MULTIDIMENSIONAL OPTICAL SENSING, IMAGING, AND VISUALIZATION SYSTEMS (MOSIS)

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Overview of our Activities on Imaging

- 3D Display/Head Mounted Display-3D Smart Glasses
- 3D Profilometry, Visualization & Computational imaging
- Flexible 3D Sensing
- 3D Microscopy and Healthcare Applications
- 3D imaging in turbid water, 3D Tracking with Occlusion
- 3D Imaging with few photons
- Multimodal 3D: Polarimetric, spectral, compressive sensing
- Long range passive 3D imaging
- Automated Detection of biological micro organisms
- Healthcare Applications of 3D
- Quantum imaging & authentication
- Anti counterfeiting of Integrated Circuits

Our focus in this presentation

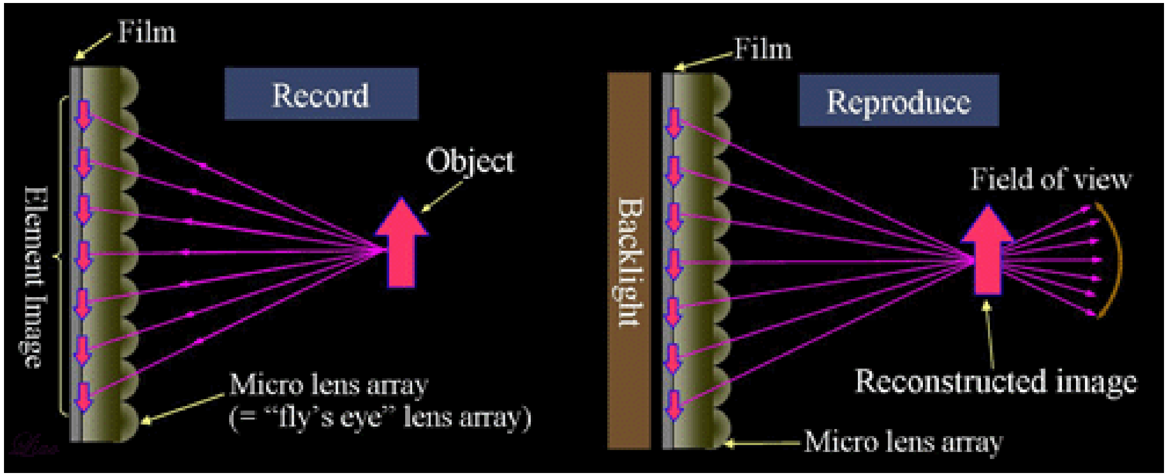
- 3D Image Capture & Display
- Dynamic 3D Integral Imaging to increase Field of View (FoV)
- Head Tracking to increase Field of View in 3D Integral Imaging
- Augmented Reality (Head Mounted) Display
- 3D Object Visualization with Smart Glasses
- Flexible 3D Sensing and Imaging
- 3D Imaging with few photons
- Long range passive 3D imaging

Computational Optical Sensing and 3D Display

Computational resources are used to obtain optical and physical information of interest

Integral Imaging

- Based on the concept of depth from disparity
- Multiple lenses form tiny images from their unique perspective
- Depth information encoded as transversal relative shift among images (disparity principle)
- Images can be captured on digital sensors
- Display is accomplished by back-projection of elemental images using display panels [LCD, etc]



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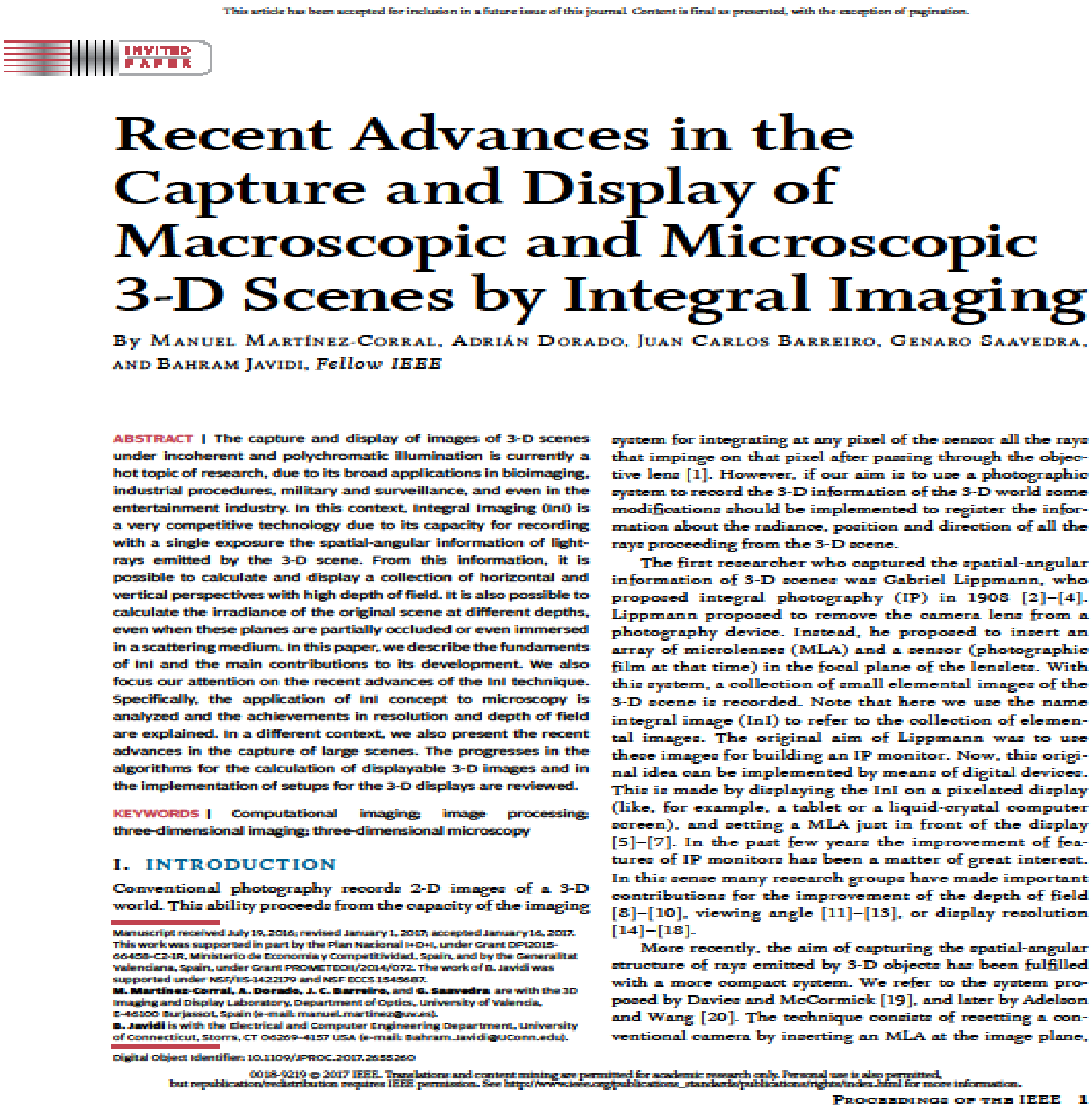

INVITED PAPER

Recent Advances in the Capture and Display of Macroscopic and Microscopic 3-D Scenes by Integral Imaging

By Manuel Martínez-Corral, Adrián Dorado, Juan Carlos Barreiro, Genaro Saavedra, and Bahram Javidi, *Fellow IEEE*

ABSTRACT | The capture and display of images of 3-D scenes under incoherent and polychromatic illumination is currently a hot topic of research, due to its broad applications in bioimaging, industrial procedures, military and surveillance, and even in the entertainment industry. In this context, Integral Imaging (InI) is a very competitive technology due to its capacity for recording with a single exposure the spatial-angular information of light-rays emitted by the 3-D scene. From this information, it is possible to calculate and display a collection of horizontal and vertical perspectives with high depth of field. It is also possible to calculate the irradiance of the original scene at different depths, even when these planes are partially occluded or even immersed in a scattering medium. In this paper, we describe the fundaments of InI and the main contributions to its development. We also focus our attention on the recent advances of the InI technique. Specifically, the application of InI concept to microscopy is analyzed and the achievements in resolution and depth of field are explained. In a different context, we also present the recent advances in the capture of large scenes. The progresses in the algorithms for the calculation of displayable 3-D images and in the implementation of setups for the 3-D displays are reviewed.

KEYWORDS | Computational imaging; image processing; three-dimensional imaging; three-dimensional microscopy

I. INTRODUCTION

Conventional photography records 2-D images of a 3-D world. This ability proceeds from the capacity of the imaging system for integrating at any pixel of the sensor all the rays that impinge on that pixel after passing through the objective lens [1]. However, if our aim is to use a photographic system to record the 3-D information of the 3-D world some modifications should be implemented to register the information about the radiance, position and direction of all the rays proceeding from the 3-D scene.

The first researcher who captured the spatial-angular information of 3-D scenes was Gabriel Lippmann, who proposed integral photography (IP) in 1908 [2]–[4]. Lippmann proposed to remove the camera lens from a photography device. Instead, he proposed to insert an array of microlenses (MLA) and a sensor (photographic film at that time) in the focal plane of the lenslets. With this system, a collection of small elemental images of the 3-D scene is recorded. Note that here we use the name integral image (InI) to refer to the collection of elemental images. The original aim of Lippmann was to use these images for building an IP monitor. Now, this original idea can be implemented by means of digital devices. This is made by displaying the InI on a pixelated display (like, for example, a tablet or a liquid-crystal computer screen), and setting a MLA just in front of the display [5]–[7]. In the past few years the improvement of features of IP monitors has been a matter of great interest. In this sense many research groups have made important contributions for the improvement of the depth of field [8]–[10], viewing angle [11]–[13], or display resolution [14]–[18].

More recently, the aim of capturing the spatial-angular structure of rays emitted by 3-D objects has been fulfilled with a more compact system. We refer to the system proposed by Davies and McCormick [19], and later by Adelson and Wang [20]. The technique consists of resetting a conventional camera by inserting an MLA at the image plane,

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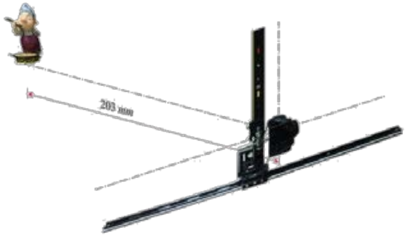
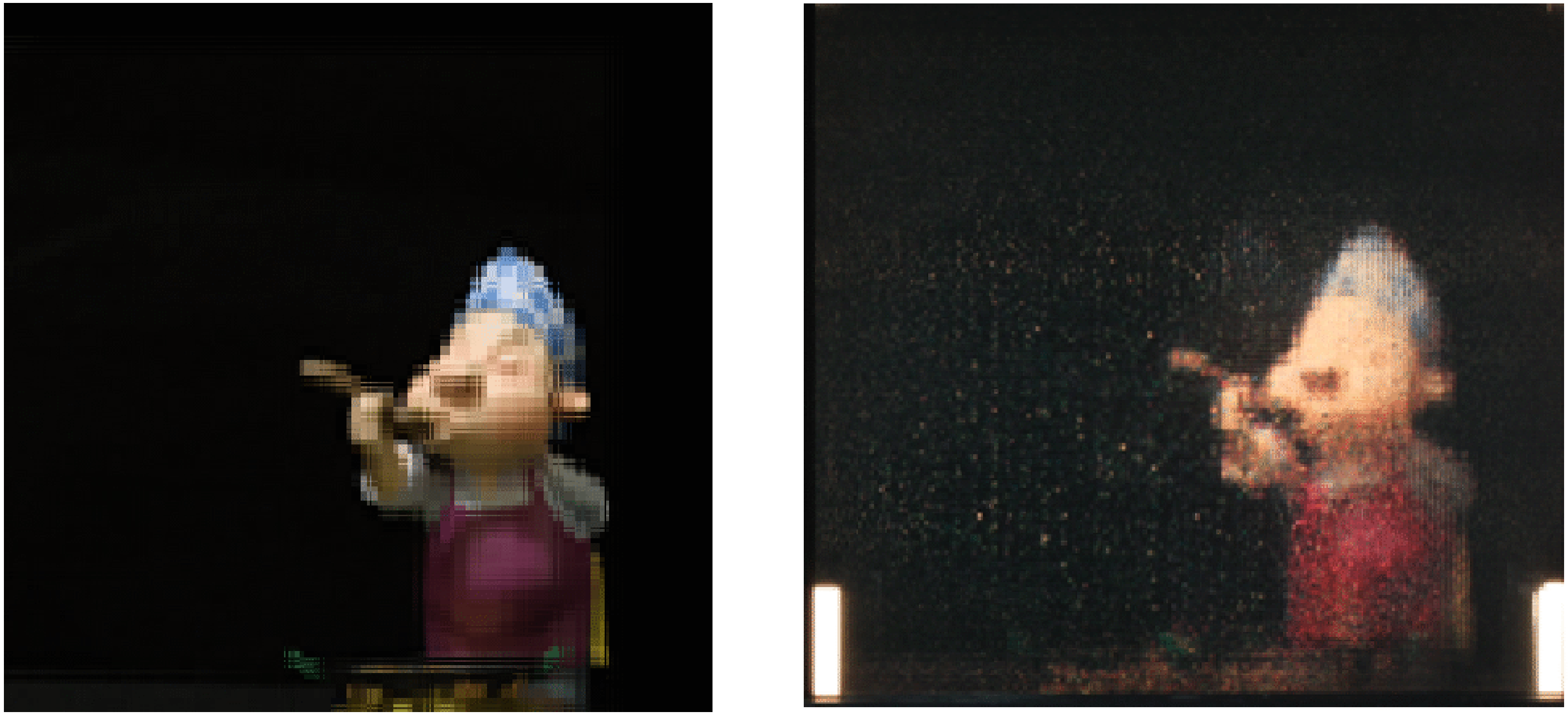
Integral Imaging 3D Visualization and Display



R. Martinez-Cuenca, G. Saavedra, M. Martinez-Corral, B. Javidi, “Progress in 3-D Multiperspective Display by Integral Imaging,” Proceedings of IEEE Journal, 97, 2009.



Intergal Imaging Display
- Full parallax; - Continuous view point; - No special glasses
- No visual fatigue and abnormal effects

M. Daneshpanah, B. Javidi, E. Watson, “3 D integral imaging with randomly distributed sensors,” Optics Express, 2008

• Views are randomly selected

- No assumption on the distribution of the sensors, however, the distribution affects imaging capabilities.
- In this example, uniform distribution is assumed.
- The blue path shows the moving direction of the image sensor. Red nodes denote the random pickup locations.

