Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

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

Partha P. Banerjee,[1] Elena Stoykova,[2] Daping Chu,[3] Jae-Hyeung Park,[4] Pietro Ferraro,[5] and John Sheridan[6]

[1] Department of Electro-Optics and Photonics, University of Dayton, Dayton, Ohio, USA
[2] Institute of Optical Materials and Technologies, Bulgarian Academy of Sciences, Sofia, Bulgaria
[3] Department of Engineering, University of Cambridge, Cambridge, UK
[4] Department of Information and Communication Engineering, Inha University, Incheon, Republic of Korea
[5] Institute of Applied Sciences & Intelligent Systems, Consiglio Nazionale delle Ricerche, Napoli, Italy
[6] School of Electrical and Electronic Engineering, University College, Dublin, Ireland

Received 24 January 2022; posted 24 January 2022; published 1 February 2022

This feature issue is a continuation of a tradition, since 2007, to follow the conclusion of the OSA Topical Meeting on Digital Holography and 3D Imaging (DH+3D). It addresses current research topics in digital holography (DH) and 3D imaging that are also in line with the topics of *Applied Optics* (AO) and the *Journal of the Optical Society of America A* (JOSA A).

https://doi.org/10.1364/JOSAA.454791

There are at least two important milestones to celebrate this time: 50 years since Gabor won the Nobel Prize for holography, and the 15th meeting of DH, which has been a success story since Ting-Chung Poon launched this conference at the request of Joe Mait. We hope that the commemorative compendium of papers and reviews in this joint feature issue will be a valuable asset for researchers in the area.

Furthermore, in the last DH+3D meeting, a new sub-group was added: Tomography & Radiographic Imaging (TRI), initiated by Zhehui (Jeph) Wang. A feature issue on this, titled Radiography, Applied Optics, and Data Science, is also scheduled to appear in AO.

To celebrate the 10th anniversary of the awarding of the Nobel Prize, Poon and Banerjee's PhD adviser Adrian Korpel, formerly from Zenith and at that time at the University of Iowa, wrote an article in *Applied Optics*, titled "Gabor: frequency, time, and memory" [Appl. Opt. 21, 3624–3632 (1982)]. Here are some excerpts from the abstract: "Dennis Gabor is well-known as the inventor of holography. Less well-known, perhaps, are his contributions to other areas. Yet they are important and, like holography, characteristic of his foresight. In the field of communications, Gabor investigated the classic dichotomy of time and frequency. Guided by analogies to quantum mechanics, he postulated a set of elementary signals and made brilliant use of time–frequency diagrams to analyze communication systems. In a completely different field, Gabor, inspired by some early work of Longuet-Higgins on models for holographic temporal recall in the brain, suggested novel approaches which contributed significantly to the understanding of associative memories."

We point out that Poon, along with Korpel, conceived the concept of optical scanning holography using the principle of acousto-optics, which was the area in which Korpel is recognized as a specialist.

It should also be mentioned that an informal "brotherhood/sisterhood" group called Holoknights was founded by Hans Rottenkolber in 1988, to bring together as friends the top researchers in the field of holography. The charter of the order promotes cooperation, hospitality, and friendship among themselves and their countries. Members are selected not only for their technical leadership but also for their reputation for hospitality, openness, and assistance to others. Four of the authors invited to contribute in this feature issue are holoknights: Malgorzata Kujawinska (Poland), James Trolinger (United States), Fernando Santoyo (Mexico), and Byoungho Lee (Republic of Korea).

The DH+3D topical meeting itself reflects this true international spirit. This conference has been held (pre-COVID) around the world. In 2021, it was part of the OSA Imaging Congress, held virtually, and had 172 papers: 2 tutorial, 2 keynote, 27 invited, 114 contributed (oral), 16 contributed (poster), and 11 post-deadline papers. Approximately 37% were from Europe, 33% from Asia, 27% from America, and 3% from Africa.

