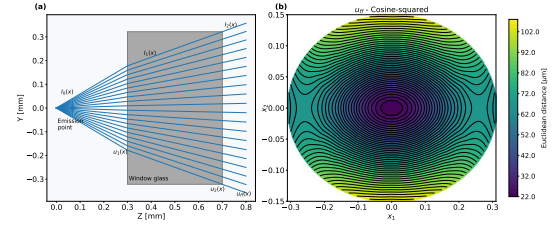


Fig. 1 (a) Schematic representation for the laser diode system considered in this case. The emission region is modeled as a point emitter followed by a window glass with a thickness of 400 μm . All of the interfaces $u(x)$ and the associated intermediate ray-directions $I(x)$ are directly included in the Hamilton's characteristic function H . (b) Obtained surface profile after running the iterative algorithm.

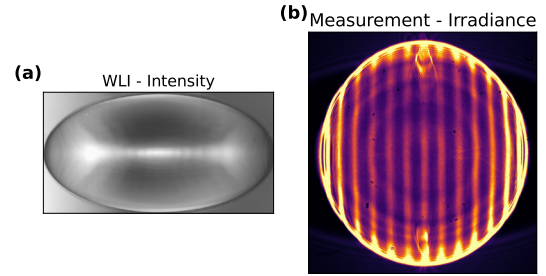


Fig. 2 (a) Intensity record by employed white-light interferometer system. (b) Recorded irradiance distribution from freeform lens fabricated directly on top of LD system.

Supported by: This work was supported by the German Research Foundation (DFG)

Project: 5375199884 and GRK2642

References

- [1] L.B. Romijn, et. al., An iterative least-squares method for generated Jacobian equations in freeform optical design, *SIAM Journal on Scientific Computing* **43**, B298 (2021).
- [2] C. Jimenez, A. Herkommer. "3D printed freeform micro-optics meets generated Jacobian equations based inverse designs." *EPJ Web of Conferences* 335, 02003 (2025), EOSAM 2025
- [3] Jimenez, Carlos, Andrea Toulouse, and Alois Herkommer. "Design of freeform beam shaping micro-optics for single photon sources." *Optics Express* 33.11 (2025): 22805-22815.

3D-printing of luminescent microstructures

V. Aslani, A. Herkommer, A. Toulouse

Femtosecond direct laser writing (fs-DLW) enables 3D-printing of microstructures with exceptional design freedom, yet functionalization of commercial photoresists for integrated optical sensing remains limited. We introduce a novel platform that combines fs-DLW with the unique photophysical properties of lanthanides, allowing the fabrication of functional luminescent microstructures directly on optical fiber tips [1]. This strategy exploits the exceptional photostability, narrow emission lines, and long luminescence lifetimes of lanthanides to overcome spectral overlap and photobleaching commonly seen with organic fluorophores.

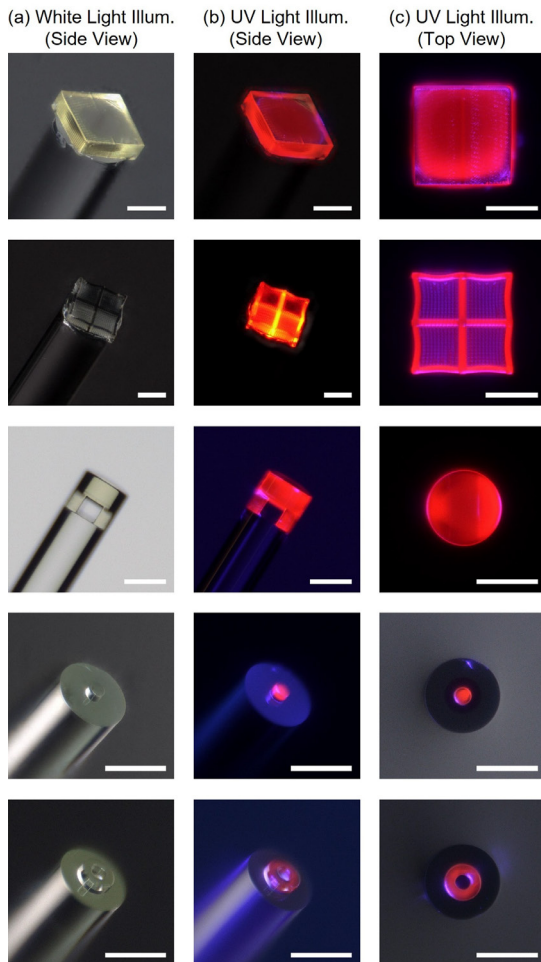


Fig. 1 Microscope images of different luminescent microstructures that were printed directly onto the tip of optical fibers. (a) When illuminated with white light, all structures appear mostly transparent. (b)-(c) If UV-light is used for illumination, the structures show red emission. The white scale bars represent a length of 100 μm .

For the manufacturing of the luminescent microstructures, the methodology developed in [2] and a wrapped writing configuration [3, 4] that protects the objective lens from potential discoloration and damage was used. By incorporating lanthanide complexes - specifically europium complexes - into commercial 3D-printing resists (OrmoComp and IP-Visio), porous, periodic, and solid luminescent microstructures with optical-grade quality and sub-micrometer feature size can be fabricated. Five distinct structures are shown in Fig. 1 (top to bottom): two woodpile structures for temperature and redox sensing, a Fabry-Pérot cavity for refractive index detection, and disc and annular geometries for spatially selective excitation. Leveraging spectral, temporal, and spatial multiplexing, this approach establishes a versatile platform for fiber-based sensing that allows simultaneous detection of distinct biochemical and physical parameters.

Supported by: This work was supported by Global Glimpse (Grant No. DFG UP31/1), the Bundesministerium für Bildung und Forschung (DAAD PPP Australia 2024, Grant No. 57701620), the Baden-Württemberg Stiftung (Elite Programme for Postdocs), and the German Research Foundation (DFG) (Project Numbers: 409474577; 537519988).

In cooperation with: University of South Australia (S. Baghapour, S. Warren-Smith, W. Zhang, E. Ebadati, S. Plush, S. Afshar V.)

References

- [1] V. Aslani, S. Baghapour, S. C. Warren-Smith, W. Zhang, E. Ebadati, S. E. Plush, A. M. Herkommer, A. Toulouse, and S. Afshar V., "3D Micro-printing of Structures with Lanthanide-based Fluorophores on Optical Fibers for Multiplexed Sensing," *Advanced Optical Materials* (2025).
- [2] V. Aslani, A. Toulouse, M. Schmid, H. Giessen, T. Haist, and A. Herkommer, "3D printing of colored micro-optics," *Optical Materials Express* **13**(5), 1372 (2023).
- [3] A. Toulouse, S. Thiele, K. Hirzel, M. Schmid, K. Weber, M. Zyrianova, H. Giessen, A. M. Herkommer, and M. Heymann, "High resolution femtosecond direct laser writing with wrapped lens," *Optical Materials Express* **12**(9), 3801 (2022).
- [4] A. Toulouse, S. Thiele, and M. Heymann, "Verfahren zum optischen 3D-Drucken in einem Photolack und Verwendung einer Objektiv-Schutzvorrichtung (DE102021131132B4)," *Deutsches Patent- und Markenamt DE102021131132B4* (2025).

3D-printed immersion micro-optics enable new biophotonics and integrated photonics applications

M. Wende, K. Doth, A. Toulouse

Femtosecond 3D-printing allows manufacturing of sophisticated micro-optics with extremely flexible optical designs and diameters as small as a human hair. Such miniaturized micro-optics can advance cutting edge optical applications by reducing system size, reagent consumption and hence overall system cost. Available materials and manufacturing strategies, however, restricted their utility when immersed into liquids, important in life sciences and integrated photonics packaging.

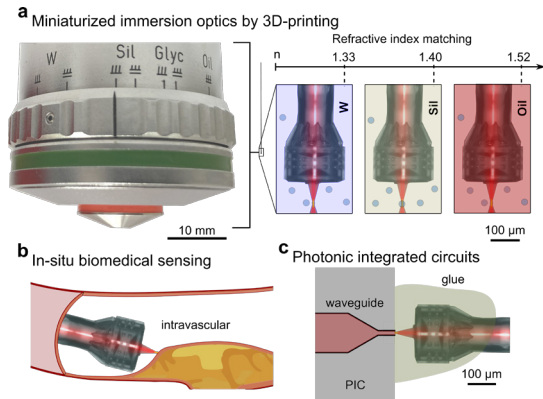


Fig. 1 3D-printed immersion micro-optics are highly sought after for in-situ applications. **a** State-of-the-art macroscopic immersion objective lenses are about 100x larger than 3D-printed micro-optics. The flexible 3D-printing approach enables adaptable designs for different immersion media. **b** Compact immersion optics enable applications in confined cavities, e.g. spectroscopy in small arteries. **c** They could also provide stable coupling between fibers and photonic integrated circuits by immersion into glue, active alignment, and subsequent fixing.

We developed a new microfluidic sealing strategy for 3D-printed micro-optics, to protect critical optical surfaces from harmful contact with surrounding liquids. With this new method, we demonstrated manufacturing of high-quality micro-optics for operation in water-, silicone-, and oil-immersion [1]. Such immersed micro-optics have high translation potential to advance miniaturized analytical devices for biomedical research [2], stable integrated circuit coupling, and keyhole-access medical endoscopy [3].

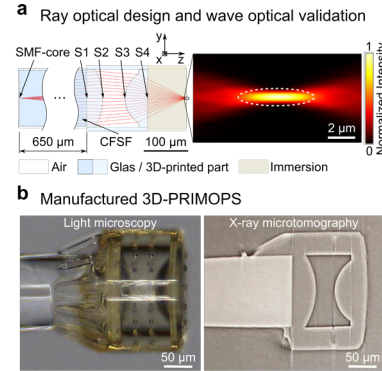


Fig. 2 a Ray optical design of 3D-printed immersion micro-optics at the tip of a single mode fiber. With four surfaces S1-S4, the optics tightly focus light into the liquid immersion medium. A wave-optical simulation (FPWM), [4] predicts diffraction-limited focusing. **b** Light microscopy- and X-ray microtomography images of 3D-printed immersion micro-optics (3D-PRIMOPS) show the air-filled cavity and the sealed encapsulation.

Supported by: Carl-Zeiss-Stiftung (Endo-Print3D), University of Stuttgart (RiSC). M. Wende is supported by an Add-on fellowship by the Joachim Herz foundation.

In cooperation with: Institute of Biomaterials and Biomolecular Systems, University of Stuttgart (M. Heymann)

References

- [1] M. Wende, K. Doth, M. Heymann, and A. Toulouse, "3D-printed immersion micro optics," *Light: Advanced Manufacturing* **6**, 1–7 (2025).
- [2] K. Doth, M. Wende, J. Drozella, T. Haist, A. Herkommer, and A. Toulouse, "Miniaturized holographic twin trap 3D-printed via two-photon lithography," *Journal of Optical Microsystems* **5**(2), 024501–024501 (2025).
- [3] C. Imiolczyk, M. Wende, A. Kushwaha, L. Xiang, N. Soltan, H. Giessen, R. McLaughlin, C. Jones, A. Toulouse, and J. Li, "3D Printed Encapsulated Microlens for Endoscopic Optical Coherence Tomography," in *European Conference on Biomedical Optics*, pp. W4D–3 (Optica Publishing Group, 2025).
- [4] M. Wende, J. Drozella, A. Toulouse, and A. M. Herkommer, "Fast algorithm for the simulation of 3D-printed microoptics based on the vector wave propagation method," *Optics Express* **30**(22), 40161–40173 (2022).

Fringe projection elastography for tissue differentiation in oncology

Ö. Atmaca, V. Aslani, T. Haist, A. Toulouse, A. Herkommer

Pathologically altered tissue exhibits differences compared to healthy tissue, which can be observed as changes in electrical, chemical, optical, or even mechanical properties, where the haptic feedback is an important indicator for tissue differentiation in surgery. In minimally invasive surgery, however, the haptic feedback is drastically reduced. Therefore, it is necessary to use optical sensor systems for contact-free tissue differentiation. To re-enable minimally invasive tissue differentiation based on optical elastography, a fiber-mounted, 3D-printed microoptical fringe projection system [1] (Fig. 1) was used to project a spatially modulated illumination pattern onto the tissue (Fig. 2) and to reconstruct the surface profile of indented tissue caused by an indentation force via air or water jet impulse. This sensor system enables a fast and full-field assessment of viscoelastic indentation as shown in Fig. 3 and was even successfully integrated into the working channel of a commercially available cystoscope [2], showing reliable reconstruction of the viscoelastic indentation under suboptimal viewing conditions [3]. The highly miniaturized nature of the projection and force application also allows for integration next to any camera-based imaging setup. Therefore, it was also used in conjunction with a hyperspectral imaging setup for multi-modal robust tissue differentiation [4].

