

PROCEEDINGS OF SPIE

# ***Optical Measurement Systems for Industrial Inspection XIII***

**Peter Lehmann**  
*Editors*

**26–29 June 2023**  
**Munich, Germany**

*Sponsored and Published by*  
SPIE

**Volume 12618**

Proceedings of SPIE 0277-786X, V. 12618

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

Optical Measurement Systems for Industrial Inspection XIII, edited by Peter Lehmann,  
Proc. of SPIE Vol. 12618, 1261801 · © 2023 SPIE · 0277-786X  
doi: 10.1117/12.3006937

Proc. of SPIE Vol. 12618 1261801-1

The papers in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. Additional papers and presentation recordings may be available online in the SPIE Digital Library at [SPIDigitalLibrary.org](http://SPIDigitalLibrary.org).

The papers reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from these proceedings:  
Author(s), "Title of Paper," in *Optical Measurement Systems for Industrial Inspection XIII*, edited by Peter Lehmann, Proc. of SPIE 12618, Seven-digit Article CID Number (DD/MM/YYYY); (DOI URL).

ISSN: 0277-786X  
ISSN: 1996-756X (electronic)

ISBN: 9781510664456  
ISBN: 9781510664463 (electronic)

Published by  
**SPIE**  
P.O. Box 10, Bellingham, Washington 98227-0010 USA  
Telephone +1 360 676 3290 (Pacific Time)  
[SPIE.org](http://SPIE.org)  
Copyright © 2023 Society of Photo-Optical Instrumentation Engineers (SPIE).

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of fees. To obtain permission to use and share articles in this volume, visit Copyright Clearance Center at [copyright.com](http://copyright.com). Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher.

Printed in the United States of America by Curran Associates, Inc., under license from SPIE.

Publication of record for individual papers is online in the SPIE Digital Library.

**SPIE. DIGITAL LIBRARY**  
[SPIDigitalLibrary.org](http://SPIDigitalLibrary.org)

---

**Paper Numbering:** A unique citation identifier (CID) number is assigned to each article in the Proceedings of SPIE at the time of publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online and print versions of the publication. SPIE uses a seven-digit CID article numbering system structured as follows:

- The first five digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc. The CID Number appears on each page of the manuscript.

# Contents

ix	<i>Conference Committee</i>
xi	<i>Introduction</i>

---

## ARTIFICIAL INTELLIGENCE IN METROLOGY

---

12618 02	<b>The use of deep learning for computational optical imaging: from data driven to physics driven (Keynote Paper)</b> [12618-1]
12618 03	<b>AI-based solution for robust detection with optical microresonators</b> [12618-2]
12618 04	<b>Thin-film thickness measurement based on spectral reflectometer using artificial neural network algorithm</b> [12618-3]
12618 05	<b>AI-guided numerical-aperture-controlled scatterometry for measurement of deep HAR and thin-film structures with a large depth variation</b> [12618-4]

---

## PROCESS-INTEGRATED AND IN-SITU MEASUREMENT

---

12618 06	<b>In-process powder bed monitoring with angular illumination</b> [12618-5]
12618 08	<b>Laser drilling controlled by laser-generated sound</b> [12618-7]
12618 09	<b>Sensor-guided machining of large-scale CFRP components based on resin transfer molded features</b> [12618-8]
12618 0B	<b>Improving the accuracy and precision of OCD measurement by systematic error correction in self-interference pupil ellipsometry</b> [12618-124]

---

## INTERFEROMETRIC TECHNIQUES AND SHEAROGRAPHY

---

12618 0C	<b>Simultaneous orthogonal shearography using two pairs of parallel slits and a tetra-split lens</b> [12618-11]
12618 0D	<b>A fibre optic angle sensing tape for applications in robotics and automation</b> [12618-12]
12618 0E	<b>Multiwavelength study of etalon effects in LCOS-based spatial light modulators</b> [12618-13]