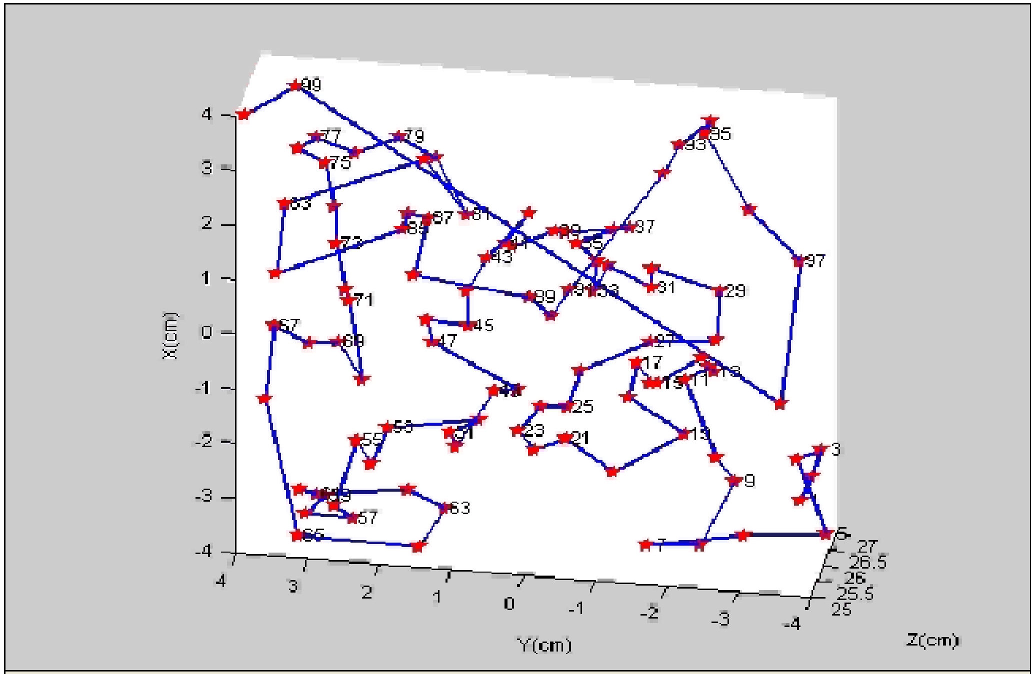
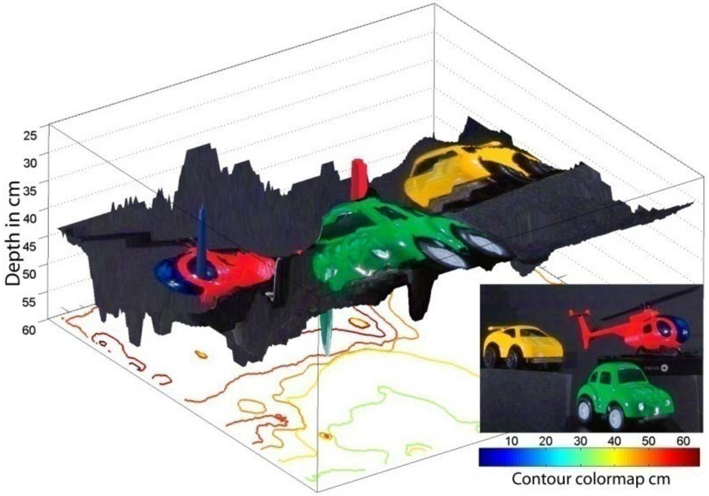
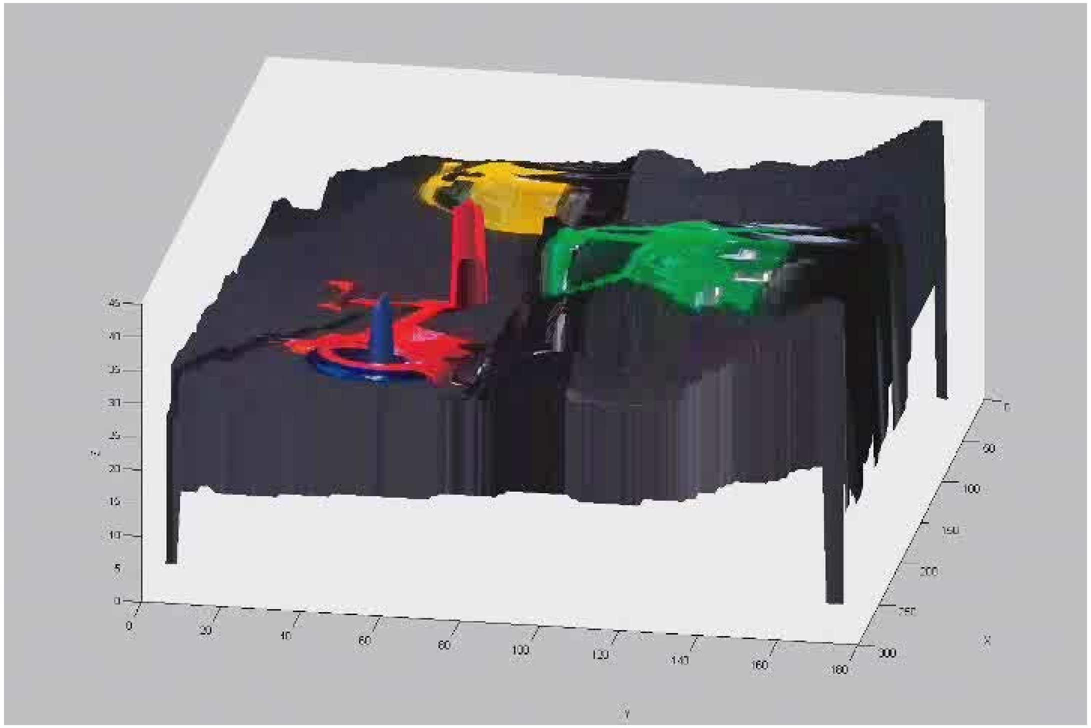


Fig2

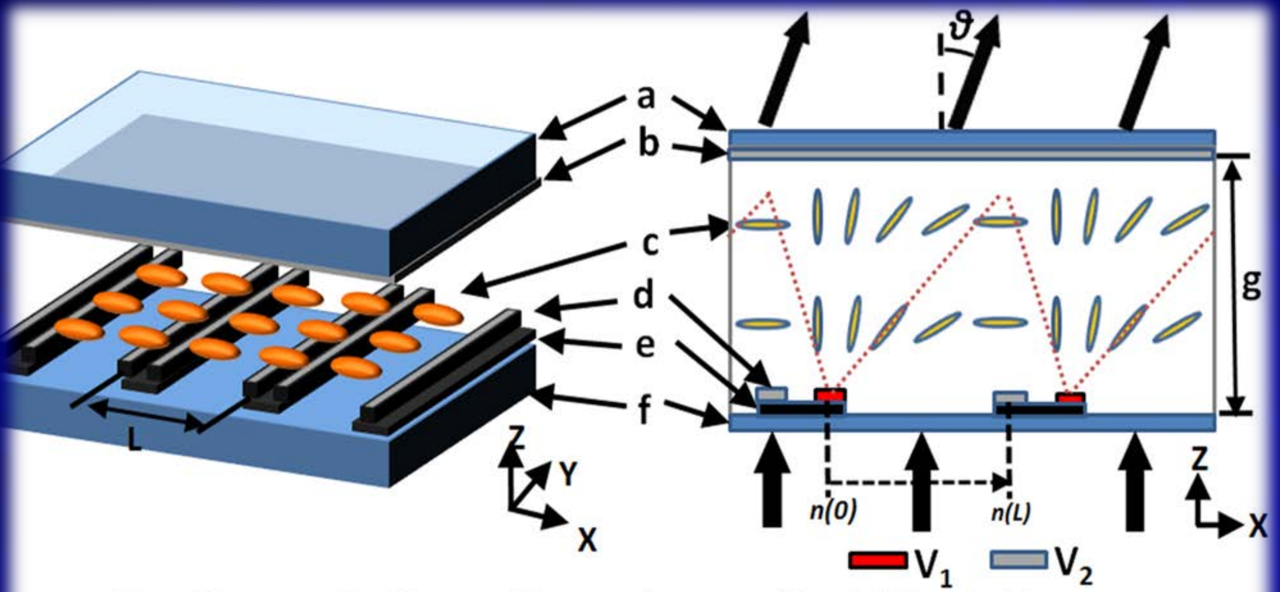
Profilometry and Optical Slicing (M. Daneshpanah and B. Javidi, “ Profilometry and optical slicing by passive 3D imaging,” Optics Letters, Vol. 34, 1 April 2009)

Specular points deviate from Lambertian assumption.





Dynamic Integral Imaging Displays by Liquid Crystal Device to Improve FoV



a: Top Glass ; b: Planar Electrode ; c: Liquid Crystal Layer
d: Controlled Electrodes; e: Black Matrix; f: Bottom Glass ;
g: Cell Gap;

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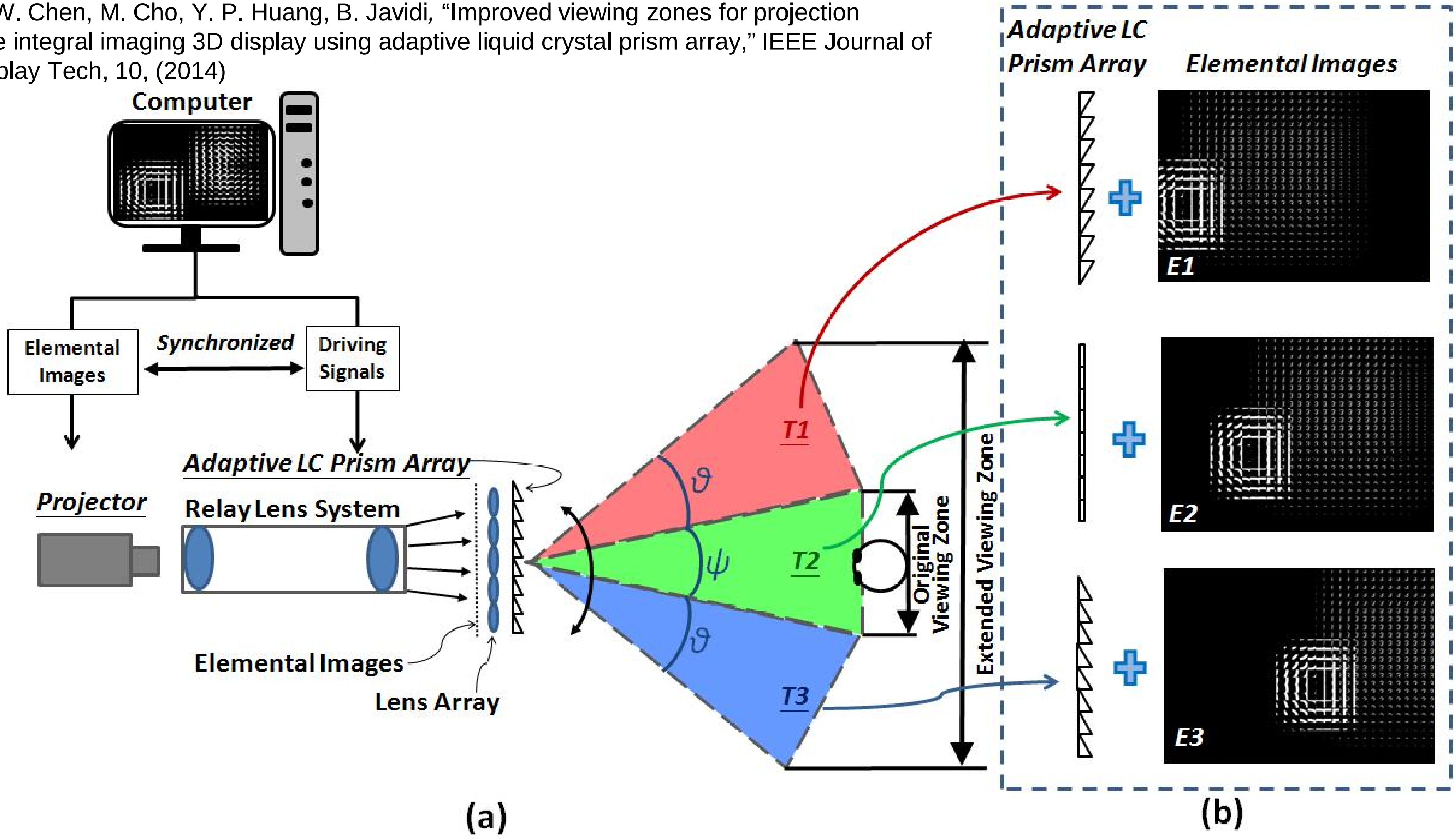
Extended Field of View by LC prism

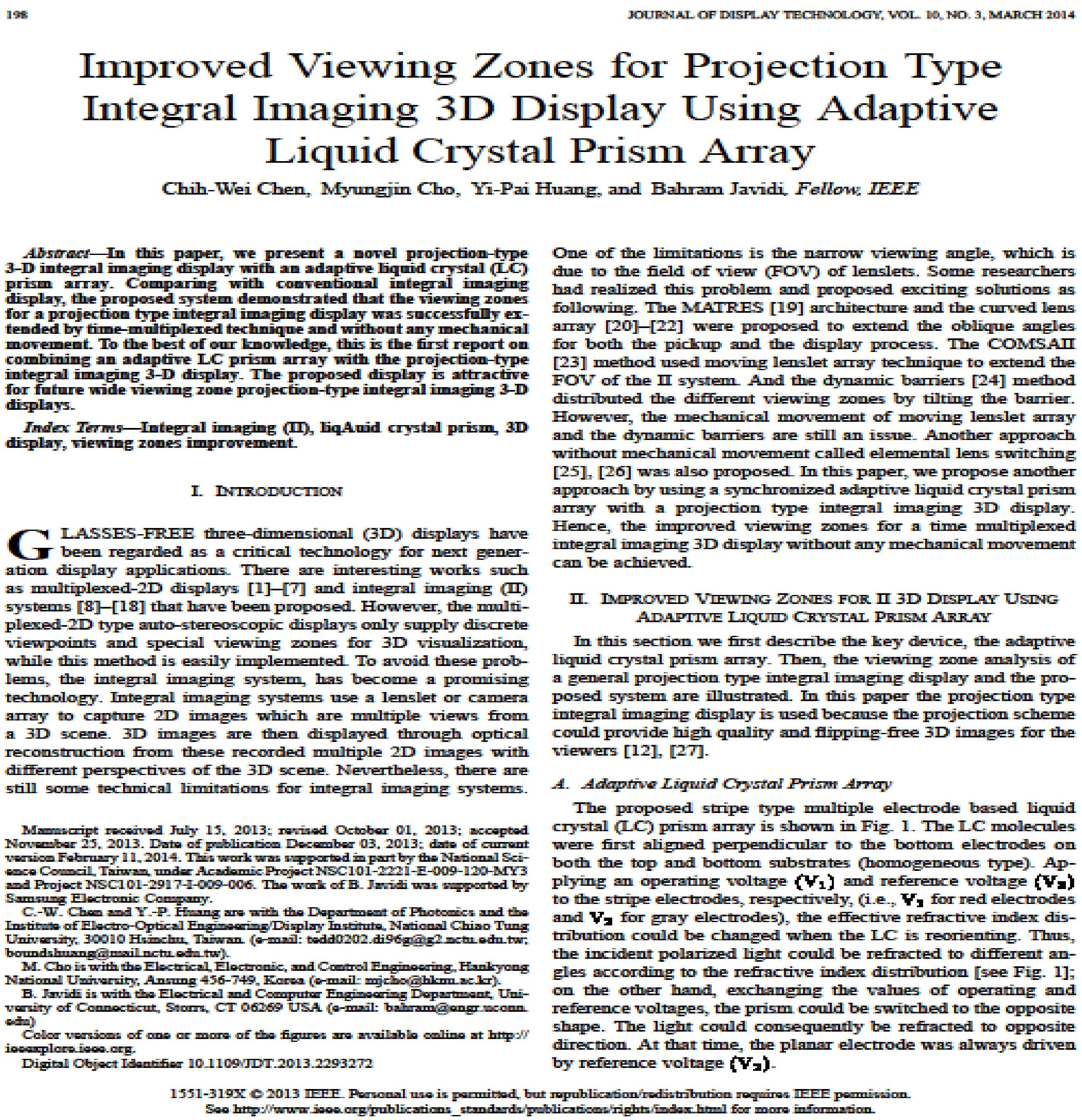
C. W. Chen, M. Cho, Y. P. Huang, B. Javidi, “Improved viewing zones for projection type integral imaging 3D display using adaptive liquid crystal prism array,” IEEE Journal of Display Tech, 10, (2014)



$\theta = \tan^{-1}(\Delta n * d / L)$

$\Psi = 2\tan^{-1}(p/2f)$

Total Viewing Angle $\Phi_{max} = (\psi + 2\,\theta)$



Improved Viewing Zones for Projection Type Integral Imaging 3D Display Using Adaptive Liquid Crystal Prism Array

Chih-Wei Chen, Myungjin Cho, Yi-Pai Huang, and Bahram Javidi, *Fellow, IEEE*

***Abstract*—In this paper, we present a novel projection-type 3-D integral imaging display with an adaptive liquid crystal (LC) prism array. Comparing with conventional integral imaging display, the proposed system demonstrated that the viewing zones for a projection type integral imaging display was successfully extended by time-multiplexed technique and without any mechanical movement. To the best of our knowledge, this is the first report on combining an adaptive LC prism array with the projection-type integral imaging 3-D display. The proposed display is attractive for future wide viewing zone projection-type integral imaging 3-D displays.**

***Index Terms*—Integral imaging (II), liqAuid crystal prism, 3D display, viewing zones improvement.**

I. INTRODUCTION

GLASSES-FREE three-dimensional (3D) displays have been regarded as a critical technology for next generation display applications. There are interesting works such as multiplexed-2D displays [1]–[7] and integral imaging (II) systems [8]–[18] that have been proposed. However, the multiplexed-2D type auto-stereoscopic displays only supply discrete viewpoints and special viewing zones for 3D visualization, while this method is easily implemented. To avoid these problems, the integral imaging system, has become a promising technology. Integral imaging systems use a lenslet or camera array to capture 2D images which are multiple views from a 3D scene. 3D images are then displayed through optical reconstruction from these recorded multiple 2D images with different perspectives of the 3D scene. Nevertheless, there are still some technical limitations for integral imaging systems. One of the limitations is the narrow viewing angle, which is due to the field of view (FOV) of lenslets. Some researchers had realized this problem and proposed exciting solutions as following. The MATRES [19] architecture and the curved lens array [20]–[22] were proposed to extend the oblique angles for both the pickup and the display process. The COMSAII [23] method used moving lenslet array technique to extend the FOV of the II system. And the dynamic barriers [24] method distributed the different viewing zones by tilting the barrier. However, the mechanical movement of moving lenslet array and the dynamic barriers are still an issue. Another approach without mechanical movement called elemental lens switching [25], [26] was also proposed. In this paper, we propose another approach by using a synchronized adaptive liquid crystal prism array with a projection type integral imaging 3D display. Hence, the improved viewing zones for a time multiplexed integral imaging 3D display without any mechanical movement can be achieved.