It is therefore fitting for this feature issue to appear in *Applied Optics* along with JOSA A, since the topics encompass the interests of both journals. The joint feature issue comprises 54 papers: 42 in AO and 12 in JOSA A. There are 16 invited papers (11 in AO; 5 in JOSA A), of which 6 are reviews (5 in AO, 1 in JOSA A). Papers cover a diverse range of topics, including the history of holography and DH, holographic displays, computer generated holograms (CGHs), digital holographic microscopy (DHM), spatial light modulators (SLMs), machine learning and deep neural networks in DH.

The invited review paper of de la Toree *et al*. (AO) is dedicated to 50th anniversary of Dennis Gabor's Nobel Prize. The aim of the review is to cover a few of the holographic applications in optics while scanning the electromagnetic spectrum. The invited paper of Trolinger and Mansoor (JOSA A) is dedicated to the 60th anniversary of off-axis holography. After a brief introduction to the fundamentals of DH, it follows the "periods of rise and fall" of DH during its long evolution. Many new emerging techniques, applications, and potential future usages are described on the basis of metrological experiments of the authors. The invited paper of Zhang *et al*. (JOSA A) advances off-axis optical scanning holography for elimination of heterodyning required for the phase retrieval, thus avoiding complicated and expensive electronic processing. An optical scanning theory is developed for holographic imaging that shows the possibility of performing coherent and incoherent holographic recording. A 15-year development of Fresnel incoherent correlation holography (FINCH) is analyzed in the invited review paper of Brooker and Siegel (AO). Analysis starts from the first FINCH system and goes to high quality "3D microscopic widefield or confocal imaging that doubles optical resolution beyond the Rayleigh limit to about 100 nm in a single snapshot." The invited review paper of Rosen *et al*. (AO) also discusses FINCH by considering several main milestones in DH with dynamic diffractive phase apertures. FINCH has an aperture of a diffractive lens and is used for "3D imaging, fluorescence microscopy, super-resolution, image processing, and imaging with sectioning ability." Fourier incoherent single-channel holography and coded aperture correlation holography are also described in this review. The review paper of An *et al*. (AO) focuses on a holographic video display, which is still under development, and on key requirements for its commercial use. This paper considers the existing solutions for such types of displays as operation principles and systems from the dawn of holographic video as well as the recent advances in the field. The topic of holographic displays is discussed also in the invited paper of Yoo *et al*. (JOSA A), in which machine learning is used to elaborate a hologram generation technique, which allows for compensation of spatially varying aberrations of holographic displays. Instead of using a point-wise integration method for CGH synthesis, the authors propose to accelerate computation by a combination of fast Fourier transform (FFT)-based convolutions and forward computation of a deep neural network. Teich *et al*.'s paper (AO) considers limitations of today's state-of-the-art automotive head-up displays with single- or double-layer focal planes. A real-time holographic head-up display with continuous depth is presented with a natural way of viewing.

The feature issue includes papers dedicated to CGH synthesis. A comprehensive review in the invited paper of Zhang *et al*. (AO) brings the essence of polygon-based CGHs and provides insights for future research. The paper presents traditional methods, recent developments, and progress by comparing computational reconstructions in terms of calculation speed and image quality. A fast analytical method called the fast 3D affine transformation method is described for calculation of a polygon-based CGH of the face of a real person without usage of graphics processing units (GPUs) with further numerical and optical reconstruction. In the invited paper of Shimobaba *et al*. (AO), a real-valued diffraction calculation without any complex-valued operation is proposed in computational holography by using several pure real-valued transforms, including also the Hartley transformation. The invited paper of Kavakli *et al*. (AO) addresses the mismatch between the results from the CGH algorithms and from a physical holographic display. A dataset is generated by capture of the image reconstructions of optimized holograms using a camera and a holographic display. A complex-valued convolution kernel is found out for propagation of holograms to captured photographs, thus improving the simulation accuracy. Watanabe *et al*. (AO) propose the world's first system for fast CGH synthesis from a large-scale outdoor sports scene. The scene is captured with multiple RGB cameras. A fast calculation method focusing on hidden region continuity is introduced. The method is 5–10 times faster than the point-based method. In the paper of Zheng *et al*. (AO), a depth-division multiplexing method with dynamic compensation is proposed for full-color holographic display by placing orderly three monochromatic RGB images at different positions of the same optical axis and updating iteratively the complex amplitudes of the three object planes. Cviljusac *et al.* (AO) show a low-cost method for printing a CGH by using computer-to-film graphical processing with improved software, and increased resolution is presented for security applications. Christopher *et al*. (JOSA A) demonstrate an "intermediate domain" technique, which decomposes the Fourier transforms used in the iterative Fourier transform algorithms into multiple sub-transforms, to improve hologram generation for phase-modulating SLMs.

