

ADVANCED TELEVISION TECHNOLOGY ISSUE

# Information DISPLAY

Official Monthly Publication of the Society for Information Display • [www.informationdisplay.org](http://www.informationdisplay.org)

**SID**  
SOCIETY FOR INFORMATION DISPLAY

Nov./Dec. 2014  
Vol. 30, No. 6

## The Next Generation of TV

A woman with long brown hair is sitting in a black leather armchair, looking at a large flat-screen TV. She is holding a remote control in her right hand. The TV displays a vibrant image of a city skyline (resembling Chicago) with a green lawn in the foreground and a blue sky with white clouds. Above the city, a white airplane is flying. In the upper left corner of the TV screen, a colorful spiral galaxy is visible against a dark blue background with stars. The room is dimly lit, and a patterned rug is on the floor.

**ADVANTAGES OF  
OLED TVs**

**PROGRESS IN LIGHT-  
FIELD 3-D DISPLAYS**

**PERSONAL NEAR-TO-EYE  
LIGHT-FIELD DISPLAYS**

**Plus**

**Touch and Interactivity at Display Week 2014**

**UHD-TV MARKET  
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**ON THE COVER:** The state of the art of large-screen TV continues to evolve whether it be UHD or curved screens. And the rich diversity and potential that light-field displays offer will enhance the viewing experience for both multiple-user systems and personal/portable devices.



Cover Design: Acapella Studios, Inc.

## In the Next Issue of Information Display

### Flexible OLEDs and Wearables

- Key Enabling Technologies for Foldable AMOLEDs
- State-of-the-Art Flexible AMOLEDs
- Flexible AMOLEDs Based on Organic TFT Technology for Wearable Devices
- Market Outlook for Wearables
- Roundup of Commercially Available Wearables
- Regional Business Report: Japan

INFORMATION DISPLAY (ISSN 0362-0972) is published 6 times a year for the Society for Information Display by Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; William Klein, President and CEO. EDITORIAL AND BUSINESS OFFICES: Jay Morreale, Editor-in-Chief, Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; telephone 212/460-9700. Send manuscripts to the attention of the Editor, *ID*. SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008; telephone 408/879-3901, fax -3833. SUBSCRIPTIONS: *Information Display* is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues \$100.00). Subscriptions to others: U.S. & Canada: \$75.00 one year, \$7.50 single copy; elsewhere: \$100.00 one year, \$7.50 single copy. PRINTED by Wiley & Sons. PERMISSIONS: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limits of the U.S. copyright law for private use of patrons, providing a fee of \$2.00 per article is paid to the Copyright Clearance Center, 21 Congress Street, Salem, MA 01970 (reference serial code 0362-0972/14/\$1.00 + \$0.00). Instructors are permitted to photocopy isolated articles for noncommercial classroom use without fee. This permission does not apply to any special reports or lists published in this magazine. For other copying, reprint or republication permission, write to Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008. Copyright © 2014 Society for Information Display. All rights reserved.

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## Ending the Year with a Look at Trends and TV

by Stephen Atwood

We find ourselves at the end of another year of exciting innovations and new discoveries in our industry. We have seen exciting breakthroughs in many areas, including back-lighting of LCDs yielding wider color gamuts and even more efficiency, continuing increases in resolution and pixel density of LCDs, commercialization of large-format

OLED panels, commercialization of flexible and curved displays of many sizes and technologies, new anti-reflection glass coatings, alternative transparent conducting materials for touch and display applications, novel demonstrations of 3-D light field and holographics, and much more. New application categories have emerged, such as “wearable” – which we used to call mobile or personal devices – and new paradigms for touch and gesture inputs appeared in several new products this year. (All of this makes for a very interesting holiday shopping season as we browse in stores and on-line for gifts.) The marketplace for displays is even more diverse and vibrant as we look forward to the great innovations to come in 2015. Hopefully, each issue of *ID* this year has helped you better understand the newest display innovations and what they mean to the devices and applications they enable.

Since this is the end-of-the-year issue for *ID*, our focus once again is on the world of television displays as we take an in-depth look at several important innovation areas, including ultra-high definition (UHD), 3-D light-field displays, and curved displays. All of these are important elements in the formula for future advancements of television. In fact, it was in our television issue from back in 2011 that industry analyst and contributing editor Paul Semenza wrote about “The Ultimate TV” in his article, “The TV of the Future.” Paul wrote: “By 2015, we can expect much higher resolutions to be available (at least 4K × 2K), enabled by new backplane technologies. Some of the additional resolution will likely be utilized to implement glasses-free (autostereo-scope) 3-D.” Well, here we are today with LCDs utilizing oxide and poly-Si TFTs, the availability of many versions of UHD-resolution screens, and lots of exciting work under way in the area of true 3-D displays that are even capable of creating parallax and image occlusion effects identical to the way we actually see physical objects.

Of course, we are a few years away from having light-field TVs in our living rooms, but thanks to some help from guest editor Nikhil Balram this month, we can bring you two important articles on the subject: the first is an amazing in-depth description of the technology of light-field displays and all the various ideas for embodiment being demonstrated or theorized up to the present by authors Xu Liu and Haifeng Li in their Frontline Technology feature, “The Progress of Light-Field 3-D Displays.” What strikes me as most hopeful is that because of the advancements in supporting technologies such as computing power in silicon and speed and resolution of light modulating devices (imagers), the technology is rapidly evolving and looking a lot more commercially viable than it seemed even a year or so ago.

We follow this up with our next Frontline Technology feature on the subject titled “Personal Near-to-Eye Light-Field Displays,” in which authors Wanmin Wu, Kathrin Berkner, Ivana Tošić, and Nikhil Balram explore the many possible embodiments and applications for personal-use true 3-D displays. These are not just augmented stereo-scope glasses but a family of devices that render true augmented-reality displays with

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## Blue-LED Inventors Named for Nobel Prize in Physics

Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura recently won the 2014 Nobel Prize in Physics “for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources.” The Royal Swedish Academy of Sciences explained in a press release that when the scientists “produced bright blue light beams from their semiconductors in the early 1990s, they triggered a fundamental transformation of lighting technology. Red and green diodes had been around for a long time, but without blue light white lamps could not be created .... The [white] LED lamp holds great promise for increasing the quality of life for over 1.5 billion people around the world who lack access to electricity grids: due to low power requirements it can be powered by cheap local solar power.” In terms of displays, the GaN technology for blue LEDs that the three men invented has made significant contributions. LEDs have replaced CCFL backlighting systems, achieving both wider color gamut and lower power consumption.

Isamu Akasaki is with Meijo University and Nagoya University in Nagoya, Japan; Hiroshi Amano is with Nagoya University in Japan; and Shuji Nakamura is with the University of California in Santa Barbara. Both Nakamura and Akasaki received the Society for Information Display’s Karl Ferdinand Braun Prize in 2004 and 2013, respectively. In 2011, Nakamura delivered a Display Week keynote address: “Nitride-Based LEDs and Laser Diodes: Current Status, Bright Prospects!”

## Henkel to Acquire Bergquist

Henkel Adhesive Technologies has signed an agreement to acquire The Bergquist Company, a privately held leading supplier of thermal-management products for the global electronics industry. According to Henkel, the transaction will provide it with a stronger position in thermal management in the specific areas of automotive, consumer, and industrial electronics as well as emerging applications in LED lighting.

Both parties agreed not to disclose any financial details about the transaction, which is subject to approval from anti-trust authorities.

## BREAKING GROUND

### DOW Builds Nanoco Quantum-Dot Plant in Korea

The Dow Chemical Company recently announced that construction has begun on a quantum-dot manufacturing plant in Korea, with production scheduled to begin in the first half of 2015. The quantum dots are based on technology from Nanoco Group plc, a leading developer of cadmium-free quantum dots and a global licensing partner with Dow. According to the two companies, this will be the world’s first large-scale cadmium-free quantum-dot plant capable of supporting the manufacture of “millions of cadmium-free quantum-dot televisions and other display applications.”

Preparatory work for construction of the plant, at an existing Dow site in Cheonan, South Korea, is well under way. The Nanoco quantum dots produced there will be marketed by Dow under the brand name TREVISTA Quantum Dots.

### Tianma to Build New G6 LTPS LCD Line

Tianma Microelectronics and Wuhan East Lake High-Tech Development Zone state that construction will begin at the end of this year on their jointly funded G6 LTPS production line (1500 × 1850 mm) in Wuhan, China. The project will include a color-filter (CF) production line and matching cell and module line. Its capacity will be 30,000 sheets of LTPS TFT-LCD panels a month and 30,000 sheets of CF sheets a month. The application area will be for small-to-medium-sized LCDs and liquid-crystal modules (LCMs) used in mid-to-high-end smartphones and tablet PCs. Production is scheduled to begin in 2016. The anticipated annual sales volume will be approximately RMB 10 billion (about \$1.63 billion U.S.) after the line reaches its full yield.

## LG Display Introduces 4K Monitor for Digital Cinema

LG Display has introduced a new 4K (4096 × 2160) monitor designed to meet the standards of the Digital Cinema Initiative (DCI). The LG 31MU97’s resolution and life-like colors are designed for photographers, video editors, and graphic artists.

Its 31-in. IPS display (Fig. 1) supports over 99.5% of the Adobe RGB color space and provides users with several coloring options and modes. A dual-color-space feature allows the monitor to display two different color modes at once so that users can compare different perspectives of their work simultaneously. ■



*Fig. 1:* LG Displays’s new 31-in. monitor has a resolution of 4096 × 2160 and supports over 99.5% of the Adobe RGB color space.



# guest editorial



## The Next Wave of 3-D – Light-Field Displays

by Nikhil Balram

In May of 2013, for our last special issue on 3-D, I wrote a guest editorial with the title “Is 3-D Dead (Again)?” The 3-D in question was stereoscopic 3-D for consumers. In that editorial, I focused on a fundamental limitation of stereoscopic 3-D – the vergence-accommodation conflict.

This conflict is caused by the fact that presentation of stereoscopic images on a single plane results in an unnatural decoupling of vergence (the point at which our two eyes converge) and accommodation (the point at which our two eyes focus), in contrast to real-world viewing where these two are always closely coupled.

This conflict has been shown to cause viewer discomfort that manifests itself in different ways such as nausea, headaches, and tiredness. In that editorial, and the two articles that accompanied it, the hypothesis put forward was that the likely path toward a natural 3-D experience was through volumetric displays, with light-field displays in particular being the closest to first commercial implementation. In this issue, I want to build further on that hypothesis by providing an update on the exciting developments in light-field displays and a vision of what lies ahead. Holographic displays are the other major category of volumetric displays. But, in my opinion, the state of the art, while continuing to advance impressively, is a decade or more away from a first significant commercial deployment. So, I chose to focus again on light-field displays.

The most fundamental segmentation in the design of display systems is between displays designed for group or multi-user viewing and those designed for personal or portable use. The critical issues and the approaches to solving them are very different for these two categories. Hence, they are discussed separately in the two invited articles in this issue.

The first article is from Professor Xu Liu and his colleagues at Zhejiang University, who have produced an impressive body of work in different types of group-viewable or multi-user light-field displays. “The Progress of Light-Field 3-D Displays” starts by providing a reminder of the fundamental definition of the light field and the basic principles of light-field displays. This is an important starting point because there have been some inconsistencies and ambiguities in how various authors have used the term in the literature. The article goes on to present the two main types of approaches for multi-view/multi-user light-field displays – time sequential (temporal multiplexing) using various types of scanning systems and spatial multiplexing using arrays of projectors or panels – and to discuss the state of the art and the tradeoffs.

The second article is from Dr. Kathrin Berkner and her colleagues at Ricoh Innovations Corporation in Silicon Valley. Their piece, “Personal Near-to-Eye Light-Field Displays,” takes a different approach from the first paper, arriving at portable, personal (single-user), near-to-eye light-field displays from the point of view of mobility. This work arises from a project initiated by me 3 years ago that sought to define the next-generation mobile platform after the smartphone. We came to the realization that this next-generation platform, which we call the Mobile Information Gateway (MIG), would need a near-to-eye light-field display to satisfy the big gaps in the human interface offered by the current mobile platform. This article lays out the logic leading to the definition of the requirements of this system and provides an overview of the state of the art in the various approaches that have been taken thus far. Here as well the

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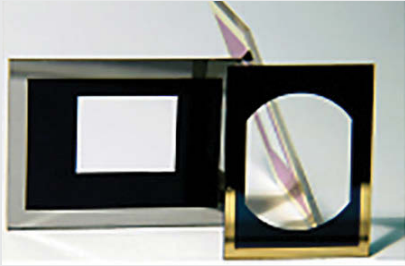
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# The Progress of Light-Field 3-D Displays

*Light-field displays represent an exciting and promising technology for the future. We introduce the principles of light-field displays, describe different types of multi-user light-field systems, and discuss their relative merits.*

by Xu Liu and Haifeng Li

**T**HREE-DIMENSIONAL display technologies have been a topic of research for over a century.<sup>1,2</sup> Many techniques have been developed to create ideal displays with a 3-D effect, from classical stereoscopy, autostereoscopy,<sup>3,4</sup> and integral displays<sup>5</sup> to volumetric or holographic displays.<sup>6-9</sup>

Traditionally, researchers have used the theory of geometric optics in the construction of 3-D displays; examples include stereoscopic displays, autostereoscopic displays,<sup>3,4</sup> and classical integral displays.<sup>2,5</sup> In these systems, the presentation of 3-D scene content to the observers' left and right eyes is considered according to the image perception principles of human vision. But in the case of holographic displays,<sup>10,38</sup> wave-optics theory is used, which means both the light amplitude and phase distribution describe the radiation of the light from a real 3-D scene. A display that can represent both the intensity and the phases of a 3-D scene would be considered the "ideal" 3-D display.

Light-field displays derive from the concept of computational imaging. They are based on the distribution of light rays in a 3-D scene that are used to generate a 3-D display. They convert the phase distribution of a wavefront into angle distributions of light rays, and thus can enable occlusion and the correct perception of the 3-D scene.

*Xu Liu and Haifeng Li are with the State Key Laboratory of Modern Optical Instrumentation in the Department of Optical Engineering at Zhejiang University located in Hangzhou, China. X. Liu can be reached at [liuxu@zju.edu.cn](mailto:liuxu@zju.edu.cn).*

## The Principles of Light-Field Displays

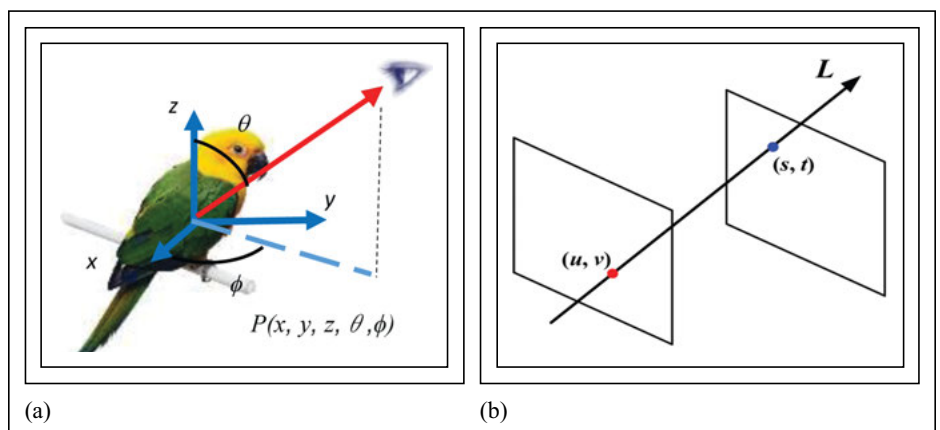
As mentioned previously, the concept of light-field displays comes from "light field" imaging in the area of computation imaging. The phrase "light field" was coined by Gershun<sup>11</sup> in a paper on the radiometric properties of light in 1936. The "light field" was redefined by Adelson and Bergen<sup>12</sup> in 1991 as part of a description of the plenoptic function of a natural scene that was used to present an imaging effect in computer graphics.

The plenoptic function can be expressed in the following way:  $P(x, y, z, \theta, \phi, \lambda, t)$ , where  $x, y, z$  are the 3-D coordinates that describe the location from which light is being viewed or analyzed;  $\theta, \phi$  describe the direction of the light; and  $\lambda$  and  $t$  are the wavelength of the light and the time of the observation, respectively.

For simplicity, the light field of a 3-D scene can be described with five-dimensional spatial parameters  $(x, y, z, \theta, \phi)$ , as shown in Fig. 1(a). These form a 5-D spatial parameter space.

Considering the flat boundary around the 3-D scene, Gottler<sup>13</sup> and Levoy<sup>14</sup> in 1996 put forward a 4-D parameter space for the light-field presentation  $P(s, t, u, v)$  instead of 5-D space. The 4-D parameter space can perfectly describe the light-field distribution from the geometrical point of view, as shown in Fig. 1(b).

It is clear that the dimensions of the parameter space are different among volumetric, stereoscopic, horizontal parallax only, and holographic displays. For holographic displays, we generally use the wave-optics theory, in which the light wave is expressed as



**Fig. 1:** The spatial parametrization of plenoptic and light-field models are shown at left and right, respectively. (a) The plenoptic model. (b) The light-field model.



$$E(\vec{r}, t) = E(\vec{r})\exp[-i(\omega t - \vec{k} \cdot \vec{r})]$$

where  $r$  is expressed as  $(x, y, z)$ , and the direction of  $k$  can be expressed as  $(\theta, \phi)$ . Thus, holographic displays have the same parameter space as the plenoptic-rays model.