II. IMPROVED VIEWING ZONES FOR II 3D DISPLAY USING ADAPTIVE LIQUID CRYSTAL PRISM ARRAY

In this section we first describe the key device, the adaptive liquid crystal prism array. Then, the viewing zone analysis of a general projection type integral imaging display and the proposed system are illustrated. In this paper the projection type integral imaging display is used because the projection scheme could provide high quality and flipping-free 3D images for the viewers [12], [27].

A. Adaptive Liquid Crystal Prism Array

The proposed stripe type multiple electrode based liquid crystal (LC) prism array is shown in Fig. 1. The LC molecules were first aligned perpendicular to the bottom electrodes on both the top and bottom substrates (homogeneous type). Applying an operating voltage $(\mathbf{V_1})$ and reference voltage $(\mathbf{V_2})$ to the stripe electrodes, respectively, (i.e., $\mathbf{V_1}$ for red electrodes and $\mathbf{V_2}$ for gray electrodes), the effective refractive index distribution could be changed when the LC is reorienting. Thus, the incident polarized light could be refracted to different angles according to the refractive index distribution [see Fig. 1]; on the other hand, exchanging the values of operating and reference voltages, the prism could be switched to the opposite shape. The light could consequently be refracted to opposite direction. At that time, the planar electrode was always driven by reference voltage $(\mathbf{V_2})$.

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Color versions of one or more of the figures are available online at http://ieeexplore.ieee.org.

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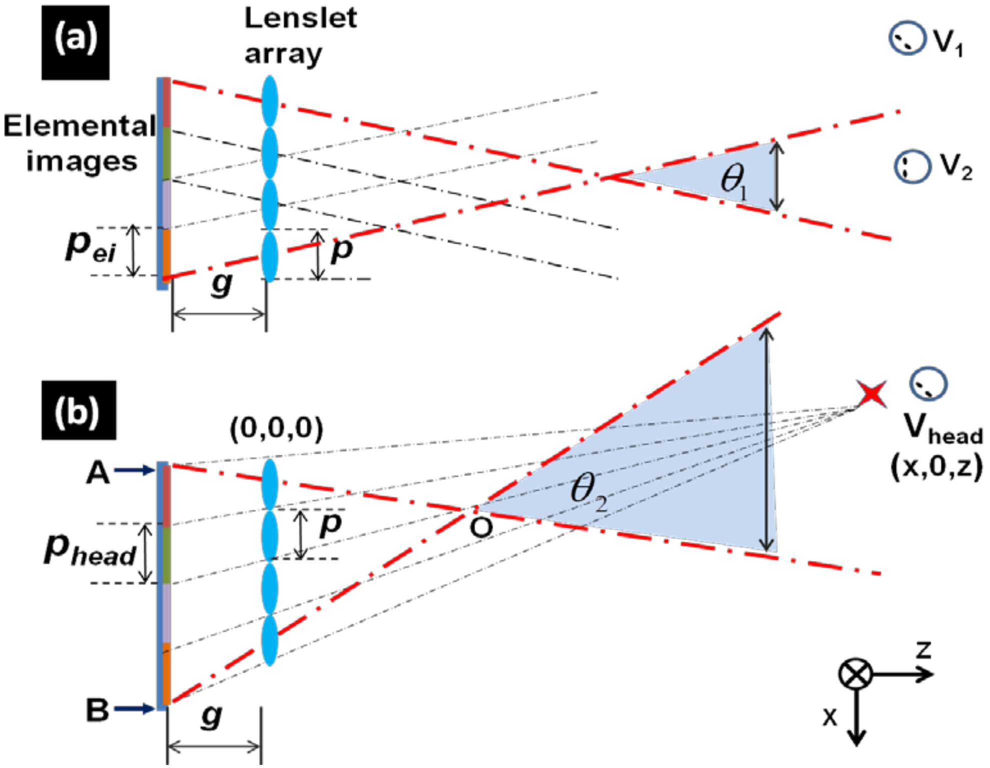
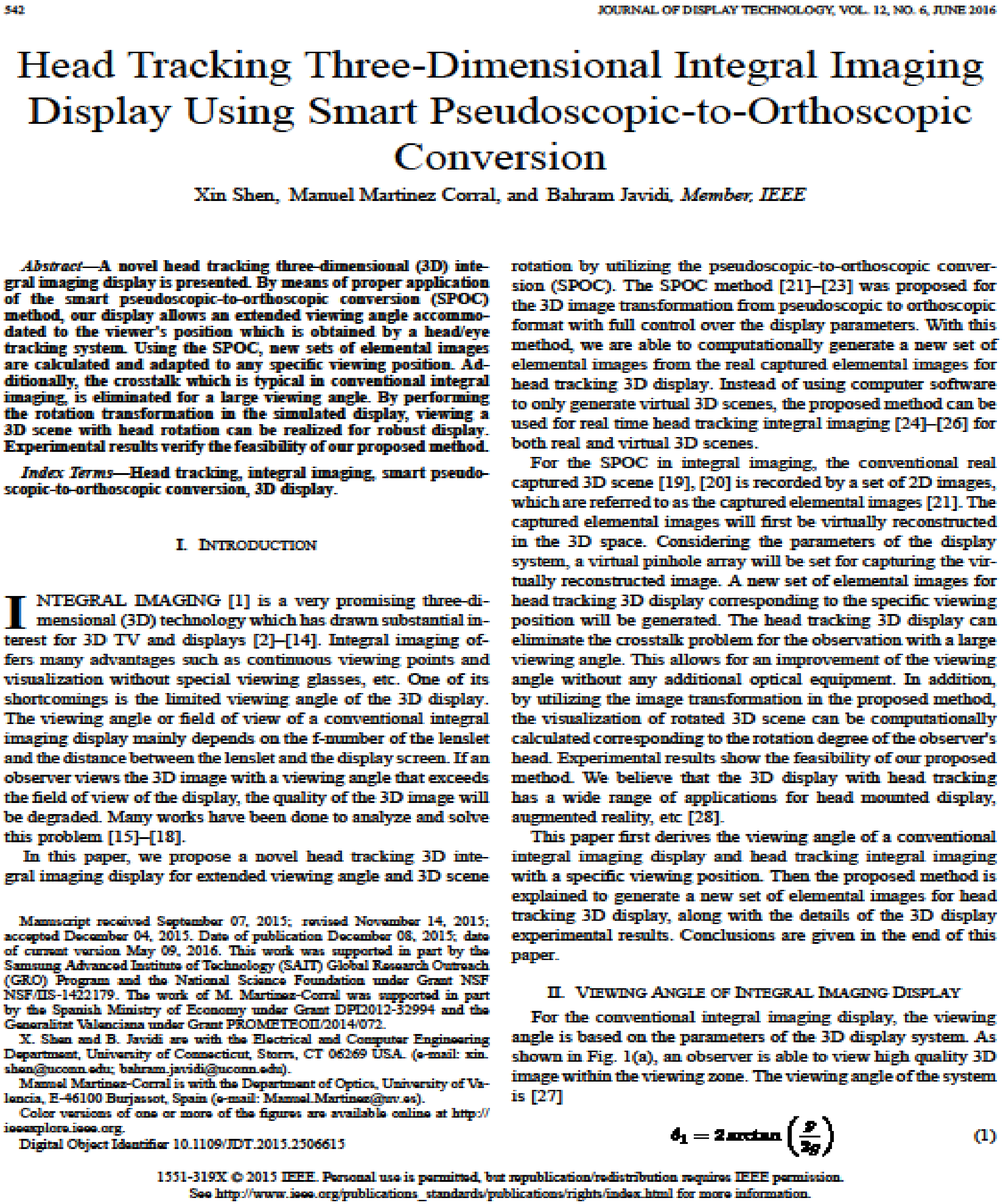
Head tracking integral imaging display

Acknowledgement: Dr. DongKyung Nam



X. Shen, M. Martinez-Corral, B. Javidi, “Head Tracking Three-Dimensional Integral Imaging Display Using Smart Pseudoscopic-to-Orthoscopic Conversion,” IEEE/OSA Journal of Display Technology, June 2016.

The viewing angle of an integral imaging display. (a) For the conventional integral imaging. (b) For the head tracking integral imaging with a specific viewing position. p is the pitch of the lenslet, p_{ei} and p_{head} are the elemental image size of conventional and head tracking display, respectively. θ_1 and θ_2 are the viewing angle of conventional and head tracking integral imaging, respectively.



Head Tracking Three-Dimensional Integral Imaging Display Using Smart Pseudoscopic-to-Orthoscopic Conversion

Xin Shen, Manuel Martinez Corral, and Bahram Javidi, *Member, IEEE*

***Abstract*—A novel head tracking three-dimensional (3D) integral imaging display is presented. By means of proper application of the smart pseudoscopic-to-orthoscopic conversion (SPOC) method, our display allows an extended viewing angle accommodated to the viewer's position which is obtained by a head/eye tracking system. Using the SPOC, new sets of elemental images are calculated and adapted to any specific viewing position. Additionally, the crosstalk which is typical in conventional integral imaging, is eliminated for a large viewing angle. By performing the rotation transformation in the simulated display, viewing a 3D scene with head rotation can be realized for robust display. Experimental results verify the feasibility of our proposed method.**

***Index Terms*—Head tracking, integral imaging, smart pseudoscopic-to-orthoscopic conversion, 3D display.**

I. INTRODUCTION

INTEGRAL IMAGING [1] is a very promising three-dimensional (3D) technology which has drawn substantial interest for 3D TV and displays [2]–[14]. Integral imaging offers many advantages such as continuous viewing points and visualization without special viewing glasses, etc. One of its shortcomings is the limited viewing angle of the 3D display. The viewing angle or field of view of a conventional integral imaging display mainly depends on the f-number of the lenslet and the distance between the lenslet and the display screen. If an observer views the 3D image with a viewing angle that exceeds the field of view of the display, the quality of the 3D image will be degraded. Many works have been done to analyze and solve this problem [15]–[18].

In this paper, we propose a novel head tracking 3D integral imaging display for extended viewing angle and 3D scene rotation by utilizing the pseudoscopic-to-orthoscopic conversion (SPOC). The SPOC method [21]–[23] was proposed for the 3D image transformation from pseudoscopic to orthoscopic format with full control over the display parameters. With this method, we are able to computationally generate a new set of elemental images from the real captured elemental images for head tracking 3D display. Instead of using computer software to only generate virtual 3D scenes, the proposed method can be used for real time head tracking integral imaging [24]–[26] for both real and virtual 3D scenes.

For the SPOC in integral imaging, the conventional real captured 3D scene [19], [20] is recorded by a set of 2D images, which are referred to as the captured elemental images [21]. The captured elemental images will first be virtually reconstructed in the 3D space. Considering the parameters of the display system, a virtual pinhole array will be set for capturing the virtually reconstructed image. A new set of elemental images for head tracking 3D display corresponding to the specific viewing position will be generated. The head tracking 3D display can eliminate the crosstalk problem for the observation with a large viewing angle. This allows for an improvement of the viewing angle without any additional optical equipment. In addition, by utilizing the image transformation in the proposed method, the visualization of rotated 3D scene can be computationally calculated corresponding to the rotation degree of the observer's head. Experimental results show the feasibility of our proposed method. We believe that the 3D display with head tracking has a wide range of applications for head mounted display, augmented reality, etc [28].

This paper first derives the viewing angle of a conventional integral imaging display and head tracking integral imaging with a specific viewing position. Then the proposed method is explained to generate a new set of elemental images for head tracking 3D display, along with the details of the 3D display experimental results. Conclusions are given in the end of this paper.

II. VIEWING ANGLE OF INTEGRAL IMAGING DISPLAY

For the conventional integral imaging display, the viewing angle is based on the parameters of the 3D display system. As shown in Fig. 1(a), an observer is able to view high quality 3D image within the viewing zone. The viewing angle of the system is [27]

$$\theta_1 = 2\arctan\left(\frac{p}{2g}\right) \qquad (1)$$

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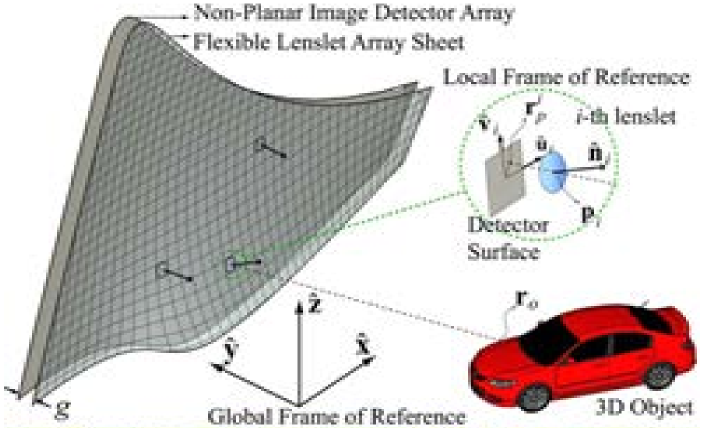
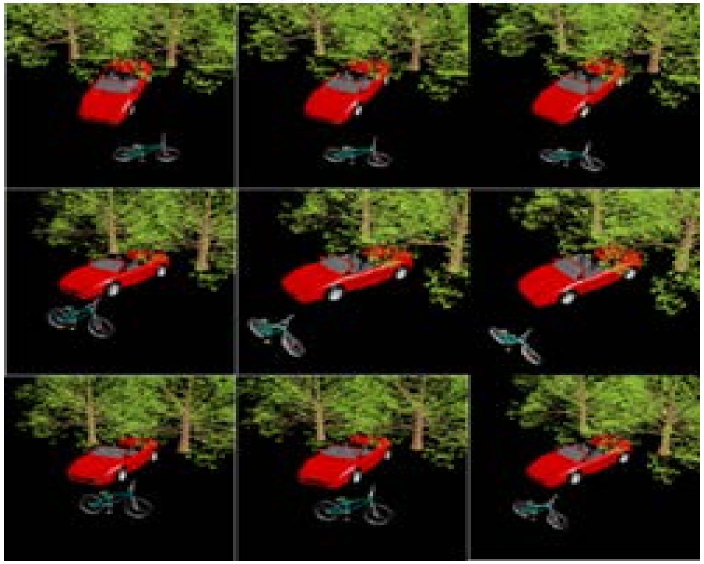
Digital Object Identifier 10.1109/JDT.2015.2506615