There are several papers dedicated to computational issues in DH. Xiao *et al*. (JOSA A) perform a systematical analysis on the sampling of all Fresnel diffraction fields in different planes from the perspective of phase space optics. This comprehensive sampling analysis facilitates numerical calculations of various diffraction fields. Tian *et al*. (AO) relate the ringing artifacts in lensless holographic projection to the bandwidth properties of the reconstructed wave field. A band-limited iterative algorithm is proposed to optimize the phase hologram in the Fresnel domain. In the paper of Velez-Zea *et al*. (AO), a modified hologram plane constraint is introduced for improving the performance of the global Gerchberg–Saxton algorithm used for multiplane phase-only hologram generation. The constraint increases the mean correlation coefficient between the reconstructed planes from a multiplane hologram and the corresponding amplitude targets for each plane. Zhou *et al*. (AO) use the coupling between the transport of intensity equation and the transport of phase equation for improving the phase retrieval solutions from the first equation. A non-recursive fast FFT-based phase retrieval method is presented, and a correction factor is introduced to improve the phase retrieval accuracy. Kakue *et al*. (JOSA A) propose a numerical simulation based on fast Fourier transform for light-in-flight recording by holography. The point-spread function is modified by considering the optical path lengths of the object and reference light pulses and their interference. The computational time is shortened substantially. The proposed method is confirmed by experiment. In the paper of Zhang *et al*. (AO), a one-stage network is proposed for 3D particle volumetric reconstruction that retrieves the 3D coordinates of the particles directly from the holograms. No high-fidelity image reconstruction at each depth slice is needed. The paper of Wang *et al*. (AO) is dedicated to continuous-wave terahertz computed tomography. The authors achieve 75% data acquisition time reduction by applying the total variational minimization iterative algorithm. Zhang *et al*. (AO) propose a dual-frame phase-shifting interferogram phase recovery technique by normalization of the first-order norm. Dual-frame interferograms are added and subtracted to form a set of sine and cosine components, and the phase distribution is obtained through the arctangent operation. The paper of Serabyn (JOSA A) is dedicated to a ray-trace simulation of a type 1 light-field imager to prove that significantly better resolutions are achieved in the reconstructed images of isolated point-like sources by computationally projecting the system pupil onto the lenslet-array plane.