For volumetric 3-D displays,<sup>7,8</sup> all the spatial voxels have the same luminance regardless of observation angle so that there is no angular parameter. These displays have a three-dimensional spatial parameter space  $P(x, y, z)$ .

For stereoscopic displays, right eye and left eye images are needed; therefore, the parameter space is just two dimensional. In the case of a high-density viewing-angle autostereoscopic display, assuming the number of views

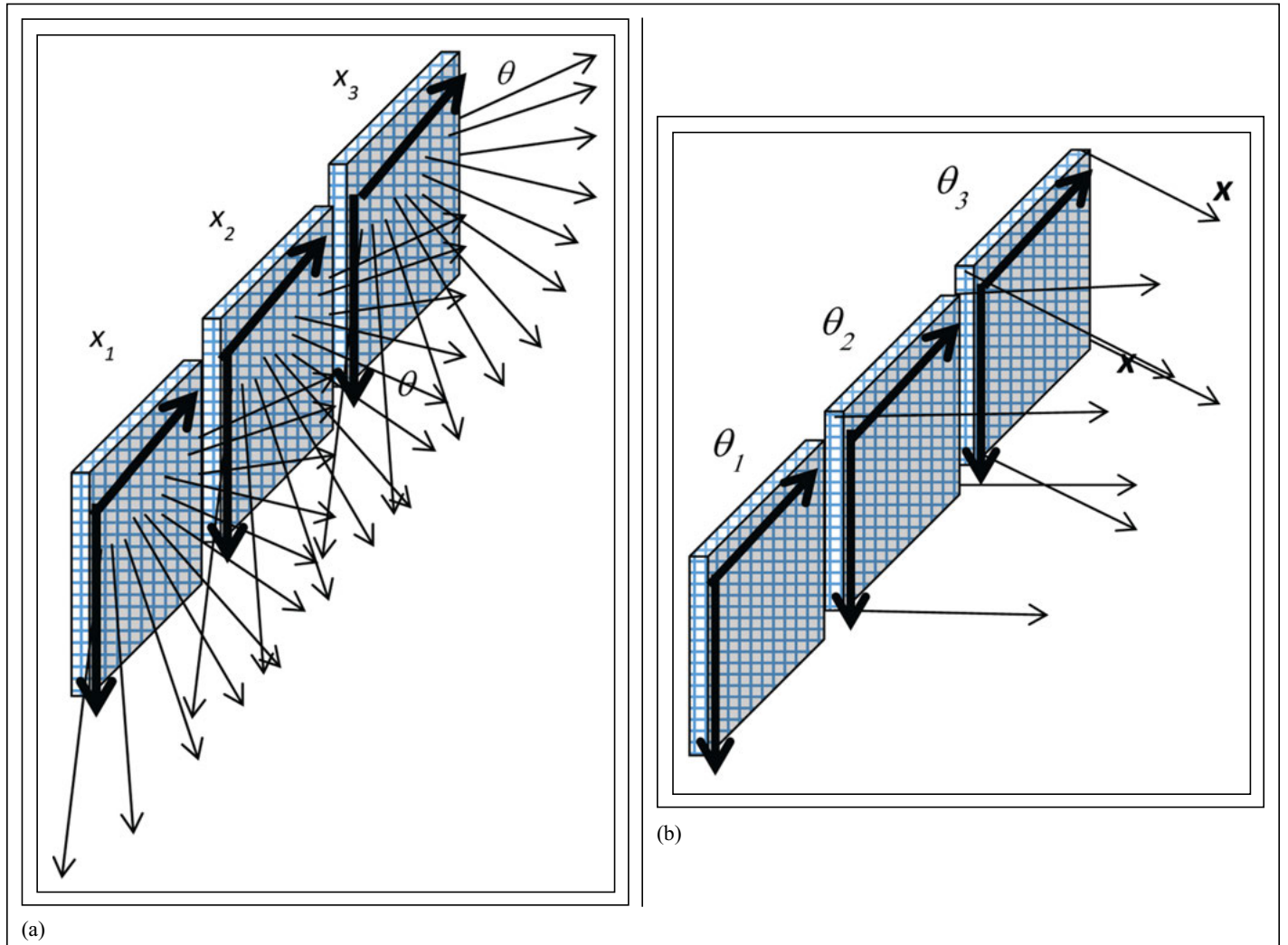
is  $N$ , the parameter space is  $N$  times the two-dimensional parameter space  $N \times P(x, y)$ .

It is obvious that the more dimensions the parameter space of the light field has, the more “real” the 3-D scene it presents can be. Light-field parameter space analysis helps determine whether a 3-D display technique is or is not a “real” 3-D display.

The four parameters for describing the light field  $(s, t, u, v)$  or  $(x, y, \theta, \phi)$  indicate that in order to display a true 3-D image, two additional dimensional parameters are needed than with a 2-D display. If we take 1000 picture elements in one dimension, the light-field 3-D display will have a data rate at least  $10^6$  times higher than the 2-D display because of the two extra dimensions. This data rate cannot be

accomplished by a normal-video-speed spatial light modulator (SLM). It needs an SLM with a much higher data-rate display ability, either high speed or high resolution, or both. Using a single high-speed SLM, we could optically scan the image with mirrors or other means while displaying the video data in a time-sequential manner to create the light-field display. Alternately, we could employ many SLMs in parallel and optically align them together to reduce the data rate required on each one.

There are two possible ways to generate the light field: (1) The first we will call the “rays angular multiplex” (or angular light integral) method, and, in this case, each SLM presents its own array of rays with unique distribution



**Fig. 2:** Above are two possible configurations of SLMs for the generation of light fields. (a) Rays angular multiplex. (b) Image multiplex.

$x, y, \theta, \phi$  to form all the distribution of light rays from a single  $x, y$  image location. These SLMs then together form the array of different spatial images for the 3-D display [Fig. 2(a)]. (2) The second case we will call the “image multiplex” (or image integral) method, and in this case each SLM presents all the  $x, y$  values at a unique  $\theta, \phi$  to form a unique viewpoint. In this case, the observer can see one SLM image in one direction and the light field of viewpoints is again made up from the total array of SLMs [Fig. 2(b)].

In practice, because of the low data rate of current display devices, we typically reduce the whole space parallax to the horizontal parallax only, to bring the spatial parameter space to three parameters ( $x, y, \theta$ ). This type of display system just ensures the perfect horizontal light field, but omits the light-field difference in the vertical direction. Almost all the techniques reviewed here are horizontal-parallax-only light-field-display systems.

There are two possible ways to meet the high data rate needed for a good 3-D light-field display: (1) time multiplexing or (2) spatial multiplexing. Time multiplexing approaches use a scanning type of light-field display based on a high-speed lighting source or high-speed modulator. These types of systems will be discussed in the next section. Spatial-multiplexing approaches use an integral type of light-field display based on multi-projector arrays. These are discussed in the section after the next one. In either method, one can use either rays-angular-multiplexing or image-multiplexing techniques. The various combinations are described in the next two sections.

## Scanning-Type Light-Field-Display Systems (with Rotating Structure)

**Scanning LED Arrays:** LEDs have a very fast lighting speed (about 50 nsec), so they can do high-speed signal modulation and are a good candidate for 3-D light-field displays. Conventional LEDs are a Lambertian light emitter, but we can use a moving light slit in front of an LED to create directional light rays. Using a rotating cylindrical distributed LED array together with a higher-speed rotating light slit scanner, we can create a 3-D light-field display as shown in Fig. 3.

Endo<sup>16</sup> had proposed the basic theory behind this method in 2000. And a display system with a few colors was shown in 2005 by Yendo.<sup>17</sup> Sony developed an LED-based

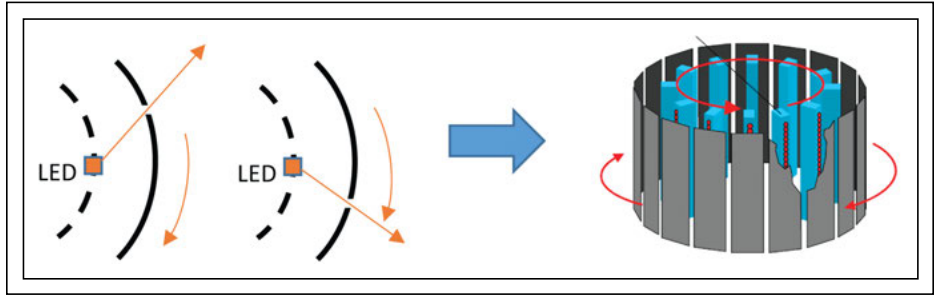


Fig. 3: The basic principle behind scanning LED-type light-field displays is shown above.<sup>17</sup>

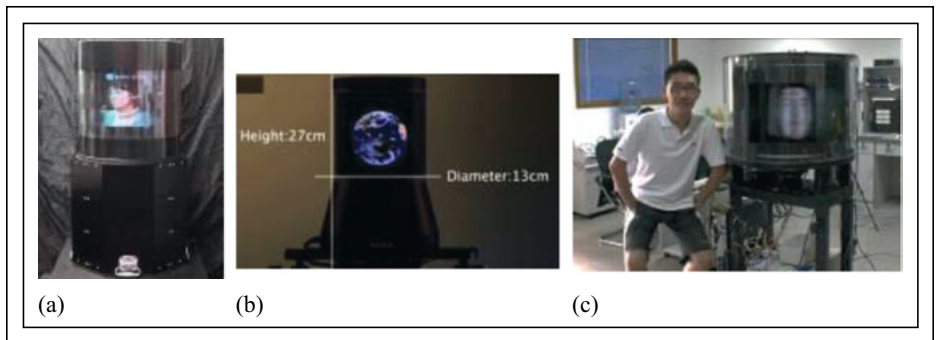


Fig. 4: Scanning LED-type light-field-display systems are shown from (a) Yendo, (b) Sony, and (c) ZJU.

small “RayModeler,” a 360° autostereoscopic 3-D display prototype with a display size of 27 cm in height and 13 cm in diameter, in 2009. In 2010, Zhejiang University (ZJU)<sup>18</sup> developed the biggest color-scanning LED light-field-display system to date, with a size of 65 cm in height by 80 cm in diameter. The system presented dynamic video and 3-D color imagery and also demonstrated an inter-

active effect. These three scanning LED systems are shown in Fig. 4.

Another way to use LEDs as a light-field-display medium was proposed by Yan.<sup>18</sup> He used a high-density color LED display panel combined with a light-ray controller screen to form a high-speed display panel. This method is based on image multiplex synthesis. The panel rotates around its center axis and is



Fig. 5: Above are two different views of the 45°-tilted special-diffusion screen technique as implemented by the black-and-white 3-D light-field display from Jones's system.

addressed sequentially while the image light field is synchronized with the rotation.

Principally, if we increase the number of LEDs in each array and increase the LED array number in the circle, we can achieve better performance. But, in practice, due to the size limit of current color LEDs, this technique is more suitable for large-sized 3-D displays.

**Scanning 45°-Tilted Special Diffusion Screen Technique:** Cossairt<sup>19</sup> proposed a method to address the lack of occlusion in volumetric displays by changing the scanning diffusion screen into a direction diffusion screen. His method simulates the generation of a light-field 3-D display. In 2007, Jones proposed the theory of light-field displays, and it was the first time that people began using the term “light-field display” and that a real light-field single-color dynamic display had been presented.<sup>20</sup>

Jones used the concept of light-field imaging in 3-D displays by inverting the light-ray propagation direction. He proposed a rendering method for light-field displays in which



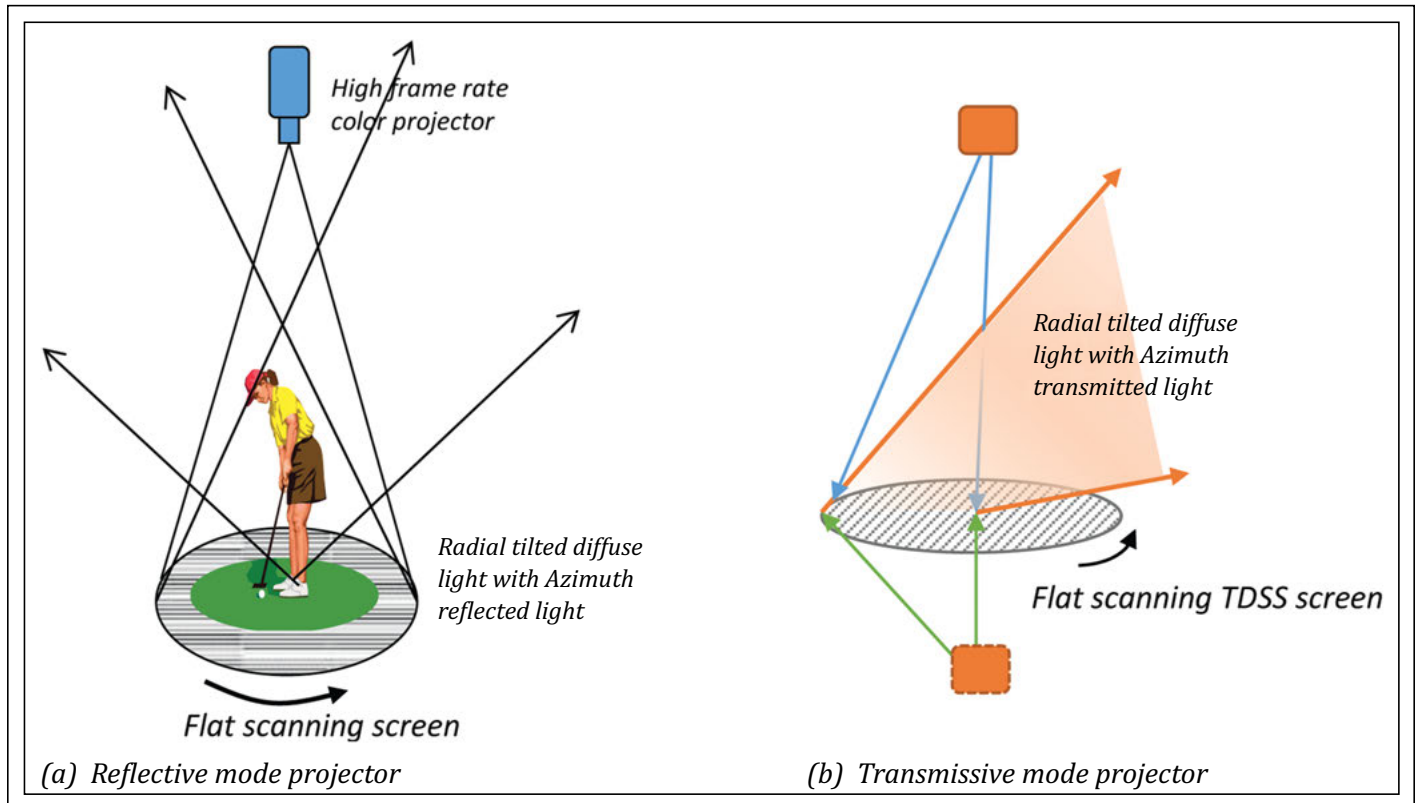
**Fig. 6:** Above are shown the 45°-tilted special-diffusion screen technique implemented by Zhejiang University (left) and views from different angles of a 3-D image displayed by the system (right).

the observer sees the image composed by different projector images (see Fig. 5).

This system used one high-speed DMD SLM to form a high-frame-rate black-and-white projector. It employed a standard programmable graphics card to render over 5,000 images/sec of interactive 3-D graphics, projecting 360° views with 1.25° separation with up to 20 updates/sec and a 45°-tilted diffusion selective reflection screen (DSRS) rotated at 30 revolutions/sec.

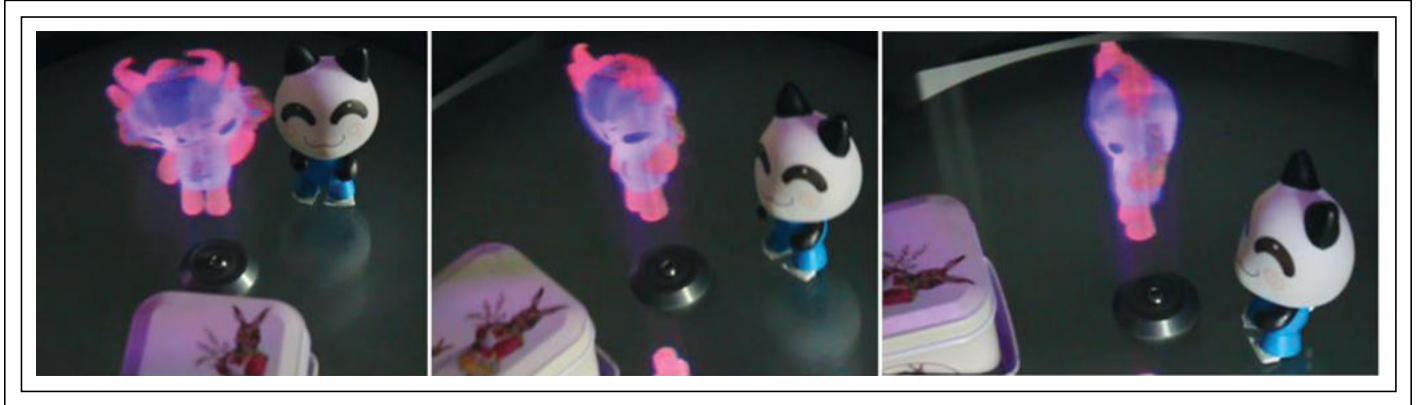
Later on, researchers at Zhejiang University developed a special LED color-sequential high-speed projector.<sup>21</sup> It can project 8,000 single-bit images/sec with a resolution of  $1024 \times 768$ . Combined with a 45°-tilt DSRS, it was the first time that vivid colors were shown with dynamic 3-D light-field imagery (see Fig. 6).

