Webinar on 3-D Imaging and Display Technologies
Introduction

Professor Bahram Javidi
University of Connecticut, USA
Bahram Javidi (USA) and Murat Tekalp (Turkey), Special Issue of the Proceedings of the IEEE on Emerging 3D Imaging and Display Technologies:

http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5&isnumber=7906639

• Bahram Javidi, University of Connecticut, USA (Moderator)
• Jung Yong Son, Konyang University, S. Korea
• Masahiro Yamaguchi, Tokyo Institute of Technology, Japan
• Hong Hua, University of Arizona, USA
• Manuel Martinez, University of Valencia, Spain
• Osamu Matoba, Kobe University, Japan
• Yi Pai Huang, National Chiao Tung University, Taiwan
Holographic Displays: Strengths and Weaknesses

Stephen A. Benton, V. Michael Bove, Holographic Imaging Jr., Wiley 20018.

3D Imaging and Visualization: 3D Microscopy

→ Provides phase information
→ Real-time cell morphology
→ low power Laser
→ Detector – CCD/CMOS

RBC imaged with digital holographic microscopy.
Integral Imaging

- Based on the concept of depth from disparity
- Multiple lenses form 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]
The 3D image is reconstructed by ray-bundles intersection. The setup provides each eye with a different perspective of the object, so that binocular observation produces the relief sensation:

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

3D Movie on an i-Phone


No viewing devices, full parallax, no visual fatigue
Collaboration with Prof. Manuel Martinez Corral
Bahram.Javidi@uconn.edu
Visualization improvement (J. Jang, B. Javidi, "Improved viewing resolution of 3D integral imaging with non-stationary micro-optics," Optics Letters, 2002.)

Time multiplexing: Moving array-lenslet technique to overcome the fill factor:

- Full parallax;
- Continuous view point;
- No special glasses
- No visual fatigue and abnormal effects
Dynamic Integral Imaging Displays by Liquid Crystal Device

Tai-Hsiang Jen, Xin Shen, Gang Yao, Yi-Pai Huang, Han-Ping D. Shieh, and Bahram Javidi, “Dynamic integral imaging display with electrically moving array lenslet technique using liquid crystal lens,” Optics Express, 23, 2015

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Dynamic Integral Imaging
Fast Scanning LC Lenses Array for High Resolution Integral Imaging Display

Moving s times $\rightarrow$ n*s times information could be generated

Dynamic Integral Imaging

Fast Response LC Lenses Array for Improved Depth of Field of Integral Imaging Display

Elemental image (n pixels)

Static Lens Array

3D Image

n points

Improved DOF of Integral Imaging Display by varying Focal lengths Sequentially

\[
\frac{1}{f} = \frac{1}{g} + \frac{1}{L}
\]

f: lens focal length

g: distance between display and lens array

L: distance between 3D image and lens array


Limitation --- Field of View of Integral Imaging Display

Field of view of a lenslet

Example

Lens pitch=1.09mm, focal length=3.7mm
ψ = 8.6°

In viewing angle (0°)

Out of viewing angle (>8.6°)

ψ = 2tan⁻¹(p/2f)

f: lens focal length
p: lens diameter

Ref: Okano et al., 1999.
Enlarged Viewing Angle of Integral Imaging Displays by Liquid Crystal Prisms

\[ \theta = \tan^{-1}\left( \Delta n \cdot d / L \right) \]
\[ \Psi = 2\tan^{-1}\left( p/2f \right) \]

Total Viewing Angle \( \Phi_{\text{max}} = (\Psi + 2\theta) \)

H. Hua, B. Javidi, “3D integral imaging optical see-through head-mounted display,” Optics Express, 2014
Passive 3D Imaging in Degraded Environment


Experimental setup for objects placed in turbid water. (a) 3D scene in clear water. (b) Sample 2D image for objects in turbid water. (c) 3D imaging experimental setup.

3D reconstruction results for objects placed in turbid water. (a)–(d) illustrate the focused 3D reconstruction planes for the bug, treasures, small fish, and large fish, respectively.


THANK YOU!