The feature issue contains several papers in the field of DHM. In the invited paper of Baczewska *et al*. (AO), DHM is used as an effective label-free imaging technique for analyzing the effects of low-level laser therapy on biological cells. A full methodology is proposed for creating correct synthetic aperture phase maps for further extensive, highly accurate statistical analysis. In this way, a basis is provided for many other biological experiments based on quantitative phase imaging. The invited paper of Bazow *et al*. (AO) is dedicated to multi-wavelength DHM by applying deep learning convolutional neural networks for computational phase synthesis to obtain high-speed simultaneous phase estimates on different wavelengths. Data-driven computational techniques are used to perform accurate dual-wavelength hologram synthesis, dual-wavelength phase synthesis, direct phase-to-index prediction using a single wavelength, hologram-to-phase prediction, and 2D phase unwrapping with sharp discontinuities. Brault *et al*. (AO) describe a new method to achieve autofocus in DHM based on inserting calibrated objects into a sample placed on a slide. By using the inverse problems approach, it becomes possible to precisely locate the inserted objects from the reconstructed hologram and to determine the slide plane location. In the paper of Sirico *et al*. (AO), a locomotion in 3D environment of Tetraselmis microalgae is studied by off-axis DHM with a fast and semiautomatic criterion for tracking the path of a microalgae in a 3D volume. A full set of the kinematic parameters of the analyzed microorganisms is obtained. The developed method offers to marine biologists a clear 3D representation of all the parameters of the kinematic set. Denneulin *et al*. (JOSA A) propose an unsupervised regularized inversion method for the reconstruction of the 3D refractive index map of a sample in tomographic diffractive microscopy by minimization of the generalized Stein's unbiased risk estimator to automatically estimate optimal values for the hyperparameters of one or several regularization terms (sparsity, edge-preserving smoothness, total variation). The criterion used to find suitable regularization weights enables reducing the amount of required data. Buitrago-Duque and Garcia-Sucerouia (AO) present an ImageJ plugin for realistic simulation and real-time reconstruction in DHM. Both recording and reconstructing simulation modules are discussed, and their efficiency is proven by experiments. In the paper of Schiebelbein and Pedrini (AO), high resolution lensless phase imaging microscopy is achieved from multiple intensity diffraction patterns. The experiments are carried out with phase and amplitude samples under coherent and partially coherent illumination. Lopera and Trujillo (AO) present a digital lensless holographic microscope with a linear polarization-states generator and a linear polarization-states analyzer. The microscope is sensitive to the linear diattenuation by biological samples.

The feature issue includes many different measurement approaches by means of DH and other related methods. In the invited paper of Machikhin *et al*. (JOSA A), wavelength-multiplexed DH imaging is reported. The method relies on simultaneous Bragg diffraction of wide-band light by several ultrasound waves of different frequencies created in crystalline media. The proposed technique enables single-shot acquisition by a single monochrome sensor and avoids spectral scanning. The method is realized with a Mach–Zehnder interferometer with an acousto-optical tunable filter operating in multi-frequency mode. In the invited paper of Giri and Berg (AO), DH is applied to image stationary micro-particles in color by using a Michelson interferometer and three wavelengths, 430 nm, 532 nm, and 633 nm, as primary light sources. A three-CMOS prism sensor records simultaneously three separate backscattered holograms. The reconstructed images are combined by additive color mixing. The invited paper of Liang *et al*. (AO) is dedicated to Huygens' meta-surfaces for phase front manipulation. The authors demonstrate almost perfect tuning of electric and magnetic dipole resonances over a large wavelength range in a silicon meta-surface by using anisotropic meta-atoms. A near-unity transmission and 2π phase control in the range from 760 nm to 815 nm are shown using cuboidal nanoantennas. Munera *et al*. (AO) use a digital holographic interferometry setup with a dual-wavelength recording for high-speed micro-deformation measurement. The numerical processing is carried out using GPUs. The paper of Xia *et al*. (AO) proposes dual-wavelength arbitrary phase-shifting DH with automatic phase-shift detection. The space-division multiplexing technique is used to record information simultaneously in one image. The proposed approach provides simultaneous phase-shifting of the reference beams at the two wavelengths. Guo *et al*. (AO) demonstrate a simple robust straightforward non-interferometric incoherent light ray propagation model using structured light for single-shot 3D profiling of transparent objects with thicknesses from mm to cm. Analysis of the distorted captured image behind the object is performed for a 2D cosine fringe distribution in the incident reference image by monitoring the local change in the period. Grachev *et al*. (AO) present a holographic detection module developed for a single scan spatially resolved measurement of the distribution of a pulsed terahertz field. The module incorporates a motorized translation stage for introducing the time delay. All mounts of the optical elements of the module are produced by 3D printing. The paper of Lin *et al*. (AO) proposes a solution of the problem of rapid and non-contact measurement of a high-precision aspherical cylindrical (acylindrical) lens. Both finite-difference and noise-reduction finite-difference methods are used for solving transport equation of intensity for surface reconstruction. The paper of Hashimoto *et al*. (AO) proposes "a simultaneous imaging technique of both sound propagations and spatial distribution of acoustic frequencies." Parallel phase-shifting DH is used at the framerate of 100,000 fps. The distribution of the acoustic frequencies is made by short-time Fourier transform analysis. Hong *et al*. (AO) focus on technology of 5D optical data storage in transparent materials. The authors present a compact system based on a single phase-only LCOS SLM for simultaneous control of the holographic image and its polarization state. Meng *et al*. (AO) propose a far-field nano-focusing metalens with actively tuned focal shifting in the visible region. The metalens is based on a metal–insulator–metal subwavelength structure for excitation of surface plasmon polaritons. In the paper of Blagoeva *et al*. (AO), chiral structures induced by irradiation with elliptically polarized light in thin films of four azopolymers are studied. Real-time kinetics of azimuth rotation at different irradiation wavelength and intensity is also analyzed. The chiral structure formation is much faster than the induction of linear birefringence. Inoue *et al*. (AO) experimentally demonstrate a motion picture imaging technique for recording a magnified image of light pulse propagation. This extends the recordable time of digital light in-flight recording by holography. The paper of Goodman *et al*. (AO) is dedicated to integration of chirped frequency modulated continuous wave LIDAR techniques into DH. This makes possible range selective holographic imaging with increased resolution. Hoffmann *et al*. (AO) introduce an incoherent, long-range, sub-centimeter resolution LIDAR. A centimeter-scale reflection holography at extremely long ranges is achieved with this system consisting of a pulsed laser and photon-counting receiver. The paper of Gianfelice and Westphal (JOSA A) focuses on electron holography by describing "the holographic process with electron backscatter diffraction as a non-invasive surface structure analysis." The authors prove the possibility of collecting sufficient data for holographic reconstruction. Pensia *et al*. (AO) present detection of cracks in ceramic tableware using a portable digital holographic camera. The camera operation is based on double exposure digital holographic interferometry. Digital image processing techniques are applied on amplitude and phase of the numerically reconstructed wavefronts to locate the position of the defect.