- 12618 OF **Three-channel space-qualified high-power pulsed fiber laser system for accurate velocity detection in bistatic configuration** [12618-14]
- 12618 OG **The Nyquist criterion and its applicability in phase-stepping digital shearography** [12618-15]

---

#### FRINGE PROJECTION, STRUCTURED ILLUMINATION, AND PHOTOGRAMMETRY

---

- 12618 OH **Thermal single-shot 3D shape measurement of transparent objects: optimization of the projected statistical LWIR pattern** [12618-16]
- 12618 OI **Identification and correction of magnification factor deviations of a telecentric fringe projection system** [12618-18]
- 12618 OJ **Metrology inside a cryostat using a cutting-edge periscope** [12618-19]
- 12618 OK **Photogrammetry for optical metrology of metal additively manufactured parts** [12618-20]

---

#### HIGH-RESOLUTION TOPOGRAPHY MEASUREMENT

---

- 12618 OL **Microsphere-assisted microscopy: challenges and opportunities (Keynote Paper)** [12618-22]
- 12618 ON **EUV reflective coherent diffraction imaging system for wafer metrology** [12618-24]

---

#### TOPOGRAPHY MEASUREMENT AND PROFILOMETRY

---

- 12618 OP **Indirect geometry measurement method based on confocal microscopy and fluorescent microparticles** [12618-26]
- 12618 OQ **Robust measurement of surface topography for additive manufacturing using imaging confocal microscopy** [12618-27]
- 12618 OR **Double-pass modulated differential confocal microscopy for closed-loop axial control of direct laser writing** [12618-28]
- 12618 OS **Construction of a time-domain full-field OCT for non-contact volumetric layer thickness measurement** [12618-29]
- 12618 OT **Improved 3D form profiler based on extending illumination aperture** [12618-30]
- 12618 OU **Sparse surface profile reconstruction from scattering light distributions** [12618-31]
- 12618 OV **Computational self-correction of scanning nonlinearities in optical profilometry** [12618-32]

---

#### HOLOGRAPHIC TECHNIQUES

---

- 12618 0W **Robust semiconductor overlay metrology with non-uniform illumination beams using digital holographic microscopy** [12618-33]
- 12618 0X **Self-assembling of microlenses by pyro-electric effect for the development of compact systems** [12618-34]
- 12618 0Y **Non-isoplanatic lens aberration corrections in digital holographic microscopy** [12618-35]
- 12618 0Z **Nanoscale surface topography using low-cost digital holographic microscopy** [12618-75]

---

#### JOINT SESSION (TRACOPTIC) II: MODELLING AND CHARACTERISATION OF QUANTITATIVE MICROSCOPES

---

- 12618 12 **Compatibility analysis of profile and areal material measures** [12618-39]
- 12618 13 **Investigations on the accuracy and evaluation of the uncertainty of stitching in optical surface metrology** [12618-40]

---

#### MEASUREMENT OF PRECISION COMPONENTS AND OPTICAL SYSTEMS

---

- 12618 15 **Improved alignment of the setup for traceable measurements of the modulation transfer function (MTF)** [12618-42]
- 12618 16 **Long-term wavelength stabilisation of widely modulated lasers** [12618-43]
- 12618 17 **Precision form measurement of biconic surfaces using scanning Fizeau interferometry** [12618-44]
- 12618 18 **Versatile modulation transfer function and direct point spread function measurement with a random target method** [12618-45]

---

#### SPECIAL SESSION: METROLOGY FOR AUTONOMOUS VEHICLES

---

- 12618 1A **Development of a LiDAR system for low visibility conditions** [12618-47]
- 12618 1B **A lightweight laser scanner for UAV-based applications** [12618-48]
- 12618 1C **Towards image-free object detection for autonomous vehicles under harsh environmental conditions** [12618-49]

12618 1D **Coherence-gated digital holographic imaging through extended scattering media for autonomous driving vehicles** [12618-50]

