Emerging 3-D Imaging and Display Technologies

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We have become an information-centric society vastly dependent on the collection, communication, and presentation of information. At any given moment, it is likely that we are in the vicinity of some form of a display as displays play a prominent role in a variety of devices and applications. Three-dimensional imaging and display technologies are important components for presentation and visualization of information and for creating real-world-like environments in communication. There are broad applications of 3-D imaging and display technologies in computers, communication, mobile devices, TV, video, entertainment, robotics, metrology, security and defense, healthcare, and medicine.

> This special issue provides an overview of the state of the art in 3-D imaging and displays.

While 2-D imaging has become a mature technology with high-quality and low-cost sensors and displays, 3-D images are more realistic due to the presentation of depth information that their 2-D counterparts cannot provide. However, our daily experiences have been mainly limited to the 2-D visualization in computer displays, mobile devices, visual entertainment, etc. This is due to the remaining challenges to realize high-quality, visual-fatigue-free, and low-cost 3-D systems particularly for real-time 3-D display of dynamic scenes. These challenges include producing high lateral and longitudinal resolutions, large depth of focus, large view angle, compactness, low cost, large bandwidth, eliminating adverse human factors, and ability for real-time operation in 3-D systems.

Our pursuit of 3-D imaging and displays has been around for centuries. Even before photography was in widespread use, stereoscopic effects were experimented with paintings. Later, stereophotography was introduced, followed by stereo movies with 3-D effects. Recently, head-mounted devices (HMDs), virtual reality, and augmented reality systems with 3-D viewing capabilities have been experimented with for diverse applications.

Advances in optics, photonics, optoelectronic devices, low-cost light sources and lasers, low-cost high-resolution image sensors such as CMOS sensors with high quantum efficiency (CMOS cameras), spatial light modulators (SLMs), computer hardware, large data storage capability, advanced numerical algorithms and apps in mobile devices, and fabrication capabilities have had a huge impact on advancing 3-D systems as evidenced by substantial R&D in design and fabrication of 3-D imaging and displays. The ability to produce high frame rate, high-resolution, and high light efficiency SLMs to display large dynamic range complex amplitude data continues to be a challenge. These devices are necessary to implement compact real-time 3-D displays.

As mentioned before, early 3-D displays were stereoscopic. In the 20th century, several novel and important 3-D approaches were introduced. One approach was the invention of integral photography by the Nobel Laureate Gabriel Lippmann in the early 20th century. The other approaches were the inventions of holography by the Nobel Laureate Dennis Gabor, and off-axis holography by Leith and Upatneik in the mid-20th century. Since then, there have been substantial R&D attempts to improve, implement, develop, and commercialize 3-D systems based on these inventions. The integral photography interfaced with digital systems has led to modern research known as integral imaging displays, light-field displays, plenoptic cameras, etc. Notable is the work of Fumio Okano and his colleagues at Japan NHK in the 1990s to use

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integral photography implemented with modern cameras and displays for 3-D TV applications. Holography interfaced with digital systems evolved into digital holography and computer-generated holography. The applications of these approaches are beyond entertainment and include medical, military, and industrial applications. An emerging application for 3-D systems is the HMDs such as smart glasses which integrate microdisplays and optics for augmented and virtual reality applications.

This Special Issue on Emerging 3-D Imaging and Display Technologies is a collection of overview papers by prominent 3-D researchers and practitioners from academia, industry, and government laboratories to review the state of the art in 3-D imaging and displays. The papers in the special issue are selected based on some of the most promising 3-D approaches and critical issues such as holographic techniques, integral imaging, head-mounted displays, augmented reality displays, visual fatigue, 3-D perception, stereo systems, 3-D microscopy, lensless imaging, algorithms for 3-D image processing, and their applications.

The following is a brief summary of the papers in the special issue. The paper by Son *et al.* describes digital-holographic and light-field or integral imaging displays which can provide continuous parallax and which are typical in natural scenes and real objects. Hua presents the nature of vergence-accommodation conflict problem in head-mounted displays and the associated visual artifacts, followed by a comprehensive review on the various technical approaches toward rendering proper focus cues in head-mounted displays for both virtual reality (VR) and augmented reality (AR) applications.

Martínez-Corral *et al.* describe the fundaments of integral photography and the main contributions to its development. Also, recent advances in both macroscopic and microscopic 3-D integral imaging are discussed. Arai *et al.* overview integral 3-D capturing methods and displaying stages, and recent work for capturing high-resolution integral imaging information. Javidi *et al.* present passive multidimensional optical sensing and imaging systems (MOSIS), which can be used for 3-D visualization, seeing through obscurations, material inspection, 3-D endoscopy, and object recognition from microscales to long-range imaging. This integral imaging system utilizes many degrees of freedom such as time and space multiplexing, depth information, and polarimetric, temporal, photon flux, and multispectral information to record and reconstruct the multidimensionally integrated scenes.

Nam *et al.* present an autostereoscopic light-field 3-D display architecture, rendering, and calibration method to provide realistic 3-D visual effects with a resolution comparable to the conventional multiviews displays.