This technique used a DMD as a high-speed SLM and could achieve a data rate



**Fig. 7:** The flat special diffusion screen technique is shown in two working modes.





**Fig. 8:** Shown above are examples of 3-D display performance from a system based on the flat special diffusion screen technique.

approaching 3 Gbit/sec, which is very good for a low-resolution horizontal-parallax-only 3-D light-field display. Through the scanning of the tilted DSRS, one can get a good light-field display, but the display region is combined with the rotating DSRS region, and the influence of the movement of mechanical parts in the ambient light causes problems. Moreover, as the display size increases, the tilted DSRS will increase greatly, further increasing the problems caused by the mechanical movement.

**Scanning Flat Special Diffusion Screen Technique:** The scanning flat DSRS technique was proposed in 2010.<sup>22,23</sup> In this technique, in place of a 45°-tilted DSRS, we used a special DSRS screen that can reflect diffuse light tilted 30° (see Fig. 7) in a vertical direction and reflect only in the horizontal direction. This flat screen was used as the light-ray scanner. It rotated at 1800 rpm, and the high-speed color projector projected 21,000-frames/sec images on the screen. Through the scanning, one can create a vivid 3-D-scene light field floating above the flat screen.

There are two types of screens that can be used as the scanner. One is the reflective DSRS screen. The display works in the reflective mode. The projector is put on top of the scanning screen. For the reflective mode, the scanning screen is a highly reflective diffusion selective screen. Therefore, the ambient illumination light has serious influence. The other one is the transmissive mode. The projector is working in the transmitted form, and a transmitted diffusion selective screen (TDSS) is used. In this case, the TDSS scanning screen has low reflectance of ambient light, resulting in better contrast and, hence, better 3-D performance in high-ambient-light situations.

In order to get that better performance, we developed an RGB color projector system using three high-speed DMDs to generate the R, G, B high-frame-rate images, respectively. Each RGB channel has a capability of 21,000 frame/sec.<sup>23</sup> This provides a near-perfect color effect in the display.

The flat-scanning-screen technique can enable an interactive floating 3-D display. It

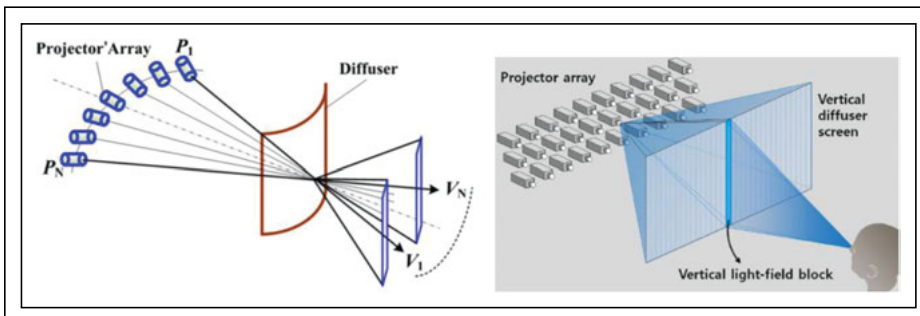
produces a very “real” floating 3-D image display that can be made interactive by monitoring the observers’ gestures and eye movements with a camera and responding to them. In Fig. 8, the 3-D display Olympic mascot Jingjing appears next to the real toy. The floating image has obvious volume.

As mentioned above, this system currently can only deliver a horizontally correct light-field display. Su<sup>24,25</sup> proposed a method that uses interactive effects to achieve vertical light-field-display information. He used a specially designed 360° lens imaging system to track the surrounding observers’ eyes and displayed the corresponding correct vertical light-field imaging to the corresponding observer.

## Integral-Type Light-field-Display System (with Multi-Projector Array)

An integral-type light-field display is different from the scanning variety. Instead of using a high-speed SLM or a light modulation source, we used a large number of image generators working in parallel to project images on a special directional transmission diffusion screen (DTDS). Through the special diffusion effect and with a large number of display image generators, we can achieve high-data-rate processing and generate the entire light-field distribution of the 3-D scene. In principle, to achieve good light-field-display performance, the multi-projector array works in an angular multiplex mode. It means that each projector must have its outlet pupil seamlessly adjacent with those of its neighboring projectors, as shown in Fig. 9.

Obviously, the key issues here are how to work a large number of SLMs in parallel and



**Fig. 9:** The principles of an angular multiplex light-field-display system<sup>30</sup> are shown above.

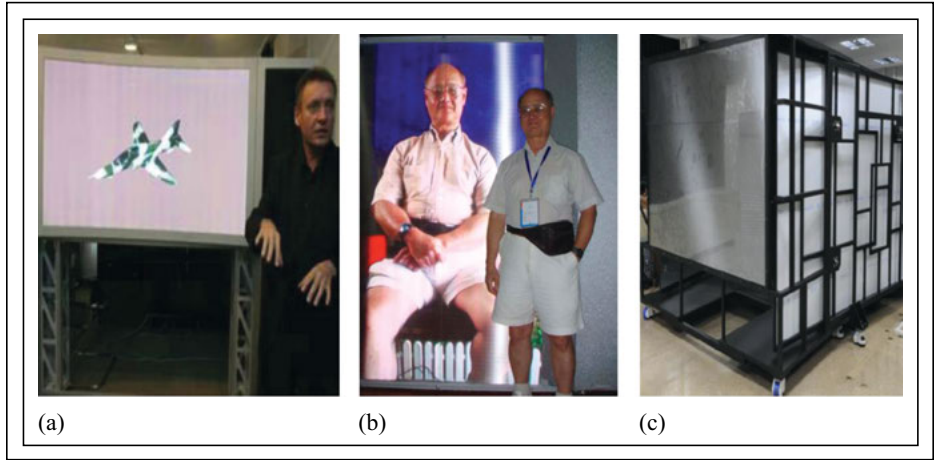
what is the DTDS that can direct the SLM light to the desired direction? Different DTDSs require different image-generation methods and different arrangements of the image generators.

In general, there are flat screens with multi-projector systems, curved screens with multi-LCD systems, and surround-type light-field display systems.

**Flat Screen with Multi-Projector System:** There are many papers that present the 3-D light-field displays with flat special diffusion screens and multi-projector systems. The first near-commercial product is the work by the team from Holografika,<sup>26, 27</sup> in which multiple projectors are arranged in such a way that the output pupil of each projector seamlessly abuts the ones from its nearest neighbors. Shang<sup>28, 29</sup> used a special holographic screen to meet the needs of the DTDS's properties and set up a large flat-screen multi-projector light-field-display system in 2009. Samsung presented its large flat-screen system at Display Week in 2013<sup>30</sup> with a 300-Mpixel multi-projection 3-D display that had a 100-in. screen and a 40° viewing angle (Fig. 10).

Because micro-projectors have become cheaper, many people have tried to use micro-projector arrays to generate the flat-screen 3-D display systems.<sup>31</sup>

It must be mentioned that for the flat DTDS, the field of view is limited by the field

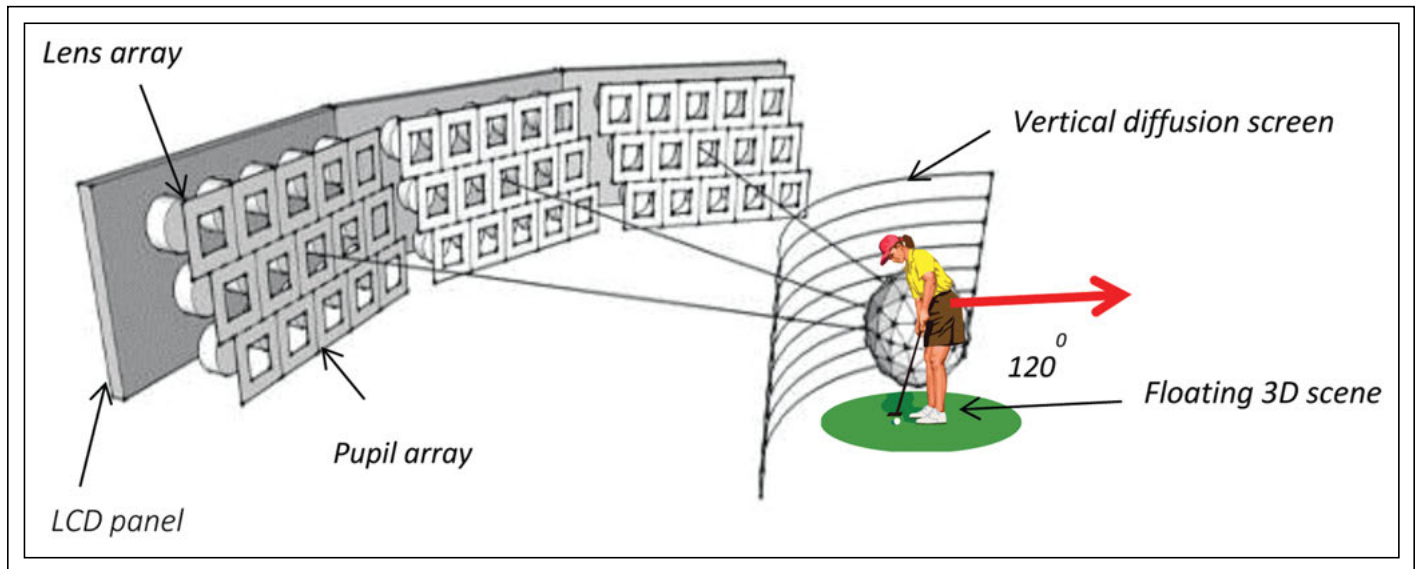


**Fig. 10:** Shown above are three different embodiments of multi-projector systems with flat special diffusion screens. (a) the HoloVizio system.<sup>27</sup> (b) Shang's system. (c) Samsung's system.

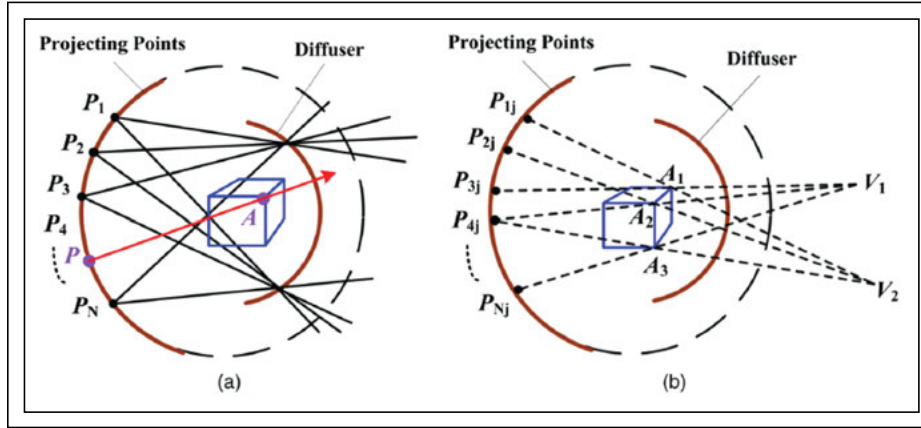
angle of each projector lens. The curved screen has an advantage in increasing the field of view. Because large numbers of projectors have been used in the display, the degradation due to mismatching fringes in the display is a problem that needs to be solved.<sup>30</sup>

**Curved Screen with Multi-LCD System:** This configuration employs three LCD units together with an arc DTDS, forming the light field of a 3-D scene in the central region. All three units and the diffuser are set in different concentric arcs.<sup>33,34</sup> As shown in Fig. 11, the LCD panels are divided into numerous sub-

display regions (or mosaic images) for different views. The number of sub-displays determines the number of views (angular resolution), and the number of pixels in each sub-display region determines the spatial resolution of the 3-D image. There is a direct tradeoff between the spatial and angular resolution since the product of the number of sub-displays and the number of pixels per sub-display is fixed and equal to the total pixel count of the LCD panel. Each lens and corresponding LCD region make up a so-called projector. All the light beams projected by these "projectors"



**Fig. 11:** The basic configuration for a three-panel curved-screen light-field system uses LCDs and a vertical diffusion screen.



**Fig. 12:** The projection principle of surrounding-type light-field 3-D displays appears above. (a) The light rays formed on DTDS. (b) Different views:  $v_1$  and  $v_2$ .

converge at the arc center that is defined as the center of the reconstruction area.

The 3-D display unit is scalable so that multiple display units are utilized to provide a large viewing range horizontally with the most feasible modularization. Each lens projects the pixels of an LCD sub-image in the form of a series of directional rays, which then construct the light field with other rays projected by the lens array. This 3-D display is limited by the pixel count of the LCD.

#### Surround-Type Light-Field Displays:

The surrounding-type light-field display can increase the observers' angular range to  $360^\circ$ . It is a system that can display the 3-D light-field image in the center of a certain volume. The observers can move around the volume to obtain a different point of view from different positions.<sup>36,38</sup> The system consists of  $N$  projectors aligned in the same horizontal plane and arranged such that the lens pupils of successive projectors form a continuous region from  $P_1$  to  $P_N$  (Fig. 12). Because of a limited number of projectors, rays are projected discontinuously and horizontally from these discretely positioned projectors. That is to say, without a cylindrical directional diffuser, screen observers would only obtain a series of discontinuous emitting exit pupils of the projectors. To smooth the discontinuity of rays, a cylindrical directional diffuser screen is set in the front.

A display system with 360 projectors has been set up in ZJU.<sup>37</sup> The projectors used here are DMD-based LED-light-source color projectors with  $800 \times 600$  pixels. The cylindrical diffusion selective screen is 4 m in

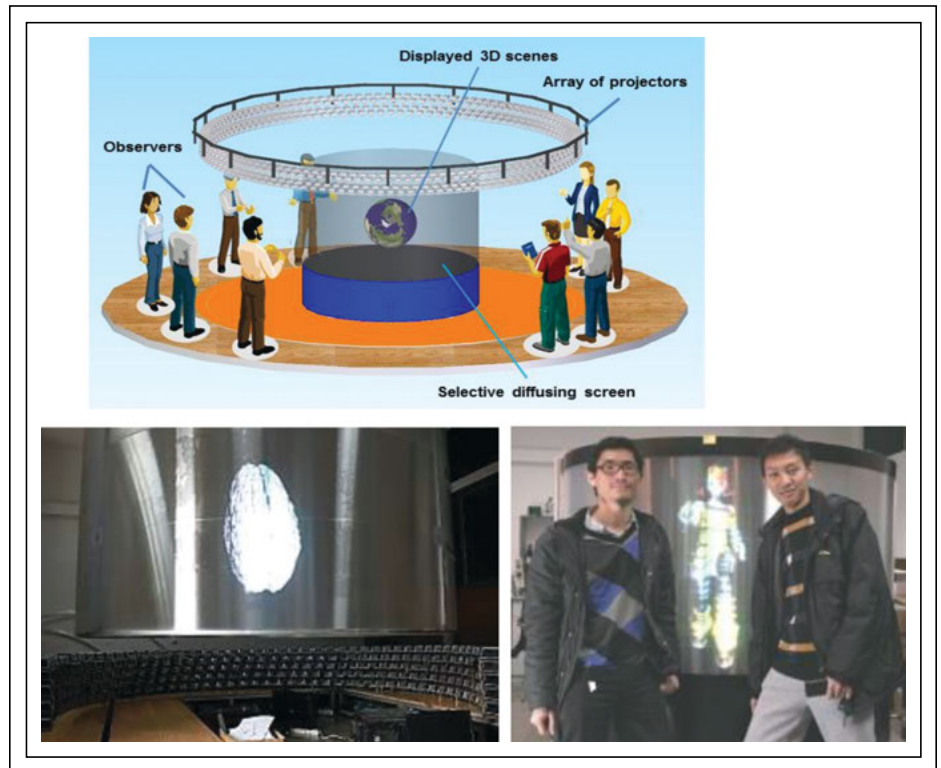
diameter and 1.8 m high. The screen diffuses the light vertically about  $60^\circ$  and diffuses about  $5^\circ$  horizontally (Fig. 13).