---

#### SCATTERING, DIFFRACTION, AND SPECKLE TECHNIQUES

---

12618 1E **Digital holographic microscopy with functionally-integrated waveguide illuminator (Keynote Paper)** [12618-51]

12618 1F **Surface roughness measurement of large areas with high spatial resolution by spectral speckle correlation** [12618-52]

12618 1G **Application and performance of laser speckle odometry applied to a mobile industrial robot** [12618-53]

12618 1I **Portable low-cost setup for outdoor implementation of dynamic speckle technique** [12618-55]

---

#### POLARIMETRIC, SPECTROSCOPIC, AND NONDESTRUCTIVE TECHNIQUES

---

12618 1K **Optimal Mueller matrix imaging polarimeter in the visible band based on division-of-aperture** [12618-56]

12618 1L **An infrared optical sensor for quantitative inline inspection of nanocoatings on plastic products** [12618-57]

12618 1M **Diffraction-limited mid-infrared hyperspectral single-pixel imaging microscopy** [12618-58]

12618 1N **Tolerance analysis and design optimization of additively manufactured mechanical structure for a Raman spectrometer system** [12618-59]

12618 1O **In-line fluorescence detector for production control in robot-driven environments** [12618-60]

---

#### LARGE-AREA, LARGE, AND MULTISCALE MEASUREMENTS

---

12618 1Q **Laser tracker system supporting 3D digital image correlation with dispersed measurement fields of view** [12618-65]

12618 1S **Accelerated measurement and defect characterization on large optical components** [12618-63]

12618 1T **An extended model for the kinematic identification of a tiltable laser plane in adaptive light-section triangulation** [12618-64]

12618 1U **Digital holography in a machine tool: measuring large-scale objects with micron accuracy** [12618-66]

## POSTER SESSION

---

- 12618 1V **Forging measurement using passive stereo vision** [12618-10]
- 12618 1W **Measurement analysis of optical micrometers with polygonal mirror-based laser scanners** [12618-68]
- 12618 1X **Comparative performance of high and medium resolution cameras for defect detection in carbon-fiber reinforced composites by digital shearography** [12618-69]
- 12618 1Z **Uncertainty reduction of CO<sub>2</sub> laser calibration system in National Institute of Metrology (Thailand)** [12618-71]
- 12618 20 **Photoelastic and Stokes images through deep convolutional neural networks: a comparison of stress fields** [12618-72]
- 12618 21 **Optical design of refractive imaging spectrometer for semiconductor metrology** [12618-73]
- 12618 23 **Interferograms analysis for measuring the thickness of aluminum thin films** [12618-77]
- 12618 24 **Laser-based measurement system for the detection of delamination in tunnel linings** [12618-78]
- 12618 25 **OCT versus x-ray imaging in the inspection of ball grid arrays (BGAs)** [12618-80]
- 12618 26 **Thickness analysis of double-layered thin-film sample using spectral reflectometry** [12618-81]
- 12618 29 **Intensity-based dynamic speckle method for analysis of variable-rate dynamic events** [12618-85]
- 12618 2A **High NA lens assessment using self-interference incoherent digital holography** [12618-86]
- 12618 2D **Adaptive Shack-Hartmann wavefront system with extended dynamic range for lens characterization** [12618-89]
- 12618 2E **Accurate spectral transmittance measurement method of highly-opaque materials in the UV-to-IR using optical attenuators** [12618-90]
- 12618 2K **Automated assessment for grinding spots on aircraft landing gear components using robotic white light interferometry** [12618-96]
- 12618 2L **Characterization of the maximum measurable slope of optical topography measuring instruments** [12618-97]
- 12618 2N **Detection of geometrical patterns of self-assembled gold nanospheres and top-down fabricated nanostructures using coherent Fourier scatterometry** [12618-99]
- 12618 2O **Studies on micromanipulation capabilities of micro-objects and combined Raman spectroscopy based on photonic jet fiber optic** [12618-100]