Memmolo *et al.* review the most effective techniques for numerically manipulating digital holograms to achieve improved image reconstructions. The topics of extended focus imaging (EFI), synthesis of 3-D holographic scenes, and enhanced 3-D display are discussed throughout the paper. Matoba *et al.* describe imaging techniques using phase, polarization, fluorescence, and spectra based on digital holography. These techniques are developed for multimodal imaging based on the combination of digital holography and other optical microscopies. Anand *et al.* present an overview of the development of compact digital holographic microscopes and their applications in 3-D cell imaging, cell parameter extraction, and cell classification for potential automated disease identification. Yamaguchi describes the evolution of light-field 3-D displays, in particular those which employ holographic technology, and their application to 3-D touch interface for intuitive 3-D human-computer interaction. Finally, Bimber and Koppelhuber summarize their progress toward a fully transparent, flexible, and scalable thin-film image sensor and review lensless imaging approaches.

As with any special issue of this kind, it is not possible to present all the various 3-D approaches and techniques, or to cite all the possible researchers in the field. Therefore, we apologize in advance if any such work is not represented or cited in this special issue. We would like to thank all the authors of this special issue for their outstanding contributions. We are grateful to the anonymous reviewers for their comments and reviewing the manuscripts. We thank the Proceedings of the IEEE Editorial Board and the editorial staff, in particular, Vaishali Damle and Jo Sun, for giving us the opportunity to put together this special issue and for their assistance in the preparation of this special issue. ■

ABOUT THE GUEST EDITORS

Bahram Javidi (Fellow, IEEE) received the B.S. degree from George Washington University, Washington, DC, USA and the M.S. and Ph.D. degrees from the Pennsylvania State University, University Park, PA, USA, all in electrical engineering.

He is the Board of Trustees Distinguished Professor at the University of Connecticut, Storrs, CT, USA. He has over 1000 publications, including nearly 450 peer-reviewed journal articles, over 450 conference proceedings, including over 120 Plenary Addresses, Keynote Addresses, and invited conference papers. His papers have been cited 33 000 times according to the Google Scholar Citations *(h-index = 85, i10-index = 537)*. He is a coauthor on nine Best Paper Awards.

Prof. Javidi received the Quantum Electronics and Optics Prize for Applied Aspects by the European Physical Society in June 2015. He has been named Fellow of several scientific societies, including the Optical Society of America (OSA) and the International Society for Optics and Photonics (SPIE). In 2010, he was the recipient of The George Washington University's Distinguished Alumni Scholar Award, University's highest honor for its alumni in all disciplines. In 2008, he received a Fellow award by John Simon Guggenheim Foundation. He received the 2008 IEEE Donald G. Fink prized paper award among all (over 150) IEEE transactions, journals, and magazines. In 2007, The Alexander von Humboldt Foundation awarded him with the Humboldt Prize for outstanding U.S. Scientists. He received the Technology Achievement Award from SPIE in 2008. In 2005, he received the Dennis Gabor Award in Diffractive Wave Technologies from SPIE. He was the recipient of the IEEE Photonics Distinguished Lecturer Award twice in 2003/2004 and 2004/2005. He was awarded the IEEE Best Journal Paper Award from the IEEE Transactions on Vehicular Technology twice in 2002 and 2005. Early in his career, the National Science Foundation named him a Presidential Young Investigator and he received The Engineering Foundation and the IEEE Faculty Initiation Award. He was selected in 2003 as one of the nation's top 160 engineers between the age of 30 and 45 by the National Academy of Engineering (NAE) to be an invited speaker at The Frontiers of Engineering Conference which was cosponsored by The Alexander von Humboldt Foundation. He is an alumnus of the Frontiers of Engineering of The National Academy of Engineering (2003). He has served on the Editorial Board of the Proceedings of the IEEE (ranked #1 among all electrical engineering journals), the advisory board of the IEEE Photonics Journal, and he was on the founding board of editors of the IEEE /OSA Journal of Display Technology.

A. Murat Tekalp (Fellow, IEEE) received the M.S. and Ph.D. degrees in electrical, computer, and systems engineering from Rensselaer Polytechnic Institute (RPI), Troy, NY, USA, in 1982 and 1984, respectively.

He was with Eastman Kodak Company, Rochester, NY, USA, from 1984 to 1987, and with the University of Rochester, Rochester, NY, USA, from July 1987 to June 2005, where he was promoted to Distinguished University Professor. Currently, he is a Professor of Electrical and Electronics Engineering at Koc University, Istanbul, Turkey. He served as Dean of Engineering between 2010 and 2013. He authored the book *Digital Video Processing* (Englewood Cliffs, NJ, USA: Prentice-Hall, 1995), the substantially revised second edition of which was published in 2015. His research interests are in digital image and video processing, including video compression and streaming, video filtering, super-resolution, video analysis, multiview, and 3-D video processing.

Prof. Tekalp was elected a member of Academia Europaea. He was named Distinguished Lecturer by the IEEE Signal Processing Society. He received the TUBITAK Science Award (highest scientific award in Turkey) in 2004 and Koc University Outstanding Faculty Award in 2016. He was the Editor-in-Chief of the *EURASIP Journal Signal Processing: Image Communication* published by Elsevier between 1999 and 2010. He served as an Associate Editor for the IEEE Transactions on Signal Processing (1990–1992) and the IEEE Transactions on Image Processing (1994–1996). He was on the Editorial Board of the IEEE Signal Processing Magazine (2007–2010). He has been on the Editorial Board of the Proceedings of the IEEE since 2014. He chaired the IEEE Signal Processing Society Technical Committee on Image and Multidimensional Signal Processing between January 1996 and December 1997. He was also a founding member of the IEEE Technical Committee on Multimedia Signal Processing in 1997 and served on the committee until 2002. He was the General Chair of IEEE ICIP 2002.