The other type of surrounding light-field display involves a projector array surrounding the outside of a cylindrical direction diffusion

screen. The observer is located at the central region of the cylindrical screen. In this case, a strong immersion effect will be perceived with a very wide viewing angle.<sup>37</sup>

#### Ongoing Challenges of Big Data and More

As discussed above, light-field 3-D displays can show a very good-looking 3-D image "floating" in the air, and the observers can watch a real 3-D scene from different points of view around the display with the naked eye. But to display a high-quality 3-D image, one needs a huge amount of display data. The minimum amount of 3-D display data needed depends on the 3-D scene volume displayed. The angular resolution of the human eye is about 1 arc minute. For a given spatial volume of a V-sized 3-D display, if  $N$  is the number of display voxels, then  $N/V$  is the density of display voxels. If the observer watches the 3-D scene from a distance  $L$ , the neighboring voxels will provide an angular interval of about  $(V/N)^{1/3}/L$  to the observer. If we take  $1'$  as the limiting resolution of the eyes, we will have the relation:



**Fig. 13:** The above images show schematics (top) and display performance of a surrounding light-field display with 360 projectors.<sup>37</sup>



$$(V/N)^{1/3} \leq PI \cdot L/60/180/2$$

If we want to have a 3-D display with a volume of about  $10 \text{ cm}^3$ , and the observer is 50 cm from the display, we can estimate that the minimum number of voxels required is  $10^9$ . This number is achievable with the current state-of-the-art SLM devices through the use of parallelism and multiplexing.

As we have explained, for techniques showing light-field 3-D, no matter what scanning or multiplex SLM integral approach is used, the total available data rate is limited. In this case, we have to decide how much of the data should be used to present the angular information and how much for the resolution information, in the 3-D scene. We must balance these two parameters by considering the light-field-display method used and observation position in order to obtain the best possible 3-D display quality.

To compare the performance of the different techniques, we can look at the data rate of the display system. The higher data rate a display system uses to present an image, the better the performance should be. Currently, for a  $360^\circ$  surrounding light-field display system  $10 \text{ cm}^3$  in size, a data rate of at least 10 Gbit/sec is needed for displaying. This means that the development of high-data-rate spatial light modulators and data-processing methods are the key factors in the further development of high-performance 3-D displays.<sup>39</sup> The other way to achieve high performance is to use high-density low-data-rate SLMs to operate in parallel so the system as a whole can get to the required high data rate. From the current state of the art and the advances that are being made, we can expect that 3-D light-field displays will be the first feasible “real” 3-D display technology of the near future.

## Acknowledgment

These works were supported by several research funds. We thank the National Basic Research Program of China (973 Program) (2013CB328802), the National High Technology Research and Development Program of China (2012AA011902), and the National Nature Science Foundation of China (61177015).

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# Personal Near-to-Eye Light-Field Displays

*In order for people to achieve true mobility – the ability to do anything, anywhere, anytime – there needs to be an entirely new class of mobile device.*

by Wanmin Wu, Kathrin Berkner, Ivana Tošić, and Nikhil Balram

**S**MARTPHONES AND TABLETS are becoming super-computing, super-communications, and super-sensory systems.<sup>1</sup> Over the last few years, their deployment has been growing much faster than that of the conventional PC platform. It is projected that by 2015 the installed base of mobile devices will be twice that of PCs.<sup>2</sup>

Despite this pervasiveness, the existing human interface of smartphones and tablets has fundamental limitations. Due to the constraints imposed by mobility, the human interface is provided by a small screen. This results in a field of view (FoV) that is too narrow to display certain types of information satisfactorily (Fig. 1, top left). This also limits information input and digital object manipulation (Fig. 1, top right). Furthermore, the promise of “augmented reality” (AR) applications that “allow users to see the real world with virtual objects superimposed upon or composited with the real world”<sup>3</sup> is lost because the small screen offers too tiny a window over the real world and the handheld form factor makes continuous usage awkward (Fig. 1, bottom left). Last but not least, current screens lack the capability to deliver a true (volumetric) 3-D experience (Fig. 1, bottom right).

In an earlier article on mobility published in the 2014 *IMID Digest*,<sup>4</sup> we presented the argument that to achieve true mobility – the ability to do anything, anywhere, anytime –

there needs to be an entirely new class of mobile device. We call this new category the Mobile Information Gateway (MIG), and it will comprise a compute–communication module (CCM) and a human-interface module (HIM), as shown in Fig. 2.

In order to provide a wide FoV under the mobility constraint, the next-generation human-interface module will logically need to be a wearable display positioned near the eyes of the user. To support unobstructed and immersive interaction with the surrounding 3-D real world, the near-to-eye (NTE) display

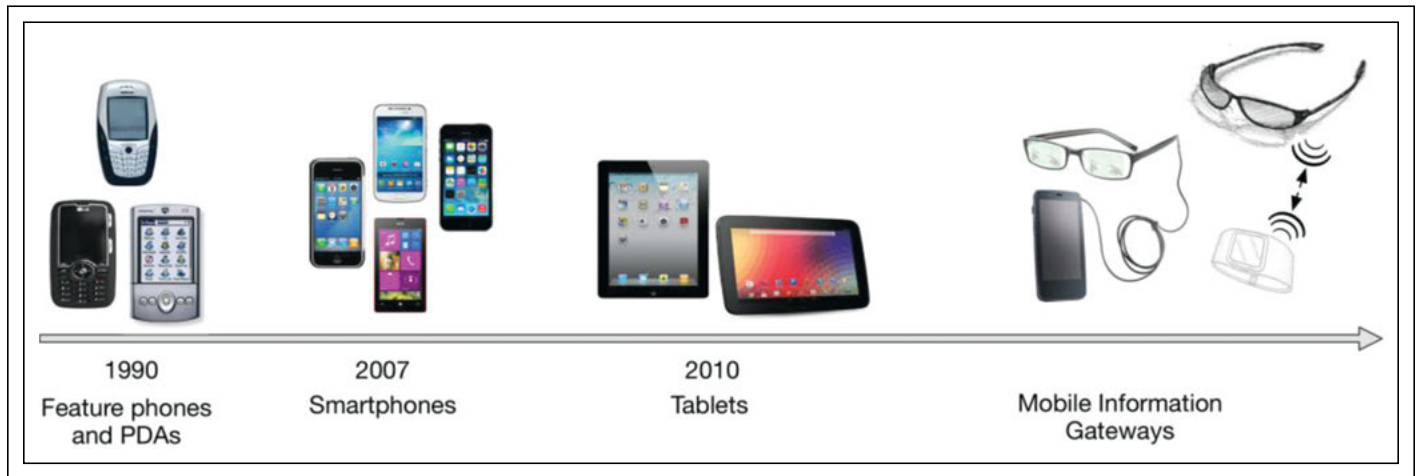
will need to have binocular, optical see-through, and true 3-D visualization capabilities. To minimize the weight and form factor, the primary computation and communication electronics will reside in a separate compute–communication module that will be an evolution of the current mobile platform.

In this article, we focus our discussion on the NTE display system. A number of attempts have been made in the past decade to build personal NTE light-field-display prototypes (e.g., see Refs. 11, 12, and 16). They all have different tradeoffs based on the



*Fig. 1: Human interfaces with existing mobile devices (e.g., smartphones and tablets) are fundamentally limited in their field of view and interaction capabilities.*

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**Fig. 2:** *Mobile Information Gateways – a new family of devices that combine a personal NTE light-field display and a mobile computer – will be the next-generation mobile platform.*

design choices, and thus will apply to different classes of applications. Our immediate goal is to discuss the capabilities and limitations of these approaches and to report the implications to future MIG system developers so that they can make a more informed decision when choosing a path for their specific applications.

### Key Requirements

The NTE component of a MIG needs to provide four key interface features:

- A wide FoV to enable a viewing experience comparable to that of using a large screen.
- A perceptually correct positional overlay of digital information over objects in the real 3-D world surrounding the user.
- True (volumetric) 3-D projection of digital objects.
- The ability to capture and interpret gestures to enable information input capabilities in any environment without the need of a physical keyboard or mouse.

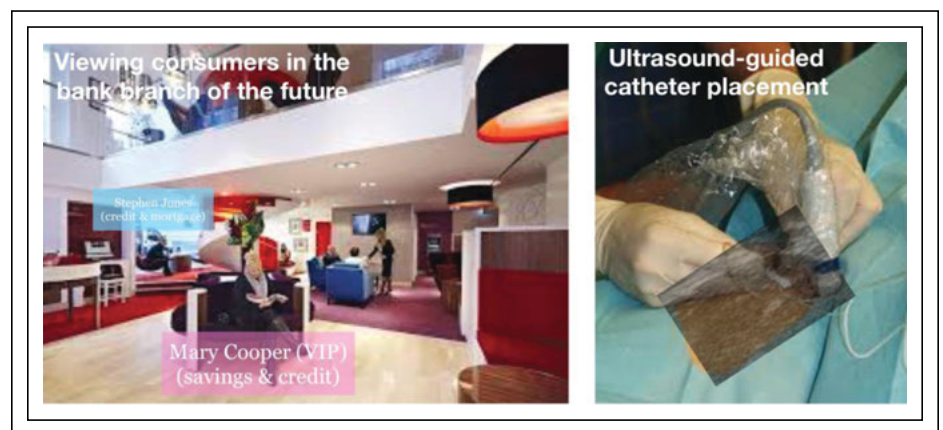
We believe that one of the most promising approaches to providing all of those key display-related attributes is through a binocular personal (single-user) light-field NTE see-through display.

In the most general sense, a light-field display refers to a device that emits an approximation of the light field of a 3-D scene, which is represented as a high dimensional array of light modalities, including

spatial, angular, wavelength, and temporal information of light.<sup>10</sup> The approximation is achieved by designing a specific sampling topology of the light field, where that topology depends on the display architecture. For example, light-field displays based on microlens arrays have a reduced spatial sampling frequency in order to allow for the angular sampling of light. On the other hand, multifocal displays based on high-speed digital micromirror devices (DMDs) maintain high spatial resolution but utilize temporal multiplexing to emit different spatio-angular slices of the light field at separate time instances.

Binocular NTE light-field displays with a large field of view can revolutionize how humans interact with the world. Two exam-

ples are illustrated in Fig. 3. In the example on the left, customer-facing professionals, such as employees working in a futuristic bank branch, can use the system to see their waiting customers with detailed profile information overlaid. Information overly associated with customers positioned at different distances from the viewer requires accurate positioning of overlay information, not only with correct 2-D positional alignment but also with correct 3-D depth cues. In the example on the right, during an ultrasound-guided catheter insertion procedure, a doctor could see ultrasound images superimposed on the patient while inserting the catheter, avoiding the continuous look-away required for conventional ultrasound displays.



**Fig. 3:** *These examples of augmented-reality applications use binocular see-through light-field displays.*

There are a large number of such potential applications. However, existing mobile-display technologies such as smartphones, tablets and various NTE displays<sup>24</sup> are inadequate to support these applications.

## Taxonomy of NTE Displays

To understand personal NTE light-field displays, it is useful to understand the taxonomy of NTE displays. As shown in Fig. 4, NTE displays can be classified into virtual-reality (VR) displays and augmented-reality (AR) displays. VR displays such as described in Ref. 9 show only virtual information to the users and block the real-world views completely. AR displays, in contrast, allow the users to see both the virtual world and the real world at the same time.

AR displays can be further classified into video-overlay displays and optical see-through displays. Video-overlay displays block the real-world view optically, but capture it with a miniature camera and present the video view to the user with virtual information overlaid. Although this approach has its advantages, such as latency hiding and simplified overlay, it suffers from a number of drawbacks such as sensory conflicts between vision and proprioception (the sense of one's own body), perceived

resolution loss, viewpoint mismatch, altered color and brightness, and user trust issues.

Optical see-through AR displays can be further classified into monocular and binocular displays. Google Glass<sup>8</sup> is a well-known example of a monocular see-through display. It has a small FoV of about 13°. Monocular displays have no 3-D display capabilities and provide only limited AR support because the set of real-world locations that can be overlaid with AR information is constrained. On the contrary, binocular optical see-through displays relax the constraints on the placement of overlay information, allowing more natural placement in a real-world scene. Therefore, we envision the next-generation mobile interface to be a binocular optical see-through display and, more specifically, a binocular optical see-through display with light-field projection capabilities.

## Personal NTE Light-Field-Display Technologies

Among the aforementioned key requirements for the NTE component of the next-generation mobile-platform MIG – wide FoV, virtual-physical object overlay with optical see-through capability, true 3-D display, and gesture interpretation – the most challenging

is probably the true 3-D display of a scene.

Conventional stereoscopic 3-D displays (such as the Epson Moverio shown in Fig. 4) are designed to create a 3-D perception of a scene, but they suffer from the fundamental problem of vergence-accommodation conflict. This conflict causes visual discomfort and fatigue, distortion in perceived depth, and degradation in visual performance and stereoacuity.<sup>5</sup> Avoiding the vergence-accommodation mismatch is crucial for a MIG system to be able to create a comfortable 3-D viewing experience and be used for a sustained period of time without compromising visual comfort or performance. Researchers have proposed various 3-D display systems to avoid this fundamental conflict, including integral 3-D displays,<sup>23</sup> compressive light-field displays,<sup>18</sup> holographic displays,<sup>19</sup> and volumetric displays.<sup>20,21</sup> However, these systems are significantly burdened by the requirement of being multi-user/multi-view and are not designed to be mobile.

The NTE component of a MIG should be a single-user/single-viewpoint, 3-D volumetric display. Past research has indicated that this path may be practically achievable by a multi-focal display, where the number of depth planes needed to provide conflict-free 3-D viewing can be six or even fewer.<sup>7</sup> In an article presented at SIGGRAPH,<sup>6</sup> Akeley *et al.* built a prototype of a single-user display that could display four planes and demonstrated that it enabled natural vergence-accommodation coupling during viewing. We expect the next-generation mobile interface to be a compact NTE version using the same concept.

As mentioned earlier, different types of approaches have been proposed in the past to construct personal NTE light-field displays, e.g. see Refs. 11, 12, and 16. They all have different tradeoffs and may be suited for different applications. In the remainder of this article, we will survey those approaches, classify them, and offer insights on how they compare to each other.

## Major Components

Before we discuss the various approaches, it is useful to understand the main components of a personal light-field-display system. The existing systems primarily consist of the following elements, e.g.,

- **Light source:** LEDs, OLEDs, laser diodes.

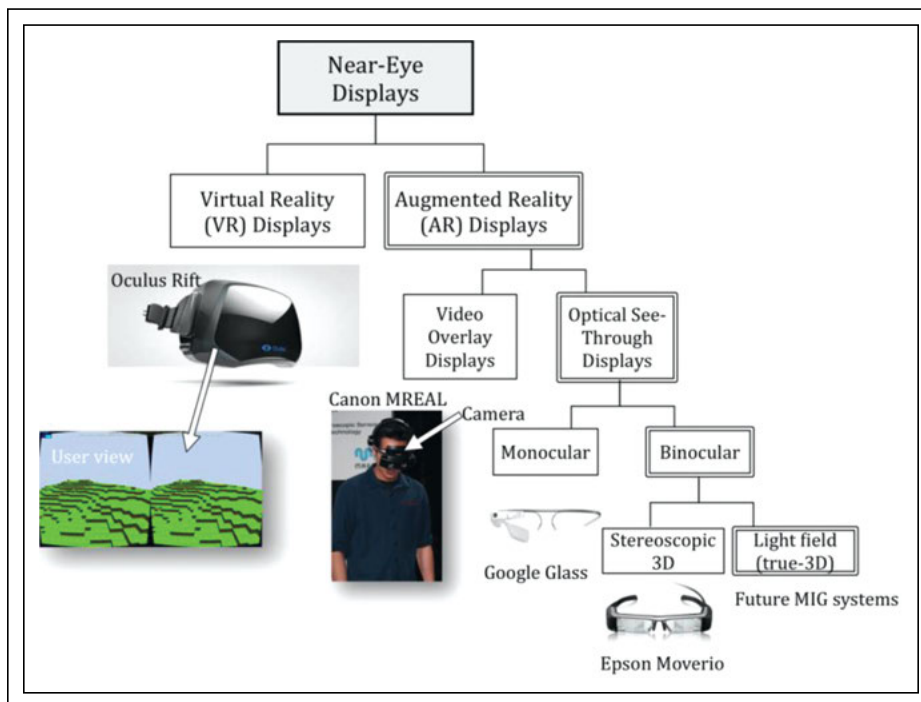


Fig. 4: A taxonomy of NTE displays includes commercial or near-commercial examples.



- **Image source:** reflective DMDs, emissive OLED devices, scanners (with fiber optics).
- **Optical subsystem/path:** including relay, field lens, combiner (such as a beamsplitter or mirror, waveguide, and free-form optics), focus actuator [such as a liquid lens and a deformable membrane mirror device (DMMD)], and eyepieces.
- **Electrical subsystem:** power and signals (including sensors and controls).

The active display component, including the light source and the image source, forms an image that is, in turn, relayed by the optical subsystem into the retinae of the eyes. The optical subsystem typically needs to include an optical combiner that simultaneously reflects the projected information and transmits light originating from the real-world scene. In some cases, as explained below, the optical subsystem includes a focus actuator to adjust the position of the image plane at different distances from the eye, resulting in a 3-D content display at multiple focal planes. The electrical subsystem provides power and signals.

In the following sections, we mainly focus on the active display component and the focus actuator (if any) because they are the key components that realize the true 3-D projection capability. For a review of the other parts of NTE display systems (e.g., optical combiners), we refer readers to Refs. 24 and 25.

### A Survey of NTE Light-Field Displays

To achieve true 3-D projection in a wearable display is a non-trivial problem. There have primarily been two ways proposed to tackle it: matrix-display based and laser-scan based.