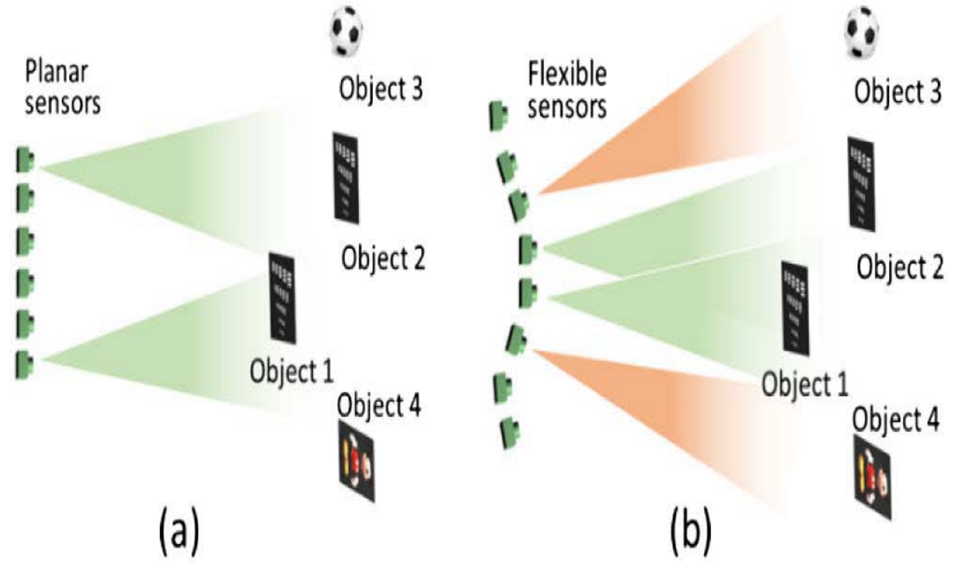
3D Imaging with Flexible Sensing

M. Daneshpanah, B. Javidi, “3D imaging with detector arrays on arbitrarily shaped surfaces,” Optics Letters, 36,2011.

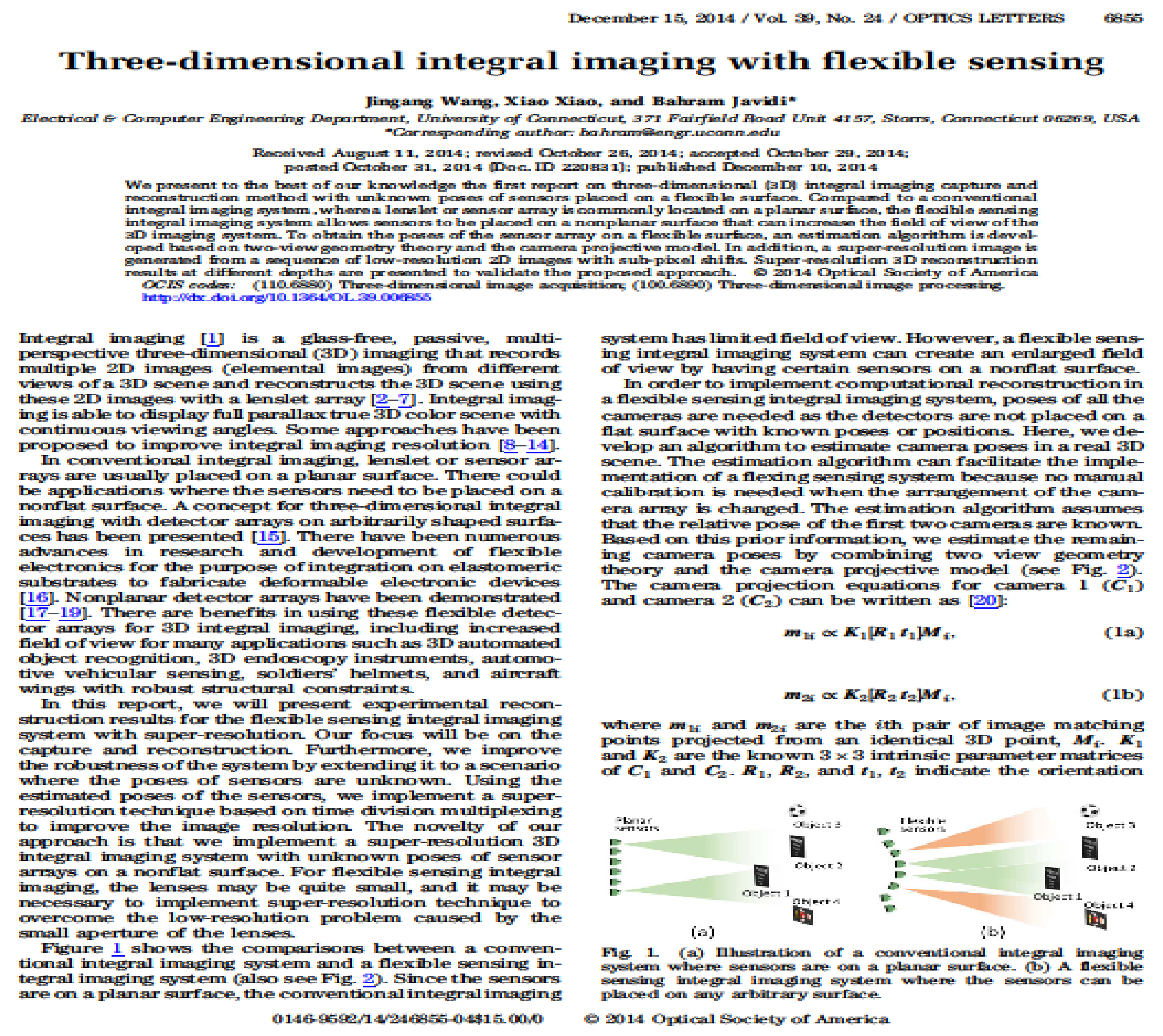




Collaboration with Univ. Michigan, Northwestern, Washington



Conventional (a) vs Flexible Imager (b)



December 15, 2014 / Vol. 39, No. 24 / OPTICS LETTERS 6855

Three-dimensional integral imaging with flexible sensing

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We present to the best of our knowledge the first report on three-dimensional (3D) integral imaging capture and reconstruction method with unknown poses of sensors placed on a flexible surface. Compared to a conventional integral imaging system, where a lenslet or sensor array is commonly located on a planar surface, the flexible sensing integral imaging system allows sensors to be placed on a nonplanar surface that can increase the field of view of the 3D imaging system. To obtain the poses of the sensor array on a flexible surface, an estimation algorithm is developed based on two-view geometry theory and the camera projective model. In addition, a super-resolution image is generated from a sequence of low-resolution 2D images with sub-pixel shifts. Super-resolution 3D reconstruction results at different depths are presented to validate the proposed approach.

OCIS codes: (110.6880) Three-dimensional image acquisition; (100.6890) Three-dimensional image processing.
http://dx.doi.org/10.1364/OL.39.006855

Integral imaging [1] is a glass-free, passive, multi-perspective three-dimensional (3D) imaging that records multiple 2D images (elemental images) from different views of a 3D scene and reconstructs the 3D scene using these 2D images with a lenslet array [2–7]. Integral imaging is able to display full parallax true 3D color scene with continuous viewing angles. Some approaches have been proposed to improve integral imaging resolution [8–14].

In conventional integral imaging, lenslet or sensor arrays are usually placed on a planar surface. There could be applications where the sensors need to be placed on a nonflat surface. A concept for three-dimensional integral imaging with detector arrays on arbitrarily shaped surfaces has been presented [15]. There have been numerous advances in research and development of flexible electronics for the purpose of integration on elastomeric substrates to fabricate deformable electronic devices [16]. Nonplanar detector arrays have been demonstrated [17–19]. There are benefits in using these flexible detector arrays for 3D integral imaging, including increased field of view for many applications such as 3D automated object recognition, 3D endoscopy instruments, automotive vehicular sensing, soldiers' helmets, and aircraft wings with robust structural constraints.

In this report, we will present experimental reconstruction results for the flexible sensing integral imaging system with super-resolution. Our focus will be on the capture and reconstruction. Furthermore, we improve the robustness of the system by extending it to a scenario where the poses of sensors are unknown. Using the estimated poses of the sensors, we implement a super-resolution technique based on time division multiplexing to improve the image resolution. The novelty of our approach is that we implement a super-resolution 3D integral imaging system with unknown poses of sensor arrays on a nonflat surface. For flexible sensing integral imaging, the lenses may be quite small, and it may be necessary to implement super-resolution technique to overcome the low-resolution problem caused by the small aperture of the lenses.

Figure 1 shows the comparisons between a conventional integral imaging system and a flexible sensing integral imaging system (also see Fig. 2). Since the sensors are on a planar surface, the conventional integral imaging system has limited field of view. However, a flexible sensing integral imaging system can create an enlarged field of view by having certain sensors on a nonflat surface.

In order to implement computational reconstruction in a flexible sensing integral imaging system, poses of all the cameras are needed as the detectors are not placed on a flat surface with known poses or positions. Here, we develop an algorithm to estimate camera poses in a real 3D scene. The estimation algorithm can facilitate the implementation of a flexing sensing system because no manual calibration is needed when the arrangement of the camera array is changed. The estimation algorithm assumes that the relative pose of the first two cameras are known. Based on this prior information, we estimate the remaining camera poses by combining two view geometry theory and the camera projective model (see Fig. 2). The camera projection equations for camera 1 (C_1) and camera 2 (C_2) can be written as [20]:

$$\boldsymbol{m}_{1i} \propto \boldsymbol{K}_1[\boldsymbol{R}_1\ \boldsymbol{t}_1]\boldsymbol{M}_i, \tag{1a}$$

$$\boldsymbol{m}_{2i} \propto \boldsymbol{K}_2[\boldsymbol{R}_2\ \boldsymbol{t}_2]\boldsymbol{M}_i, \tag{1b}$$

where $\boldsymbol{m}_{1i}$ and $\boldsymbol{m}_{2i}$ are the ith pair of image matching points projected from an identical 3D point, $\boldsymbol{M}_i$. $\boldsymbol{K}_1$ and $\boldsymbol{K}_2$ are the known 3×3 intrinsic parameter matrices of $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$. $\boldsymbol{R}_1$, $\boldsymbol{R}_2$, and $\boldsymbol{t}_1$, $\boldsymbol{t}_2$ indicate the orientation

Fig. 1. (a) Illustration of a conventional integral imaging system where sensors are on a planar surface. (b) A flexible sensing integral imaging system where the sensors can be placed on any arbitrary surface.

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H. Hua, B. Javidi, “3D integral imaging optical see-through head-mounted display," Optics Express, **22**, June 2, 2014]
Was highlighted on Optics Infobase [OSA’s Digital Library]

Optics InfoBase

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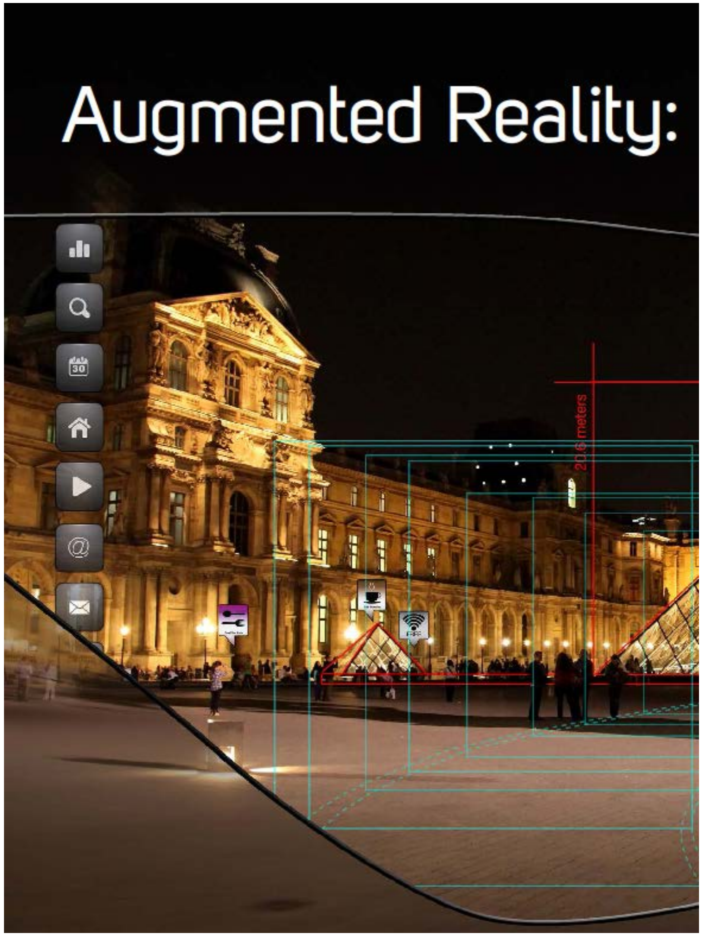
Sight for Sore Eyes: Augmented Reality without the Discomfort

New goggle-like device may lead to 3-D augmented reality technology that minimizes visual fatigue.

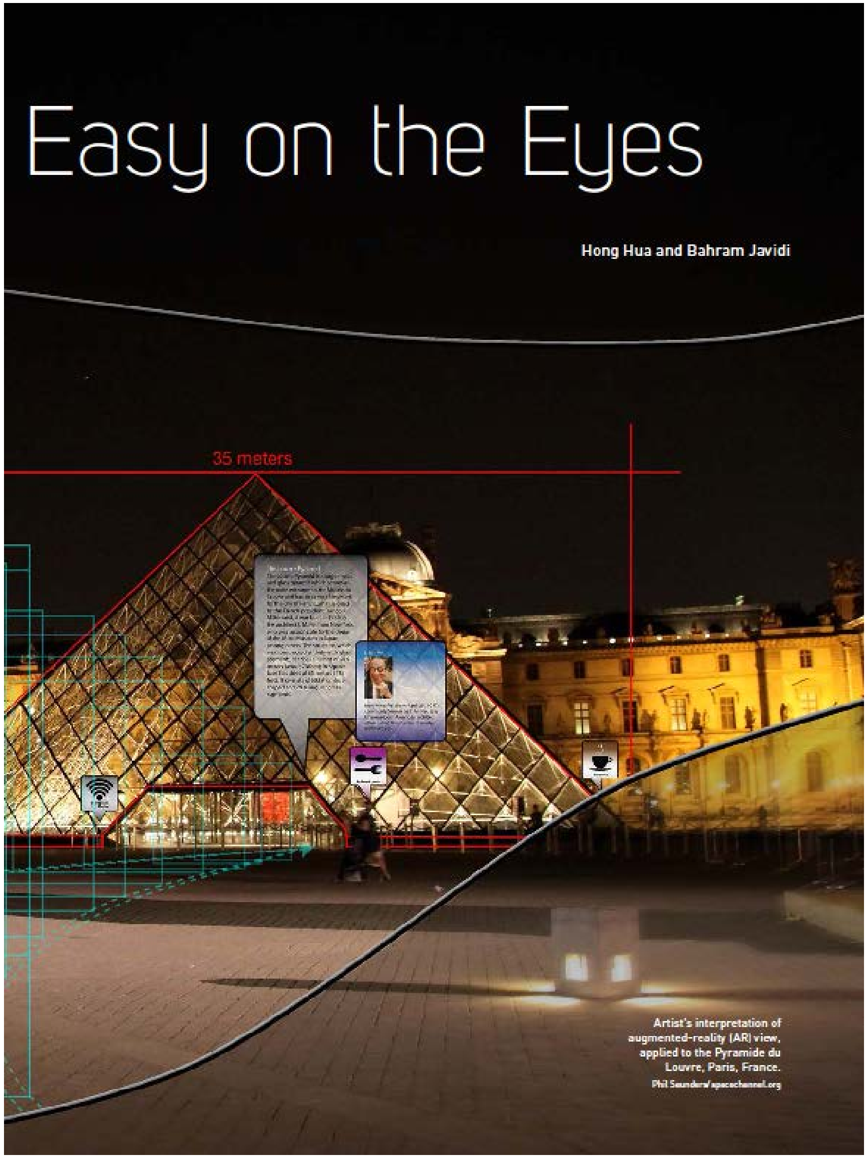
Announcements

- **May 28 2014 :** Sight for Sore Eyes: Augmented Reality without the Discomfort - Augmented reality is increasingly becoming... well ... a reality.... more
- **May 21 2014 :** Skinny Lens Makes Cheap Surve Home Use - A team of Fr has found a way to make

H. Hua and B. Javidi, OPN Feb 2015



Augmented Reality:



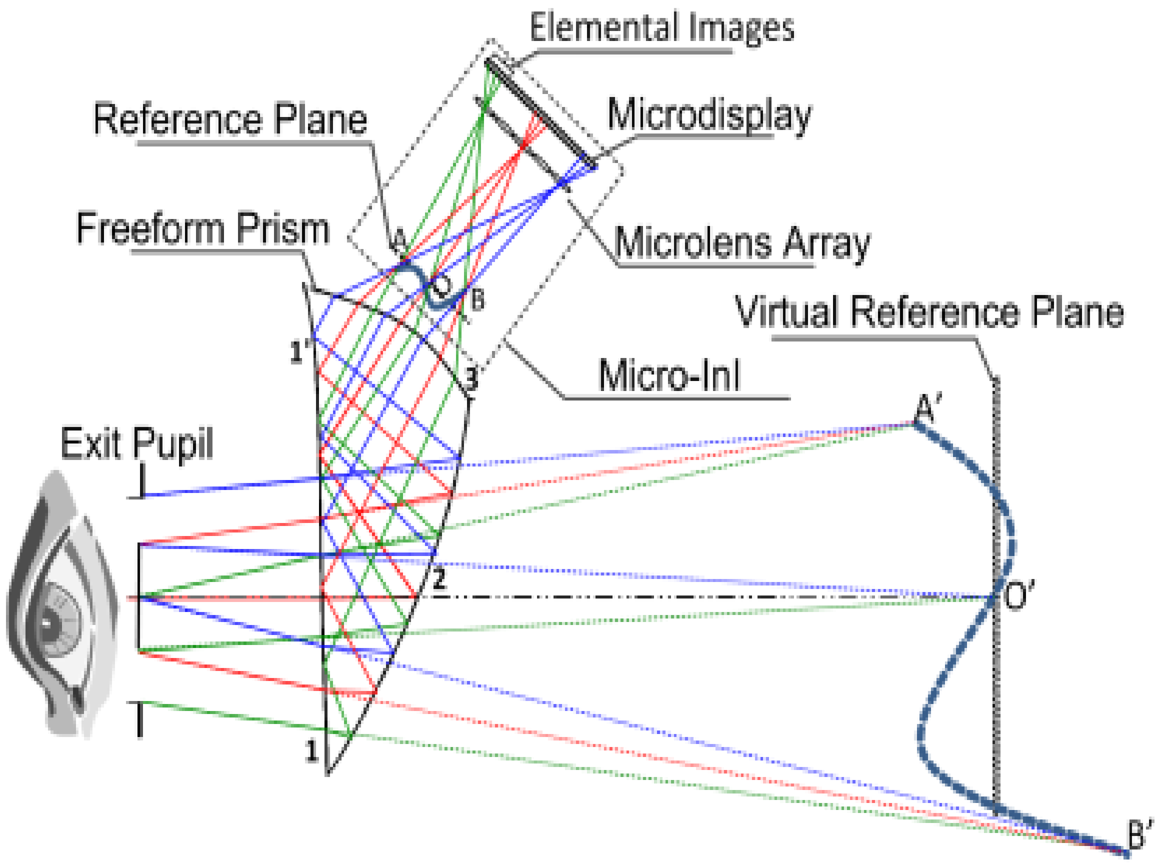
Easy on the Eyes

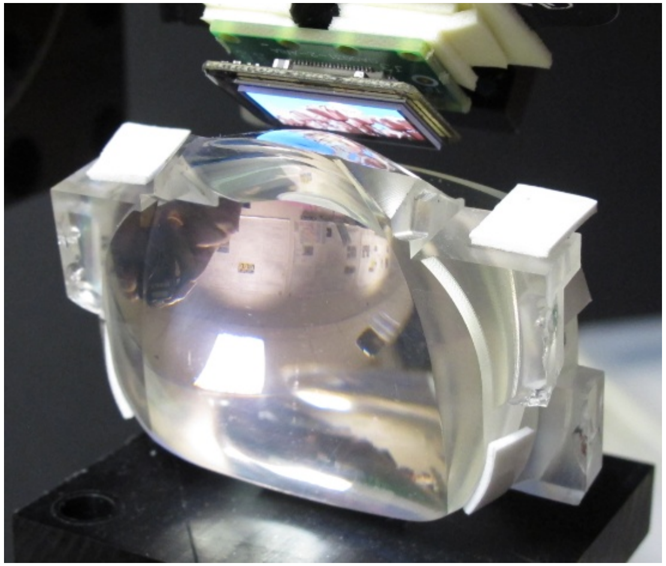
Hong Hua and Bahram Javidi

Artist's interpretation of augmented-reality (AR) view, applied to the Pyramide du Louvre, Paris, France.