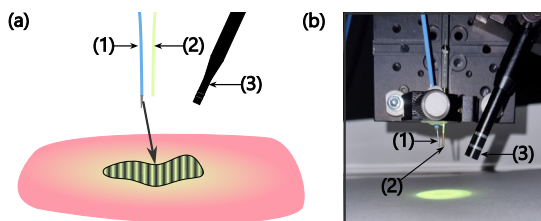


Fig. 1 Schematic (a) of the fringe projection setup (b) consisting of a cystoscopic needle connected to a pressurized air valve (1), the 3D-printed microoptical fringe projector (2), and a camera (3).

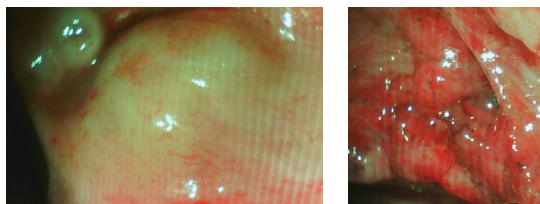


Fig. 2 Exemplary fringe images of human bladder tissue samples.

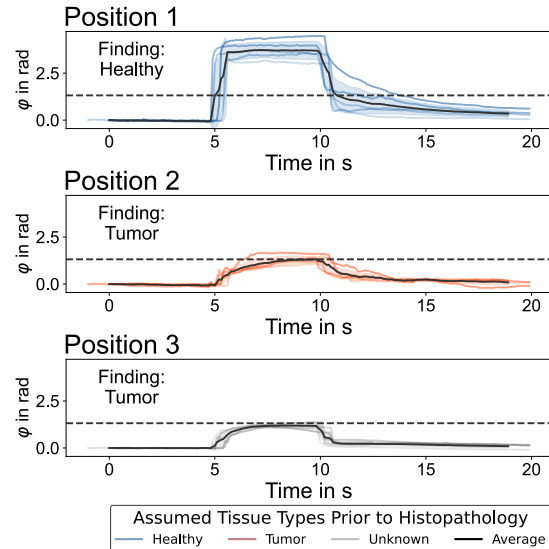


Fig. 3 Viscoelastic indentations of a human bladder sample at 3 different positions in terms of fringe phase φ together with one standard deviation as shaded areas around the average indentation and the corresponding histopathological findings. Indentations significantly above the dashed line indicate healthy tissue with lower stiffness, while below or equal to the threshold indicate tumor tissue with higher stiffness [5].

Supported by: This work was supported by the German Research Foundation (DFG).

Project: GRK 2543: "Intraoperative multi-sensor tissue identification in oncology" (Project ID 409474577 – Subproject A1)

In cooperation with: University Hospital Tübingen & Printoptix GmbH (S. Thiele)

References

- [1] S. Schmidt *et al.*, "Optikvorrichtung zum Projizieren eines Musters auf eine Oberfläche," DE102023115518A1.
- [2] V. Aslani *et al.*, "Sensorsystem zur minimalinvasiven intraoperativen Gewebedifferenzierung in der Onkologie mittels endoskopischer Streifenprojektion," in *DGaO Proc. 2023*, p. A28.
- [3] V. Aslani *et al.*, "Endoscopic measurement system for elastographic tissue differentiation based on active triangulation and 3D-printed micro-optics," in *Proc. SPIE 12817*, p. 128170E.
- [4] A. Rüdinger *et al.*, "Bimodal tissue differentiation using hyperspectral imaging and elastographic Fourier transform profilometry," *Light: Adv. Man.* **6**, 73.
- [5] Ö. Atmaca *et al.*, "Elastographic Measurements Using Fourier Transform Profilometry for Tissue Differentiation in Oncology," in *DGaO Proc. 2024*, p. P20.

Miniaturized, 3D-printed, holographic optical tweezers for particle trapping

K. Doth, M. Wende, J. Drozella, T. Haist, A. Herkommer, A. Toulouse

The significance of hand hygiene as an infection prevention measure has clearly been demonstrated during the corona virus pandemic. An early-warning system for pathogenic infections would be a useful tool in not only detecting but also preventing infections by dynamically adapting the hygiene measures in closed systems (e.g. hospitals). In the BMBF-funded project GeDeSens2Virus, the aim was to integrate a multi-sensor detection of pathogens into a dispenser system, which analyses the so-called overspray after a hand hygiene event. The ITO investigated the miniaturization of different pathogen detection methods and realized a miniaturized holographic optical tweezer for microfluidic integration [1].

Optical tweezers make use of the radiation forces present in a focused laser beam to trap particles in the focus of the beam. The trapping efficiency depends on different particle and laser parameters, which can be used to differentiate between particles. Usually, stable particle trapping requires a high numerical aperture (NA) of the focus generating microscope objective. With a counterpropagating trap, using two opposing beams with a shared focal plane, the required NA can be significantly reduced. We realized a special implementation of the counterpropagating trap, based on the holographic twin trap [2]. Within this tweezers configuration, the opposing beams are generated using only one optics, combined with a Fresnel zone plate to generate two axially separated focal spots, which are then superposed by a mirror (see Figure 1A).

We designed our system for fabrication with two-photon polymerization (2PP), which enables the direct integration of the diffractive element, as well as the possibility for fabrication of micro-optics arrays for parallelized trapping. Further, a method for encapsulating micro-optics for immersion applications [3] was implemented for microfluidic integration of the system. A sectional system print of the miniaturized holographic optical tweezer is presented in Fig. 1B. The final fabricated system was characterized and afterwards integrated into an experimental setup for trapping of polystyrene beads, as shown in Fig. 1C. We demonstrated the stable particle trapping and manipulation of 3 μm polystyrene beads in water (see Fig. 1D).

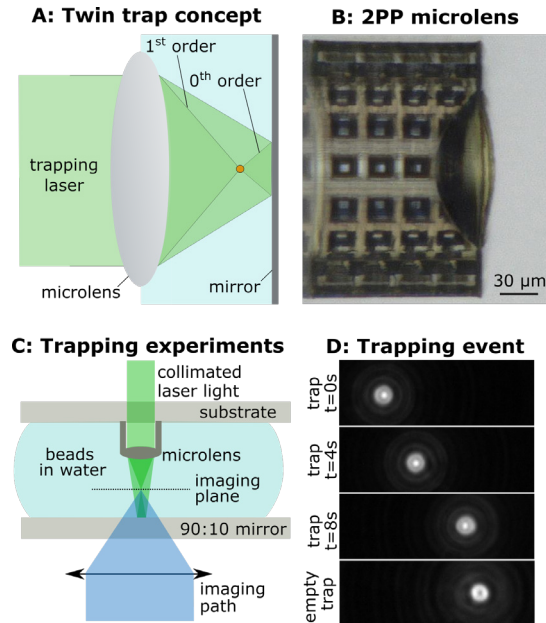


Fig. 1 Miniaturized holographic twin-trap. A: System concept scheme. B: Microscopic image of sectional system print. C: Experimental setup scheme. D: Stable trapping and manipulation of 3 μm polystyrene bead.

Supported by: This work was supported by the Federal Ministry of Education and Research (BMBF).

Project: Miniaturisiertes Elektroniksystem zur schnellen Detektion von Viren und Bakterien im Desinfektionsmittelspender (GeDeSens2Virus, 16ME0374)

In cooperation with: OPHARDT HYGIENE-TECHNIK, ALU Freiburg, ibidi, ADDI-DATA, Sciospec Scientific Instruments

References

- [1] K. Doth, M. Wende, J. Drozella, T. Haist, A. Herkommer, and A. Toulouse, "Miniaturized holographic twin trap 3D-printed via two-photon lithography," *Journal of Optical Microsystems* **5**(2), 024501–024501 (2025).
- [2] S. Zwick, T. Haist, Y. Miyamoto, L. He, M. Warber, A. Hermerschmidt, and W. Osten, "Holographic twin traps," *Journal of Optics A: Pure and Applied Optics* **11**(3), 034011 (2009).
- [3] M. Wende, K. Doth, M. Heymann, and A. Toulouse, "3D-printed immersion micro optics," *Light: Advanced Manufacturing* **6**, 1–7 (2025).

Dual fiber probe with 3D-printed micro-lens for Brillouin microscopy

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

Brillouin spectroscopy enables non-invasive mechanical analysis of biological samples, but endoscopic translation is hampered by parasitic background signals from conventional fiber setups [1]. This work [2] introduces a dual-fiber probe with a freeform, 3D-printed micro-lens (Figure 1a) that concentrates the excitation and overlaps the focal spots of the two fibers while suppressing the fiber background. With a tip diameter under 300 μm , the device maps mechanics with lateral resolution below 10 μm and axial resolution near 43 μm .

The two single-mode fibers are engineered to have overlapping beam paths in the sample region, enabling precise excitation–collection overlap in the design. The freeform micro-lenses on the fiber tips are manufactured by two-photon lithography to realize the overlap. The utilized single mode fibres are connected via standard FC APC connectors to the light source and spectrometer.

Brillouin signals from water and from polymer resin references verify enhanced collection efficiency, approximately eightfold compared with a bare dual fiber arrangement. A 660 nm laser delivers excitation and the scattered light is analyzed with a tandem Fabry–Pérot interferometer providing high spectral extinction and a 512 point spectrum. In addition to water, Brillouin spectra from three printed resins IP S, IP DIP 2 and OrmoComp illustrate the device capability to distinguish different mechanical signatures. 2D Brillouin mapping demonstrates imaging of protein droplets DDX4 in aqueous solution, with corresponding bright field imaging confirming the structure (Figure 1b).

References

- [1] I. V. Kabakova, Y. Xiang, C. Paterson, and P. Török, “Fiber-integrated Brillouin microscopy: Towards Brillouin endoscopy,” *Journal of Innovative Optical Health Sciences* **10**, 1742002 (2017).
- [2] J. Trapp, H. Mahmodi, M. Wende, L. McAlary, L. Ooi, J. Li, R. A. McLaughlin, A. Herkommer, A. Toulouse, and I. Kabakova, “Dual fiber probe with 3D-printed micro-lens for Brillouin microscopy,” *APL Photonics* **10** (2025).

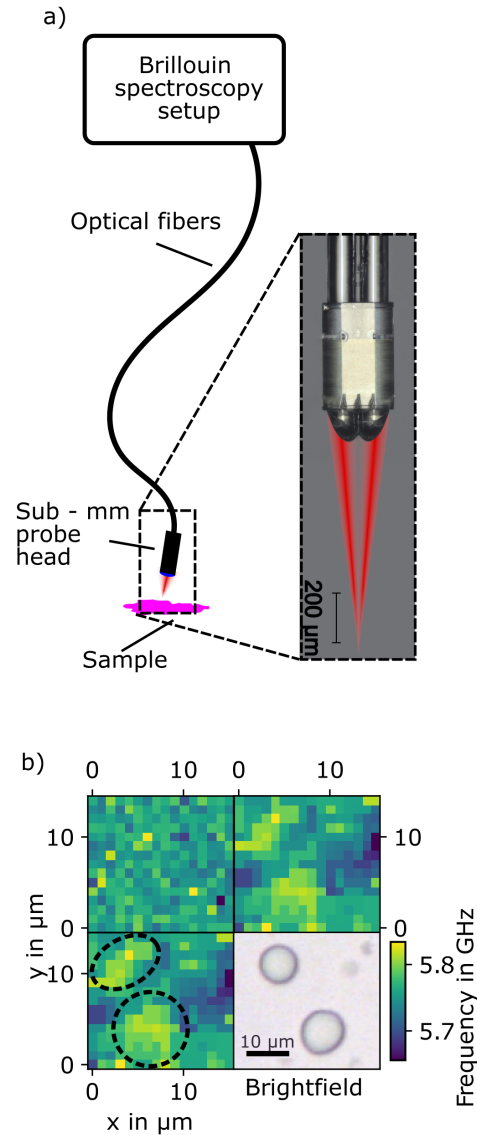


Fig. 1 a) Illustration of a fiber-based Brillouin spectroscopy probing setup, with manufactured freeform micro-optic as well as b) spatial sampling of protein droplets with Brillouin fiber probe.