#### Matrix-Display Methods with Temporal or Spatial Multiplexing

Matrix-display methods use matrix-display modules, such as a DMD or OLED, to project a 3-D volume of light by temporal multiplexing (i.e., projecting one plane at a time) or spatial-multiplexing (similar to 3-D integral imaging<sup>28</sup> but with the light path reversed).

#### Temporal Multiplexing

Temporally multiplexed systems utilize high-frequency display modules to consecutively display content in multiple focal planes, and to do so fast enough that the human eye perceives them as being displayed simultaneously. They utilize the fact that the refresh rate of DMDs is much higher than what the

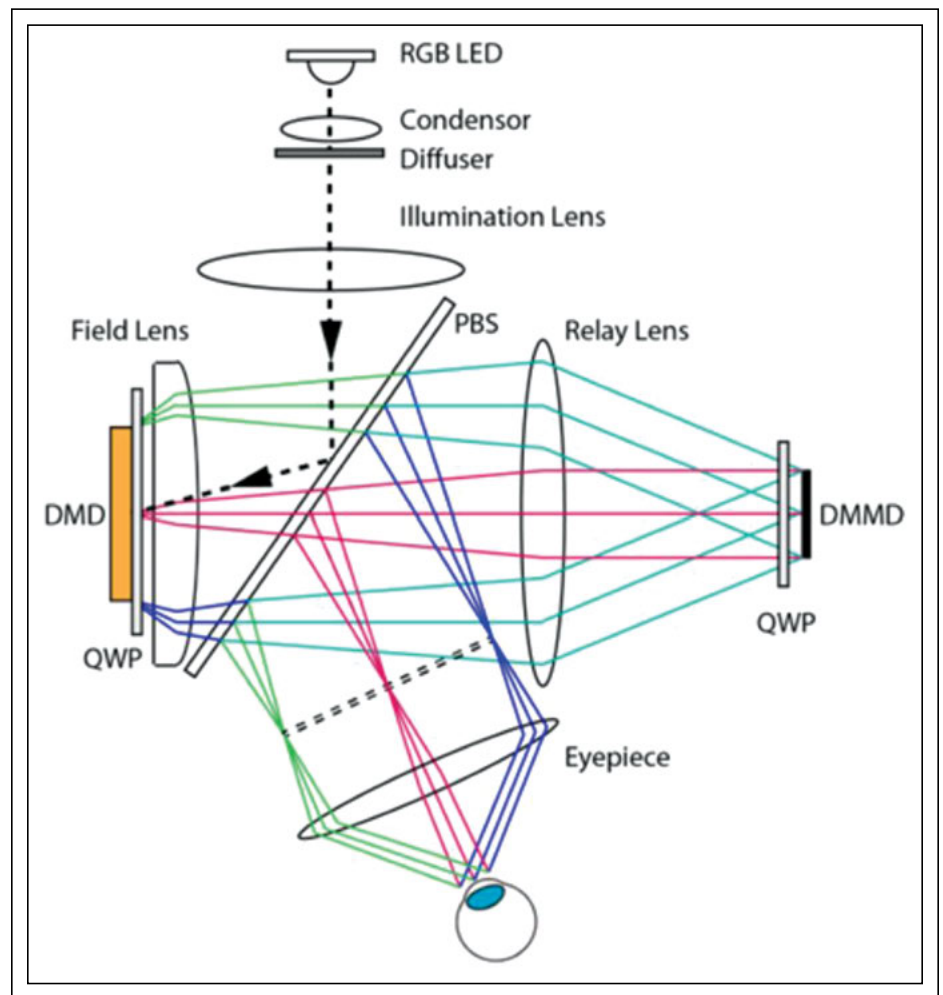
human visual system can resolve. Such systems also need to use a high-frequency focus actuator that is synchronized with the active display component to project light focused on multiple depth planes.

Furthermore, in order to approximate a continuous depth volume for accommodative responses, a technique called depth blending (also known as depth blending or depth fusing) is often used.<sup>6</sup>

For example, Liu *et al.*<sup>26</sup> developed a multi-focal optical see-through display prototype with an OLED microdisplay device as the active display component and a liquid lens as the focus modulator. The liquid lens the researchers used had a slow response time (75 msec), and thus only two planes were demonstrated at flicker-free speed.

In a 2009 article published in *Optics Express*, Love *et al.*<sup>11</sup> constructed two prototypes, both using high-frequency CRTs running at 180 Hz. In the first prototype, they used two CRTs (one for each eye) viewed through mirror prisms. They employed birefringent lenses as the focus actuator for each eye, which resulted in a maximum of four multi-focal planes. In the second prototype, they used the same principle, but with only one CRT that is time-multiplexed for two eyes (with the help of shutter glasses). The refresh rate was 45 and 22.5 Hz for prototype 1 and 2, respectively.

Hu *et al.*<sup>12,13</sup> built a prototype display using a DMD and a synchronized high-speed MEMS-based DMMD as the focus actuator. Figure 5 shows the schematic optical layout. The DMD used can display at a rate of about 23



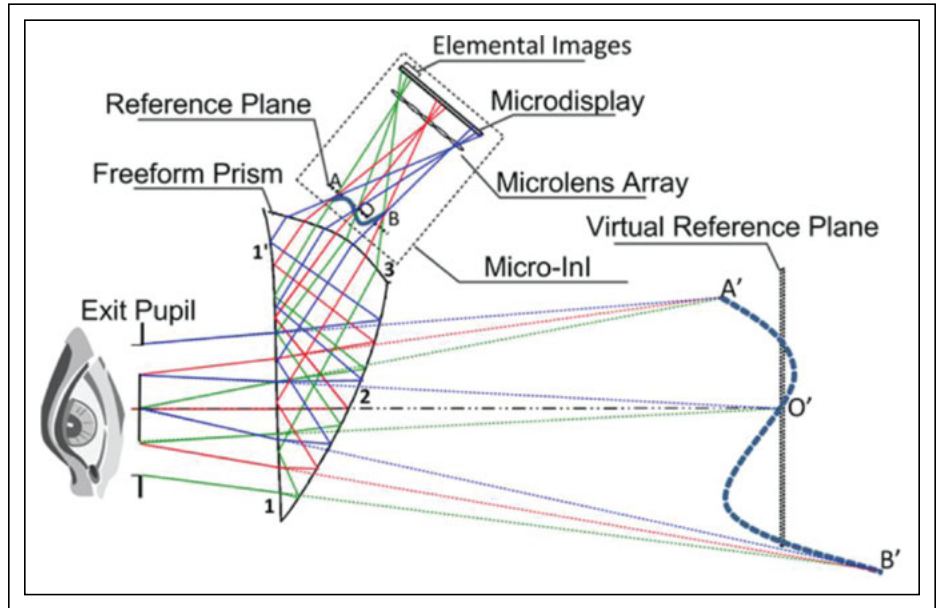
**Fig. 5:** This schematic shows a prototype for a temporally multiplexed display using a DMD and a synchronized high-speed MEMS-based DMMD.<sup>12</sup>

kHz and the DMMD has a switching speed of 1 kHz. The prototype was able to display six focal planes at a flicker-free rate (60 Hz).

## Spatial Multiplexing

In spatially multiplexed systems, the true 3-D capability is achieved by using a microlens array or a pinhole array in the optical path. This system architecture is based on the same principle as integral-imaging displays and microlens-based light-field cameras. These approaches reconstruct a full-parallax light field of a 3-D scene, and thus render focus actuators unnecessary because fixed-focus optics (e.g., free-form optics) already allow the viewer to perceive the 3-D volume. The most common active display component being used for this approach is an OLED device with high resolution and efficient form factor and power.

For example, in a paper published in the *2013 ACM Transactions on Graphics*, D. Lanman *et al.*<sup>22</sup> described a non-see-through NTE light-field display. Based on the same principle of integral-imaging displays and microlens-based light-field cameras, this system used an OLED microdisplay and a microlens array to render a light field before projecting it to the eyes. The achieved spatial resolution was  $146 \times 78$  and the FoV was  $29 \times 16^\circ$ . The authors later proposed a see-through AR display using point light sources,<sup>27</sup> but the constructed prototype only supported one focal plane. The authors provided some theoretical guidelines on how it might be extended to display a light field but acknowl-



**Fig. 6:** This schematic view shows Hua's 3-D integral-imaging see-through light-field-display prototype.<sup>14</sup>

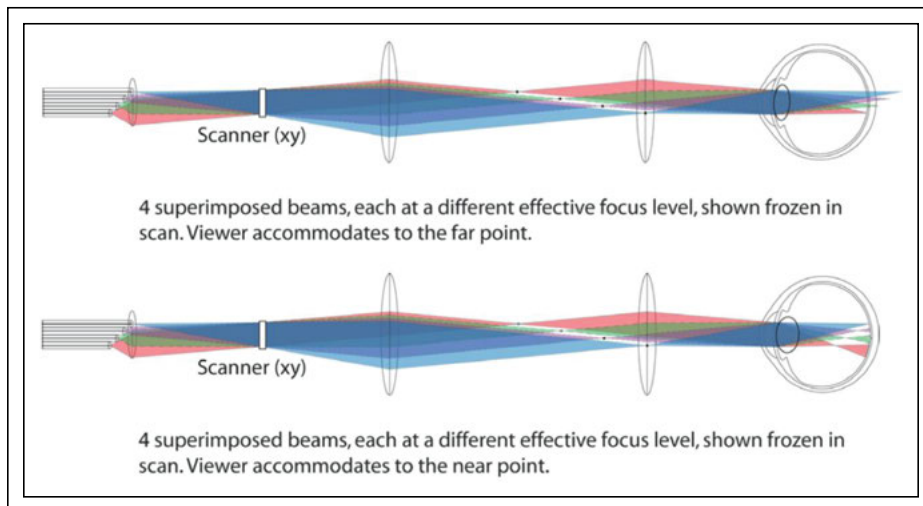
edged notable challenges and did not demonstrate any implementation or experiment.

Hua *et al.*<sup>14</sup> combined the microscopic integral-imaging (micro-InI) method and free-form optics to create a 3-D integral optical see-through light-field display. A micro-InI unit, consisting of a high-resolution OLED microdisplay and a microlens array, enabled reconstruction of 3-D volumetric shapes with both horizontal and vertical parallax. Figure 6

shows the scheme. Unlike that described in Ref. 22, the system demonstrated see-through capability with a free-form prism employed as the viewing optics that directly relayed the light field of the reconstructed scene into the eye. It achieved FoV of  $33.4^\circ$  and a depth range of 4 m.

## Laser-Scan Methods with a Single Fiber or a Fiber Array

While the above methods all rely on some type of matrix display, currently known laser-scan displays use laser diodes and fiber-optic scanners to raster-scan virtual images into the eyes. Such systems form multiple focal planes in two ways: (1) use of a single fiber and scanning different depths sequentially or (2) use of fiber arrays (with each fiber representing one depth plane) and XY scanning of the fiber bundle to generate 3-D depth volume. Laser-scan approaches are intrinsically temporal-multiplexing approaches. But compared to the previously described temporal-multiplexing matrix-display methods, the temporal tradeoff can be relaxed in laser-scanning-based systems because color and gray scale can be handled independently with three color diodes and analog modulation, not sequentially as when using DMDs. However, there is still a tradeoff between frame rate and the number of lines per frame, just as there was for CRTs.



**Fig. 7:** The above schematic view shows Schowengerdt *et al.*'s fiber array-based scheme.<sup>16,17</sup>

Schowengerdt *et al.* presented an early prototype of a laser scanning system.<sup>15</sup> In that system, a single beam of light was formed and first scanned in the Z-axis with a DMMD that dynamically adjusted the focus of the beam; the beam was then raster scanned in the X and Y axes (XY scanned). This prototype was limited by the DMMD frequency at that time and was only able to project two planes frame sequentially.

Schowengerdt *et al.* later proposed another retinal scan method to overcome this limitation. The idea was to use multiple light sources to form a composite multi-focal RGB beam and then XY scan it into the viewer's eyes.<sup>16,17</sup> An optical fiber array with end faces positioned at different angles was used to produce a multi-focal bundle of beams, as shown in Fig. 7.

### Comparison of Existing Solutions

Table 1 presents a summary of recent approaches for the personal NTE light-field displays described above.

Temporal multiplexing offers an opportunity for a better multi-focal display because one can achieve a significant depth range by placing planes as needed, from reasonably close to far away. The main drawback is that in practice the design of real systems will require careful thought behind the tradeoffs in the number of gray-scale levels, number of pixels, number of frames, and number of depth planes. Another challenge is having the whole display mechanism compact enough to make a light and comfortable NTE display.

Spatial multiplexing offers the opportunity to make a more compact light-field display suitable for consumer market segments. The main drawback is that the actual depth achieved in the scene is limited by the small amount of parallax that is possible for light fields using a microlens-array approach, but this can be mitigated using free-form optics.<sup>14</sup> The limited resolution of each spatial plane might be a disadvantage, but with OLED microdisplays going to 4K resolution, perhaps there might be enough resolution for many types of applications.

**Open Challenges**

There has been tremendous progress in the past few years in the development of personal NTE light-field displays. As discussed above,

**Table 1:** A summary of recent binocular optical see-through light-field displays includes advantages and disadvantages.

Classification	Light Source	Image Source	Multi-Focal Technique	Advantages	Disadvantages	Examples (Refs.)
Matrix-display approaches	LED	Reflective DMD	Temporal multiplexing using vari-focal lens or deformable membrane scanner	1. High spatial resolution 2. Good depth range	1. Limited number of depth planes 2. Limited color bit depth 3. Complex and bulky electronics 4. Possible jitter	12, 13, 26
	Self-emissive	Emissive OLED display	Spatial multiplexing using microlens array (temporally not possible because of response time)	1. Simple electronics 2. Thin form factor and low power consumption (for video) of OLED	1. Limited spatial resolution for each plane 2. Limited depth range	14, 22
Laser-scan approaches	Laser diodes	Fiber-optic scanner – single fiber	Temporal multiplexing using vari-focal lens or deformable membrane scanner	1. Good depth range 2. Good color depth 3. High spatial resolution possible theoretically (but not shown in practice)	1. Constraint on multiplicative factors, <i>e.g.</i> , number of planes, number of vertical lines 2. Complex electronics because of high signal bandwidth	15
	Laser diodes	Fiber-optic scanner – array of fibers	Use fiber array (with each fiber providing one depth plane)	1. Good color depth possible 2. High spatial resolution possible theoretically (but not proven) 3. Simpler electronics compared to temporal multiplexing	1. Limited depth because it is achieved by small physical skewing of individual fibers 2. Duplication of electronics required because of need to provide depth planes in parallel 3. Possible duplication of light sources	16, 17



the existing approaches all have different tradeoffs based on different design considerations. Thus far no practical design has been demonstrated that satisfies all the key requirements. As seen in Table 1, each approach has some limitations in the current implementations. But we believe that the fundamental approach of light-field sampling in spatial and angular dimensions will be the foundation of future designs that overcome the current limitations and deliver the full set of requirements for the MIG.

Further, in our opinion, the performance evaluations of the systems proposed in the current crop of papers are far from complete – most have not incorporated human studies yet, and those that have, have mostly only considered monocular accommodative responses. In other words, there is not yet enough scientific evidence to demonstrate that any approach is better than another. Overall, research in this area is still at an early stage. Thorough end-to-end system evaluation is still needed to assess these systems, for example, in terms of binocular responses, visual comfort, depth perception, etc.

Besides the challenges mentioned above, there are more open questions to answer in the development of Mobile Information Gateway (MIG) systems. The following list is by no means exhaustive; it is intended to stimulate discussion and new research in this area in the near future.

- How to evaluate the sampling topology of light-field displays to drive the system design in a practical direction?
- How to assess an end-to-end system incorporating optical and perceptual performance parameters?
- How to perceptually model the system performance?
- How to achieve seamless overlay in AR?
- How to calibrate the system to achieve the performance metrics we need in overlay and in system design?

We are confident that there will be substantial progress over the next 5 years, with the first commercial deployments occurring in specific vertical applications before the end of the decade. We believe MIG systems that encompass a NTE light-field display will ultimately revolutionize the human-computer and human-world interaction.

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# guest editorial



## The State of TVs Today

by Steve Sechrist

Stepping back to assess the state of TVs today, one cannot help but be amazed at the evolution from bulky CRT picture tubes to the current mass-produced flat panels that now dominate the large-display landscape. And the evolution continues, with goals remaining more or less the same: realistic image quality (higher pixel density), razor thin

design, growing display size, and, of course, lower cost.

In this month's issue, we ask if we are beginning to reach the limits of LCD technology in moving us to new levels of large-display performance. We explore the fundamental and structural limits of the now dominant backlight and gating crystal technology with an eye toward what large-display emissive OLED TV can offer as the heir apparent to living-room TV technology.

But beyond the materials used to build the display, what is ultimately unleashed from these evolutionary forces are expanded-use models and new applications often unintended by design. It is the unleashing of these new forces that drive development further forward in a new cycle of creativity that perpetuates its own evolution.