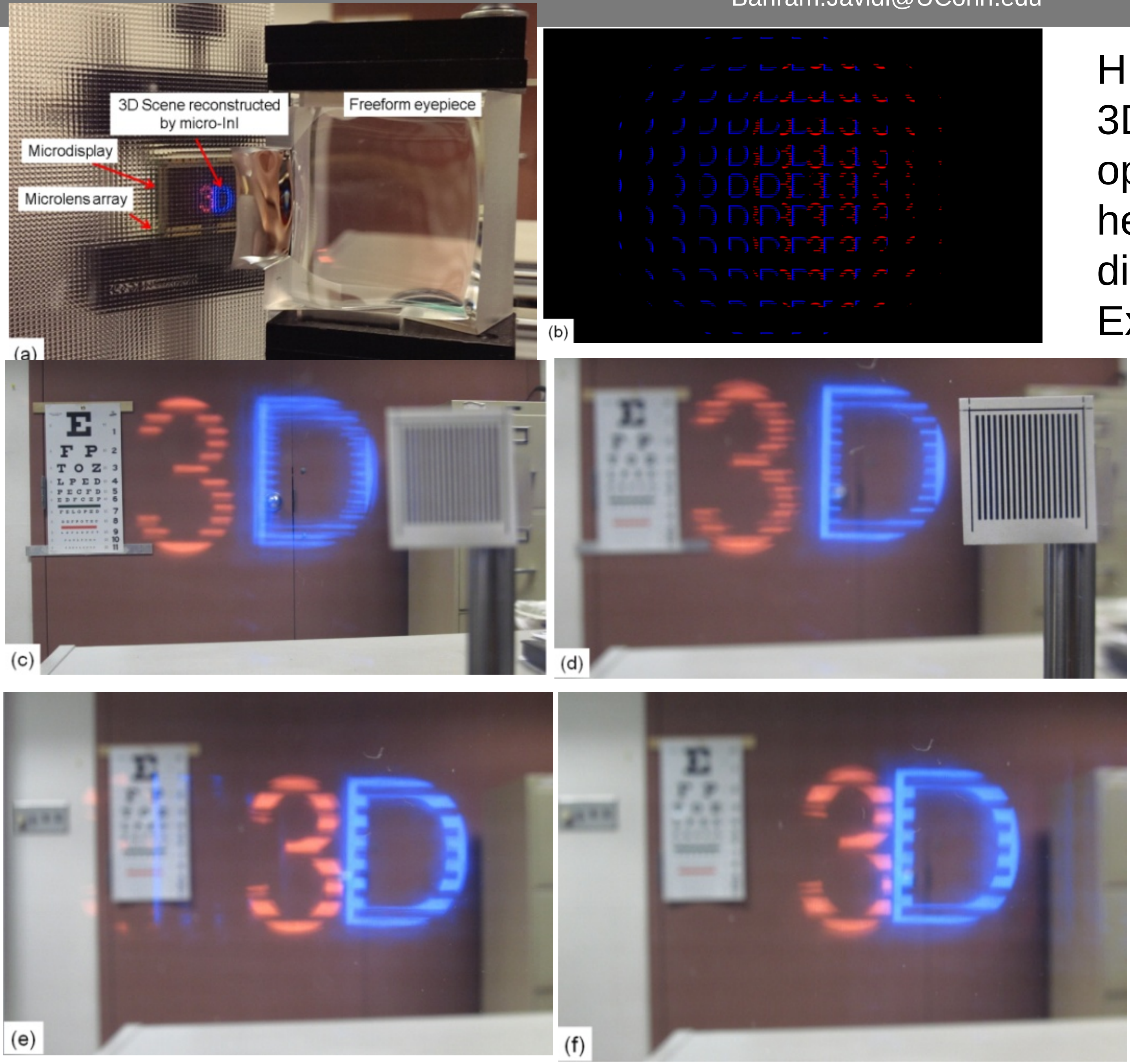
Phil Saunders/spacechannel.org

3D Augmented Reality Viewing Devices-Fatigue Free





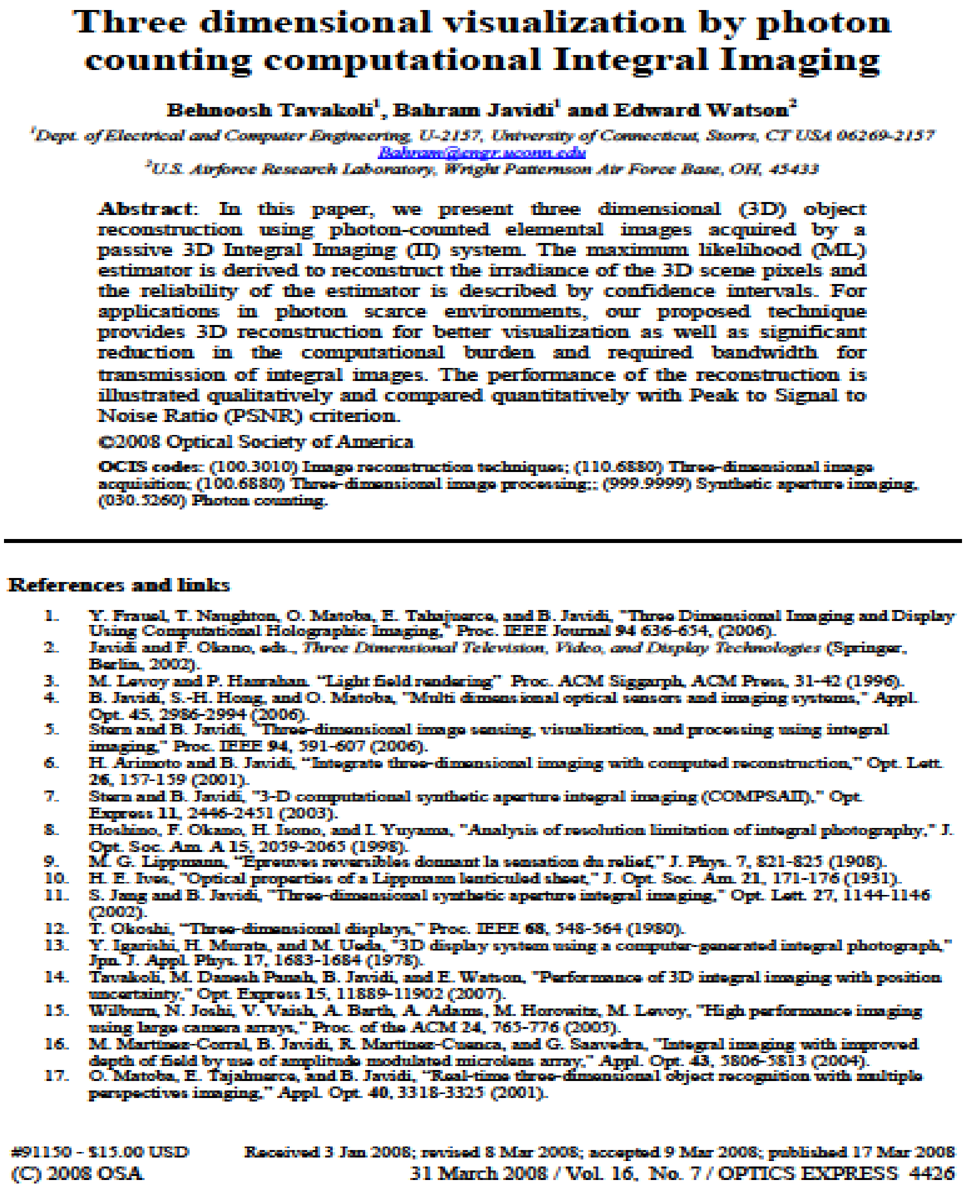
H. Hua, B. Javidi, “Augmented Reality: Easy on the Eyes,” Optics and Photonics News Magazine, February 2015.



H. Hua, B. Javidi, "3D integral imaging optical see-through head-mounted display," Optics Express, **22**, 2014]

3D Reconstruction in Photon Starved Scenery

Reconstruction using photon-counted elemental images, (Top left) scene with large photon flux; (top right) central elemental image with N_p=1000, (bottom) corresponding 3D reconstruction at the plane of the VW.



Three dimensional visualization by photon counting computational Integral Imaging

Behnoosh Tavakoli[1], **Bahram Javidi**[1] **and Edward Watson**[2]

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Abstract: In this paper, we present three dimensional (3D) object reconstruction using photon-counted elemental images acquired by a passive 3D Integral Imaging (II) system. The maximum likelihood (ML) estimator is derived to reconstruct the irradiance of the 3D scene pixels and the reliability of the estimator is described by confidence intervals. For applications in photon scarce environments, our proposed technique provides 3D reconstruction for better visualization as well as significant reduction in the computational burden and required bandwidth for transmission of integral images. The performance of the reconstruction is illustrated qualitatively and compared quantitatively with Peak to Signal to Noise Ratio (PSNR) criterion.

OCIS codes: (100.3010) Image reconstruction techniques; (110.6880) Three-dimensional image acquisition; (100.6880) Three-dimensional image processing;; (999.9999) Synthetic aperture imaging. (030.5260) Photon counting.

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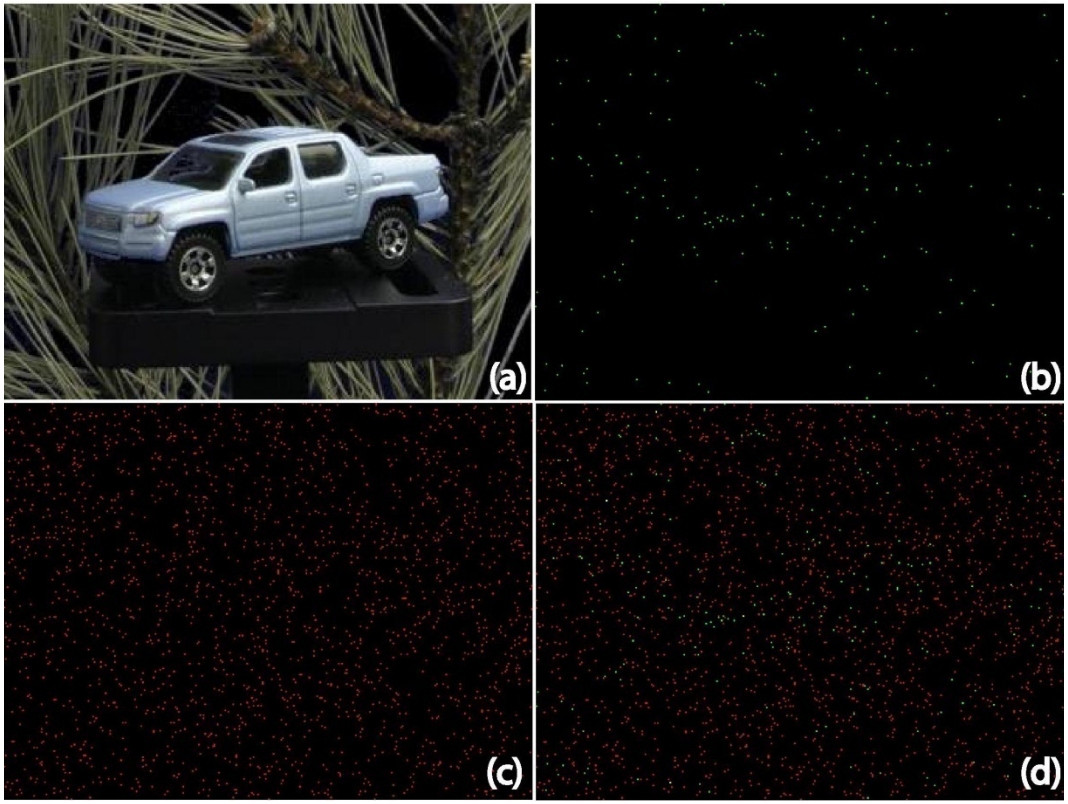
#91150 - $15.00 USD Received 3 Jan 2008; revised 8 Mar 2008; accepted 9 Mar 2008; published 17 Mar 2008

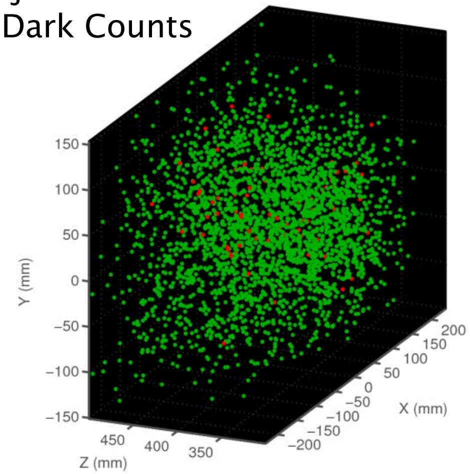
3D Object Recognition under Extremely Low Light Levels

Photon counted integral imaging appears robust to noise. Signal counts/dark counts < 0.04

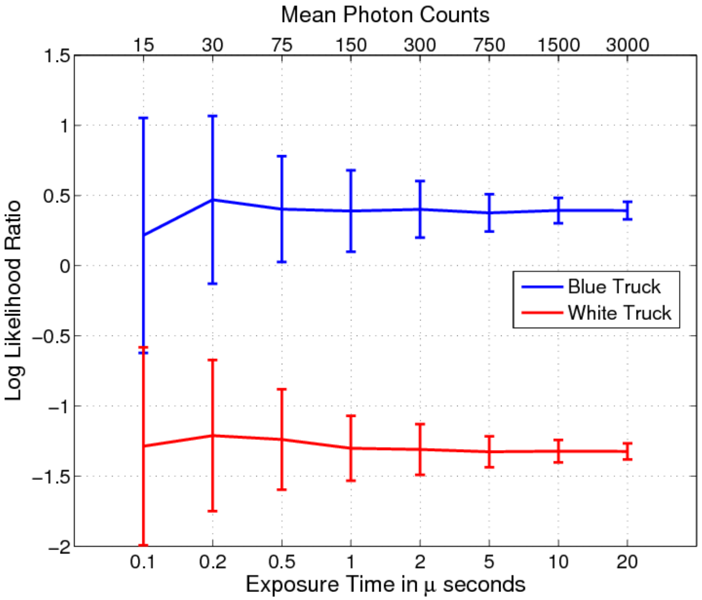
M. DaneshPanah, B. Javidi, and E. A. Watson, “Three dimensional object recognition with photon counting imagery in the presence of noise,” Optics Express (2010)