In cooperation with: University of Technology Sydney UTS (Hadi Mahmodi, Irina Kabakova), the University of Adelaide (Jiawen Li, Robert A. McLaughlin), University of Wollongong (Luke McAlary, Lezanne Ooi) and supported by Graduate School of Advanced Manufacturing GSaME of Stuttgart University

Towards endoscopic 3D bio-printing on the micro-scale

A. Toulouse, M. Wende, A. Herkommer

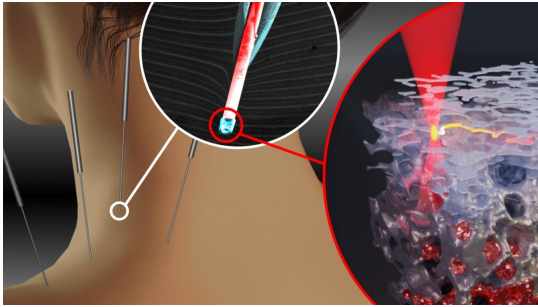


Fig. 1 Vision of an ultra-compact endoscopic 3D-printer capable of tissue reconstruction. Image credits: Kai Hirzel, Timo Gissibl, Florian Sterl.

Conventional surgery typically inflicts considerable tissue damage. Endoscopy-based keyhole interventions helped to reduce side effects, however, surgical tools continue to operate in primarily subtractive fashion and our ability to directly regenerate tissue in situ remains limited. To overcome this, we propose a highly miniaturized bio-3D-printer at the tip of an endoscope to additively fabricate tissue scaffolds on site.

To facilitate two-photon 3D printing of organotypic biomaterial-inks with sub-cellular resolution at the tip of an optical fiber, we use a 780 nm femtosecond laser combined with an anomalous dispersive pulse compression to compensate propagation through a 2.5 m long single-mode optical fiber. A custom high-NA immersion objective lens at the tip of the fiber tightly focuses the delivered femtosecond laser pulses to pattern commercial photoresist as well as custom protein based biomaterial-ink recipes. Printed scaffolds are analyzed using electron microscopy, in biocompatibility assays and for their micro-mechanical profiles.

At the tip of the fiber, we reach up to 40-fold pulse length compression leading to pulse lengths down to 110 fs or peak powers up to 1900 W. We successfully seal our 3D-printed endoscopic writing objective against photoresist intrusion [1] and demonstrate diffraction-limited focal spots at an NA of 0.625. In our experimen-

tal setup we show endoscopic 3D printing of microstructures with lateral dimensions of approx. 1 μm and axial dimensions of approx. 5 μm with commercial plastic resin. 3D printing of custom hydrogel biomaterial ink demonstrates a plausible path towards endoscopic 3D printing of tissue scaffolds.

We propose endoscopic biofabrication as a novel approach to minimal invasive microsurgery by building a two-photon bio-3D-printer at the tip of an endoscope. In a first proof of concept, femtosecond 3D printing through a single-mode fiber is successfully demonstrated by combination of pulse compression, a 3D-printed high NA immersion objective, and biomaterial-ink engineering. These results could be the seed for an endoscopic biofabrication platform addressing a broad interdisciplinary spectrum of topics from physics, optical engineering, bio-/chemical engineering, microfluidics, and medical engineering.

Based on this proof of concept, a Carl-Zeiss-Stiftung Nexus Junior Research Group was started in October 2025 by Andrea Toulouse, to investigate different methods for light-based endoscopic 3D printing in depth.

Supported by: This work was supported by the Carl-Zeiss-Stiftung.

Project: EndoPrint3D

In cooperation with: Institute for Biomaterials and Biomolecular Systems (M. Heymann) and 4th Physics Institute (H. Giessen), University of Stuttgart

References

- [1] M. Wende, K. Doth, M. Heymann, and A. Toulouse, "3D-printed immersion micro optics," *Light: Advanced Manufacturing* **6**, 1–7 (2025).

This report reproduces content from the BMT 2024 - 58th Annual Conference of the German Society for Biomedical Engineering conference proceedings.

Fabrication and characterization of a magnetic 3D-printed microactuator

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

Magnetic actuation at the microscale enables large forces, remote controllability, and high displacement, which makes it an attractive alternative to electrostatic or thermal concepts typically used in MEMS. Additive manufacturing by two-photon polymerization (2PP) further offers full geometric freedom and sub-micrometer resolution, making it possible to realize highly compact three-dimensional actuator designs.

By combination of these technologies, a 3D-printed magnetically driven microactuator with a diameter of less than 500 μm is demonstrated, consisting of a polymeric spring structure and a permanent magnet integrated within a single monolithic design (see Fig. 1). The structure is fabricated from the photoresist IP-S and the reservoir is filled with a low-viscosity two-component epoxy loaded with NdFeB microparticles. After curing, the composite is magnetized by a homogeneous 4 T pulse field. The resulting device has an overall height of 650 μm and is sufficiently compact to be printed even on non-planar substrates such as optical fiber tips [1].

Mechanical characterization reveals that the polymerized IP-S material exhibits pronounced viscoelastic behavior. Nanoindentation measurements at partner institutes allowed to create a viscoelastic model, which enables realistic prediction of actuator motion and highlights design constraints imposed by material behavior. The deeper understanding of the system allowed to develop a control mechanism for the position of the optics.

For magnetic actuation, the permanent magnet is attracted by the field of a microcoil wound around a FeNi tube core. Increasing the coil current generates stronger magnetic fields and thus larger axial displacements. Actuation experiments resulted in displacements of up to 90 μm .

This actuation principle could be used to realize a prototype of a 3D-printed endo-microscope with cellular resolution for hard-to-access, confined spaces [2]. The required large numerical aperture results in a small depth of field that prohibits sharp imaging of volumetric structures. Combining the 3D-printed micro-optics with the above magnetic actuator at the tip of an imaging fiber bundle allows fast axial image plane scanning with high lateral resolution and thus allows the acquisition of sharp images of 3D structures (see Fig. 2).

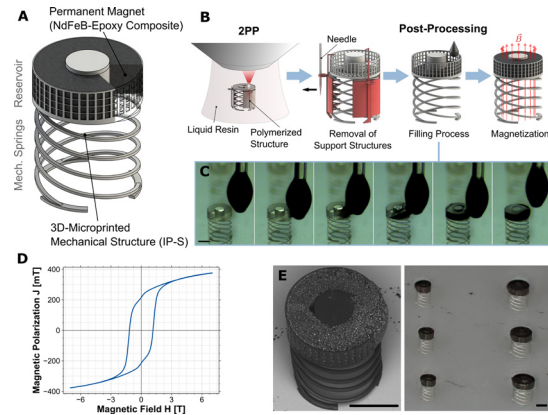


Fig. 1 (A) Principle of the magnetic actuator, (B/C) fabrication details, (D/E) characterization.

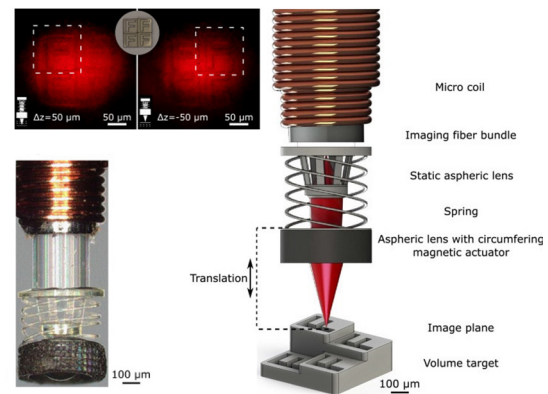


Fig. 2 Visualization and images of the 3D-printed actuated endo-microscope

Supported by: This work was supported by the German Science Foundation (DFG)

Project: Mimao - project 461765984

In cooperation with: Mikrop AG, Printoptix GmbH, FAU Erlangen, Max-Planck Stuttgart, Uni Kassel, 4PI Stuttgart and Univ. Arizona

References

- [1] Rothermel, Florian, et al. "Fabrication and Characterization of a Magnetic 3D-printed Microactuator." *Advanced Materials Technologies* 9.12 (2024): 2302196. <https://doi.org/10.1002/admt.202302196>
- [2] Wende, Marco, et al. "3D-printed endo-microscope with a fast magnetic actuator for axial image plane scanning." *Optics Letters* 50.7 (2025): 2243-2246. <https://doi.org/10.1364/OL.546292>

3D-printed soft actuatable micro optics

A. Toulouse, J. Grunewald, A. Herkommer

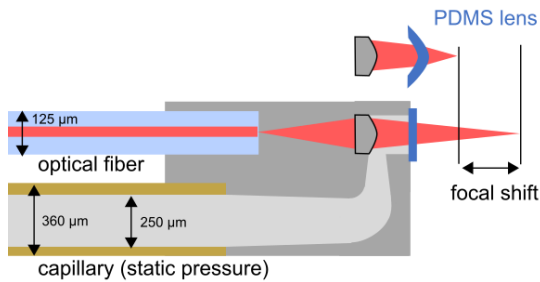


Fig. 1 Concept of an integrated varifocal lens on the tip of an optical fiber.

Actuators are essential to optimally adapt an optical system to a sample, such as in biomedical diagnostics. For instances, a sample may need to be refocused, or optically trapped particles may be moved. Implementing active optical actuation becomes ever more challenging, the smaller the involved components become, as for example in minimally invasive endoscopy. At distances below the capillary length of about 300 μm surface forces become dominant, which renders strategies to simply scale down common mechanical elements such as hinges or cogs futile. Hence micromechanical actuation strategies primarily resort to flexure mechanisms, in which an active mechanical element is constructed as a single part with thin sections intended to comply (actuate) under load.

Accordingly, we sought to realize micromechanical 3D actuation strategies for ultracompact optical components (Fig. 1). Our approach combines lenses that are directly 3D printed onto optical fibers using femtosecond direct laser writing with a new PDMS photoresist chemistry. PDMS photoresist was recently released for 2 photon 3D printing. Due to its intrinsic flexibility and also biocompatibility, PDMS is ideal for biomedical applications.

We were able to cointegrate the competencies of ITO (3D printed microoptics) and the Institute of Biomaterials and Biomolecular Systems (IBBS, microfluidics) in a single optofluidic device. We quickly established a fully integrated lens actuation mechanism based on 3D-printed PDMS for optical purposes (Fig. 2). While assembly and microfluidic actuation on the fiber tip

became continuously more reliable throughout the project, the PDMS printing process turned out to be surprisingly challenging. In contrast to all other 2 photon resins previously used for 3D micro-optics, the recently introduced PDMS resin showed a very narrow processing window. Despite extensive optimization, we only recently achieved surfaces that are homogeneous and precise enough to be suitable for advanced optical application.

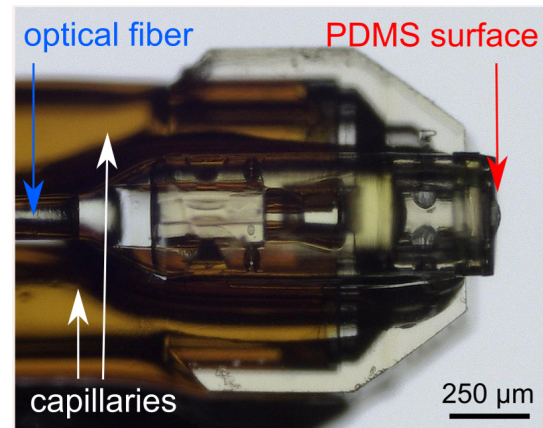


Fig. 2 Proof-of-concept prototype showing full integration of the optical fiber, capillaries, optics, and membrane. The membrane is notably deformed under static pressure.

This project pursued a novel approach for fully integrated fiber-based active optical components that are a few 100 μm in diameter small. We successfully engineered an integration platform and evaluated a soft PDMS-based micro-optofluidic lens on the tip of an optical fiber, noting that the surface quality of the membrane still leaves room for improvement for future work.

Supported by: This work was supported by the Deutsche Forschungsgemeinschaft (DFG) and the Baden-Württemberg Stiftung.