Finally, the feature issue also includes papers dedicated to accuracy analysis. The invited paper of Montresor *et al*. (JOSA A) reviews reduction of speckle noise in coherent imaging by deep-learning algorithms. The review focuses on four classes of applications: optical coherence tomography, synthetic aperture radar imaging, DH amplitude imaging, and fringe pattern analysis. Recently developed and new deep learning approaches associated with phase-shifting procedure are included. Stoykova *et al*. (AO) propose lossy JPEG or JPEG2000 compression of speckle images acquired for dynamic speckle imaging for monitoring of processes in 3D objects without loss of accuracy. In the paper of Pavlicek and Hicklova (AO), the signal formation of an optical 3D sensor for measurement of object shapes is analyzed for smooth and optically rough surfaces. The impacts of both surface roughness and the parameters of the sensor on the measurement accuracy are taken into account. Tong *et al*. (AO) study the degradation caused by phase flicker at both device and application levels. On the device side, the impacts of the flicker and the frame rate on phase modulation resolution are quantitatively analyzed. On the application side, the impact of real phase flicker is found for blazed gratings and image holograms. Lam *et al*. (JOSA A) present ensemble deep-learning invariant occluded hologram classification to solve problems related to occlusions and speckle noise. Over 95% accuracy in the classification of holograms is achieved for partially occluded handwritten numbers contaminated with speckle noise.

We would like to sincerely thank all the invited authors and all the contributors who have made this feature issue possible. The DH and 3D Imaging meeting is scheduled to be held simultaneously at the University of Cambridge, at Optica headquarters, and online, from August 1 to August 4, 2022. We wish this meeting continued growth and success, and look forward to your participation.