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GUEST EDITORIAL

Special Section Guest Editorial: Lensless Imaging in Optical Metrology

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In recent years, lensless imaging techniques have gained increasing interest. In comparison with conventional optical imaging methods they offer great advantages, including the realization of measurement systems that are often significantly more compact, lightweight, and flexible. These attributes are beneficial for inspection tasks, where bulky and heavy sensors place limitations on both accessibility and motion dynamics. Furthermore, lensless approaches do not suffer from inherent disadvantages of imaging optics, such as aberrations and dispersion. This is particularly instrumental in the field of microscopy, where the amount of information per image, i.e., the space-bandwidth-product, is primarily limited by lens aberrations. Additionally, lensless methods facilitate accurate imaging in regions of the electro-magnetic spectrum where imaging optics are either very expensive or even unavailable, such as x-ray or deep UV.

This special section of *Optical Engineering* is dedicated to showcasing current advancements in the field of lensless techniques. It covers a broad scope of topics ranging from microscopy to non-reconstructive methods, lensless holographic projection, and x-ray imaging.

A thematic focus is on microscopy, as lensless methods offer a particular advantage here. Digital holography is very established in this field, mostly due to its ease of application. An important aspect in holographic microscopy is the shape of the reference wave, since it determines the achievable image quality. Commonly we assume a perfect spherical reference wave, which is often not the case. In their first contribution, Buitrago-Duque et al. compare various ways to create an accurate reference illumination, including pinholes, aspheric lenses, and high-NA fibers. The techniques are rated by various parameters, such as robustness, compactness, ease of application, and imaging performance.

A crucial step in digital holographic microscopy is the numerical propagation of the recorded wavefield, since it facilitates the imaging process. Often Fresnel propagation is used for this task, because it inherently transforms the pixel pitch of the images to the diffraction limited resolution. However, the accuracy of Fresnel propagation is limited by the Fresnel approximations and is significantly reduced for high numerical apertures. Here, Müller et al. introduce a simple solution by incorporating higher orders of the binomial approximation into the Fresnel approximations. The method enables Fresnel propagation with optical resolution far below the pixel pitch of the camera. But smart numerical imaging approaches can do even more. Combining multiple digital holograms from different viewing angles enables imaging of partially or even fully occluded objects. This is reported by Buitrago-Duque et al. in their second contribution. Their approach combines multiple recorded holograms into a composite hologram, to remove the present occlusion and thus increasing the reconstructed field of view. Finally, Buitrago-Duque et al. also present the design of a cost-effective DIY digital lensless holographic microscope, with special emphasis on the correction of distortions occurring from a non-ideal illumination source.

Extremely high resolutions can be achieved in the x-ray domain. Here, Hoshino et al. explore the possibility to achieve nanometer lateral resolution based on diffraction patterns obtained from grazing incidence of hard x-ray radiation. The basic concept is a generalization of the scatterometry scheme to isolated structures, which only consist of a few lattices across a large area. They verify the feasibility by means of simulations using rigorous methods.

In addition to digital holography, there are alternative methods for recording the wave field in the camera plane. A prominent example is phase retrieval based on the transport of intensity equation (TIE). Here, several intensity images are recorded along the propagation direction and without a reference wave. Kumar, Gupta, and Nishchal demonstrate how this can be achieved in a microscopy setting under low light conditions. They specifically investigate the optimum separation distance of the recording planes. One of the prime applications of lensless microscopy is the investigation of biological specimens at the cellular level. Lin et al. present a method based on neural networks to facilitate high throughput cell segmentation based on recordings obtained from lensless digital holographic microscopy. To enhance the performance even for large images, they use a Swin transformer network for the encoding part but employ a standard convolutional neural network for the decoding.

Having access to the wavefield in the recording plane enables encoding either for encryption or analysis purposes without imaging at all. Javidi et al. give an overview of the current state of the so called non-reconstructing methods. These methods typically involve random phase encoding and neural networks for object analysis. A major application is cell identification and cell analysis in general. The method can also be applied outside the realm of microscopy as shown by Aschenbrenner et al. for the case of long-range infrared sensing. Zhou et al. introduce a method based on optical chaos and a quadrature amplitude modulation scheme to provide image encryption, and Tounsi et al. present wavefield analysis on speckle level. They compare phase derivatives obtained from a shearing process to those obtained from a Riesz transform of a phase shifted interferogram or hologram.

Holographic lensless techniques can also be used to project light. Kreis discusses referenceless phase holography, which allows full control of amplitude and phase of a wavefield by means of two spatial light modulators. This can be used for 3D visualization and display, image projection and optical metrology. Finally, Hiller and Wallaschek give an intriguing perspective for the application of holographic projection towards automotive industry. They present a manufacturing technique for volume holographic elements which can be employed for the design of automotive exterior lighting, such as headlamps, rear lamps, or signal lamps.

The collection of papers presented here demonstrates that lensless imaging methods are a dynamic and evolving field with strong potential for future research and technological innovation. The contributions highlight the broad scope and the expanding capabilities of these methods across various applications. As editors we hope that this collection not only provides valuable insights into the current state of lensless imaging but also inspires further investigation and sparks new ideas in this fascinating domain.

Claas Falldorf holds a PhD degree in physics and has over 20 years of expertise in coherent optics. He serves as the head of the Coherent Optics and Nanophotonics Group at the Bremer Institute für angewandte Strahltechnik (BIAS) in Bremen, Germany, and gives lectures at the University of Bremen. One of his primary objectives is to bridge the gap between the latest advancements in optical metrology research and their practical implementation in industry. He authored and coauthored more than 150 publications in areas such as optical metrology, light field synthesis, digital holography, and signal processing, and is co-author of the book *Digital Holography and Wavefront Sensing*, which is considered a standard work in the field of digital holography.

Pascal Picart is a professor at Le Mans Université, France. He graduated from the Institute of Optics in 1992 (Palaiseau) and received his PhD in physics from the University of Paris XI (France) in 1995. He has over 32 years of expertise in optical metrology, coherent imaging, and holography. He is author of 118 journal papers and more than 160 proceedings in international and national conferences. He coordinated 4 books and co-founded one start-up. His current research topics are connected with coherent imaging based on digital holography and its various applications to acoustics, mechanics, and fluid mechanics.

Cosme Furlong is a professor in the Mechanical and Materials Engineering Department at Worcester Polytechnic Institute (WPI), Worcester, Massachusetts, USA. With over 30 years of experience, he is the current director of the Center for Holographic Studies and Laser micro-mechaTronics (CHSLT) at WPI. He received his BEng from the University of the Americas, Mexico, and his MS and PhD from WPI. His professional interests, involvement, and publications record include combination of modeling and simulation with quantitative optical metrology, fiber optic sensors, digital holography, NDT, materials characterization, and optimization of mechanical and microelectromechanical components and systems (MEMS).

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