One such example is the growing trend of UHD and higher-pixel-density displays that go well beyond the limits of human visual acuity. Despite the critics' commentary that this is being done "simply because we can," enhanced 4K displays and beyond are providing a brand new canvas from which to paint completely new viewing experiences. These are perhaps the next killer applications that will go beyond the full-screen (UHD content) image with the advent of display-screen real estate and the multiscreen living-room experience. They hold the promise of creating a staggering ripple effect on content creation and display innovation (including new models of content monetization).

And what new unintended consequences will this future hold? We already have Amazon's Dynamic Perspective technology, a type of internal 3-D effect that uses all those spare (imperceptible) pixels along with parallax viewing to go deep into the display, revealing sub-folders, data, and content buried deep within the file structure. This technology is empowering HD phone displays by addressing the fundamental mobile-display problem of more imagery than can be handled on a limited-sized screen. This paradigm surely holds for all display sizes.

Finally, the frontiers of displays also include human interactivity because visual perception is simply the genesis of an ultimate human-machine interface that eventually will extend to all manner of human perceptibility. As leading interface display expert Dr. Jennifer Colegrove from Touch Display Research recently forecast in her "Touchless Human-Machine Interaction Market Report," up to one-third of TVs will adopt voice control by 2020, and gesture control and motion sensor fusion will also increasingly penetrate TV applications.

One thing is certain: the state of large-screen TV continues to evolve, whether it be UHD and curved OLED screens, new content display paradigms, or interactivity that discerns user intent. And it is the development itself that will continue to push us further and beyond as the technology continues to reflect the true nature of its origin – the marvelous human mind.

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# UHD TV Strives for Consumer Recognition

*Sales of ultra-high-definition (UHD) panels are on the increase, but are unlikely to replace full-high-definition (FHD) panels for at least another 5 years.*

by Jusy Hong and Veronica Thayer

WHILE consumer awareness of ultra-high-definition (UHD) TVs is rising, a strong marketing push by manufacturers and retailers is needed for the technology to gain the kind of widespread acceptance that high-definition (HD) TVs achieved a decade ago. To drive consumer interest, Sony and Samsung have been highlighting UHD technology in their store-within-a-store formats at Best Buy locations in the U.S., and these promotions will pick up speed as the holiday selling season hits. Sony launched a cross promotion with Sony Pictures Home Entertainment and Best Buy featuring a 30-sec promotional spot with 4K outtakes of *The Amazing Spider-Man 2* at AMC and Regal Entertainment movie theaters. The promotion underscored how consumers can get UHD resolution with Sony TVs. The promotions are being paired with falling prices for UHD TVs as the average global retail tag hits \$1,925 this year, down from more than \$3,000 a year ago. The average prices will tumble to \$1,438 in 2015.

While UHD TVs will carry a premium over similarly featured HD models, the combination of falling prices and manufacturer promotions is raising the technology's profile.

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Global unit sales will jump to 14.5 million units this year, up from 2.0 million in 2013, and will rise to 31.9 million in 2015. At the same time, UHD-TV's share of the LCD-TV market will widen to 17.9% in 2015, up from about 3% this year.

Among the top 13 brands for liquid-crystal-display (LCD) TVs worldwide, the share of UHD-TV shipments reached 5% in May 2014, up from 4% in April, 3% in March, and 2% in February (Fig. 1).

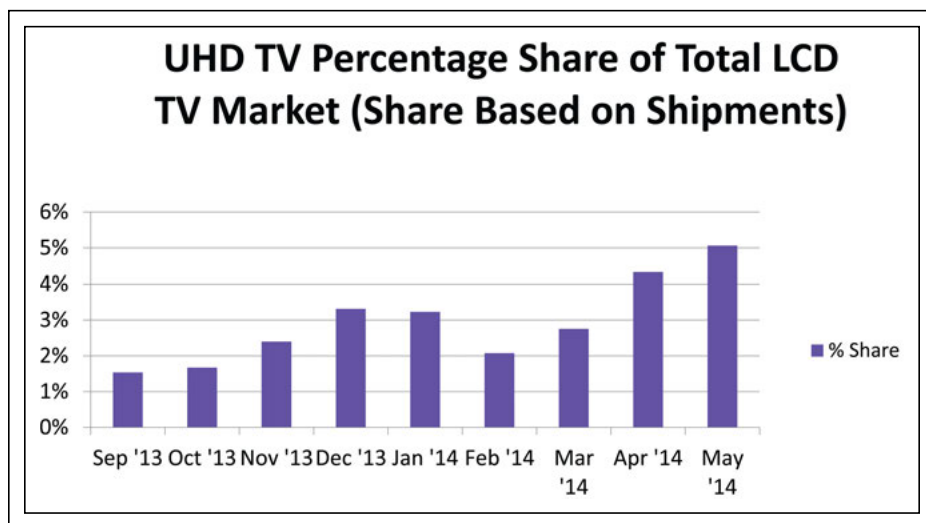
## UHD What?

The sales gains will be underscored by a growing consumer awareness of UHD-TV technology. Only 25% of the 1,000 consumers

who responded to an IHS online survey in 2013 were familiar with UHD technology. And just 13.4% of consumers surveyed said they planned to buy a UHD set in the next 12 months (Fig. 2).

Yet, the promotions and price cuts this year may be starting to turn the tide. Nearly 75% of U.S. consumers who viewed UHD TVs in a retail store were interested in buying a set at some point, while 34% of those who did not see them still had interest in owning one, according to a 2014 online survey of 1,062 consumers conducted by the Consumer Electronics Association (CEA).

The retail stores are critical to selling the new technology, with 73% of consumers who



**Fig. 1:** Sales of UHD TVs as a percentage of total LCD-TV sales climbed from 2% in February 2014 to 5% in May of the same year. Source: IHS Technology.



had seen or heard about UHD TVs in stores viewing it positively. As part of the study, consumers visited the stores to view UHD TVs and then responded to some questions. Many of the consumers who went to the stores doubted beforehand that UHD delivered a better picture than their HD sets, CEA said. After watching live UHD demonstrations, they left the stores with a significantly better impression of the technology, according to CEA. Of course, the draw of UHD TV was higher resolution, with 43% of those surveyed noticing improved picture quality, CEA said.

### Not Content with the Content

Consumers' reluctance to buy a UHD TV in 2013 also was tied to a lack of 4K content, an issue that is being addressed this year. About 55% of those surveyed last year by IHS said they were not planning to buy a 4K set because there were not any movies or TV programs available in that format. And in the CEA study, 43% of those surveyed were concerned about lack of content.

With 4K programming being delivered this year by over-the-top (OTT) providers like Netflix, Amazon Prime, and Hulu, UHD content is gradually working its way into consumer homes. Netflix has been the main source for UHD content this year, starting with the *House of Cards* series. OTT content providers see UHD as a major opportunity to offer premium content to consumers that will build the brand and take viewers away from cable, satellite, and broadcast programming.

Yet, while UHD content from OTT providers is available, getting access to it at full 4K resolution is proving to be a problem for consumers. UHD programming requires a 15-Mbps connection. And if the link does not support that speed, the resolution defaults to 1080p. Netflix has said it will eventually support 60-fps streams and 10-bit color, but neither is available for *House of Cards*. Receiving UHD content through a TV app requires built-in HEVC decoding – something most TV makers are supporting. Sony, Samsung, LG Electronics, and Vizio all field sets with HEVC decoding and have partnerships with Netflix.

Samsung UHD TVs also will be able to stream the Amazon Instant Video app with 4K content from Lionsgate, 20th Century Fox, Warner Brothers, and the Discovery Channel. Samsung has a partnership as well with M-Go for 4K movies and TV programs, including

some HD titles converted from 1080p by Technicolor, which is an investor in M-Go along with DreamWorks. DirecTV and Comcast likewise are making 4K content available for Samsung TVs through an app.

To further spur UHD adoption, CEA and media companies joined forces to form the Secure Content Storage Association (SCSA), which is seeking to fashion an open ecosystem of 4K content that could be purchased at retail or downloaded for storage or playback on compatible UHD TVs. The founding members include Fox Home Entertainment, SanDisk, Warner Home Entertainment, and Western Digital. Among the titles slated to be available through SCSA are *Dawn of the Planet of the Apes*, *X-Men: Days of Future Past*, and *The Fault in Our Stars*. The X-Men title was available for download in September and was scheduled to ship for DVD and Blu-ray in mid-October. (For more about standards and other initiatives designed to move UHD TV forward, see the article “UHD Calls for New TV Infrastructure” in this issue.)

Broadcasters will likely be the last to deliver 4K programming because they must purchase new equipment. The BBC's Research and Development group broadcast parts of the Glasgow 2014 Commonwealth Games live in UHD at the Glasgow Science Center earlier this year as a demonstration of

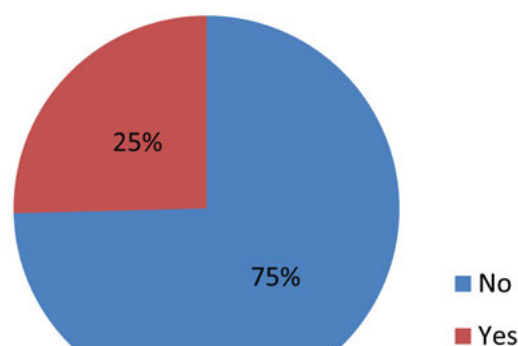
the technology. In Japan, Sky Perfect's JSAT Corp.'s Channel 4K has begun regular UHD broadcasts. And manufacturers also are building conversion technology into UHD TVs to boost HD signals to the higher-resolution format, giving consumers a sampling of the promise of 4K programming.

The boldest move in achieving near-UHD quality has been Sharp's 60-, 70- and 80-in. Quattron Plus (Q+) panels, which use a technology that splits each red, green, blue, and yellow subpixel in half horizontally. This results in 2,160-line vertical resolution and 16 million subpixels, about 10 million more than found in HD sets, but less than the 24 million in 4K sets with conventional RGB pixels. The Quattron Plus sets take native 4K signals and downconvert them for display on Q+ TVs. The result is sets with better resolution than 1080p models, at a price lower than that of 4K sets.

### Following in the Footsteps of 3-D, or HD?

The widespread support for 4K contrasts sharply with the much heralded launch of 3-D TVs several years ago. A lack of content – ESPN and DirecTV eventually shut down dedicated 3-D TV channels – coupled with consumers having to wear 3-D glasses as they do to view movies, relegated the technology to a niche market. While 3-D proved to be a

## Question: Have You Ever Heard of Ultra-High Definition or 4K TV?



**Fig. 2:** Only 25% of the 1,000 consumers who responded to an IHS online survey in 2013 were familiar with UHD technology. Source: IHS Technology.

novelty that wore off after a few movies, 4K will likely follow the same path as HD in gaining acceptance. This is because manufacturers, content developers, OTT providers, cable and satellite operators, and broadcasters are backing the technology.

For viewing the 4K content, consumers are increasingly choosing larger screen sizes. While 55- and 65-in. TVs were the initial standard bearers for UHD, they have since been joined by a range of sizes stretching from 39 to 105 in. The 50-in. screen size has been the top seller for UHD and is expected to account for 21.1% of LCD UHD-TV sales this year, followed by the 55 in. (20.9%), 42 in. (15.7%), and 40 in. (9.9%).

Part of the reason for 50-in. and larger TVs dominating the market for UHD is that consumers typically watch TV at a distance of 8–10 ft., which is optimal for noticing the improvement in resolution. In smaller screen sizes at the same distance, the difference in resolution between HD and UHD is not as evident. As UHD sales rise to 31.9 million units in 2015, shipments of FHD LCD sets will drop to 107.8 million from 120.8 million. UHD TV's share of the 50-in.-and-up TV sales is expected to hit 60% by 2019. While low-end UHD TVs from Seiki Digital and others that retailed for less than \$1,000 stole headlines in late 2013, they only accounted for 6.7% of sales and will not expand much this year, due largely to the low-cost panels being used in the sets.

### China Wants Its UHD TV

The bulk of UHD-TV sales are expected to remain in China this year, driven largely by a contingent of Chinese suppliers who combined will ship 10 million units, up from 1 million in 2013. Overall, UHD-TV sales in China will account for 59.6% of the global market, followed by North America and Europe at 12% and 8.6%, respectively, in 2014.

China will remain the largest UHD-TV market through 2019, driven largely by widespread support for the high-resolution technology from Chinese-based suppliers. In China, Hisense has the top market share at 18.2% in the first half of 2014, followed by Skyworth at 16.6%, TCL at 14.6%, Samsung at 13.3%, Changhong at 12.4%, Konka at 11.3%, Haier at 5.6%, and others totaling 6.1%. The penetration rate in China, which is expected to total 17% this year, will slow down after 2015, amid vendor concerns about being able

to turn a profit. In advanced markets, UHD-TV penetration will continue to increase.

China's share of the UHD-TV global market also will be driven by sharply lower prices than other regions of the world. UHD LCD panels being deployed in China carry a 5–8% lower cost than those from South Korean manufacturers, enabling prices in China that range from \$659 for a 40-in. set to \$3,629 for a 65-in. model. Among the low-end brands in China are Panda, Rowa, LeTV, and Coocaa.

The combined top-six Chinese-based UHD-TV suppliers' sales will be 10 million this year in shipments followed by Samsung (2.5 million units), LG Electronics (1.3 million units), Sony (980,000), others (700,000), Toshiba (350,000), Sharp (250,000), and Panasonic (150,000).

### Panel Premium

Despite a strong push, UHD TVs are unlikely to fully replace FHD models for at least 5 years, owing to the premium being charged for the technology. An open-cell 55-in. FHD panel without a backlight typically sells for \$255, while a similar UHD model carries a \$430 price.

UHD-TV manufacturers will be supplied by a varied assortment of LCD panel makers, 52% of whom are delivering low-end panels in 39–50-in. screen sizes largely for the China market. Innolux will ship 7.8 million UHD panels this year, across 39–98-in. screen sizes, up from 1.9 million units last year. Innolux is trailed by AU Optonics (5 million), Samsung Display (4.2 million), and LG Display (3.8 million). Among the Chinese suppliers, China Star will deliver 2 million units, including a 98-in. panel, while BOE ships 1 million panels. The panels are designed and produced for the China market.

Lastly, organic light-emitting-diode (OLED) TVs are worth a final mention here. UHD-TV sales thus far have largely remained the province of LCDs, with OLED models making only a slight dent in the market, owing largely to much higher prices for the latter. LCD-TV manufacturers also have made improvements in the sets that bring the performance of LCD comparable to that of OLEDs, which once enjoyed an edge in black level, contrast ratio, and color gamut. The better performance of LCDs has largely been driven by the deployment of LED-backlight local dimming, quantum-dot usage, and wide-

color-gamut technology. Because of the gains in LCD performance, consumers are proving less willing to pay more for an OLED TV set. OLED-TV shipments are expected to hit 100,000 units this year before increasing to 500,000 units in 2015 and 1.4 million units in 2016. ■

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# UHD Calls for New TV Infrastructure

*To deliver UHD performance, service providers must develop and deploy a new generation of set-top boxes and other equipment that take advantage of a new set of standards.*

by Wade Wan

**M**ANUFACTURERS are hoping that the promise of a dramatic new immersive TV viewing experience will compel consumers to invest in ultra-high-definition (UHD) TV. Also known as 4K TV, UHD is already being embraced by major content producers in both film and television. In 2013 alone, the number of movies filmed in 4K resolution increased five-fold from 10 to 50. The infrastructure for filming in this format is nearly complete, so finding a way to deliver this next-generation content to home viewers is the next big hurdle (Fig. 1).

Content providers in particular will need ways to deliver premium content at higher resolutions than are possible with current delivery methods – all while providing seamless quality of service to subscribers. To find a solution to this dilemma, multiple players in the industry have collaborated to develop the new standards necessary to enable cable, satellite, and OTT (Over the Top, meaning via the Internet) providers to efficiently and cost effectively deploy UHD TV offerings in the near term. Those efforts are already yielding promising results.

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UHD is supported via a more efficient video-compression standard, High-Efficiency Video Coding (HEVC), which was ratified in January 2013. The transition to HEVC marks a major shift in the industry.

**The Coming Change in Technical Specs** HDTV offers 8-bit resolution of  $1920 \times 1080$  pixels in an interlaced format of 60 fields/sec, which can be delivered at a bit rate of about 6 Mbits/sec (Mbps) using the current AVC compression standard. UHD TV, on the other hand, will deliver a 10-bit resolution of  $3840 \times 2160$  pixels in a progressive format of 60 frames/sec. This would require about 30 Mbps if the current AVC compression standard is used, which would be quite signifi-

cant and costly, but use of the HEVC compression standard can lower the bit rate to about 15 Mbps, making it more realizable for cost-efficient implementation and deployment (Table 1).

Given the exponential increase in size and bandwidth required to deliver uninterrupted 4K 60-frame/sec transmissions, the HEVC standard significantly speeds the transmission of 4K content, allowing operators and users to receive UHD content in half the time or at 50% of the bit rate compared to the current AVC coding standard.

UHD displays that are fully compliant with the new standards will also offer an exponentially greater array of colors (color gamut). The UHD color-gamut standard, BT.2020,



**Fig. 1:** High definition provided 6× the resolution of standard definition; now UHD offers 4× the resolution of high definition.

replaces the BT.709 gamut standard previously used for HDTV. Because BT.2020 can display more colors, it requires a larger bit depth than BT.709 to properly represent all the possible colors in this wider color gamut. Thus, the 10- and 12-bit coding of BT.2020 will replace the 8- and 10-bit coding of BT.709.