- 12618 2P **Investigation to evaluate the aging condition utilizing UV radiation of carbon black filled rubber compounds as measured by ATR spectroscopy** [12618-101]
- 12618 2Q **Improving the phase modulation of spatial light modulator using Shack-Hartmann wavefront sensor** [12618-102]
- 12618 2R **Conical null-screen design for evaluating fast free-form convex surfaces** [12618-103]
- 12618 2S **Shape measurement of phase objects using fringe projection technique** [12618-104]
- 12618 2T **Detection of delaminated areas in thermal barrier coatings by active infrared thermography using different heat sources** [12618-105]
- 12618 2U **Rapid surface metrology of freeform shapes using CGH interferometry** [12618-106]
- 12618 2V **Non-destructive evaluation of thermal barrier coating thickness using IR thermography in chemical removal processes** [12618-107]
- 12618 2W **Development of a liquid interferometric optical microscope (L-IOM) in phase-shift mode with standard Mirau objectives** [12618-109]
- 12618 2X **New wafer shape measurement technique for 300mm blank vertically held silicon wafers** [12618-111]
- 12618 2Y **3D hologram optical element for angle measuring devices and sighting systems** [12618-112]
- 12618 2Z **Fabrication and test of functional panels for multimission modular satellite platform** [12618-113]
- 12618 31 **Pyro-electrohydrodynamic printing of liquid crystals** [12618-115]
- 12618 33 **Robotization of engineering equipment to improve the safety of emergency rescue operations using optical methods** [12618-117]
- 12618 34 **Block-based multi-scale image enhancement method for industrial inspection system** [12618-118]
- 12618 35 **Development of a full-field polarization interferometer for measurement of wafer surface profile** [12618-119]
- 12618 36 **Absolute flatness measurement based on shift-rotation method using the second deviation** [12618-120]



# Conference Committee

## *Symposium Chairs*

**Marc P. Georges**, Université de Liège (Belgium)  
**Jörg Seewig**, Technische Universität Kaiserslautern (Germany)

## *Conference Chair*

**Peter Lehmann**, Universität Kassel (Germany)

## *Conference Co-chairs*

**Wolfgang Osten**, Universität Stuttgart (Germany)  
**Armando Albertazzi Gonçalves Jr.**, Universidade Federal de Santa Catarina (Brazil)

## *Conference Programme Committee*

**Oleg V. Angelsky**, Yuriy Fedkovych Chernivtsi National University (Ukraine)  
**Andrei G. Anisimov**, Technische Universiteit Delft (Netherlands)  
**Anand Krishna Asundi**, Nanyang Technological University (Singapore)  
**Partha P. Banerjee**, University of Dayton (United States)  
**Ralf B. Bergmann**, Bremer Institut für angewandte Strahltechnik GmbH (Germany)  
**Harald Bosse**, Physikalisch-Technische Bundesanstalt (Germany)  
**Rémi Bourgois**, Safran Reosc (France)  
**Jan Burke**, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)  
**Chau-Jern Cheng**, National Taiwan Normal University (Taiwan)  
**Jürgen W. Czarske**, Technische Universität Dresden (Germany)  
**Peter J. de Groot**, Zygo Corporation (United States)  
**Konstantinos Falaggis**, The University of North Carolina at Charlotte (United States)  
**Pietro Ferraro**, CNR-Institute of Applied Sciences and Intelligent Systems "Eduardo Caianiello" (Italy)  
**Andreas Fischer**, Bremer Institut für Messtechnik, Automatisierung und Qualitätswissenschaft (BIMAQ), (Germany)  
**Cosme Furlong**, Worcester Polytechnic Institute (United States)  
**Marc P. Georges**, Université de Liège (Belgium)  
**Sen Han**, University of Shanghai for Science and Technology (China)  
**Yoshio Hayasaki**, Utsunomiya University (Japan)  
**Xiangqian Jiang**, University of Huddersfield (United Kingdom)  
**Myung K. Kim**, University of South Florida (United States)