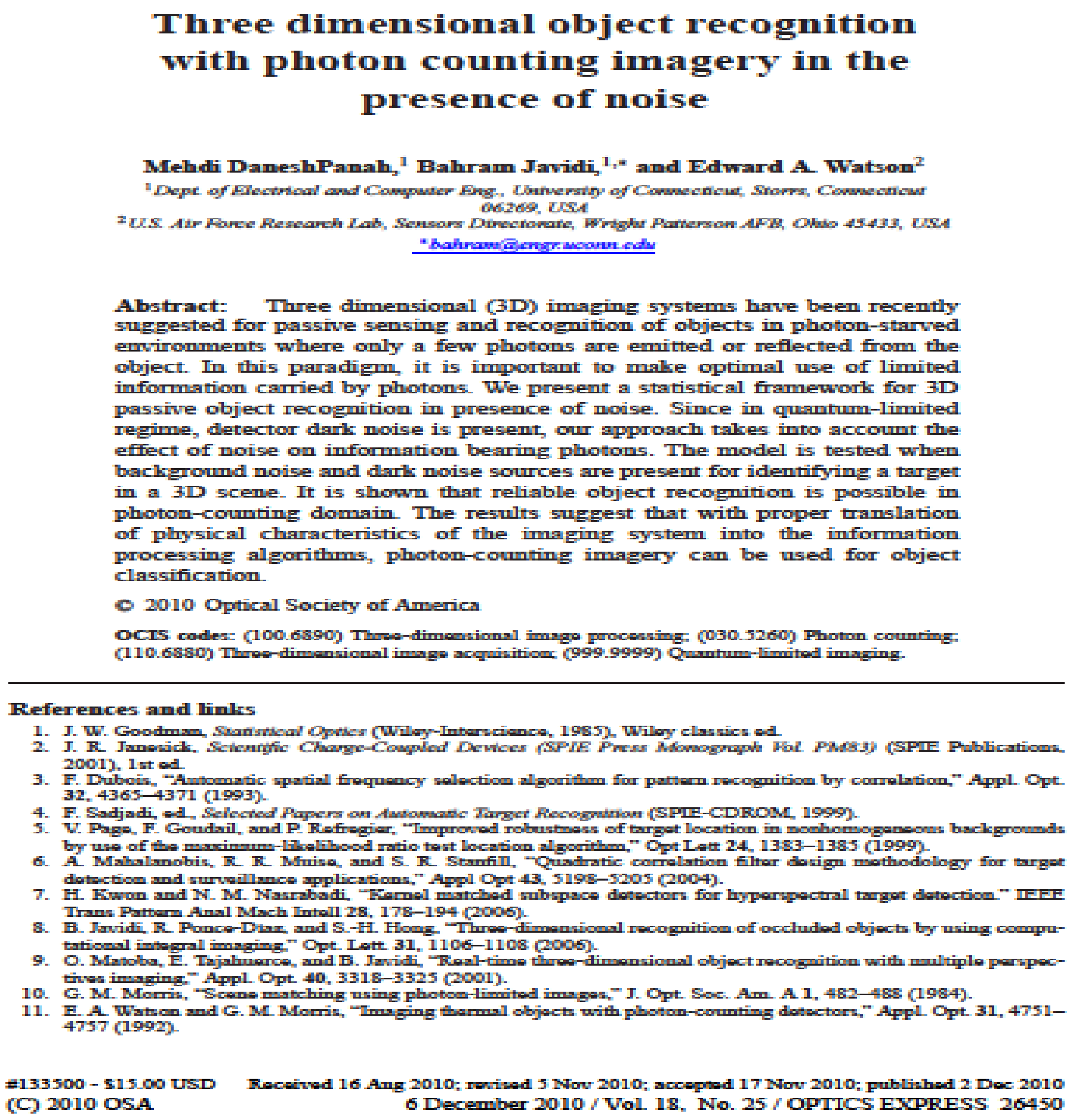
From 121 El. Images
~100 photons, ~2500 dark counts
Red: Object Photons
Green: Dark Counts



(b)



(d)



Three dimensional object recognition with photon counting imagery in the presence of noise

Mehdi DaneshPanah,[1] **Bahram Javidi,**[1,*] **and Edward A. Watson**[2]
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Abstract: Three dimensional (3D) imaging systems have been recently suggested for passive sensing and recognition of objects in photon-starved environments where only a few photons are emitted or reflected from the object. In this paradigm, it is important to make optimal use of limited information carried by photons. We present a statistical framework for 3D passive object recognition in presence of noise. Since in quantum-limited regime, detector dark noise is present, our approach takes into account the effect of noise on information bearing photons. The model is tested when background noise and dark noise sources are present for identifying a target in a 3D scene. It is shown that reliable object recognition is possible in photon-counting domain. The results suggest that with proper translation of physical characteristics of the imaging system into the information processing algorithms, photon-counting imagery can be used for object classification.

OCIS codes: (100.6890) Three-dimensional image processing; (030.5260) Photon counting; (110.6880) Three-dimensional image acquisition; (999.9999) Quantum-limited imaging.

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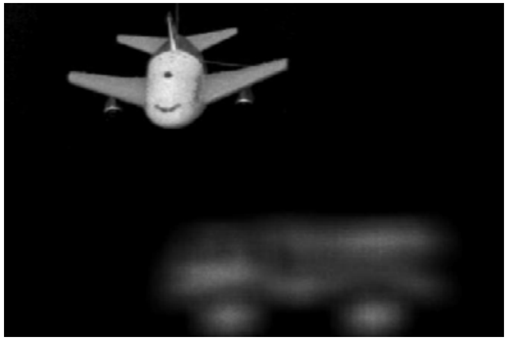
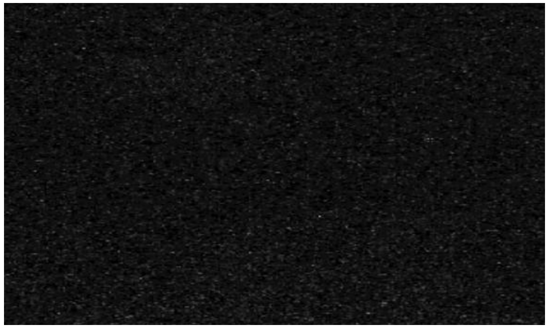
#133500 - $15.00 USD Received 16 Aug 2010; revised 5 Nov 2010; accepted 17 Nov 2010; published 2 Dec 2010
(C) 2010 OSA 6 December 2010 / Vol. 18, No. 25 / OPTICS EXPRESS 26450

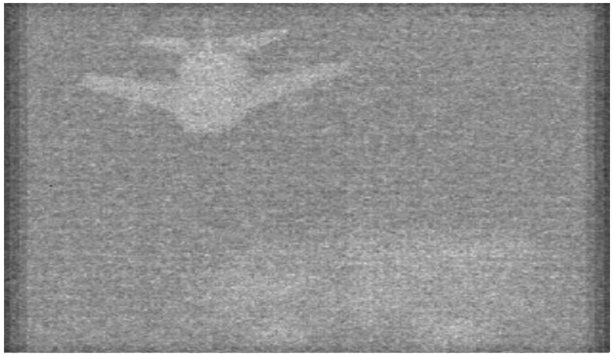
3D Photon Counting Experiments using Cooled CCD camera



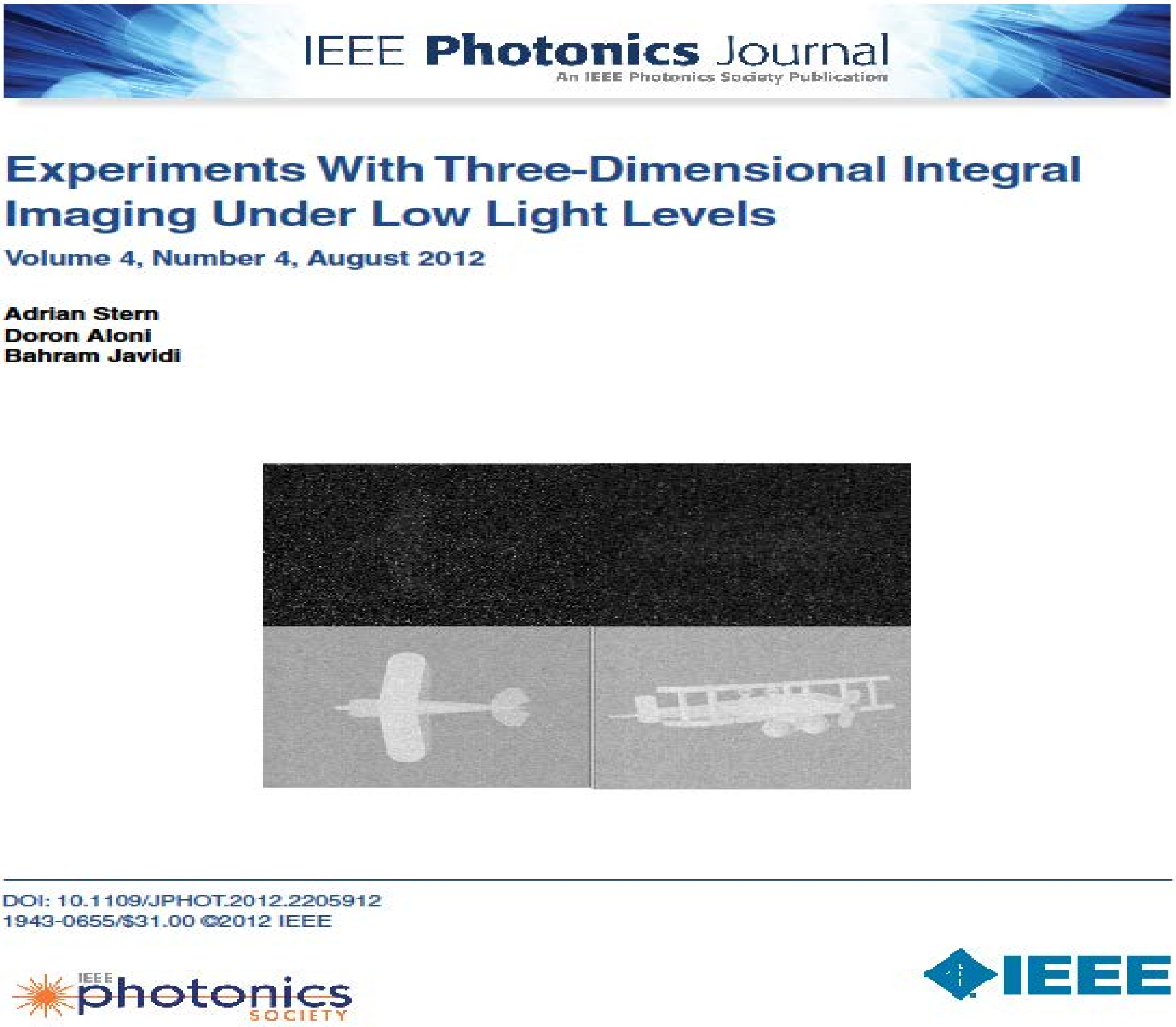
3D Reconstruction with Large photon flux



Low photon flux elemental image 3.8 photons/pixel



3D reconstruction



IEEE Photonics Journal
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Experiments With Three-Dimensional Integral Imaging Under Low Light Levels

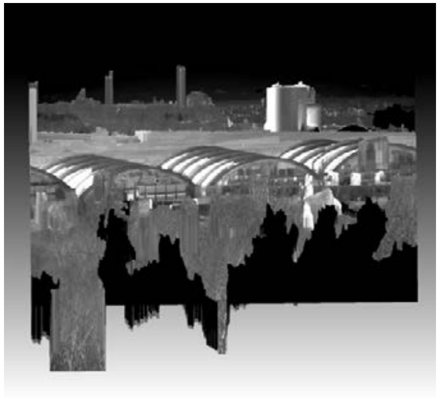
Volume 4, Number 4, August 2012

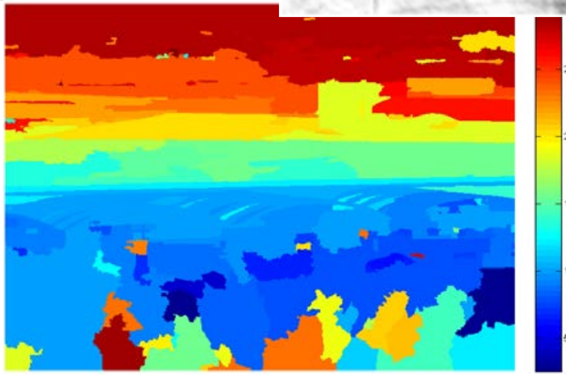
Adrian Stern
Doron Aloni
Bahram Javidi

DOI: 10.1109/JPHOT.2012.2205912
1943-0655/$31.00 ©2012 IEEE

Long Range (kms) 3D Integral Imaging (Passive Sensing): Task Specific Sensing (ATR, Tracking)

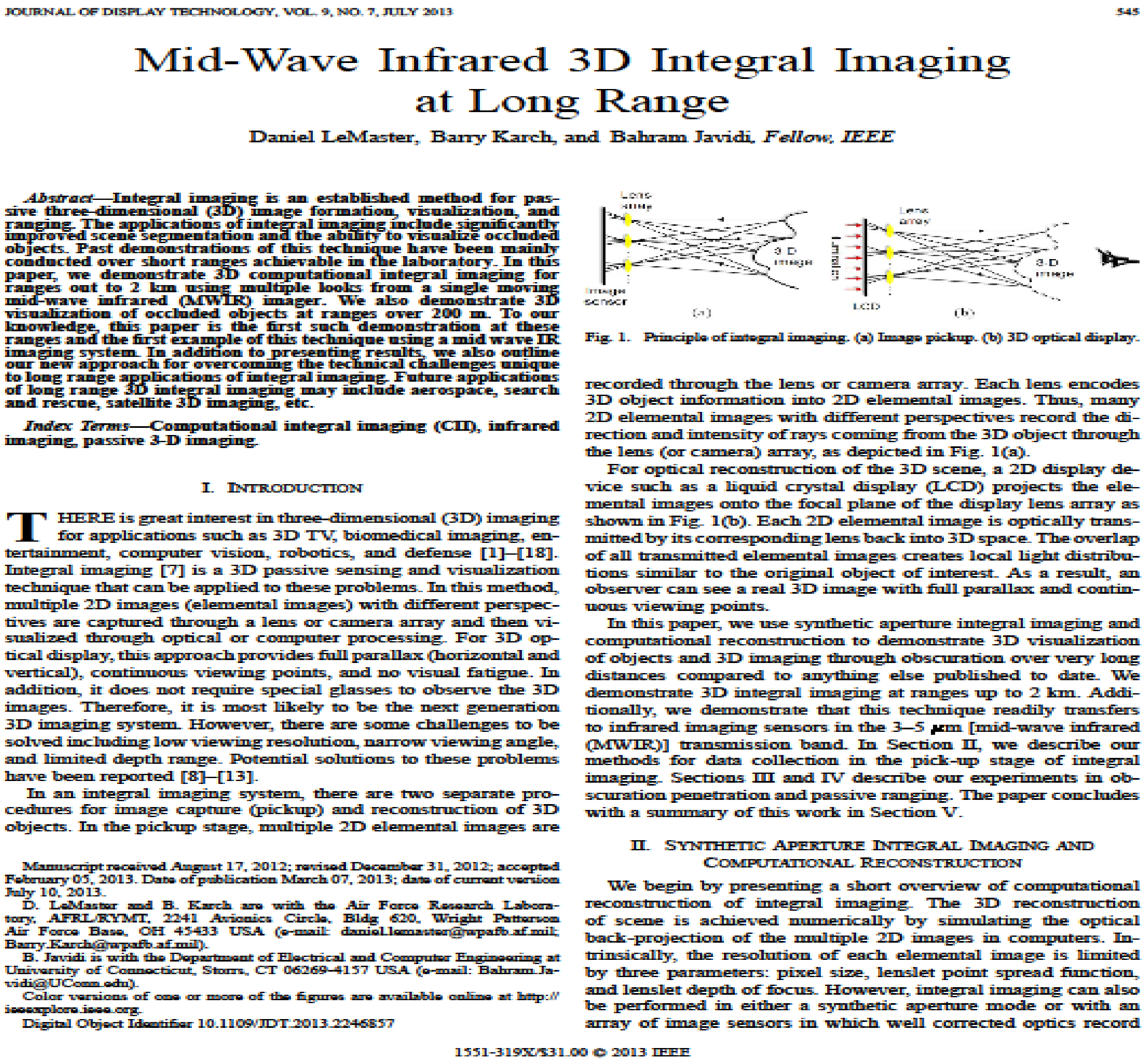
Tests were conducted from the AFRL Sensors Directorate tower and camera rail (Daniel LeMaster, Barry Karch, and B. Javidi, "Passive Long Range 3-D Integral Imaging," Proceedings of the Parallel Military Sensing Symposium (SENSIAC, 2012))





Range Map and Scene Projection: computational integral imaging

D. LeMaster, B. Karch, B. Javidi, "Mid-Wave Infrared 3D Integral Imaging at Long Range," IEEE Journal of Display Tech, 2013



JOURNAL OF DISPLAY TECHNOLOGY, VOL. 9, NO. 7, JULY 2013 545

Mid-Wave Infrared 3D Integral Imaging at Long Range

Daniel LeMaster, Barry Karch, and Bahram Javidi, *Fellow, IEEE*

***Abstract*—Integral imaging is an established method for passive three-dimensional (3D) image formation, visualization, and ranging. The applications of integral imaging include significantly improved scene segmentation and the ability to visualize occluded objects. Past demonstrations of this technique have been mainly conducted over short ranges achievable in the laboratory. In this paper, we demonstrate 3D computational integral imaging for ranges out to 2 km using multiple looks from a single moving mid-wave infrared (MWIR) imager. We also demonstrate 3D visualization of occluded objects at ranges over 200 m. To our knowledge, this paper is the first such demonstration at these ranges and the first example of this technique using a mid wave IR imaging system. In addition to presenting results, we also outline our new approach for overcoming the technical challenges unique to long range applications of integral imaging. Future applications of long range 3D integral imaging may include aerospace, search and rescue, satellite 3D imaging, etc.**

***Index Terms*—Computational integral imaging (CII), infrared imaging, passive 3-D imaging.**

I. INTRODUCTION

THERE is great interest in three-dimensional (3D) imaging for applications such as 3D TV, biomedical imaging, entertainment, computer vision, robotics, and defense [1]–[18]. Integral imaging [7] is a 3D passive sensing and visualization technique that can be applied to these problems. In this method, multiple 2D images (elemental images) with different perspectives are captured through a lens or camera array and then visualized through optical or computer processing. For 3D optical display, this approach provides full parallax (horizontal and vertical), continuous viewing points, and no visual fatigue. In addition, it does not require special glasses to observe the 3D images. Therefore, it is most likely to be the next generation 3D imaging system. However, there are some challenges to be solved including low viewing resolution, narrow viewing angle, and limited depth range. Potential solutions to these problems have been reported [8]–[13].