Project: Terra Incognita Biomedical Systems Seed Fund (Uni Stuttgart), Eliteprogramme for Postdocs

In cooperation with: Institute for Biomaterials and Biomolecular Systems (M. Heymann)

Low-cost optical demonstrators

A. Herkommer

Optical sensing, imaging, and data acquisition are key technologies across manufacturing, mobility, and software-defined production. Within the InnovationCampus Future Mobility (ICM) project *Demo3* [1] of the Karlsruhe Institute of Technology and the University of Stuttgart, a set of low-cost modular optics kits was developed to support outreach into schools and higher education facilities for demonstration of modern imaging and sensor concepts in a hands-on way. Building upon the BaKaRoS system [2], the kits combine simple lenses, camera modules, microcomputers, and 3D-printed mechanics. They were tested in workshops and exhibitions in Stuttgart and Karlsruhe, addressing students from schools and universities.

As an example, a low-cost AR-system was developed, based on a monocular optical combiner and a programmable OLED display. With the device GPS data are projected into the user's field of view. The system enables navigation to user-defined coordinates and demonstrates the principle of augmented optical information display (see Fig. 1). Five demonstrators were built, including complete construction instructions and an open-source Arduino code [2].

A compact digital microscope was realized using a bare WebCam sensor and modular optics. Two LEDs illuminate the object, and the magnified live image can be viewed via USB. With the open-source software ITOM [3], image processing, pattern recognition, and filtering can be demonstrated (see Fig. 2).

A related kit extends the visual BaKaRoS spectrometer [2], based on a diffractive grating and simple lenses, towards a digital spectrometer. By combining it with a WebCam the visible spectrum can be digitally recorded by the WebCam and analyzed via ITOM in real time. The system was integrated into an NV-center quantum demonstrator: Here fluorescence from a diamond sample, excited by green light, reveals magnetic field variations as red emission.

The developed kits show how optical sensing, visualization and image processing can be demonstrated with inexpensive components. Their modularity enables long-term use in school workshops, student projects and public exhibitions. The systems illustrate core aspects of optics, manufacturing, mobility and quantum photonics and can be extended towards AI-based image analysis, projection systems and advanced sensor concepts.



Fig. 1 GPS-based optical data glasses: demonstrator in operation and mechanical design.

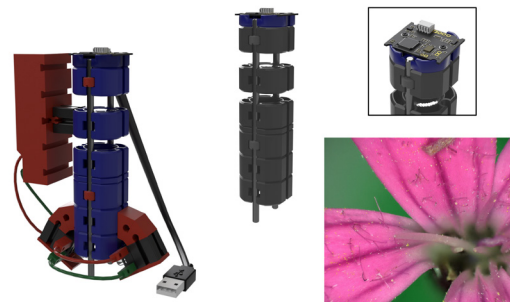


Fig. 2 Modular digital microscope based on a USB WebCam image sensor with example microscopic image.

Supported by: This work was supported by the InnovationCampus Future Mobility ICM.

Project: Demo3 - BaKaRoS@ICM

In cooperation with: IAT University Stuttgart and Fraunhofer IAO Stuttgart, J. Witzl, T. Le

References

- [1] InnovationCampus *Future Mobility* is a joint research platform of the Karlsruhe Institute of Technology (KIT) and the University of Stuttgart: <https://www.icm-bw.de/en/projects/mobile-research-laboratories>.
- [2] A webpage for all open-source code, parts lists and construction kits is provided at: <https://www.BaKaRoS.de>.
- [3] ITO provides an open-source metrology library ITOM at: <https://github.com/itom-project>

Invited lectures on international conferences

2023 — 2025

S. Reichelt, G. Pedrini

Digital Holography vs. Display Holography – What are their differences and what do they have in common?

6th International Conference on Machine Vision and Applications (ICMVA 2023), Singapore, March 2023

S. Reichelt

Optical metrology at the nanoscale

International Workshop on Optics, Biology, and Related Technologies, (IWOB 2023), Nasu, December 2023

A. Herkommer

Design, Simulation and Applications of 3D-Printed Micro-Optics

ISLOP-Conference, Munich, April 2024

A. Toulouse

A 3D-printed fiber core multiplexing endoscope

3D Printed Optics and Additive Photonic Manufacturing IV, SPIE Photonics Europe, Strasbourg, France, April 2024

A. Herkommer

3D-printed micro-optics for biomedical applications

IWOB-Conference, Utsunomiya, JP (Online), Dec. 2024

A. Herkommer

Fragen an die Wissenschaft: Wie 3D-Druck Mini-Endoskope herstellen und Organe reparieren kann

VHS Stuttgart, May 2025

S. Reichelt

Single-shot optical metrology: Principles, methods, and applications

126. Jahrestagung der DGaO, Stuttgart, June 2025

A. Herkommer and A. Toulouse

Optical Design, Simulation and Applications of 3d-printed Microoptics

EOS-Conference, Delft, August 2025

S. Reichelt

High-precision optical metrology at ITO

International Symposium on Precision Measurement and Industrial Testing, Suzhou, November 2025

S. Reichelt

Single-shot optical metrology - From concepts to applications (Plenary)

International Workshop on Optics, Biology, and Related Technologies, (IWOB 2025), Utsunomiya, December 2025

Awards

2023 — 2025

A. Toulouse

Bürkert University Prize for Dissertations of the year 2021 of the Christian Bürkert Foundation

11/2023

M. Wende

Add-on Fellowship for Interdisciplinary Life Science in 2024 from the Joachim Herz Foundation

11/2024

A. Toulouse

Global Glimpse Fellowship (funded by the University of Stuttgart) & DAAD PPP Adelaide funding (see grants),

Scheduled research visit: University of Technology Sydney and University of Adelaide, Australia

3/2024

M. Wende

Global Glimpse Outgoing Fellowship, University of Stuttgart, for a research stay at the University of Arizona, Tucson, Arizona, USA

1/2025

A. Toulouse

“Physikerin der Woche”, German Physical Society (DPG)

4/2024

M. Wende

SPIE Medical Imaging, San Diego: Pitch-talk award (3rd place); Poster award (honorable mention)

2/2025

A. Toulouse

2024 Participation-fellowship for the Lindau Nobel Laureate Meetings, Carl Zeiss Foundation

6/2024

S. Geißler (Supervisor: J. Trapp)

CC UPOB Young Scientist Award 2025 for the BSc-thesis “Metrologie additiv gefertigter Mikro-Polymerstrukturen – Oberflächen-optimierung zur Vermessung steiler Flanken”

3/2025

M. Wende

2024 Participation-fellowship for the Lindau Nobel Laureate Meetings, Carl Zeiss Foundation

6/2024

S. Amann

Young Scientist Award of the “Deutsche Gesellschaft für angewandte Optik (DGaO)” for the best PhD thesis in 2024 “Neuartige Konzepte zur Realisierung eines miniaturisierten Computed Tomography Imaging Spectrometer”

6/2025

V. Aslani

2023 Optical Materials Express (OMEx) Emerging Researcher Best Paper Prize

8/2024

A. Brenner

Young Scientist Award of the “Deutsche Gesellschaft für angewandte Optik (DGaO)” for the best master thesis in 2024 “Kalibrierung von Lichtmodulatoren mit physikalisch interpretierbaren neuronalen Netzen”

6/2025

Awards

2023 — 2025

*F. Rothermel, S. Thiele, C. Jung, A. Krapf, S. E. Ilse, B. Merle,
H. Giessen, A. Herkommer*

Publication Award 2024 of the University
Stuttgart (Fac. 7) for the article „Fabrication
and Characterization of a Magnetic 3D-printed
Microactuator“ in Advanced Materials
Technologies

7/2025

Membership of Editorial Boards

A. Herkommer

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

S. Reichelt

Section Editor of “Optics, Visual System,
Human Factors” in Springer “Handbook of
Visual Display Technology” (3rd Edition),
Edited by: Karlheinz Blankenbach,
Qun (Frank) Yan, Robert J. O’Brien

A. Toulouse

DGaO Jahrestagung
(Program Committee), 2023-2025

A. Toulouse

SPIE Photonics West, Laser 3D Manufactur-
ing (Program Committee), 2023-2025

A. Toulouse

SPIE Photonics Europe, Optical Instrument
Science, Technology and Applications (Pro-
gram Committee), 2024

A. Toulouse

SPIE Journal of Optical Microsystems, 2025:

- Special Section “3D printed optical
microsystems”
 - Associate Editor
-

A. Toulouse

Elected member of the German Committee
of Optics (Deutsches Optisches Komitee),
2025

M. Wende

DGaO Jahrestagung (Program Committee),
2025

Reviewed papers

2023

Please also note our homepage with linked publications: <https://www.ito.uni-stuttgart.de/institut/publikationen/reviewed-paper/>

S. Amann, T. Haist, A. Gatto, M. Kamm, A. Herkommer

Design and realization of a miniaturized high resolution computed tomography imaging spectrometer

Journal of the European Optical Society-Rapid Publications, vol. 19, no. 2, 34

F. Fischer, K. Frenner, M. Granai, F. Fend, A. Herkommer

Data-driven development of sparse multi-spectral sensors for urological tissue differentiation

Journal of the European Optical Society-Rapid Publications, vol. 19, no. 1, p. 33

V. Aslani, A. Toulouse, M. Schmid, H. Giessen, T. Haist, A. Herkommer

3D printing of colored micro-optics

Optical Materials Express vol. 13, no. 5, pp. 1372-1384

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

Simulation of realistic speckle fields by using surface integral equation and multi-level fast multipole method

Optics and Lasers in Engineering, vol. 162, p. 107438

R. Beisswanger, C. Pruss, S. Reichelt

Retrace error calibration for interferometric measurements using an unknown optical system

Opt. Express, vol. 31, no. 17, pp. 27761-27775

A. Gröger, G. Pedrini, D. Claus, I. Alekseenko, F. Gloeckler, S. Reichelt

Advantages of holographic imaging through fog

Applied Optics vol. 62, no. 10, pp. D68-D76

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

Evaluation of a time-gated-single-pixel-camera as a promising sensor for autonomous vehicles in harsh weather conditions

Journal of the European Optical Society-Rapid Publications, vol. 19, no. 1, 27

A. Gröger, G. Pedrini, F. Fischer, D. Claus, I. Alekseenko, S. Reichelt

Two-wavelength digital holography through fog

Journal of the European Optical Society-Rapid Publications, vol. 19, no. 1, 25

S. Crowell, T. Haist, M. Tscherpel, J. Caron, E. Burgh, B. Moore III

Performance and polarization response of slit homogenizers for the GeoCarb mission

Atmospheric Measurement Techniques, vol. 16, no. 1, pp. 195-208

T. Haist, R. Hahn, K. Michel

Imaging device for imaging at least one object

(2023) US Patent App. 18/050,334

D. Didychenko, S. Esser, F. Beirow, A. Savchenko, C. Pruss, T. Graf, M. Abdou Ahmed

Generation of a radially polarized beam in a polycrystalline ceramic Yb:Lu2O3 thin-disk laser

Applied Physics B, vol. 129, no. 9, p. 146

T. Haist, R. Hahn, S. Reichelt

Diffraction-based dual path multispectral imaging

tm - Technisches Messen, 2023

Reviewed papers

2023

S. Hartlieb, C. Schober, T. Haist, S. Reichelt

Field evaluation of a novel holographic single-image depth reconstruction sensor

Journal of the European Optical Society-Rapid Publications, vol. 19, no. 1, 20

E. Istrate, G. Pedrini, and S. Reichelt

Lensless microscopy by multiplane recordings: sub-micrometer, diffraction-limited, wide field-of-view imaging

Optics Express, vol. 31, Art. no. 22

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

Design studies of a far-field plasmonic superlens with an enlarged field of view

Optical Materials, vol. 138, p. 113688

J. Liu, Ö. Atmaca, P. P. Pott

Needle-Based Electrical Impedance Imaging Technology for Needle Navigation

Bioengineering vol. 10, no. 5, 590

M. Raza, Y. Chen, J. Trapp, H. Sun, X. Huang, and W. Ren

Smoldering peat fire detection by time-resolved measurements of transient CO₂ and CH₄ emissions using a novel dual-gas optical sensor

Fuel, vol. 334, p. 126750, Feb. 2023

S. Wagner, K. Treptow, S. Weser, M. Drexler, S. Sahakalkan, W. Eberhardt, T. Guenther, C. Pruss, A. Herkommer, A. Zimmermann

Injection Molding of Encapsulated Diffractive Optical Elements

Micromachines vol. 14, no.6, 1223

S. Walz, V. Aslani, O. Sawodny, A. Stenzl

Robotic radical cystectomy – more precision needed?