The changes in technical specifications of UHD TV versus HDTV systems even reach down to the specs for the HDMI port, which affect both transmitters like STBs and receivers like display devices. The present HDMI 1.4 interface standard does support UHD, but in a very limited fashion, offering support only when the pixel data standard is no more than 8 bit, the frame rate is no more than 30 frames/sec, and the maximum throughput is no more than 10.2 Gbits/sec (Gbps). To overcome those limitations, a new HDMI 2.0 standard was developed that increases the bandwidth supported across the HDMI interface to 18 Gbps. The new specification can then support UHD resolutions at 50 or 60 Hz over a single interface, which potentially avoids the hassle of needing multiple cables and connectors to handle the increased throughput of UHD services. Without HDMI 2.0, video would need to be cut into separate sections before the HDMI transmitter, then run separately through multiple HDMI links and assembled back together correctly with care to ensure every section came from the same picture.

Another crucial technical requirement for UHD services is content protection. High-Bandwidth Digital Content Protection (HDCP) is a digital copy protection and digital rights management specification for securing audio-visual content between devices. HDCP version 2.2 for mapping to the HDMI interface was established in February 2013. Securing

the HDMI digital interface with HDCP 2.2 is regarded as the minimum requirement for securing the transmission of UHD content in order to satisfy the distribution requirements of content providers.

As a system-on-chip (SoC) developer, Broadcom has been one of the most influential companies in the development of the HEVC/H.265 standard and has launched a broad portfolio of HEVC-enabled chipsets that are available for the full range of cable, satellite, and broadcast providers to expand current HD offerings and launch UHD content to subscribers.

Broadcom anticipates healthy adoption of HEVC/H.265 and has publicly engaged with leading encoder vendors, operators, and partners to ensure this codec's success in the marketplace, whether that be through technology demonstrations or new service offerings to subscribers around the world in 2014.

We believe that HEVC enables consumer-electronics manufacturers and service providers to bring faster video delivery to subscribers over consumer devices thanks to higher compression rates. The compression standard also allows service providers to provide both higher-quality streaming media services at a lower bit rate and the same or even more content at an equivalent bit rate. In the end, service providers can choose how to capitalize on this increased efficiency, from putting more channels on the same bandwidth to delivering similar quality video at half the bit rate or delivering better services using the same bit rate.

### Potential Hurdles: Interoperability and Interlaced Content

One key technical hurdle for UHD may be the time it takes for the ecosystem to develop; more specifically, the interoperability between different implementations. This is not a problem with how standards are specified, but rather reflects the fact that advanced technologies and specs do not immediately interoperate when a specification is published. However, this begins a whole new phase in which true industry interoperability can be proved as devices are actually tested among different vendors. As a key provider of these technologies, Broadcom has made considerable efforts in areas such as HEVC and HDMI interoperability, and one can easily see that much progress has been made since these standards were first published.

**Table 1: This chart compares the technical specs for standard HDTV to UHD TV, demonstrating the overall increase in bandwidth UHD requires.**

Parameter	HDTV Format	UHD TV Format
Spatial Resolution (pixels/frame)	1920 × 1080	3840 × 2160
Pixel Depth (bits/pixel)	8	10
Frame Rate (frames/sec)	30	60
Uncompressed Pixel Rate (Mbits/sec)	497.664	4,976.640

The coding of interlaced content is a heavily debated issue for HEVC as well. In fact, there was initial confusion in the market that HEVC could not support interlaced formats, which is incorrect. That said, critics still debate today whether interlaced content is as well supported in HEVC as it is in AVC, despite such support being a conscious decision of the HEVC standardization committee during evaluation.

### Further UHD Support Is Needed

UHD has already spurred the introduction of new displays and set-top boxes and has been used to great effect in the production of films such as *X-Men Origins: Wolverine*, *Night at the Museum*, and *World War Z*, just to name a few. And when it comes to sporting events, nothing delivers live action better than UHD, in part due to the frame rate and color depth incorporated into the new technology. This year's live UHD broadcasts of the Sochi Olympics and World Cup represented a significant proof point. According to market information advisory firm DisplaySearch, the 2014 World Cup played a significant role in boosting adoption of UHD TVs. In fact, analysts at Digitimes Research predict that UHD-TV panel shipments will have increased 475% by the end of 2014 alone.<sup>1</sup>

In summary, UHD TV is poised to deliver a major new viewing experience to consumers with doubling of both the horizontal and vertical resolution available and a tenfold increase in the raw pixel data rate over HDTV. But to deliver this superior performance, service

### Standards Sources

- High-Efficiency Video Coding (HEVC): Jointly developed by the ISO/IEC Moving Picture Experts Group (MPEG) and ITU-T Video Coding Experts Group (VCEG)
- AVC: Advanced Video Coding (MPEG-4)
- BT.2020: <https://www.itu.int/rec/R-REC-BT.2020-1-201406-1/en>
- HDMI 2.0: [http://www.hdmi.org/manufacture/hdmi\\_2\\_0/](http://www.hdmi.org/manufacture/hdmi_2_0/)
- HDCP 2.2: <http://www.digital-cp.com/>

providers must develop and deploy a new generation of set-top boxes and other equipment to meet the new industry standards for improved video compression, wider color gamut, HDMI interface, and content protection.

### References

<sup>1</sup>Digitimes Research; [www.digitimes.com/news/a20140529PD216.html?chid=](http://www.digitimes.com/news/a20140529PD216.html?chid=) ■

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# OLED TV Provides Superior Viewability

*Advances in design and manufacturing are making OLED TVs a very appealing option.*

by David Choi

**T**Vs have evolved to offer bigger screens, higher resolutions, slim and light designs, and overall better picture quality. LCD-TV technology in particular has achieved market dominance with outstanding picture quality and a slim footprint. However, the design of an LCD TV will always be based on the fundamental structure of a transmissive LC panel illuminated by some type of backlight system. The performance of this system, while continuing to achieve incremental improvements each year, will always be constrained because it cannot self-emit light in the same way that a phosphor or OLED panel can.

OLED technology provides new solutions by overcoming the fundamental structural limitations of LCD technology. OLED TV, for which the latest generation of advanced designs was first introduced in early 2013, is based on a much simpler structure of self-emission from the pixel matrix surface and can therefore reproduce more natural colors and better picture quality than an LCD TV (see comparisons of key features in Table 1).

OLEDs are composed of self-luminous organic light-emitting diodes that form each pixel. Because every pixel emits its own light, color contrast is optimized. In addition, an OLED can produce perfect blacks and an infinite contrast ratio with deeper and richer colors because there is no light leakage from a backlight. Even under typical living-room lighting conditions of 200 lux, OLEDs have better contrast because the reflection of an OLED screen is typically lower than that of an LCD screen. The LCD screen may have

higher luminance at white, but OLED's darker blacks will provide better contrast.

The outstanding broadcast picture quality of OLED TV highlights its superiority. With a pixel gray-to-gray-level response time of more than 5,000 times faster than that of an LCD TV, OLED TV also delivers smooth images of fast-moving events, such as soccer games, that are completely life-like because they are blur-free.

## The Ultimate Display

In LCD panels, color saturation and brightness decrease in low-gray-scale scenes as the color gamut deteriorates. This is because color bleeding increases in dark scenes due to light leakage between the pixels. In addition, gray-level tracking between the three primary colors is typically not uniform at low gray levels, adding to color shift at very low gray-

scale scenes. For example, reds in the low gray scale appear more washed out because the color gamut deteriorates toward white color coordinates due to light leakages from adjacent green and blue subpixels.

However, OLED TV provides vivid colors in any scene because it maintains consistent color gamut even as the gray level changes. Therefore, food looks more delicious and skin-tone colors are more life-like. It can even produce colors that are outside of the current broadcast color gamuts such as BT.709 (Fig. 1).

These results are shown in a recent study of color theory by Hongik University's Color Research Lab (this is a thesis in progress, with an expected release date of December 2014.) According to the survey, color preference for OLED TV is 2.4 times higher than for LCD TVs and viewers surveyed mentioned that OLED TV is more "vivid," "warm," and "comfortable," and provides more "life-like" colors.

## Effective Curvature

Because an OLED TV has a wide viewing angle and no light leakage, it delivers consistent picture quality and color performance from any angle. In the case of a typical 55-in. VA-type curved LCD TV viewed from a distance of 2.1 m, the color wash becomes noticeable from an angle of 22° from the center. While other LCD types may perform better or worse in terms of color wash, OLED technology will still perform better at wider viewing angles. This forces people watching TV to gather together in the middle, but with a 55-in. curved OLED TV people can watch from any angle in the room and enjoy the same high picture quality with crisp and vivid colors (Fig. 2).

**Table 1: The chart compares key optical parameters between earlier and later generations of LCDs and current curved OLEDs. Viewing angles are measured at the angle at which the luminance becomes 50% of normal. The contrast is measured in a dark room.**

	Technology development of LCD		OLED
	'99	'14	
Contrast	500:1	5,000:1	∞
Viewing angle	70°	100°	160°
Response time	20 ms	5 ms	0.001 ms
Thickness	90 mm	15 mm	3.x mm

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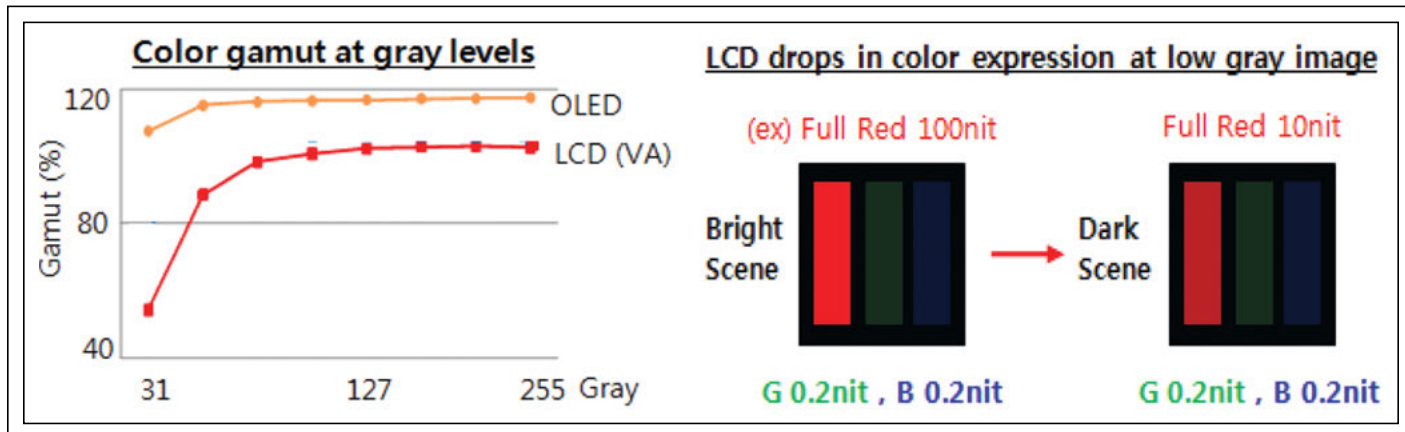


Fig. 1: Color-gamut maintenance is shown in all gray levels at BT.709 coverage of the CIE1976.

### Manufacturing and Flexibility

As is generally known, manufacturing yields have proved a challenge, but LG has succeeded in improving yield rate and scalability by working with oxide TFTs and WRGB patterning technologies. The company has been improving the yield rate for OLED TV about twice as fast as it was able to in the initial stages of LCD-TV development. LG is now achieving satisfactory yield rates that are enabling lower production costs.

LG Display is building a new OLED manufacturing line, the world's largest Gen 8 line,

with a monthly capacity of 26,000 input glass sheets. Once completed, it will make it easier to produce large-sized and ultra-high-resolution OLED panels while making the cost of a OLED TV more affordable, setting the stage for a mass consumer market.

In addition, LG is also developing transparent and flexible OLED displays, which emphasize the natural advantages of OLED technology. The company rolled out 18-in. flexible and transparent displays in July 2014 and has been developing larger and higher-

resolution displays that are transparent as well as flexible. We are confident that by 2017, we will successfully develop an UHD flexible and transparent OLED panel of more than 60 in., which will have a transmittance of more than 40% and a curvature radius of 100R.

In the shorter term, OLED TV has demonstrated high picture quality and stunning design since its launch. It's been a challenging road, but yield has reached the point at which additional commercial launches are a reasonable expectation. ■

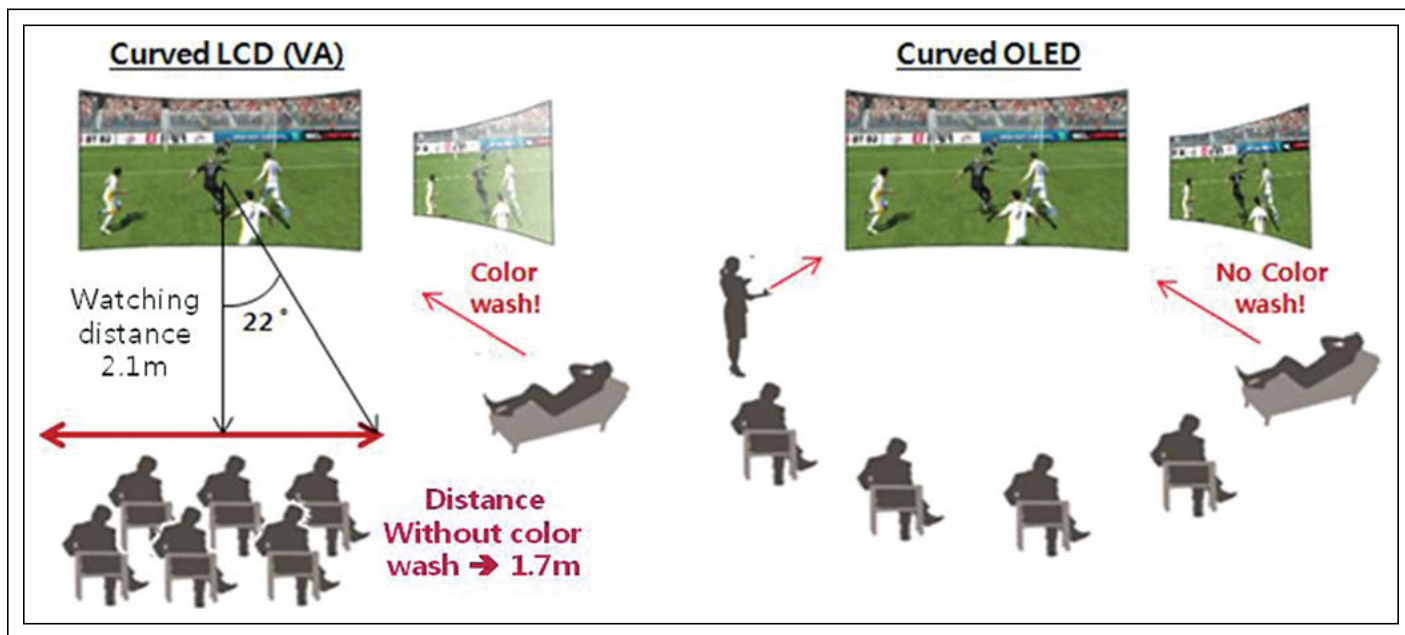


Fig. 2: The above schematics illustrate how curved OLED TVs offer a viewing angle that allows more people in a room to enjoy a positive viewing experience.



# The Curved Display Makes an Impression

*Curved televisions, introduced last year, are entering the marketplace in greater numbers. These TVs offer viewers an enhanced immersive display experience compared to previous designs.*

by Nam-Seok Roh

IN today's marketplace, most monitors and televisions for sale use flat-panel displays (FPDs). Last year, the landscape of FPDs changed dramatically when the world's first concave curved televisions were announced by several companies. However, most of these televisions were organic light-emitting-diode (OLED) based and much more expensive than conventional liquid-crystal-display (LCD) TVs. At IFA 2013, Samsung announced the world's first ultra-high-definition (UHD) LCD-based curved television and began selling it in the first quarter of 2014. The curved-TV market is growing, and many television manufacturers are planning to sell curved TVs in the coming months and years.

## Benefits of Curved Displays

Some critics have been skeptical of the benefits of curved TV, dismissing it as a marketing ploy. It is easy to see why people would come to this conclusion, especially since some aspects of a curved screen work against one of the main advantages of the FPD – its thin profile. A video currently on CNET<sup>1</sup> lists five reasons not to buy curved TVs: (1) They are only a fad. (2) The price is too high. (3) The central viewing position is too narrow for groups of viewers. (4) The curved immersion effect works only in a very large (80 in. plus) form factor or if viewers are close up. (5) Curved TVs stick out from the wall.

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These five criticisms are for the most part not valid: (1) For the following reasons and more, as explained in the rest of this article, curved TVs are not a marketing gimmick, although, admittedly, some people might choose to buy them because they are cool

(Fig. 1). (2) The retail price for a curved model is just slightly higher than a comparable flat-panel TV; for example, the best models of Samsung's curved UHD TV and Sony's flat UHD TV are similarly priced at around \$3,000. (3) The ideal viewing position is not



**Fig. 1:** The world's first curved UHD display from Samsung Electronics features an immersive viewing experience in a novel form factor.

as restricted as expected, which will be explained later in this article. (4) Smaller curved displays, for use in applications such as desktop monitors, are in development and are said to provide an effective immersive gaming environment. (5) The depth of a 55-in. curved TV is less than 4 in. (3 3/4 in. actually) and although it is a matter of personal preference, to most viewers these TVs look very nice when mounted on a wall.