In an integral imaging system, there are two separate procedures for image capture (pickup) and reconstruction of 3D objects. In the pickup stage, multiple 2D elemental images are recorded through the lens or camera array. Each lens encodes 3D object information into 2D elemental images. Thus, many 2D elemental images with different perspectives record the direction and intensity of rays coming from the 3D object through the lens (or camera) array, as depicted in Fig. 1(a).

Fig. 1. Principle of integral imaging. (a) Image pickup. (b) 3D optical display.

For optical reconstruction of the 3D scene, a 2D display device such as a liquid crystal display (LCD) projects the elemental images onto the focal plane of the display lens array as shown in Fig. 1(b). Each 2D elemental image is optically transmitted by its corresponding lens back into 3D space. The overlap of all transmitted elemental images creates local light distributions similar to the original object of interest. As a result, an observer can see a real 3D image with full parallax and continuous viewing points.

In this paper, we use synthetic aperture integral imaging and computational reconstruction to demonstrate 3D visualization of objects and 3D imaging through obscuration over very long distances compared to anything else published to date. We demonstrate 3D integral imaging at ranges up to 2 km. Additionally, we demonstrate that this technique readily transfers to infrared imaging sensors in the 3–5 μm [mid-wave infrared (MWIR)] transmission band. In Section II, we describe our methods for data collection in the pick-up stage of integral imaging. Sections III and IV describe our experiments in obscuration penetration and passive ranging. The paper concludes with a summary of this work in Section V.

II. SYNTHETIC APERTURE INTEGRAL IMAGING AND COMPUTATIONAL RECONSTRUCTION

We begin by presenting a short overview of computational reconstruction of integral imaging. The 3D reconstruction of scene is achieved numerically by simulating the optical back-projection of the multiple 2D images in computers. Intrinsically, the resolution of each elemental image is limited by three parameters: pixel size, lenslet point spread function, and lenslet depth of focus. However, integral imaging can also be performed in either a synthetic aperture mode or with an array of image sensors in which well corrected optics record

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B. Javidi is with the Department of Electrical and Computer Engineering at University of Connecticut, Storrs, CT 06269-4157 USA (e-mail: Bahram.Javidi@UConn.edu).

Color versions of one or more of the figures are available online at http://ieeexplore.ieee.org.

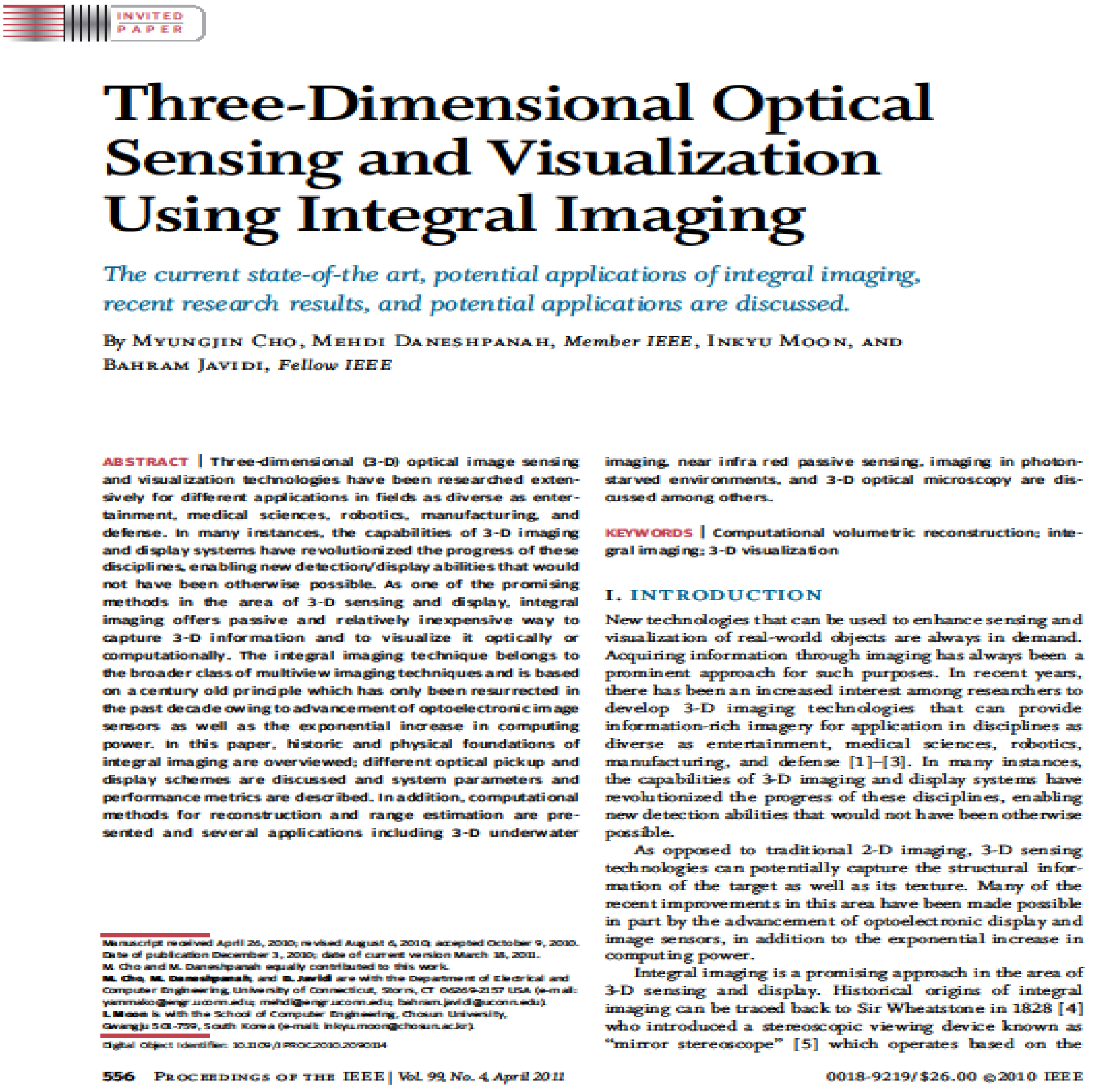
Digital Object Identifier 10.1109/JDT.2013.2246857

Summary

- Passive 3D sensing, imaging, and visualization can be used for a variety of applications including:
- 3D Image Capture & Display
- Augmented Reality (Head Mounted) Display
- 3D Object Detection and Recognition with Smart Glasses
- MOSIS: Multimodal 3D: Polarimetric, spectral, compressive sensing
- Flexible 3D Sensing
- 3D Imaging with few photons
- Long range passive 3D imaging
- Human Activity Recognition
- 3D Visualization in Obscurations & Computational imaging
- 3D Tracking with Occlusion
- 3D imaging in turbid water
- persistent surveillance

THANK YOU!

Bahram.Javidi@UConn.edu



INVITED PAPER

Three-Dimensional Optical Sensing and Visualization Using Integral Imaging

The current state-of-the art, potential applications of integral imaging, recent research results, and potential applications are discussed.

By Myungjin Cho, Mehdi Daneshpanah, *Member IEEE*, Inkyu Moon, and
Bahram Javidi, *Fellow IEEE*

ABSTRACT | Three-dimensional (3-D) optical image sensing and visualization technologies have been researched extensively for different applications in fields as diverse as entertainment, medical sciences, robotics, manufacturing, and defense. In many instances, the capabilities of 3-D imaging and display systems have revolutionized the progress of these disciplines, enabling new detection/display abilities that would not have been otherwise possible. As one of the promising methods in the area of 3-D sensing and display, integral imaging offers passive and relatively inexpensive way to capture 3-D information and to visualize it optically or computationally. The integral imaging technique belongs to the broader class of multiview imaging techniques and is based on a century old principle which has only been resurrected in the past decade owing to advancement of optoelectronic image sensors as well as the exponential increase in computing power. In this paper, historic and physical foundations of integral imaging are overviewed; different optical pickup and display schemes are discussed and system parameters and performance metrics are described. In addition, computational methods for reconstruction and range estimation are presented and several applications including 3-D underwater imaging, near infrared passive sensing, imaging in photon-starved environments, and 3-D optical microscopy are discussed among others.

KEYWORDS | Computational volumetric reconstruction; integral imaging; 3-D visualization

I. INTRODUCTION

New technologies that can be used to enhance sensing and visualization of real-world objects are always in demand. Acquiring information through imaging has always been a prominent approach for such purposes. In recent years, there has been an increased interest among researchers to develop 3-D imaging technologies that can provide information-rich imagery for application in disciplines as diverse as entertainment, medical sciences, robotics, manufacturing, and defense [1]–[3]. In many instances, the capabilities of 3-D imaging and display systems have revolutionized the progress of these disciplines, enabling new detection abilities that would not have been otherwise possible.

As opposed to traditional 2-D imaging, 3-D sensing technologies can potentially capture the structural information of the target as well as its texture. Many of the recent improvements in this area have been made possible in part by the advancement of optoelectronic display and image sensors, in addition to the exponential increase in computing power.

Integral imaging is a promising approach in the area of 3-D sensing and display. Historical origins of integral imaging can be traced back to Sir Wheatstone in 1828 [4] who introduced a stereoscopic viewing device known as "mirror stereoscope" [5] which operates based on the

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M. Cho and M. Daneshpanah equally contributed to this work.

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Advances in three-dimensional integral imaging: sensing, display, and applications [Invited]

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Three-dimensional (3D) sensing and imaging technologies have been extensively researched for many applications in the fields of entertainment, medicine, robotics, manufacturing, industrial inspection, security, surveillance, and defense due to their diverse and significant benefits. Integral imaging is a passive multiperspective imaging technique, which records multiple two-dimensional images of a scene from different perspectives. Unlike holography, it can capture a scene such as outdoor events with incoherent or ambient light. Integral imaging can display a true 3D color image with full parallax and continuous viewing angles by incoherent light; thus it does not suffer from speckle degradation. Because of its unique properties, integral imaging has been revived over the past decade or so as a promising approach for massive 3D commercialization. A series of key articles on this topic have appeared in the OSA journals, including Applied Optics. Thus, it is fitting that this Commemorative Review presents an overview of literature on physical principles and applications of integral imaging. Several data capture configurations, reconstruction, and display methods are overviewed. In addition, applications including 3D underwater imaging, 3D imaging in photon-starved environments, 3D tracking of occluded objects, 3D optical microscopy, and 3D polarimetric imaging are reviewed.

OCIS codes: 110.6880, 150.6910, 120.2040.

1. Introduction

New technologies for three-dimensional (3D) sensing and visualization of real-world objects have been pursued by scientists and engineers for many decades. As opposed to traditional two-dimensional (2D) imaging techniques, 3D imaging technologies can potentially capture the 3D structure, range, and texture information of objects. Additionally, 3D imaging technologies are robust to partial scene occlusion. There are many 3D imaging technologies, such as holography and related interferometry techniques, stereoscopy, pattern illumination techniques, ladar, and time-of-flight techniques. Passive multiperspective 3D imaging technique has garnered recent interest for its unique properties. Multiperspective 3D imaging obtains 3D scene information by recording conventional 2D incoherent images from multiple views. Because standard 2D images are used, multiperspective 3D imaging systems can be built using a single inexpensive camera with a lenslet array or an array of inexpensive imagers. Also, 3D multiperspective imaging systems can be deployed for short-range or long-range applications, making the technology more scalable than many of the competing 3D imaging technologies.

In 1908, Lippmann proposed a novel technique, named integral photography (IP), which can reconstruct true 3D images that can be observed with full

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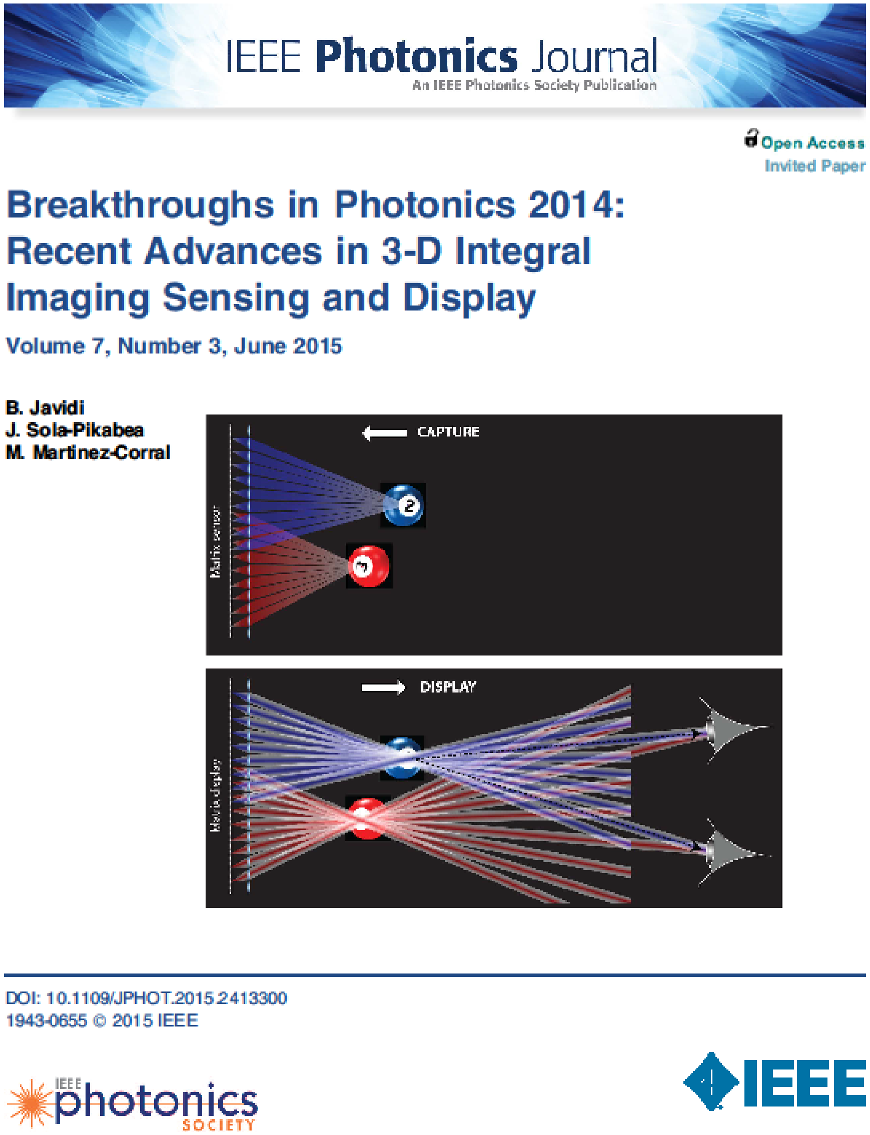

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Invited Paper

Breakthroughs in Photonics 2014: Recent Advances in 3-D Integral Imaging Sensing and Display