Current Opinion in Urology vol. 33, no. 2, p 157-162

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

Fast bidirectional vector wave propagation method showcased on targeted noise reduction in imaging fiber bundles using 3D-printed micro-optics

Optics Express, vol. 31, no. 18, p. 28874

J. Wu, T. Grabe, J. Götz, J. Trapp, A. de Souza, T. Biermann, A. Wolf, P. Ley, K. Duan, R. Lachmayer, W. Ren

Linear scalability of dense-pattern Herriott-type multipass cell design

Applied Physics B, vol. 129, no. 6, p. 87

Reviewed papers

2024

Ö. Atmaca, J. Liu, T. J. Ly, F. Bajraktari, P. P. Pott

Spatial sensitivity distribution assessment and Monte Carlo simulations for needle-based bioimpedance imaging during venipuncture using the finite element method

International Journal for Numerical Methods in Biomedical Engineering, vol. 40, no. 7

I. Fortmeier, J.-M. Asfour, R. Beisswanger, A. Beutler, T. Dresel, F. Fleischmann, M. Gregory, R. Henselmans, H. Klawitter, R. Kometer, J. Liebl, R. Meeß, W. A. C. M. Messelink, C. Pruss, M. Schulz, F. Weidner, M. Wendel, R. Windemuth, F. Löffler

Results of round robin form measurements of optical aspheres and freeform surfaces

Measurement Science and Technology, vol. 35, no. 8, p. 085012

A. Gröger, R. Kuschmierz, A. Birk, G. Pedrini, S. Reichelt

Two-wavelength holographic micro-endoscopy

Optics Express, vol. 32, no. 13, p. 23687

S. Hartlieb, Z. Wang, A. Rüdinger, T. Haist, S. Reichelt

Large dynamic range Shack–Hartmann wavefront sensor based on holographic multipoint generation and pattern correlation

Optical Engineering, vol. 63, no. 2, p. 024107

P. Laux, A. Schiller, A. Bertz, D. Carl, S. Reichelt

Spectral speckle displacement in defocused and tilted imaging systems

Optics Express, vol. 32, no. 10, p. 16831

Q. Min, J. Trapp, T. Fang, R. Hu, F. Wang, Z. Zhang, X. Liu, A. Dai, C. Yang, J. Guo, G. Situ

Varifocal Metalens for Compact and Accurate Quantitative Phase Imaging

ACS Photonics, vol. 11, no. 7, p. 2797–2804

G. Pedrini, R. Li, L. Cao, S. Reichelt

Lensless imaging in one shot using the complex degree of coherence obtained by multiaperture interferences

Optics Letters, vol. 49, no. 3, p. 718

F. Rothermel, S. Thiele, C. Jung, A. Krapf, S. E. Ilse, B. Merle, H. Gießen, A. M. Herkommer

Fabrication and Characterization of a Magnetic 3D-printed Microactuator

Advanced Materials Technologies, vol. 9, no. 12, p. 2302196

C. Ryan, T. Haist, G. Laskin, S. Schröder, S. Reichelt

Technology Selection for Inline Topography Measurement with Rover-Borne Laser Spectrometers

Sensors, vol. 24, no. 9

K. Weber, S. Thiele, M. Hentschel, A. Herkommer, H. Giessen

Front Cover: Positional Accuracy of 3D Printed Quantum Emitter Fiber Couplers

Advanced Quantum Technologies, vol. 7, no. 11

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

Fast vector wave optical simulation methods for application on 3D-printed microoptics

Journal of Optical Microsystems, vol. 4, no. 2, p. 024501

Reviewed papers and book chapter

2025

V. Aslani, S. Baghapour, S. C. Warren-Smith, W. Zhang, E. Ebadiati, S. E. Plush, A. M. Herkommer, A. Toulouse, S. Afshar V.

3D Microprinting of Structures with Lanthanide-Based Fluorophores on Optical Fibers for Multiplexed Sensing

Advanced Optical Materials, 12 2025

R. Chen, F. Rothermel, R. Fitridge, C. A. Bursill, P. J. Psaltis, H. Giessen, A. Herkommer, R. A. McLaughlin, A. Toulouse, J. Li

Low background fluorescence 3D-printed micro-lens for imaging of vulnerable atherosclerotic plaques

APL Photonics, vol. 10, no. 4

D. Didychenko, F. Li, A. Savchenko, J. Zideluns, M. Stehlik, L. Gallais, J. Lumeau, F. Lemarchand, P. Karvinen, M. Kuittinen, C. Pruss, D. Jamon, T. Graf, M. Abdou Ahmed

Analysis of laser-induced damage threshold of circular grating waveguide structures exposed to sub-picosecond laser radiation centered at a wavelength of 1030 nm

Applied Physics B, vol. 131, no. 3, p. 39

K. Doth, M. Wende, J. Drozella, T. Haist, A. Herkommer, A. Toulouse

Miniaturized holographic twin trap 3D-printed via two-photon lithography

Journal of Optical Microsystems, vol. 5, no. 2, p. 024501

P.-E. Hansen, T. Pahl, L. Fu, I. Nielsen, F. Rosenthal, S. Reichelt, P. Lehmann, A. T. Rømer

Digital Twins for 3D Confocal Microscopy: Near-Field, Far-Field, and Comparison with Experiments

Sensors, vol. 25, no. 7, p. 2001

S. Hartlieb, A. Zeller, T. Haist, A. Reichardt, C. Tarin Sauer, S. Reichelt

Advanced Imaging-Based Metrology for Precise Deformation Monitoring: Railway Bridge Case Study

Structural Control and Health Monitoring, vol. 2025, no. 1

H. Hooshmand, T. Pahl, P.-E. Hansen, L. Fu, A. Birk, M. Karamahmedović, P. Lehmann, S. Reichelt, R. Leach, S. Piano

Comparison of rigorous scattering models to accurately replicate the behaviour of scattered electromagnetic waves in optical surface metrology

Journal of Computational Physics, vol. 521, p. 113519

P. Laux, A. Bertz, D. Carl, S. Reichelt

Large area roughness measurements using spectral speckle correlation

Optical engineering, vol. 64, no. 7, p. 074101

P. Laux, A. Schiller, C. Bett, A. Bertz, D. Carl, S. Reichelt

Influence of object motion on roughness measurements using spectral speckle correlation

Optics Express, vol. 33, no. 23, p. 48575

V. Neu, G. Pedrini, I. Soldatov, S. Reichelt, R. Schäfer

Lensless magneto-optical imaging

Scientific Reports, vol. 15, no. 1, p. 28277

I. Ortlepp, S. Eisele, K. Treptow, J. Rühle, C. Pruß, T. Haist, S. Reichelt, O. Sawodny, E. Manske, T. Kissinger

Enhanced Vectorial Measurement Uncertainty Model

Metrology, vol. 5, no. 2, p. 19

S. Reichelt, E. Istrate

Principles of display holography

in Handbook of Visual Display Technology, K. Blankenbach, Q. Yan and R. J. O'Brien, Eds., Springer, 2025, pp. 1-29

F. Rothermel, A. Toulouse, S. Thiele, C. Jung, J. Drozella, R. Steinhoff, H. Giessen, A. M. Herkommer

Magnetically actuatable 3D-printed endoscopic microsystems

Communications Engineering, vol. 4, no. 1, p. 69

Reviewed papers and book chapter

2025

A. Rüdinger, Ö. Atmaca, V. Bahlinger, E. Weisser, S. Matovina, A. Rohner, A. Strauß, V. Aslani, S. Thiele, A. Toulouse, T. Haist, A. Staebler, S. Brucker, F. Fend, A. Herkommer, S. Reichelt

Bimodal tissue differentiation using hyperspectral imaging and elastographic Fourier transform profilometry

Light: Advanced Manufacturing, vol. 6, no. 0, p. 1

C. Ryan, T. Haist, S. Reichelt

Holographic detection for fast fringe projection profilometry of deep micro-scale objects

Optics Express, vol. 33, no. 1, p. 983

A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt

Effect of sample thickness on etching rate: Simulations and experiments

Journal of the European Optical Society-Rapid Publications, vol. 21, no. 2, p. 52

J. Trapp, H. Mahmodi, M. Wende, L. McAlary, L. Ooi, J. Li, R. A. McLaughlin, A. Herkommer, A. Toulouse, I. Kabakova

Dual fiber probe with 3D-printed micro-lens for Brillouin microscopy

APL Photonics, vol. 10, no. 4

M. Wende, K. Doth, M. Heymann, A. Toulouse

3D-printed immersion micro-optics

Light: Advanced Manufacturing vol. 6, no. 19

M. Wende, F. Rothermel, E. Stilson, F. Kübler, T. Sawyer, A. Herkommer, A. Toulouse

3D-printed endo-microscope with a fast magnetic actuator for axial image plane scanning

Optics Letters, vol. 50, no. 7, pp. 2243-2246

M. Zimmermann, A. Brenner, T. Haist, S. Reichelt

Improved far-field holograms using spatial light modulators and camera-in-the-loop optimization

Optical Engineering, vol. 64, no. 9, p. 094102

Conference proceedings and journals

2023

S. Amann, T. Haist, A. Gatto, M. Kamm, S. Reichelt

Parallelized computed tomography imaging spectrometer

Digital Optical Technologies 2023, vol. 12624, pp. 71-77

S. Amann, T. Haist, A. Gatto, M. Kamm, A. Herkommer

Intermediate image free computed tomography imaging spectrometer

Photonic Instrumentation Engineering X 2023, vol. 12428, p. 124280G

V. Aslani, T. Haist, S. Thiele, A. Herkommer

Sensorsystem zur minimalinvasiven intraoperativen Gewebedifferenzierung in der Onkologie mittels endoskopischer Streifenprojektion

DGaO Proceedings 2023

J. Baumgärtner, A. Puchta, B. Bertschinger, G. Kanagalingam, O. Sawodny, S. Reichelt, J. Fleischer

Increasing robot precision by stroke division

27th International Conference on Methods and Models in Automation and Robotics (MMAR) 2023, pp. 205–210

J. Baumgärtner, B. Bertschinger, K. Hoffmann, A. Puchta, O. Sawodny, S. Reichelt, J. Fleischer

Camera Placement Optimization for a Novel Modular Robot Tracking System

IEEE SENSORS 2023, pp. 1–4

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

Towards image-free object detection for autonomous vehicles under harsh environmental conditions

Optical Measurement Systems for Industrial Inspection XIII 2023, vol. 12618, p. 126181C

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

Time-gated-single-pixel-camera: a promising sensor for robust object detection in adverse weather conditions for autonomously driven vehicles

Fifteenth International Conference on Machine Vision (ICMV 2022) 2023, vol. 12701, p. 1270107

A. Birk, K. Frenner, W. Osten

Deep learning based compressed sensing in machine vision: an iterative approach to multi object detection

Fifteenth International Conference on Machine Vision (ICMV 2022) 2023, vol. 12701, p. 1270109

S. Calderón, R. Mastilo, C. Schober, C. Pruss, I. Ortlepp, G. Straube, E. Manske

Absolute determination of a large mirror surface from spatial gradients using a coordinate measuring machine

Applied Optical Metrology V 2023, vol. 12672, p. 1267205

A. Gröger, G. Pedrini, D. Claus, S. Reichelt

Coherence-gated digital holographic imaging through extended scattering media for autonomous driving vehicles

Optical Measurement Systems for Industrial Inspection XIII 2023, p. 50

A. Gröger, G. Pedrini, D. Claus, F. Fischer, S. Reichelt, S. Thiele, N. Fahrbach

World's smallest single-shot two-wavelength holographic endoscope for 3D surface measurement

Endoscopic Microscopy XVIII 2023, vol. PC12356, p. PC123560P

T. Haist, F. Lodholz, A. Faulhaber, S. Reichelt

Differential perspective as a nonexpensive distance sensing principle

Automated Visual Inspection and Machine Vision V 2023, vol. 12623, p. 126230E

Conference proceedings and journals

2023

P. Laux, A. Schiller, A. Bertz, D. Carl, S. Reichelt

Surface roughness measurement of large areas with high spatial resolution by spectral speckle correlation

Optical Measurement Systems for Industrial Inspection XIII 2023, p. 52

S. Reichelt, G. Pedrini

Digital Holography vs. Display Holography - What are their differences and what do they have in common?