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Holographic and Light-Field Imaging as Future 3-D Displays (PROCEEDINGS of the IEEE)

Jung-Young Son and Hyoung Lee
Biomedical Engineering Dept. Konyang University, Nonsan, Korea
Beom-Ryeol Lee
Next Generation Visual Computing Section, ETRI, Daejeon, Korea
Kwang-Hoon Lee
3-D Conveegence Research Center, KOPTI, Kwangju, Korea
The Ultimate Goal of 3-D Imaging: (Realizing Reality Communication)

1. Creating Natural Viewing Condition through a display → continuous parallax → No Eye Fatigue
2. Displaying a natural scene demagnified only to the size of the display panel in both depth and transversal directions → Immersive and Interactive

Photographing

Responds to our Five Senses

Reality Communication

IEEE
Light Field and Holographic Displays are currently developing to realize the Reality Communication in future
HOGIE: Holographic Image Element. Each Image Element represents a different View Image by Phase conjugated rays.

Hogel: Hologram of a point Image in a Stereo Hologram.

Perceiving/Recording Surrounding Nature

Natural Viewing Condition

Object

Image Points: Different View Images

Cone Beam

Reference Beam

A Pixel

HOGIE

Object

Hologram Recording on a Display panel/chip

Electro-Holography

Human Eye

Perceiving/Recording Surrounding Nature
How to achieve Natural Viewing Condition in IP/MV?

As a way of achieving natural viewing condition through a 3-D display, Super multiview condition was postulated to provide a continuous parallax by a group of Japanese Scientists (Kajiki et.al.) in 1995:

**Super multiview condition:**
Projecting at least two different view images simultaneously to viewer’s each eye, without overlapping between them.

The displays can meet the super multiview condition are named as Super multiview 3-D displays or lately Light Field displays.
How to provide the natural viewing condition in IP/MV?

Super-multiview condition: Projecting at least two different view images simultaneously but separately to each eye

Stereo Image  Two View Images  Three View Images  Four View Images

1 ±0.3D  1 >±0.3D  1 2 3 1 2 3 4

Images are simultaneously projected but Separately incident
Light Field Display: The displays satisfy the super multiview condition

Super-Multiview Condition

SM Zone

$\frac{r}{0.7}$

Viewer’s Depth of Field

$\frac{r}{1.3}$

$r'$ in m unit

SM (Super-Multiview) Zone: outside of Depth of Field

$D = \frac{1}{r}$ (Diopter)

$D \pm 0.3D$ : Focusable Depth Range

$D \pm 0.3D \equiv \frac{1.3}{r} : \frac{0.7}{r}$
Binocular Test: Average

(DOF Increase with increasing number of simultaneously projected images)
## Comparisons between Holographic and Light Field Displays

<table>
<thead>
<tr>
<th>Items</th>
<th>Holographic-Display</th>
<th>Light Field Display</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Unit</td>
<td>HOGIE(A Pixel)</td>
<td>*A pixel cell</td>
<td>*Elemental Image</td>
</tr>
<tr>
<td>Light Field in front</td>
<td>Coherent addition of Rays from each pixel</td>
<td>Intensity addition of fan beams from PCs</td>
<td>*PCs: Pixel Cells</td>
</tr>
<tr>
<td>Displayed Image</td>
<td>Spatial Image (Front and rear spaces)</td>
<td>*Virtual Image (Near panel)</td>
<td>*Plane Image on the Panel</td>
</tr>
<tr>
<td>Continuous Parallax</td>
<td>Present</td>
<td>* Can be present</td>
<td>*When a supermultiview condition is met</td>
</tr>
<tr>
<td>Reconstructed Image Size</td>
<td>*Smaller than Panel size</td>
<td>Close to Panel size</td>
<td>*Depends on Depth and viewing zone distance</td>
</tr>
<tr>
<td>Depth Cues</td>
<td>Parallaxes, Accommodation and Vergence</td>
<td>Parallaxes, *Accommodation and Vergence</td>
<td>*Require further researches</td>
</tr>
</tbody>
</table>
Problems with the Current Light Field and Holographic Imaging

- No Proper Display Panels for the Imaging
  - Holographic Imaging is still based on SLMs such as DMD and LCoS chips → Small and having a large pixel size (4.8 μm) → Too small viewing zone angle to view image without a screen
  - In holographic imaging, combining many SLMs by multiplexing (time and Spatial) does not create a viewing zone for the combined image.
  - LCDs have a large pixel size and limited resolutions for both imaging and OLED can be hardly used for the holographic display.

- No viewing zone forming optics with the resolving power with a few micron range exists
What have to be done to realize the Reality Communication

- A display panel specialized for both Holographic and Light Field imaging should be developed → Currently Panels with 50,000 X 50,000 array of 1 μm pixel size for holographic and with 11K array of near 10 μm pixel size for Light Field Imaging are being developed.