**Tomasz Kozacki**, Warsaw University of Technology (Poland)  
**Richard K. Leach**, The University of Nottingham (United Kingdom)  
**Eberhard Manske**, Technische Universität Ilmenau (Germany)  
**Andrew John Moore**, Heriot-Watt University (United Kingdom)  
**Gunther Notni**, Fraunhofer-Institut für Angewandte Optik und  
Feinmechanik (Germany)  
**Yukitoshi Otani**, Utsunomiya University (Japan)  
**Xiang Peng**, Shenzhen University (China)  
**Nikolay V. Petrov**, ITMO University (Russian Federation)  
**Pascal Picart**, Université du Maine (France)  
**Stephan Reichelt**, Universität Stuttgart (Germany)  
**Christian Rembe**, TU Clausthal (Germany)  
**Robert Schmitt**, RWTH (Germany)  
**Jörg Seewig**, Technische Universität Kaiserslautern (Germany)  
**Rainer Tutsch**, Technische Universität Braunschweig (Germany)  
**Eriko Watanabe**, The University of Electro-Communications (Japan)  
**Toyohiko Yatagai**, Utsunomiya University (Japan)  
**Changhe Zhou**, Shanghai Institute of Optics and Fine Mechanics  
(China)

## Introduction

This year the conference “Optical measurement systems for industrial inspection XIII” will again contribute as a substantial part to the biannual Munich SPIE symposium “Optical Metrology” and the “LASER World of Photonics Congress”. The meeting with its long tradition commits itself to encourage dialogue between scientists from academia and industry aiming at knowledge exchange and recognizing new trends, applications and developments in optical metrology.

We are happy that this year's conference, which is the thirteenth in a still running series, will take place as an international in-person meeting once again, and the number of more than 120 submitted contributions is at the same level as before the pandemic.

Again, optical metrology applications of all relevant fields of industrial production are addressed, ranging from high-precision and resolution enhancement techniques to industrial in-process and in-situ measurements.

Obviously, the acquisition of information based on reliable measurement data is still an essential prerequisite to stimulate sustainable progress in industrial manufacturing.

In addition, even new trends such as artificial intelligence and deep learning approaches are driven by the increasing availability of data and are thus pushing the broad use of optical measurement systems. Hence, recent developments support optical metrology to expand its position as a dynamic field of technology enabling to monitor, control, and improve industrial products and processes.

This year's conference includes two joint sessions linking the industrial inspection conferences and the conference 12619, Modeling Aspects in Optical Metrology. These sessions are dedicated to modelling and characterisation in quantitative microscopy and emphasize the importance of microscopy in optical metrology. They start with an invited paper on the topographic lateral resolution of interferometers by Peter de Groot. Most contributions are related to the European project TracOptic, (Traceable industrial 3D roughness and dimensional measurement using optical 3D microscopy and optical distance sensors) and the German project SiM4diM (Simulation and machine learning for high-precision dimensional microscopy).

Further, a special session named “Metrology for autonomous vehicles”, starting with an invited talk by Christoph Werner on a LiDAR system for low visibility conditions, promises detailed insight in this rapidly growing field, where optical metrology plays a major role.

Last but not least some invited keynote presentations strengthen the importance of the conference. These include talks by Guohai Situ on the use of deep learning

for computational optical imaging, by Arash Darafsheh on micro-sphere assisted microscopy and by Eriko Watanabe on imaging through scattering media.

Finally, we would like to express our sincere gratitude to the members of the program committee for their support of the conference. Additionally, many thanks are due to the SPIE staff, namely Alex Pulchart Rusova and Karin Burger, for their great, professional and cooperative work during the conference organization and the preparation of this proceedings volume.

In sum we are optimistic that the outstanding level and quality of submissions will support the success of the conference. Thus, we would also like to thank all authors, who gave added value to our community by contributing to this proceedings volume. We hope that you will enjoy it.

**Peter Lehmann**  
**Wolfgang Osten**  
**Armando Albertazzi**