Proceedings of the 6th International Conference on Machine Vision and Applications, Singapore, Singapore 2023, pp. 72–80

C. Schober, L. Lausmann, K. Treptow, C. Pruss, S. Reichelt

Complex illumination system for fast interferometric measurements

EPJ Web of Conferences 2023, vol. 287, p. 2002

C. Schober, L. Lausmann, K. Treptow, C. Pruss, S. Reichelt

Neue Designmöglichkeiten durch Zweiphotonenlithographie für ein RGB-Interferometer-Beleuchtungsmodul

DGaO Proceedings 2023

J. Schüle, V. Aslani, C. Stärk, P. Somers, C. Veil, C. Tarín, A. Herkommer, O. Sawodny

In-plane Strain Analysis by Correlating Geometry and Visual Data Through a Gradient-Based Surface Reconstruction

45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) 2023, pp. 1–6

P. Somers, M. Deutschmann, S. Holdenried-Krafft, S. Tovey, J. Schüle, C. Veil, V. Aslani, O. Sawodny, H. Lensch, C. Tarín

An Enhanced Synthetic Cystoscopic Environment for Use in Monocular Depth Estimation

45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) 2023, pp. 1–4

V. Vierhub-Lorenz, J. Gangelhoff, C. Werner, C. Bett, K. Frenner, W. Osten, A. Reiterer

Development of a LiDAR system for low visibility conditions

Optical Measurement Systems for Industrial Inspection XIII 2023, vol. 12618, p. 126181A

S. Wyss, J. Krüger, J. Grundmann, B. Bodermann, S. Gao, L. Fu, A. Birk, K. Frenner, S. Reichelt

Rigorous modeling of a confocal microscope

Modeling Aspects in Optical Metrology IX 2023, no. 12619, p. 37

Conference proceedings and journals

2024

V. Aslani, A. Toulouse, M. Schmid, H. Giessen, T. Haist, A. Herkommer

3D-Druck von farbigen Mikrooptiken

DGaO Proceedings 2024

V. Aslani, T. Haist, S. Thiele, A. Herkommer

Endoscopic measurement system for elastographic tissue differentiation based on active triangulation and 3D-printed micro-optics

Proc.SPIE 12817, Advanced Photonics in Urology 2024, p. 128170E

Ö. Atmaca, V. Aslani, V. Bahlinger, A. Strauß, A. Kielbik, S. Matovina, T. Haist, A. Toulouse, S. Brucker, B. Amend, F. Fend, A. Herkommer

Elastographic Measurements Using Fourier Transform Profilometry for Tissue Differentiation in Oncology

DGaO Proceedings 2024, p. P20

C. Bett, W. Osten

Detecting objects deep within scattering media via multi-wavelength intensity interferometry

DGaO Proceedings 2024

C. M. Bett, W. Osten

Illumination is all it takes: on the detection of objects embedded in scattering media via multi-wavelength speckle correlation

Unconventional Imaging, Sensing, and Adaptive Optics 2024, vol. 13149, p. 131491A

A. Birk, C. Bett, K. Frenner, S. Reichelt

Die Time-Gated Single Pixel Camera (TGSPC): Innovatives Konzept zur Objekterkennung durch streuende Medien

DGaO Proceedings 2024

A. Birk, K. Frenner, S. Reichelt

Time-gated single pixel camera: an innovative sensor for object detection through scattering media

Proc. SPIE PC12900, Emerging Digital Micromirror Device Based Systems and Applications XVI 2024, p. PC1290006

R. Chen, F. Rothermel, A. Toulouse, P. Flad, H. Giessen, A. Herkommer

Miniaturised 3D printed fibre-optic probe for autofluorescence detection of human plaques

Proceedings Volume PC12820, Endoscopic Microscopy XIX 2024, p. PC128200A

K. Doth, T. Haist, A. Herkommer

Miniaturisierte Holografische Doppelfalle zum optischen Einfang von Mikropartikeln

DGaO Proceedings 2024

K. Doth, T. Haist, S. Reichelt

Towards pathogen detection with 3D-printed micro-optics in microfluidic systems

Proc. SPIE 12876, Laser 3D Manufacturing XI 2024, p. 128760K

P. Hansen, T. Pahl, L. Fu, A. Romer, F. Rosenthal, L. Siaudinyte, S. Reichelt

Digital twins for 3D confocal microscopy

Proc. SPIE 12997, Optics and Photonics for Advanced Dimensional Metrology III 2024, vol. 12997, p. 129970M

C. Jimenez, A. Toulouse, A. Herkommer

Beam shaping elements for single photon sources based on 3D printed micro-optics

EPJ Web of Conferences 2024, vol. 309, p. 3007

Conference proceedings and journals

2024

*G. Kanagalingam, K. Hoffmann, J. Baumgärtner,
B. Bertschinger, S. Reichelt, J. Fleischer, O. Sawodny*

Quasi Time-Optimal Path Tracking for Pneumatic Robots Considering Third-Order Actuator Constraints

American Control Conference (ACC) 2024, pp. 5258–5263

Z. Lovasz, Ö. Atmaca, C. Veil, A. Herkommer, O. Sawodny

Numerical Analysis of Geometric Influences in Tetrapolar Electrical Impedance Spectroscopy Using Monte Carlo Simulations

Current Directions in Biomedical Engineering, vol. 10, no. 4,
pp. 432-435, 2024

A. Rüdinger, T. Haist, S. Reichelt

Hyperspectral measurement system for characterization of healthy and malignant tissue spectra

DGaO Proceedings 2024, vol. 125, p. P19

A. Savchenko, C. Pruß, A. Herkommer

Stepped mask interference laser exposure (SMILE)

DGaO Proceedings 2024

C. Schober, C. Pruß, S. Reichelt

Single-Shot Tilted-Wave-Interferometer

DGaO Proceedings 2024

C. Schober, C. Pruß, A. Herkommer, S. Reichelt

Ultimate measurement speed for flexible asphere and freeform metrology: TWISS

Optical Instrument Science, Technology, and Applications III,
2024, vol. 13024, p. 1302402

*A. Toulouse, F. Rothermel, J. Drozella, S. Thiele,
A. Herkommer*

A 3D-printed fiber core multiplexing endoscope

3D Printed Optics and Additive Photonic Manufacturing IV
2024, p. 8

A. Toulouse, S. Thiele, V. Aslani, A. Herkommer

Verfahren zum Schutz von Objektiven für neue Fotolacke in der hochauflösenden Zweiphotonenlithografie

DGaO Proceedings 2024

M. Zimmermann, S. Reichelt

Computational hologram optimization for large holographic displays using eye pupil position

Optical Architectures for Displays and Sensing in Augmented,
Virtual, and Mixed Reality (AR, VR, MR) V 2024, vol. 12913,
p. 129131C

M. Zimmermann, T. Haist, S. Reichelt

Berechnungsmethoden für Fernfeldholo- gramme – Gerchberg-Saxton Erweiterungen und Stochastic Gradient Descent Optimierer

DGaO Proceedings 2024

K. Doth, T. Haist, S. Reichelt

Towards pathogen detection with 3D-printed micro-optics in microfluidic systems

Proc. SPIE 12876, Laser 3D Man

Conference proceedings and journals

2025

V. Aslani, S. Baghapour, W. Zhang, S. Warren-Smith, S. Plush, M. Heymann, A. Herkommer, S. Afshar V., A. Toulouse

3D-Druck von fluoreszierenden Mikrostrukturen für die Sensorik

DGaO Proceedings 2025

Ö. Atmaca, J. Zehfuß, C. Jimenez, M. Wende, J. Drozella, A. Toulouse, A. Herkommer

Comparison of wave-optical and Monte Carlo light propagation simulations in scattering media

DGaO Proceedings 2025, vol. 126, p. P29

S. Baghapour, V. Aslani, W. Zhang, S. Warren-Smith, S. Plush, A. Herkommer, A. Toulouse

3D Microprinting of Lanthanide-Based Polymers on Optical Fibers: A Platform for Multiplexed Sensing

CLEO/Europe-EQEC, 2025, pp. 1–1

A. Brenner, M. Zimmermann, T. Haist, S. Reichelt

Kalibrierung von Lichtmodulatoren mit physikalisch interpretierbaren neuronalen Netzen

DGaO Proceedings 2025

L. Fu, X. Wang, K. Frenner, S. Reichelt

Efficient deep-learning ResNet architectures for Mueller-matrix Fourier scatterometry

2025, vol. Proc. SPIE 13568, p. 1356807

C. Imiolczyk, M. Wende, A. Kushwaha, L. Xiang, N. Soltan, H. Giessen, R. McLaughlin, C. Jones, A. Toulouse, J. Li

3D Printed Encapsulated Microlens for Endoscopic Optical Coherence Tomography

European Conferences on Biomedical Optics 2025, p. W4D.3

K. Leonhardt, K. Frenner, S. Reichelt

Weiterentwicklung und neue Anwendungen der Ellipso-Höhentopometrie EHT

DGaO Proceedings 2025

W. Osten, C. Pruss, A. Herkommer, C. Schober, K. Treptow, M. Wischert, H. Leue

The reconstruction, testing, and improvement of a historical giant astronomical telescope

Ultra-High-Definition Imaging Systems VIII, 2025, vol. 13389, p. 1338902

A. Rüdinger, V. Bahlinger, A. Rohner, A. Staebler, T. Haist, S. Brucker, F. Fend, S. Reichelt

Spektrale Analyse von malignem und gesundem Gewebe basierend auf hyperspektralen Bilddaten

DGaO Proceedings 2025, vol. 126, no. B10

J. Rühle, K. Treptow, C. Schober, C. Pruß, T. Haist, I. Ortlepp, O. Sawodny, S. Reichelt, T. Kissinger, E. Manske

Polarization Camera based Fringe Locking Control of a Writing Head for Scanning Beam Interference Lithography

American Control Conference (ACC) 2025, pp. 3254–3259

A. Savchenko, C. Pruß, A. Herkommer, S. Reichelt

Effect of substrate thickness on the etching rate of diffractive optical elements

DGaO Proceedings 2025

A. Schiebelbein, T. Schmitt-Manderbach, C. Glasenapp, S. Reichelt, G. Pedrini

Auflösungssteigerung in der digitalen Holographie durch adaptive Speckle-Beleuchtung

DGaO Proceedings 2025

G. Scholz, C. Pruss, P. Rothenberger, A. Brenner, A. Herkommer, I. Fortmeier

Towards absolute optical form measurement for aspheres and freeform surfaces using interferometry

Proc. SPIE 13720, p.137200F, 2025

Conference proceedings and journals

2025

S. Teves, C. Dohme, D. Kirchhoff, J. Trapp, A. Ziebel, T. Biermann, R. Lachmayer

Impact of Optical Diffuser Vats on Surface Roughness in DLP Printed Optical Components

Innovative Produktentwicklung durch additive Fertigung, Berlin, Heidelberg, 2025, pp. 151-160

S. Warren-Smith, S. Baghapour, V. Aslani, W. Zhang, E. Ebadati, S. Plush, A. Herkommer, A. Toulouse, S. Afshar V.

3D microprinting of lanthanide-doped polymers on optical fibers: a platform for multiplexed sensing

CLEO / Europe-EQEC, Munich, Germany, pp. 1-1, 2025

S. Wyss, W. Matthias, B. Bodermann, S. Gao, L. Fu, S. Reichelt

Comparison of two fit algorithms to find the maximum of a simulated confocal intensity curve

2025, vol. Proc. SPIE 13568, p. 135680Y

P. Xia, S. Teves, Z. Dai, M. Falkner, U. Wuellner, J. Trapp, T. Biermann, R. Lachmayer

Robust design for 3D-printed opto-mechanical systems

DGaO Proceedings 2025

M. Zimmermann, A. Brenner, T. Haist, S. Reichelt

Improved far field holograms using spatial light modulators and camera-in-the-loop optimization

Digital Optical Technologies 2025, vol. 13573, p. 1357304

M. Zimmermann, A. Brenner, T. Haist, S. Reichelt

Experimentelle Demonstration der Specklereduktion in Fernfeldhologrammen von SLMs durch hochgenaue Camera-in-the-loop Kalibrierung