- Both Holographic and Light Field imaging should be realized in a display panel together with the plane image → Holographic imaging for interactive and Light Field and Plane imaging for immersive environment creations.

- Viewing zone forming optics with a high resolving power should be developed for Light Field Imaging.
If two imaging methods are combined in a display, Holographic imaging for interactive and Light Field imaging for immersive environment creation purposes can be used.
Full-parallax holographic light-field 3D displays and interactive 3D touch

*Masahiro Yamaguchi*

*Tokyo Institute of Technology, School of Engineering*
Full-parallax holographic light-field 3D displays and interactive 3D touch

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Full-parallax holographic light-field 3D displays and interactive 3D touch

Light-field / Holographic Ray vs Wavefront
Holographic display assisted by light-field
High-quality computational holography
Holographic element for light-field display
Holographic light-field display for interactive 3D touch

Light-field display

Limitations of ray-based displays

Screen-plane sampling

Screen-plane diffraction

Directional sampling

No 3D glasses or goggle
Any viewpoint
Full-parallax
Natural 3D image w/o visual fatigue
Can share the 3D image

The resolution of image far from screen plane is limited.
Example: Image depth vs. Screen plane resolution

Holographic display reconstructs light-field

Wavefront reconstruction

Normal vectors of Wavefront

Hologram

Observer

What is different: Ray-based and Wavefront-based?
Light-ray reproduction vs. Wavefront reconstruction

• **Ray-based light-field display**
  • Resolution of an image far from screen plane is low.
        **Suitable for lower-resolution large displays**
        3D image near the screen

• **Wavefront-based light-field display**
  • High-resolution image even in deep 3D scene.
        **Suitable for higher-resolution deep 3D scene**
        The resolution better than that of human vision.
Holographic display assisted by light-field

Hologram computation using ray-sampling (RS) plane

Rendering: Ray-based
Propagation: Wavefront

High-resolution, realistic image even in deep 3D scene

Computational hologram printed by Kansai digital holo-studio using a laser lithography system (collaboration with Prof. K. Matsushima) 16Gpixels

Computational hologram printed by Kansai digital holo-studio using a laser lithography system (collaboration with Prof. K. Matsushima). Design directed by Dr. Setsuko Ishii (a holography artist), CG created by Shunsuke Igarashi)
Light-field display by holographic device

3D touch sensing light-field display

Detecting the light scattered by the fingertip

Diagram showing the setup of a light-field display using a holographic device. The diagram includes a color image sensor, a holographic screen, a projector, and a 3D real image. The scattered light from the fingertip is detected by the color image sensor and processed by the PC.
3D touch demonstration

Full-parallax holographic light-field 3D displays and interactive 3D touch

Light-field / Holographic Ray vs Wavefront

Holographic display assisted by light-field

High-quality computational holography

Holographic element for light-field display

Holographic light-field display for interactive 3D touch
Enabling Focus Cues in Head-Mounted Displays for Virtual and Augmented Reality

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College of Optical Sciences
The University of Arizona
Vergence—Accommodation in HMDs

Real-world viewing

Stereoscopic VR/AR display
Potential Psychophysical Consequences

- Distorted depth perception [Edgar et al. 94; Inoue and Ohzu, 1997; Davis 02; Swan et al. 06; Hoffman et al 2008]

- Artifacts: eye fatigue, diplopic vision, degraded oculomotor response, headache, etc. [Mon-Williams et al. 05; Wann et al. 95]

- In AR applications, mismatch of focus cues between the real-world scene and virtual objects may further compromise depth perception and a realistic sense of augmentation [Liu and Hua, ISMAR 08, TVCG 2010]
Methods for Enabling Focus Cues

[G. Westheimer, Maxwellian viewing system, 1966]

[K. Konrad et al., ACM SIGGRAPH2017]


[H Hua 2016]
EDOF Displays—Maxwellian View Displays

Depth of focus of HMD:

$$\Delta d = \frac{2f_{\text{eye}}}{\# C} = \frac{2f_{\text{eye}}}{D} C$$

[G. Westheimer, Maxwellian viewing system, 1966]
EDOF Displays—Engineering Invariant PSF

[Konrad et al, Accommodation-invariant computational-invariant displays, ACM SIGGRAPH2017]
Technical Methods—Vari-Focal Displays (2)

Technical Methods—Vari-Focal Displays (3)