Volume 7, Number 3, June 2015

B. Javidi
J. Sola-Pikabea
M. Martinez-Corral

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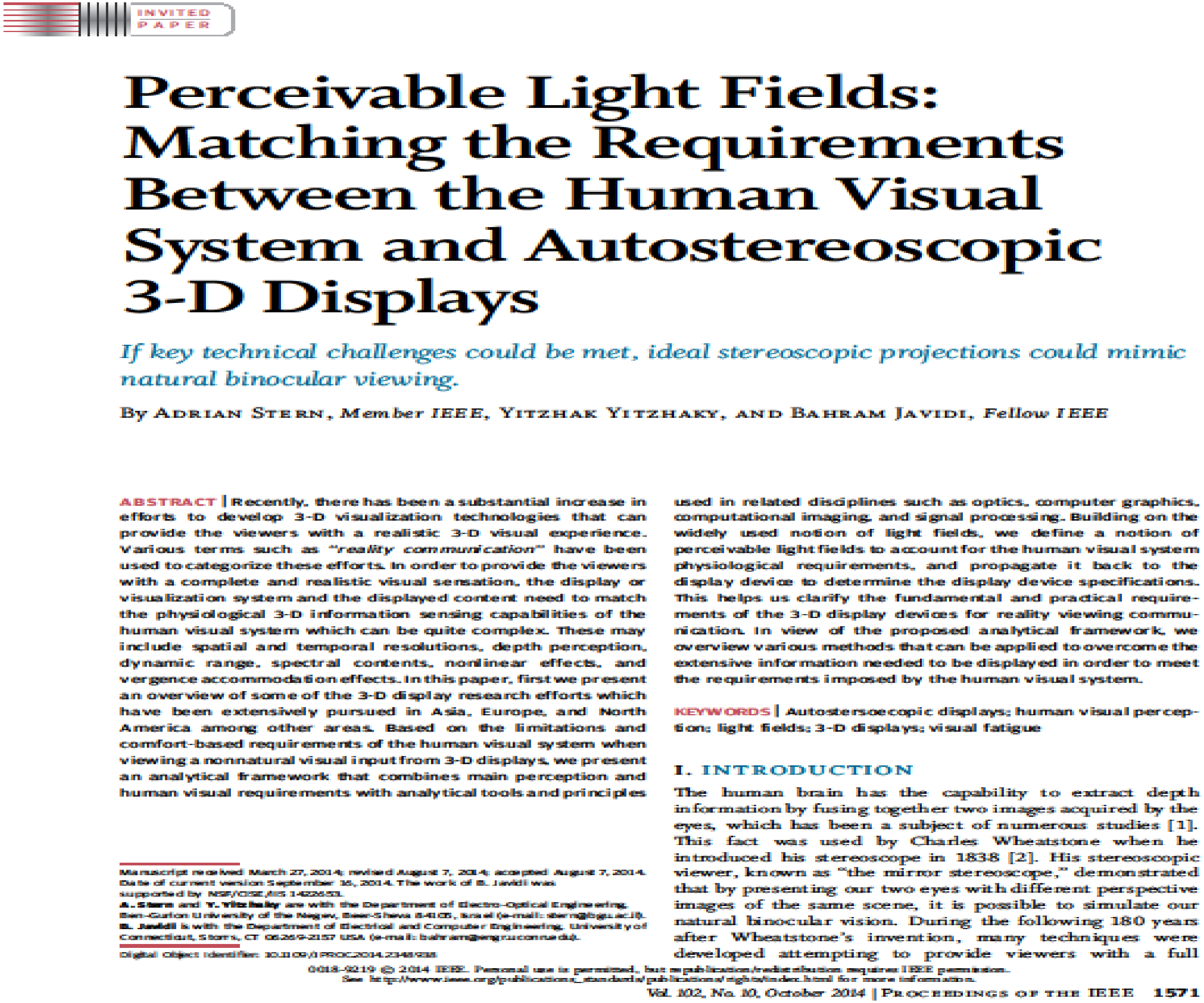

INVITED PAPER

Perceivable Light Fields: Matching the Requirements Between the Human Visual System and Autostereoscopic 3-D Displays

If key technical challenges could be met, ideal stereoscopic projections could mimic natural binocular viewing.

By Adrian Stern, *Member IEEE*, Yitzhak Yitzhaky, and Bahram Javidi, *Fellow IEEE*

ABSTRACT | Recently, there has been a substantial increase in efforts to develop 3-D visualization technologies that can provide the viewers with a realistic 3-D visual experience. Various terms such as "*reality communication*" have been used to categorize these efforts. In order to provide the viewers with a complete and realistic visual sensation, the display or visualization system and the displayed content need to match the physiological 3-D information sensing capabilities of the human visual system which can be quite complex. These may include spatial and temporal resolutions, depth perception, dynamic range, spectral contents, nonlinear effects, and vergence accommodation effects. In this paper, first we present an overview of some of the 3-D display research efforts which have been extensively pursued in Asia, Europe, and North America among other areas. Based on the limitations and comfort-based requirements of the human visual system when viewing a nonnatural visual input from 3-D displays, we present an analytical framework that combines main perception and human visual requirements with analytical tools and principles used in related disciplines such as optics, computer graphics, computational imaging, and signal processing. Building on the widely used notion of light fields, we define a notion of perceivable light fields to account for the human visual system physiological requirements, and propagate it back to the display device to determine the display device specifications. This helps us clarify the fundamental and practical requirements of the 3-D display devices for reality viewing communication. In view of the proposed analytical framework, we overview various methods that can be applied to overcome the extensive information needed to be displayed in order to meet the requirements imposed by the human visual system.

KEYWORDS | Autostersoecopic displays; human visual perception; light fields; 3-D displays; visual fatigue

I. INTRODUCTION

The human brain has the capability to extract depth information by fusing together two images acquired by the eyes, which has been a subject of numerous studies [1]. This fact was used by Charles Wheatstone when he introduced his stereoscope in 1838 [2]. His stereoscopic viewer, known as "the mirror stereoscope," demonstrated that by presenting our two eyes with different perspective images of the same scene, it is possible to simulate our natural binocular vision. During the following 180 years after Wheatstone's invention, many techniques were developed attempting to provide viewers with a full

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Profilometry and optical slicing by passive three dimensional imaging

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Passive three dimensional imaging is an enabling technology for a number of applications. We present a novel technique for profilometry and optical slicing of objects using 3D multi perspective imaging. We use *Spectral Radiation Pattern* in object space and establish its relationship to different perspective images. A novel method is proposed to infer the depth of Lambertian surfaces from the statistical properties of the SRP. Experimental results are presented to show the feasibility of this method. To the best of our knowledge, this is the first time that statistics of ray intensity-angle is used for 3D depth mapping.

OCIS codes: 110.6880, 280.4991, 150.6910.

In 3D imaging systems [1,2], measuring depth is particularly important to invoke 3D perception or when quantitative surface measurements are required. Methods ranging from Atomic Force Profilometry to stereo vision and LADAR have been developed. One depth estimation method is *stereopsis* that relies on binocular disparity and triangulation by feature extraction and matching processes [3,4]. Variants of stereopsis have been proposed to improve the performance by introducing complex a priori image models [5]. Also, as an extension to stereopsis, multi-baseline stereo matching is developed which is based on correlation between multiple stereo pairs [6]. Another approach is depth-from-defocus in which the difference in defocus blur between images with different camera settings, serves as depth cue [7]. Recently, digital slicing using Fourier domain filtering has been applied to lenslet based integral imaging method [8].

We suggest an optical–computational approach for profilometry which is inherently different from the mentioned techniques. We assume that the input is a set of perspective images that need not to be on a regular grid [9]. Such an ensemble conveys the depth information essentially by registering both the intensity and angle of the rays emanating from the objects within the depth of field, which can be extended by use of optical masks [10].

Traditionally, 3D reconstruction is done in a plane by plane fashion, i.e. each perspective image is back-projected onto the desired reconstruction distance with respect to its own perspective (pinhole position), and the results of all back-projected perspectives are averaged for the final result [11]. Here we abstain from such interpretation due to limitations that will be discussed later. Instead, we view each perspective image as an information source for ray intensity-angle at each volumetric pixel (voxel) in space. At each voxel, we define the *Spectral Radiation Pattern* (SRP) to capture the radiation intensity at a certain wavelength and direction as:

$$\mathcal{L}(\theta, \phi, \lambda) \quad \text{[a.u. of intensity]}, \tag{1}$$

in which $-\frac{\pi}{2} \leq \theta < \frac{\pi}{2}$ and $0 \leq \phi < 2\pi$ are the zenith and azimuthal parameters that determine the ray angle respectively, while λ denotes wavelength. Plenoptic function, Light Field, and Ray Phase Space also describe the intensity and direction of light ray in free space [12,13]. The SRP can be extended to include other intrinsic light parameters such as polarization as well as individual sensor characteristics for heterogenous distributed 3D sensing. With such representation, the 3D object space turns into a *function space*, i.e. a unique function $\mathcal{L}(.)$ is associated with each space voxel. Hence, 3D optical information recorded by the ensemble of sensors can be represented in form of a function space over $\mathbb{R}^3$ with unique elements $\mathcal{L}(.)$. The object space can be written as:

$$V = \left\{ \mathcal{L} : [-\frac{\pi}{2} : \frac{\pi}{2}, 0 : 2\pi, \lambda_{min} : \lambda_{max}] \rightarrow \mathbb{R} \right\}, \tag{2}$$

where $\mathbb{R}$ denotes real numbers. In contrast to conventional methods [2,11], the advantage of this interpretation is that the reconstruction at each point does not need to be a scalar intensity. Instead, this framework gathers all the information collected by sensors in the SRP of each voxel. We believe that this model can be the grounds for many tasks in 3D imaging. As examples, we present depth estimation and optical slicing. According to Fig. 1 the relationships between i-th sensor located at $(x_{p_i}, y_{p_i}, z_{p_i})$ and object space coordinates are:

$$\theta_i = \arctan \frac{\sqrt{(x_{p_i} - x)^2 + (y_{p_i} - y)^2}}{z_{p_i} - z}, \tag{3a}$$

$$\phi_i = \left(\arctan \frac{y_{p_i} - y}{x_{p_i} - x} \right) + \begin{cases} 0 & x_{p_i} \geq x \\ \pi & x_{p_i} < x \end{cases} \tag{3b}$$

Let the local coordinates on the image sensor be denoted by (ξ, η) [see Fig. 1(b)]. Also, let the image intensity on i-th sensor for different wavelengths be $I_i(\xi, \eta, \lambda)$. Using Eq. (3), the i-th sample of the SRP at point (x, y, z) is:

$$\mathcal{L}(\theta_i, \phi_i, \lambda) = \gamma_i \times I_i(\xi, \eta, \lambda) \quad \text{where} \tag{4a}$$

$$\xi = -g_i \tan\theta_i \cos\phi_i, \tag{4b}$$

$$\eta = -g_i \tan\theta_i \sin\phi_i. \tag{4c}$$

where g_i is the distance between the i-th image sensor and its corresponding pinhole. Also, $\gamma_i = R_i^2 / \min_{i=1..N} R_i^2$

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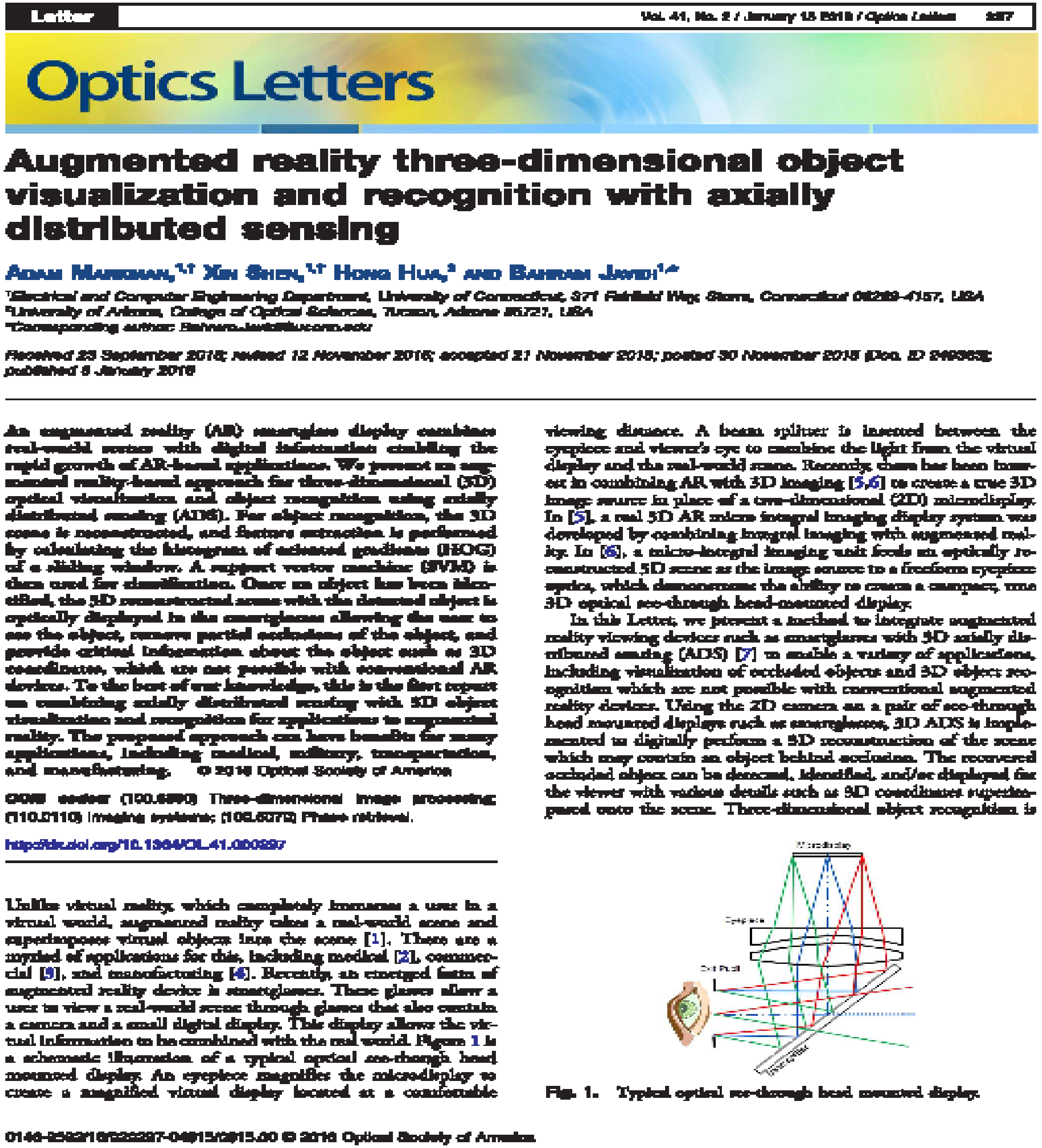

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Augmented reality three-dimensional object visualization and recognition with axially distributed sensing

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An augmented reality (AR) smartglass display combines real-world scenes with digital information enabling the rapid growth of AR-based applications. We present an augmented reality-based approach for three-dimensional (3D) optical visualization and object recognition using axially distributed sensing (ADS). For object recognition, the 3D scene is reconstructed, and feature extraction is performed by calculating the histogram of oriented gradients (HOG) of a sliding window. A support vector machine (SVM) is then used for classification. Once an object has been identified, the 3D reconstructed scene with the detected object is optically displayed in the smartglasses allowing the user to see the object, remove partial occlusions of the object, and provide critical information about the object such as 3D coordinates, which are not possible with conventional AR devices. To the best of our knowledge, this is the first report on combining axially distributed sensing with 3D object visualization and recognition for applications to augmented reality. The proposed approach can have benefits for many applications, including medical, military, transportation, and manufacturing.

OCIS codes: (100.6890) Three-dimensional image processing; (110.0110) Imaging systems; (100.5070) Phase retrieval.

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Unlike virtual reality, which completely immerses a user in a virtual world, augmented reality takes a real-world scene and superimposes virtual objects into the scene [1]. There are a myriad of applications for this, including medical [2], commercial [3], and manufacturing [4]. Recently, an emerged form of augmented reality device is smartglasses. These glasses allow a user to view a real-world scene through glasses that also contain a camera and a small digital display. This display allows the virtual information to be combined with the real world. Figure 1 is a schematic illustration of a typical optical see-through head mounted display. An eyepiece magnifies the microdisplay to create a magnified virtual display located at a comfortable viewing distance. A beam splitter is inserted between the eyepiece and viewer's eye to combine the light from the virtual display and the real-world scene. Recently, there has been interest in combining AR with 3D imaging [5,6] to create a true 3D image source in place of a two-dimensional (2D) microdisplay. In [5], a real 3D AR micro integral imaging display system was developed by combining integral imaging with augmented reality. In [6], a micro-integral imaging unit feeds an optically reconstructed 3D scene as the image source to a freeform eyepiece optics, which demonstrates the ability to create a compact, true 3D optical see-through head-mounted display.

In this Letter, we present a method to integrate augmented reality viewing devices such as smartglasses with 3D axially distributed sensing (ADS) [7] to enable a variety of applications, including visualization of occluded objects and 3D object recognition which are not possible with conventional augmented reality devices. Using the 2D camera on a pair of see-through head mounted displays such as smartglasses, 3D ADS is implemented to digitally perform a 3D reconstruction of the scene which may contain an object behind occlusion. The recovered occluded object can be detected, identified, and/or displayed for the viewer with various details such as 3D coordinates superimposed onto the scene. Three-dimensional object recognition is

Fig. 1. Typical optical see-through head mounted display.