DGaO Proceedings 2025

Patents

Patent Applications

V. Aslani, M. Decker, M. Hanft, A. Herkommer, S. Schmidt, S. Thiele

Optikvorrichtung zum Projizieren eines Musters auf eine Oberfläche

DE102023115518A1 Date of Publication: 19.12.2024
WO002024256498A1 Date of Publication: 19.12.2024

A. Brueckner, E. Hegels, A. Herkommer, D. Manssen, S. Thiele

Compact catadioptric imaging apparatus

CN000115917391A Date of Publication: 04.04.2023
EP000004214561A1 Date of Publication: 26.07.2023
WO002022073592A1 Date of Publication: 14.04.2022

N. Fahrbach, A. Herkommer, S. Thiele, A. Toulouse

Mikrooptik und Faserendoskop

DE102022122923A1 Date of Publication: 14.03.2024
US020240237885A1 Date of Publication: 18.07.2024

A. Fuhrmann, K. Körner

Programmierbare Schräglichtquelle zur Musterprojektion auf ein Objekt für Bildverarbeitung und 3D-Messtechnik, insbesondere auch mittels Triangulation

DE102023001730A1 Date of Publication: 31.10.2024

H. Giessen, A. Herkommer, J. Li, R. McLaughlin, S. Thiele

Optisches Element

AU002021312548A1 Date of Publication: 23.02.2023
EP000004185902A1 Date of Publication: 31.05.2023
EP000004185902A4 Date of Publication: 20.12.2023
US020230341668A1 Date of Publication: 26.10.2023
WO002022016230A1 Date of Publication: 27.01.2022

R. Hahn, T. Haist, K. Michel

Abbildungsvorrichtung zur multispektralen oder hyperspektralen Abbildung von mindestens einem Objekt

EP000004184136A1 Date of Publication: 24.05.2023
US020230152218A1 Date of Publication: 18.05.2023

K. Körner, S. Reichelt

An optical system and a method for chromatic confocal spectral-domain optical coherence tomography with a plurality of wavelets or for chromatic confocal two-beam interferometry

WO002025190490A1 Date of Publication: 18.09.2025

C. Pruß, C. Schober

Einzelbild-Tilted Wave Interferometer

CN000116507877A Date of Publication: 28.07.2023
EP000004248168A1 Date of Publication: 27.09.2023
US020240003672A1 Date of Publication: 04.01.2024

J. Rusch, A. Fuhrmann

Anordnung zur Erzeugung eines beabstandeten, einstellbaren Lichtfeldes für die Makrofotografie, insbesondere auch zur objektangepassten Beleuchtung mit scharfem Lichtfeldrand

EP000004533156A1 Date of Publication: 09.04.2025
WO002023227510A1 Date of Publication: 30.11.2023

A. Simon, A. Gatto, T. Haist, M. Zimmermann

Vorrichtungen und Verfahren für computertomografische Bildgebungsspektrometrie

EP000004405646A1 Date of Publication: 31.07.2024
WO002023046425A1 Date of Publication: 30.03.2023

Patents

Granted Patents

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

Verfahren zur Herstellung eines Mehrfachblendensystems zur modulierten Bildgebung und entsprechendes Mehrfachblenden-system

EP000003529656B1 Date of Publication: 16.08.2023

A. Asadollahbaik, J. Fick, H. Giessen, A. Herkommer, S. Thiele

Rotationssymmetrische dielektrische Struktur zur optischen Strahlformung, Verfahren zu deren Herstellung, Singlemode-Lichtwellenleiter mit einer solchen Struktur und Strahlformungssystem

DE102021213647B4 Date of Publication: 24.07.2025
US000011923102B2 Date of Publication: 05.03.2024

A. Fuhrmann, K. Körner

Programmierbare Schräglichtquelle zur Musterprojektion auf ein Objekt für Bildverarbeitung und 3D-Messtechnik, insbesondere auch mittels Triangulation

DE102023001730B4 Date of Publication: 28.11.2024

H. Giessen, T. Gissibl, A. Herkommer, S. Thiele

Verfahren und Vorrichtung zur Herstellung eines optischen Elements mit zumindest einem funktionalen Bereich, sowie Verwendung der Vorrichtung

EP000003162549B1 Date of Publication: 21.06.2023

H. Giessen, W. Göbel, A. Herkommer, B. Häsler, K. Irion, S. Thiele

Medizinisches Endoskop mit einer Abbildungseinrichtung

EP000003571975B1 Date of Publication: 02.07.2025

H. Giessen, A. Herkommer, C. Jung, S. Thiele

Actuatable optical device, method of fabricating the device, and use of a magnetic substance

US000012311600B2 Date of Publication: 27.05.2025

H. Giessen, A. Herkommer, J. Li, R. McLaughlin, S. Thiele

Optisches Element

EP000004185902B1 Date of Publication: 18.06.2025

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

Verfahren zur Herstellung eines Abbildungssystems und entsprechendes Abbildungssystem

EP000003655803B1 Date of Publication: 08.11.2023

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

Verfahren zur Herstellung einer Mikrooptik

DE102022122987B3 Date of Publication: 07.12.2023

R. Hahn, T. Haist, K. Michel

Abbildungsvorrichtung zur multispektralen oder hyperspektralen Abbildung von mindestens einem Objekt

EP000004184136B1 Date of Publication: 13.03.2024
US000012360036B2 Date of Publication: 15.07.2025

A. M. Herkommer, K. Körner

Verfahren und Shear-Invariantes Michelson-typ-Interferometer zur Single-Shot-Imaging-FT-Spektroskopie

EP000003760990B1 Date of Publication: 01.11.2023
US000011566998B2 Date of Publication: 31.01.2023

Patents

Granted Patents

K. Körner, A. Fuhrmann

Anordnung und Verfahren zur Beleuchtung, insbesondere auch für die Makro-Fotografie, für Bewegtbild-Aufnahmen im Nahbereich oder für Inspektionen

DE102023004572B3 Date of Publication: 20.02.2025

K. Körner, A. Fuhrmann, N. Sprint

Kompakte Leuchtmittel-Baugruppe für eine Beleuchtungsanordnung, insbesondere auch für die Makro-Fotografie oder für Bewegtbildaufnahmen im Nahbereich

DE102023004580B3 Date of Publication: 13.03.2025
DE102023004580B9 Date of Publication: 10.07.2025

B. Kroll, N. Leister, G. Futterer, R. Missbach, S. Reichelt

Light modulation device for a display for representing two- and/or three-dimensional image content

US000011914251B2 Date of Publication: 27.02.2024

N. Leister, S. Reichelt

Device for combining light beams which interact with adjacently arranged pixels of a light modulator

US000011656494B2 Date of Publication: 23.05.2023

C. Pruß, C. Schober

Einzelbild-Tilted Wave Interferometer

EP000004248168B1 Date of Publication: 09.07.2025

J. Rusch, A. Fuhrmann

Anordnung zur Erzeugung eines beabstandeten, einstellbaren Lichtfeldes für die Makrofotografie, insbesondere auch zur objektangepassten Beleuchtung mit scharfem Lichtfeldrand

DE102022001895B3 Date of Publication: 27.07.2023

Doctoral Theses

2023 — 2025



Zepp, Andreas

Modaler holografischer Wellenfrontsensor für Adaptive Optik

04/2023



Gödecke, Laura

Ein Beitrag zur modellgestützten Charakterisierung komplexer Halbleiter-Nanostrukturen mittels Weißlicht-Müller-Matrix-Fourier-Scatterometrie

04/2023



Prause, Korbinian

Development of a highly-miniaturized single-shot point distance sensor and a spectrometer free areal optical confocal metrology system

07/2023



Fischer, Felix

Gewebedifferenzierung mit ultra-sparsen Infrarotspektroskopie

07/2023



Aslani, Valese

Endoskopisches Messsystem zur elastografischen Gewebedifferenzierung basierend auf aktiver Triangulation und 3D-gedruckter Mikrooptik

08/2023

Doctoral Theses

2023 — 2025



Pruß, Christof

Neue Verfahren zur flexiblen interferometrischen Asphärenmesstechnik

03/2024



Gronle, Antonia

Stitching-Interferometrie für große asphärische und freigeformte optische Flächen

04/2024



Drozella, Johannes

Wave optical simulation framework for 3D-printed micro-optical systems and volume scattering devices

04/2024



Guerra, Flavio

Optische Deformationsmessung und Zustandsrekonstruktion hochdimensionaler flexibler Strukturen

04/2024



Pang, Hao

Intensity shaping for laser fusion cutting optimization

05/2024

Doctoral Theses

2023 — 2025



Gröger, Alexander

Digitalholografische Bilderfassung durch ausgedehnte streuende Medien

06/2024



Amann, Simon

Neuartige Konzepte zur Realisierung eines miniaturisierten Computed Tomography Imaging Spectrometer

10/2024



Beißwanger, Rolf

Tilted-Wave Interferometer in Common-Path Fizeau-Konfiguration

10/2024



Hartlieb, Simon

Hochgenaue bildbasierte Positionsmesstechnik mittels holografischer Bildvervielfachung

10/2024



Rothermel, Florian

Magnetische Aktuierung von 3D-gedruckten mikrooptischen Elementen

08/2025

Doctoral Theses

2023 — 2025



Jimenez, Carlos

Numerical analysis on 3D printed micro-optics as interfaces to single photon sources

12/2025

Master Theses

2023

Wang, Zhen

Shack-Hartmann Sensorik mittels
holographischer Multipunktgenerierung

1/2023

Kissel, Alexander Ulrich

Integration eines optischen Sensors in eine
Laserabtragsmaschine für „adaptive
machining“ bei schichtweiser Bearbeitung
und zum Einmessen und Vermessen
rotatorischer Mikrowerkzeuge

1/2023

Yu, Mengbo

Simulation von Gewebespektren durch
gewichtete Kombination latenter Räume
in Autoencodern

4/2023

Lodholz, Felix

Differentielle Perspektive zur Ermittlung von
Entfernungen im Straßenverkehr mit Hilfe
einer CNN-gestützten Segmentierung

5/2023

Krächan, Clara

Entwicklung von hocheffizienten Faser-
Chip-Schnittstellen für LNoI-Wellenleiter

5/2023

Beck, Alena Franziska

Erweiterung der Tilted Wave Interferometrie
für die Mehrwellenlängen-Interferometrie

6/2023

Vasileva, Vanina

Phase Unwrapping mittels Deep Learning
für ultradünne zweiwellenlängen-
holographische Endoskopie

7/2023

Schulz, Artur Nikita

Synthetische Datengenerierung und
Time-of-Flight-Objekterkennung mit Vision
Transformer

9/2023

Wild, Sarah

Aufbau und Evaluation eines holografischen
Stereo-Eye-Tracking Sensors

9/2023

Bronner, Laura

Kleben von Linsen für Laserstrahlführungen

10/2023

Bai, Xiaoge

Untersuchung des Verhaltens von IG-
ZO-TFTs bei separat angeschlossenen Top-
und Bottom-Gates

10/2023

Stahr, Franziska Helen

Verbesserung der Fokussierung von Laser-
strahlung auf tierische Gewebeproben in
optischen Schädigungsexperimenten

10/2023

Master Theses

2024

Yazgan, Hüseyin

Thermisches Top-Down-Budget eines
hybriden Spiegels

2/2024

Yang, Puring

Quantification and Correction of Rain-re-
lated Errors in Image-based Deformation
Detection

2/2024

Lösch, Nora Maria

Gewebeklassifikation mittels Machine
Learning und polarisationsbasierter
Snapshot-Multispektralsensorik

6/2024

Wu, Hansen

Design und Realisierung eines SBIL-Schrei-
bkopfes mit integriertem Streifen-
stabilisierungssystem für die NPMM-200

6/2024

Sdougkou, Marina

Physikalisch basiertes Rendering
für die medizinische Visualisierung

7/2024

Brendle, Tobias

Untersuchung diffraktiver Strahl-
formungskonzepte für Hohlkernfaser-
geführte ultrakurze Laserpulse bei der
Materialbearbeitung

8/2024

Schöne, Sandra

Development of a Proof-of-Concept
System for the Application of Multispectral
Photometric Stereo in Laparoscopy

9/2024

Schulz, Artur Nikita

Synthetische Datengenerierung und
Time-of-Flight-Objekterkennung mit Vision
Transformer

9/2023

Brenner, Andreas

Kalibrierung von Lichtmodulatoren mit
physikalisch interpretierbaren neuronalen
Netzen