Technical Methods—Vari-Focal Displays (4)

[Liu & Hua, 2008, 2010]
Technical Methods—Head-Mounted Light Field Displays

Retinal image vs. Reconstruction of Light Fields

2D Image Plane

I(x,y)

LF(x,y,u,v)
Multi-Focal Plane Light Field Display

Depth-fused Multi-focal-plane Display [Liu & Hua 2010, Hu & Hua 2014]

Depth-fused Six-focal-plane Display [H & Hua 2014]
Full-Parallax Integral Imaging Display


[Hua and Javidi, Optics Express, 2014]
Computational Multi-Layer Light Field Display


[Maimone & Fuchs, Proc. Of ISMAR 2013]

[Huang & Wetzstein et al, Proc. of ACM SIGGRAPH, 2015]

Enabling Focus Cues in Head-Mounted Displays

By Hong Hua

ABSTRACT | Developing head-mounted displays (HMDs) that offer uncompromised optical pathways to both digital and physical worlds without encumbrance and discomfort confronts many grand challenges, both from technological perspectives and human factors. Among the many challenges, minimizing visual discomfort is one of the key obstacles. One of the key contributing factors to visual discomfort is the lack of the ability to render proper focus cues in HMDs to stimulate natural eye accommodation responses, which leads to the well-known problem of vergence–accommodation conflict. This paper provides a comprehensive summary of various technical approaches toward enabling focus cues in HMDs for both virtual reality (VR) and augmented reality (AR) applications.

of the object from the focused distance. The accommodation and retinal image blur effects together are known as the focus cues. The vergence cue refers to the rotation action of the eyes to bring the visual axes inward or outward to intersect at a 3-D object of interest at near or far distances.

This review paper is particularly interested in the well-known vergence–accommodation conflict (VAC) in head-mounted displays (HMDs) and the technical methods that enable correct or nearly correct focus cue rendering to resolve the VAC problem. It is worth noting that the VAC problem is not unique to HMDs, but inherent to all conventional stereoscopic 3-D displays (S3D) which stimulate the perception of 3-D space and shapes from a pair of 2-D perspective images, one for each eye, with binocular disparities.
From the plenoptic camera to the flat integral-imaging display

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From the plenoptic camera to the flat integral-imaging display

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Conventional photographic cameras do not have the ability of recording the angular information carried by the rays of light passing through their objective. Instead, the irradiance received by any pixel is proportional to the sum of radiances of all the rays, regardless of their incidence angle.
The concept of plenoptic map

Much more interesting would be a system with the capacity of registering a radiance map with the spatial and the angular information of all the rays proceeding from the 3D scene. Such kind of radiance maps has been named in different ways, such as integral photography, integral image, lightfield map, or even plenoptic map.

A clever technique for recording the plenoptic map produced by 3D scenes was reported in 1908 by Lippmann, who proposed technique, named as Integral Photography, based on inserting a microlens array (MLA) in front of the photographic film. This permitted the capture of a set of elemental images storing many different, horizontal and vertical, perspectives of a 3D scene.
Plenoptic camera

\[
\frac{1}{a} + \frac{1}{a'} = \frac{1}{f} \iff M = -\frac{a'}{a}
\]

\[
z \cdot z' = f^2 \iff M = -\frac{z'}{f} = -\frac{f}{z}
\]

\[
\frac{1}{a'} + \frac{1}{g} = \frac{1}{f_{ML}}
\]

\[
f_{CL} = f_{ML}
\]
As already reported, the **microimages** recorded with a plenoptic camera are ready to be projected onto an InI monitor to produce auto-stereoscopic images. This is because the image of the 3D scene produced by the camera lens is in the neighborhood of the MLA (with some parts in front and some parts behind). Naturally, one has to make sure that the two MLAs (the one used in the plenoptic camera, and the one placed in front of the display) have the same number of microlenses and $f\#$. 
Direct InL Display

![Diagram of 3D scene with camera and microlens array]
Plenoptic image captured by CAFADIS Group. Universidad de La laguna. Tenerife, Spain.
The plenoptic camera
From Elemental Images to Micro-Images

Cropping EIs for changing the FOV
Cropping EIs for changing the FOV
Transposing from EIs to MIs
Projecting on the flat InI monitor
Multimodal imaging based on digital holography

Osamu Matoba

Kobe University, Japan

Collaboration work with Dr. X. Quan, Dr. P. Xia, Prof. Y. Awatsuji, Prof. T. Nomura published in Proceedings of the IEEE, Vol. 105, p. 906 (2017)
Digital Holography