10/2024

Machauer, Maximilian

Elektrooptischer Feldsensor zur Messung
der MRT-Sicherheit von Interventionellen
Instrumenten

10/2024

Master Theses

2025

Grunewald, Jule

Entwicklung einer integrierten 3d-gedruckten Dunkelfeldbeleuchtung für die Endomikroskopie

7/2025

Rothenberger, Peter

Bestimmung der Position eines Prüflings am Fizeau-Tilted Wave Interferometer (TWI) mittels Mehrwellenlängeninterferometrie

9/2025

Höhmnn, Tobias

Simulation und Aufbau eines Polarisationsweißlichtinterferometers zur Messung in Immersion

7/2025

Zuo, Ximing

Ein zeitbasiertes Objekterkennungs-Framework durch die Kombination von LSTM-Vorhersage und YOLOv6-Detektion

11/2025

Stollfuss, Bastian

Auslegung einer Fresnel-Linse zur fokussierten Strahlführung und deren Test in einem SPCE-Sensor

8/2025

Stölzel, Sebastian

Korrektur von Fehlstellungen bei adaptiven Fahrzeugscheinwerfern unter Einsatz von elektromechanischen Ausrichtungsmechanismen

11/2025

Hetzel, Florian

Ultrafast Second and Third Harmonic Generation from sub-50 fs Multipass-Cellcompressed IR pulses

8/2025

Hasenkrug, Jonas

Imaging NV Center based Quantum Magnetometer for Side-Channel Attacks

12/2025

Zimmermann, Anton

Entwicklung eines Beleuchtungssystems für das endoskopische Spatial Frequency Domain Imaging mit 3D-gedruckten Mikrooptiken

9/2025

Bachelor Theses

2023

Brenner, Andreas

NDIR-Gasanalyse mit tiefen neuronalen Netzen

1/2023

Bachelor Theses

2024

Hoffmann, Jakob

Design und 3D-Druck eines faserbasierten Lichtblatts

9/2024

Vukovic, Hrvoje

In situ Bestimmung der Rechtwinkligkeit der Referenzspiegelecke der NPMM-200

9/2024

Middendorf, Marinus

Modellierung und Charakterisierung eines ereignisbasierten Sensors

10/2024

Bäuerle, Marco

Remote heart rate detection, based on a diffraction grating approach

10/2024

Kayacik, Betül

Calibration and characterisation of a wearable Light Logger

10/2024

Blum, Lara Patricia

In-situ-Vermessung von Zweiphotonen-Lithographie-Objekten

11/2024

Geißler, Stephanie

Metrologie additiv gefertigter Mikro-Polymerstrukturen - Oberflächenoptimierung zur Vermessung steiler Flanken

11/2024

Weißmann, Liv

Liv Optikdesign und Femtosekunden-3D-Druck einer Dunkelfeldbeleuchtung mit mikrofluidischer Funktionalisierung einer Blende

12/2024

Bachelor Theses

2025

Hasnaoui, Wala

Fringe image enhancement for surgical purposes using dual-tree complex wavelet transform

1/2025

Schweizer, Johannes

Kalibrierung eines chromatisch konfokalen Sensors für die Formcharakterisierung optischer Elemente in der Medizintechnik

10/2025

Haile, Noel

Designvarianten für die Miniaturisierung multispektraler Bildgebung in der Medizin

2/2025

Matheis, Nina

Integration mikrooptischer Fasersonden in Kanülen zur Analyse von tief liegendem Gewebe

10/2025

Häberli-Ziefle, Julian

Deep Learning-gestützte Modellierung einer Time-Gated Single-Pixel-Kamera unter Echtzeitbedingungen

7/2025

Dorsch, Ramona

Geometrische und optische Kalibrierung endoskopischer Spatial Frequency Domain Imaging Systeme

11/2025

Stelzner, Jeremias

Realisierung eines Linnik-Weißlicht interferometers zur Vermessung latenter Zweiphotonenlithographie-Strukturen in Photolack

9/2025

Student Research Theses

2023 — 2025

Stahr, Franziska Helen

Design und Implementierung einer
Linienbeleuchtung für die chromatisch
konfokale Mikroskopie

4/2023

Mahninger, Iris

Simulationsbedingte Optimierung
von Einzelpunktmessungen bei der
ATR-Spektroskopie

6/2023

Sdougkou, Marina

Speckle Decorrelation in holographic
imaging through congruent fiber bundles

6/2023

Lu, Mengze

Arithmetik für Bildinhalte
mit Neuronalen Netzen

7/2023

Tang, Leiwen

Design und Charakterisierung einer
3D-gedruckten miniaturisierten
holografischen Doppelfalle

8/2023

Weichert, Insa-Marie

Iterative mask-based Image Reconstruction
of Cell Structures using Neural Networks

8/2023

Steinhoff, Robert

Aktuierbare Mikrooptiken zur Steigerung der
lateralen Auflösung von Faserendoskopen

8/2023

Shao, Yuzhe

3D-Topografiemessung mittels
chromatischem Depth from Focus

9/2023

Klaus, Christopher

Varianten der multispektralen Snapshot
Bildgebung in der minimalinvasiven
Chirurgie

10/2023

Mayer, Jonas

Laserschneiden von gekrümmten
Glassubstraten durch Index-Matching

10/2023

Lutz, Tobias

Konoskopische Holografie
zur Entfernungsbestimmung

10/2023

Zhang, Jize

Image Reconstruction through Sensor
Fusion based on Deep Neural Network

10/2023

Reif, Tim

Experimentelle Analyse
des Einfangs von Bakterien und Viren

10/2023

Liang, Chentao

Berechnungsmethoden zur Optimierung
von Hologrammen

11/2023

Student Research Theses

2023 — 2025

Wang, Cheng

Optimierung hyperspektraler Daten
zur Remote Pulsdetektion

11/2023

Senger, Thorsten

Optimierung des Nutzbereichs eines
Stepped Mask Interference Exposure Setup

8/2024

Deng, Yuchen

Analyse von Ellipsometrie-Daten mit
Deep-Learning-Methoden unter
Berücksichtigung der Unsicherheit

12/2023

Lyu, Meng

Retroreflexionsmessgerät zur mobilen
Vermessung von historischen Achromaten

10/2024

Laudenbach, Xenia

Minimierung des Wellenfront-
rekonstruktionsfehlers computer-
generierter Hologramme durch thermo-
chemisch generierte Marker

12/2023

Li, Shangqian

Neuartiger Entfernungssensor basierend
auf differentieller Perspektive

12/2024

Bachmann, Ada

Design und Herstellung eines miniaturisi-
erten Immersionslithographieobjektivs für
einen endoskopischen Bio-3D-Drucker

12/2023

Liu, Shuaike

Determination of optimal features in tissue
differentiation via optical sensors using deep
learning

8/2025

Rothenberger, Peter

Realisierung eines Mehrwellenlän-
gen-Fizeau-Tilted Wave Interferometer
(TWI)

10/2025

Optik-Kolloquium 2023

34. Optik-Kolloquium

mit Antrittsvorlesung Prof. Dr. Stephan Reichelt

Optik und Photonik in der Produktionstechnik
am 23. März 2023, Teilnehmer: ca. 150

Begrüßung und Einführung	Prof. Dr. Stephan Reichelt <i>ITO, Universität Stuttgart</i>
Antrittsvorlesung Prof. Dr. Stephan Reichelt Engineering Optics – Entwicklung optischer Systeme in der Praxis	Prof. Dr. Stephan Reichelt <i>ITO, Universität Stuttgart</i>
Fortschritte in der Optischen Dünnschichttechnik	Dr. Andreas Wienke <i>Laser Zentrum Hannover e.V., Hannover</i>
3D printed holograms onside of the multicore fiber facet for lensless 3D imaging with keyhole access	Prof. Dr. Jürgen Czarske <i>Professur Mess- und Sensorsystemtechnik (MST) TU Dresden</i>
Komplexe mikrooptische Komponenten und Systeme durch 3D-Druck	Dr. Simon Thiele <i>Printoptix GmbH, Stuttgart</i>
Optische Prüftechnik bei Carl Zeiss SMT - Der Weg zu EUVL-Genauigkeiten	Stefan Schulte <i>Carl Zeiss SMT GmbH, Oberkochen</i>
Digital Holography – from the lab into the production line	Dr. Daniel Carl <i>Fraunhofer-Institut für Physikalische Messtechnik (IPM), Freiburg</i>
Zentriermessung in der Montage asphärischer Linsensysteme	Dr. Aiko Ruprecht <i>TRIOPTICS GmbH, Wedel</i>
Optische Metrologie für den Maschinenbau: Aufgaben, Herausforderungen, Treiber	Dr. Andreas Lange <i>Mahr GmbH, Göttingen</i>
Structured light for ultrafast laser micro- and nanoprocessing	Dr. Daniel Flamm <i>TRUMPF SE + Co. KG, Ditzingen</i>
Optische Systeme in der Lasermaterialbearbeitung – Lösungen und Herausforderungen	Prof. Dr. Andreas Michalowski <i>Institut für Strahlwerkzeuge (IFSW), Universität Stuttgart</i>

Optik-Kolloquium 2024

35. Optik-Kolloquium

Optik und Photonik in Medizin und Life Science am 20. März 2024, Teilnehmer: ca. 100

Begrüßung und Einführung

Prof. Dr. Stephan Reichelt

ITO, Universität Stuttgart

Spectral fingerprints for dynamic measurements
in regenerative medicine

Dr. Julia Marzi

NMI Reutlingen / Universitätsklinikum Tübingen

Translational medicine: fluorescence imaging stories
from basic science discovery towards medical device
applications in clinic

Dr. Antje Haap-Hoff

Karl Storz SE & Co. KG, Tuttlingen

FluoSync – Parallele Mehrfarbfluoreszenzbildgebung
in der Mikroskopie

Christian Schulz

Leica Microsystems CMS GmbH, Wetzlar

Optische Zwillinge für medizin-
technische Anwendungen

Prof. Dr. Alwin Kienle

ILM, Ulm

Streuung von Laserlicht an Zellen und Zellclustern
eröffnet neue Einsichten in biomedizinischer Optik

Prof. Dr. Alexander Rohrbach

IMTEK, Universität Freiburg

Automatisierte quantitative digitalholographische
Phasenkontrastmikroskopie zur Zell- und Gewebeanalyse

Dr. Björn Kemper

BMTZ, Universität Münster

Using spatial light modulation to assess myopia
control spectacle lenses

Dr. Augusto Arias

ZEISS Vision Science Lab, Universität Tübingen

Endoskopisches Messsystem zur elastografischen
Gewebedifferenzierung basierend auf aktiver
Triangulation und 3D-gedruckter Mikrooptik

Dr. Valese Aslani

ITO, Universität Stuttgart

Organized International Conferences

2023 — 2025

A. Herkommer

EOS-Conference 2023 (Dijon) 2025 (Delft) Subconference TOM2 „Adaptive and Freeform Optics”

A. Herkommer

Program-Committee for International Optical Design Conference (IODC) – Quebec 2023

S. Reichelt

Conference Co-Chair: Information Photonics 2024 (IP2024) Yokohama, Japan, April 24-26, 2024

A. Herkommer

Photonics Europe 2024 (Strasbourg, France)
Subconference PE108 – 3D Printed Optics and Additive Photonic Manufacturing

S. Reichelt

Conference Chair, Program-Committee: 126. Jahrestagung der DGaO,
Stuttgart, Deutschland, June 2025

S. Reichelt

Program-Committee: Automated Visual Inspection and Machine Vision VI,
Optical Measurement Systems for Industrial Inspection XIV, SPIE Optical Metrology, München,
Deutschland, June 23-27, 2025

A. Herkommer

Program-Committee for SPIE Nonimaging Optics Conference – San Diego, August 2025

Impressum:

Berichte aus dem Institut
für Technische Optik: Band-Nr. 136

Auflage: 100 Stück

Publisher: Institut für Technische Optik
Universität Stuttgart
Pfaffenwaldring 9
D-70569 Stuttgart
www.ito.uni-stuttgart.de

Für sprachliche Überarbeitung oder Übersetzung einzelner Texte wurden KI-gestützte Werkzeuge eingesetzt.
Die Verantwortung für Inhalt und Aussage der Texte liegt bei den Autorinnen und Autoren.

ISBN: 978-3-948570-35-4



© Christina Fischer