Interferometer + Numerical Reconstruction by Computer

Hologram Recording: Digital Image Sensor

3D Object Reconstruction: Numerical Propagation by Computer

-Advantages: 3D, Dynamic, Quantitative Measurement

Applications of Digital Holography

Bioimaging (Phase & Fluorescence)
- Phase of HeLa Cell
- Simultaneous Measurement Phase & Fluorescence
- Simultaneous Measurement of mouse brain cells

Invisible phenomena (high-speed phase imaging)
- Gas flow (20,000 fps)
- Optical voice recorder


# Physical Parameters obtained by Digital Holography

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Phase</th>
<th>Fluorescence(LED)</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="a" alt="Image" /> <img src="b" alt="Image" /></td>
<td><img src="Phase" alt="Image" /></td>
<td><img src="Fluorescence" alt="Image" /></td>
<td><img src="Polarization" alt="Image" /></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Multimodal Imaging: 3D Phase + 2D Fluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Spectrum" alt="Image" /></td>
<td><img src="Multimodal" alt="Image" /></td>
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</tbody>
</table>


Multimodal Digital Holographic Microscope

3D Phase & 2D Fluorescence

Living Plant Cell

Collaboration work with Dr. Tamada, NIBB, Japan

Physcomitrella patens, the moss cells

Auto fluorescence

Phase
Mouse Brain Slice Imaging

Collaboration with Prof. H. Wake and Prof. Morita in Kobe Univ.
Off-axis Incoherent Digital Holography

- Off-axis hologram
- Stable
- Easy to compact

Dual lenses: $f_1, f_2$
+ Diffraction gratings: $d_1, d_2$

Conclusions

- Multi-modal imaging can obtain simultaneously more information of the target such as phase, polarization, fluorescence, and spectra as well as 3D distribution.

- Digital holography is a promising technique to realize the multimodal imaging technique that is useful in the bioimaging.

LC-lens for 3D Technologies

Yi-Pai Huang, Manuel Martinez Corral, and Braham Javidi
Types of Liquid Crystal Lens

The First Liquid-crystal Lens (1979) – Proposed by Prof. Susumu Sato
Shapes of Liquid Crystal Lens Array

Applications of LC-Lens for 3D Capturing

Axially Distributed Sensing Using LC-lens
Multiple all-in focused elemental images were captured without moving image sensor.

Depth images obtained with a LC-Lens inserted in a wide-field microscope

Fast axial-scanning widefield microscopy with constant magnification and resolution

LC-Lens Array for 3D Capturing

Sequentially adjust the focal length of hexagonal LC-lens array to extend depth of field.

DoF extended from 100um to 950um

Dual Layer electrode LC-lens Array can be operated both on 2D and 3D mode, with focusing adjustment for Endoscope.

- Dual layer electrode liquid crystal lens for 2D/3D tunable endoscopy imaging system, Optics Express, Vol. 24, Issue 8, pp. 8527-8538 (2016)
A dynamic InIm display using electrically movable LC-lens array to eliminate the multifacet phenomenon.

- High-Resistance Liquid Crystal Lens Array for Rotatable 2D/3D Auto-stereoscopic Display, Optics Express, pp. 2714–2724 (2014)
Switchable LC-Lens for AR Goggle

Image plane switching with Tunable LC-lens

- Electrically adjustable location of a projected image in augmented reality via a liquid-crystal lens. Optics express, 23(22), 28154-28162. (2015)
LC-Lens Array for Hybrid VR Goggle

Light Field mode: solve A.C. conflict
2D mode: compensate resolution of LF image

Apply Hybrid concept in VR device

Reconstructed Light Field image with LC-lens Array

A 2D/3D hybrid integral imaging display by using fast switchable hexagonal liquid crystal lens array

Challenges of LC-Lens for 3D Applications

**Lens Profile Control**
- Focusing point spread function (PSF) will affect the cross-talk

**Off-axis Optical Performance**
- Off-axis distortion will limited the FoV

**Numerical Aperture (N.A.)**
- Small $\Delta n$ can’t achieve high N.A., may increase the total thickness

**Response Time**
- Thicker LC cell gap (15~60um), will results in Rsp. >200ms
- Only suitable for 2D/3D switching

**Polarization Dependence**
- For AR or capturing applications, will decrease the transmittance
Questions?