### Immersive Experience

The first thing noticed when watching a curved TV is that it feels very immersive. As shown in Fig. 2, we can calculate the extension of view by the curvature and width of the screen. In the case of a 55-in. curved TV, if the viewing distance, which is the radius of curvature, is 2.26 m, there will be a 0.7° extension of the field of view compared to a similar flat-TV experience.

However, if the viewing distance, as well as the radius of curvature, is reduced to 0.61 m, the field of view increases by 24.6° compared to that of a comparable flat TV. Of course, this is an extreme example to illustrate this point because an actual curved television's curvature would not be this pronounced. But nonetheless, a curved television does provide a larger field of view over an equivalent flat model, and the result is a more immersive viewing experience.<sup>2-5</sup>

### Low Reflectance

Normally, in a home, windows or interior lighting will be reflected by the surface of the television screen. However, if the screen is curved, this reflected light will affect the television viewer to a lesser extent because the reflected light is spread out. As shown in Fig. 3, if the light source is constant, the unit area of reflection is larger in a curved screen, resulting in less reflected light being seen at any one specific location. For this reason, imagery in ambient light conditions should be much clearer in a curved display due to higher contrast levels on the curved unit compared to a similar flat-TV experience.

### Less Distortion

Returning to a consideration of the human-vision system, the eye is spherically shaped and the retina surface is curved. All the sensor cells reside in curved surfaces in the retina. As a result, some observed images might be distorted. For example, the Parthenon was

constructed as a slightly curved structure (Fig. 4). If the columns had been straight and parallel, the beauty of the structure would not be the same. The situation is similar to that of television screens, especially large screens. Also, with television, theoretically, the distance from the eyes to the screen is different at every point, especially between the center and the edge of a flat screen, resulting in a de-focus of images. However, with a curved screen, the depth of focus remains constant on all surfaces if the screen is viewed at the focal point of the curvature.

### User-Performance Improvement

Another advantage of curved screens appears to be the speed at which observers can scan and analyze information. Tests performed by Shupp *et al.*<sup>6</sup> showed an improvement in the

information scanning speed in a curved display (Fig. 5). The researchers arranged 24 monitors in 3 × 8 tiled screens to make one large flat screen and also one large 760-mm-radius curved screen. The screen displayed satellite imagery on which users were given specific tasks to perform, one of which was a route-tracing task. Route tracing requires the user to traverse a limited and specific portion of the data without losing context. Users followed a given route across the displayed landscape, marking required features along the route while their performance was timed. The results showed that use of a curved screen improved user performance by about 20–25% over that of a flat screen. Part of the reason for this improvement was because the distance from a user's eyes to the screen surface was much shorter in the case of a curved screen.

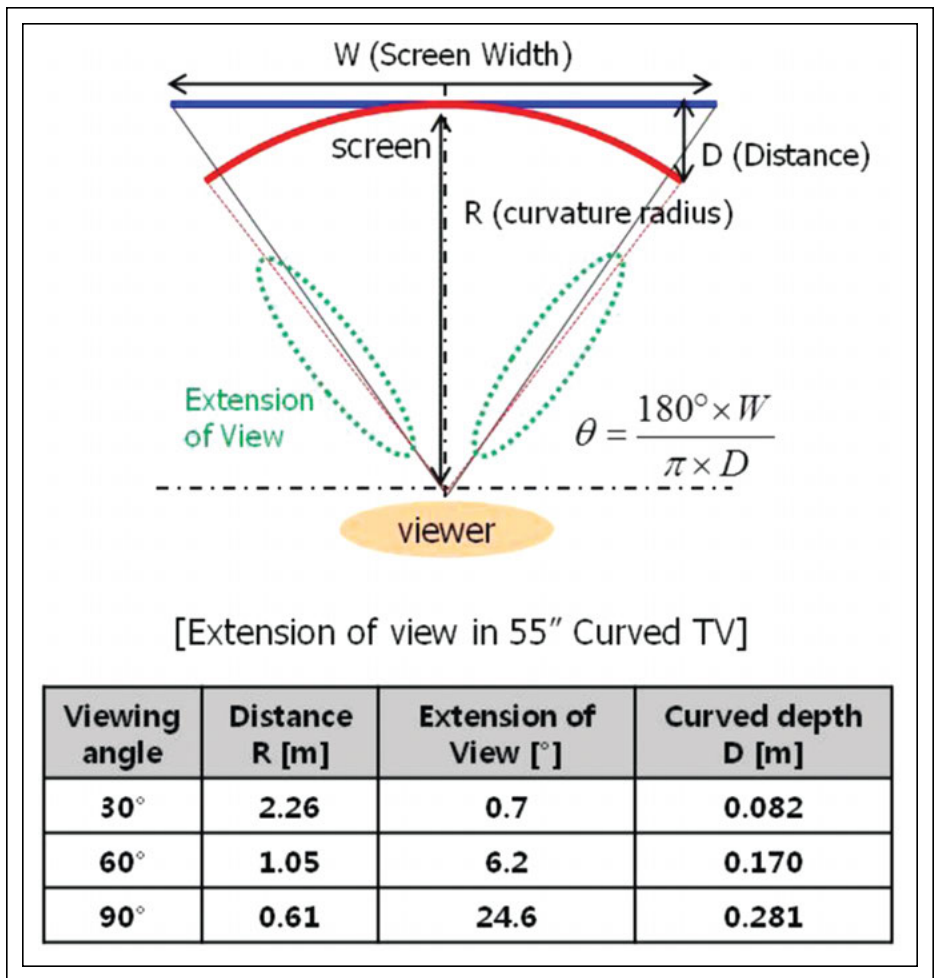
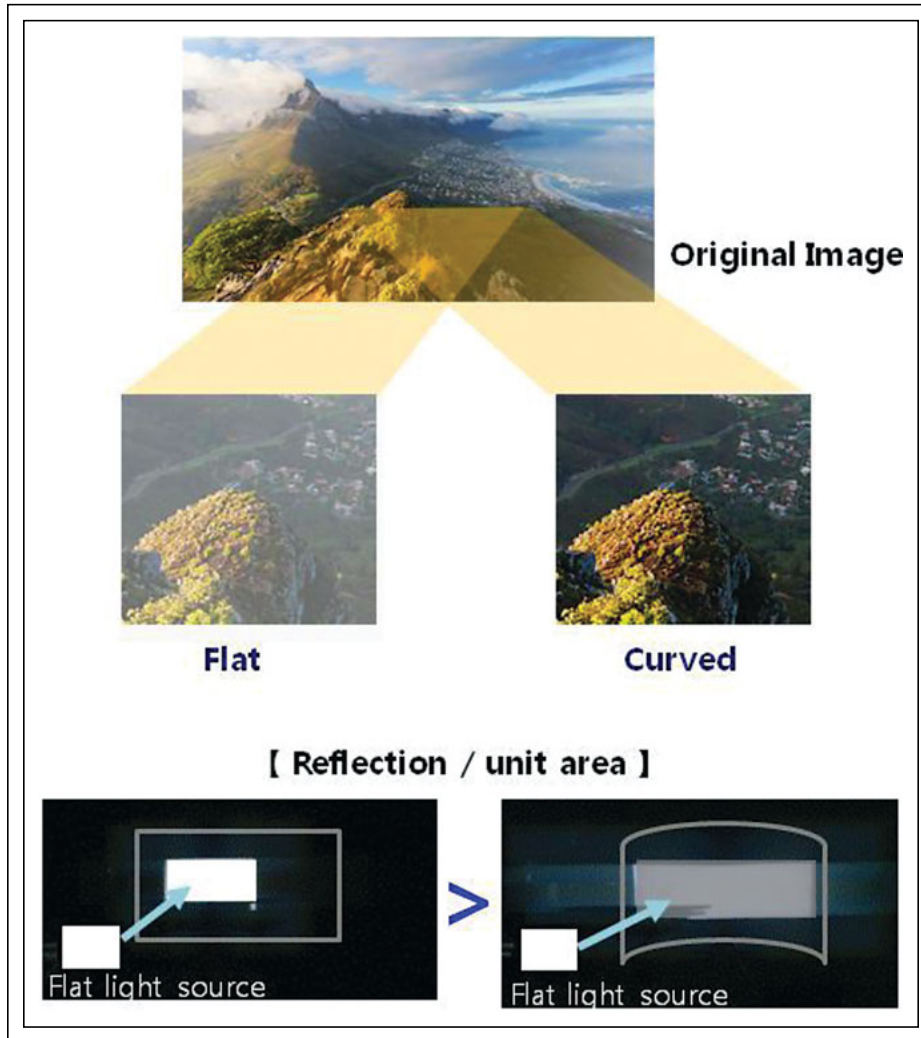


Fig. 2: An extension of view is achieved by increasing curvature.



*Fig. 3: Image-contrast degradation occurs with light reflection; there is reduced light reflection with a curved display.*

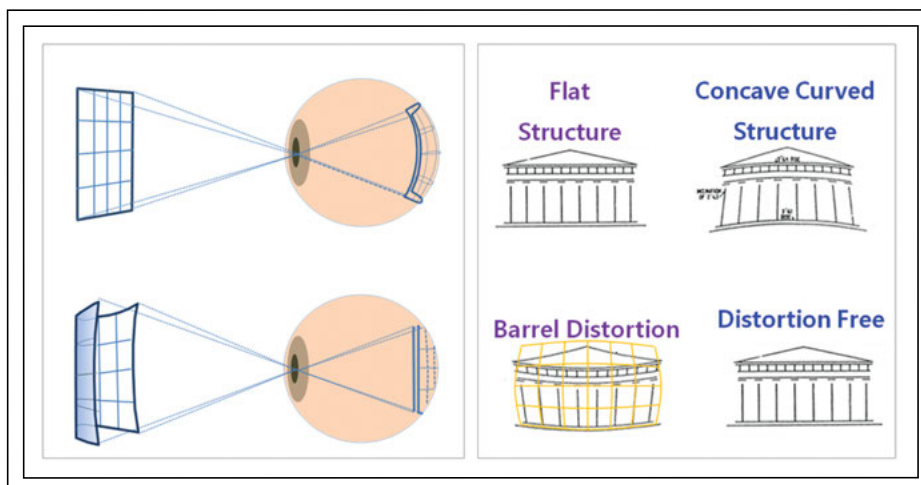
### Enhanced Side Readability

Today's displays are normally wide format. We need to scan both the center and edge areas to gain all the necessary information. As shown in Fig. 6, the entire gap between detection times is smaller in the case of curved displays. This will help when users need to analyze large amounts of on-screen data, such as for the stock market or computer gaming.

### The Best Curvature

The current generation of curved televisions has a bending radius of around 4,000–6,000 mm. But, theoretically, the radius of curvature should be same as the distance between the viewer and the display so that the distance between the viewing point and every point of the display is the same distance. There will, therefore, be a consideration of what is the best distance, or best curvature, for the display. In other words, how do we know what the optimum value is for the radius of curvature? There are several definitions for the best distance to the display. For example, if we define the viewing angle as  $30^\circ$ , which is the range that the average human eye can scan left to right without any head movement, the best distance will be approximately 1.6 times the diagonal of the display. NHK defines the best distance based on the average preference of people who watch television; this distance is 3 times the height of the display. THX says a distance of 2.5 times the diagonal of display will create the optimal feeling of immersion for movies. In the case of a 55-in.-diagonal television, the best viewing distance will be between 2 and 4 m. This means the best radius of curvature will also be between 2 and 4 m.

Of course, this is just a theoretical definition; actual curvature is dependent on how a user watches television or from what distance. As noted above, Samsung Electronics has researched worldwide television watching distances and determined that 3–4 m is the normal distance for viewing large-sized televisions. And we concluded that at this



*Fig. 4: A flat image is “distorted” when viewed by a curved eyeball.*



**Fig. 5:** Improved productivity for a curved display is shown with regard to “time to check route” in the map image. The task is 20–25% faster in the curved display because of less movement and faster scanning. Photo courtesy Shupp et al. (Ref.6).

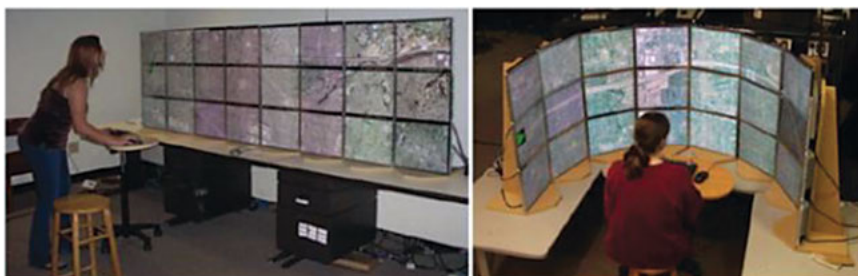
distance, 4200 mm is the optimum curvature to maximize the experience. However, some viewers might sit as close as 2 m from the television, or even closer. For monitors, the distance is quite close, so more curvature would be needed for the best viewing experience. In the author’s opinion, the final product should have an adjustable curvature for various users’ viewing-distance choices. If curvature is adjustable, we can also change the television between single-user mode and multi-user mode in order to achieve the best viewing condition. Samsung (and LG) showed adjustable-curve TVs at the Consumer Electronics Show in January 2014.

### Current Technical Limitations of Curved Displays

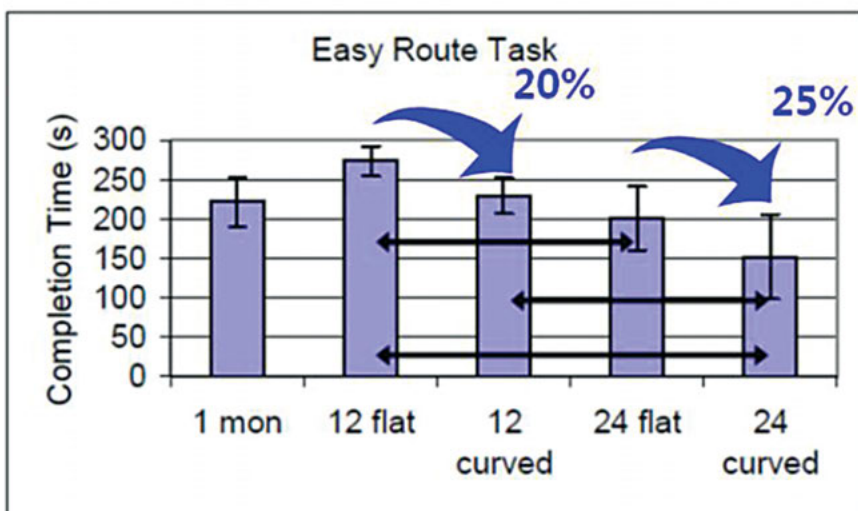
The first issue faced when making a curved LCD TV involves the stress created when the glass is made to curve. This stress will cause several problems, such as mechanical failure and optical distortion. Even a curved OLED TV has this problem if the curvature is large because current large-sized OLED TVs also use two layers of glass (one for encapsulation). Associated with this is the potential misalignment of the upper and lower layers of glass due to the curvature. For example, if a 55-in. television is curved to a radius of curvature of 4000 mm, there will be a maximum difference of a 25- $\mu$ m misalignment between the two pieces of glass at a certain position of the screen. There will be color mixing at this point. Of course, most companies can solve this problem by putting the color-filter layer on the lower glass, which involves a technology called COA (CF on Array) or COT (CF on TFT) technology.

Also a challenge is that two sandwiched glass layers in a curved configuration will cause distortion in the cell gap of the liquid crystal, creating a decrease in brightness or black uniformity. LCD manufacturers are

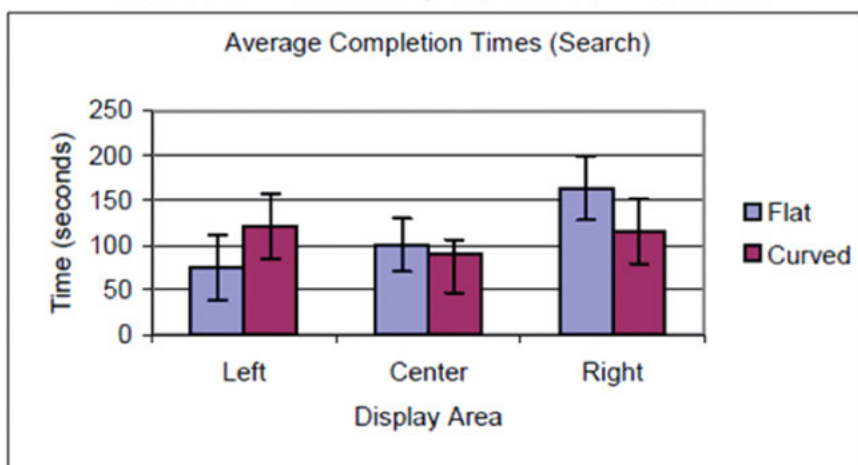
**Fig. 6:** A curved display is more effective for users seeking information over a large area. Photo courtesy Shupp et al. (Ref. 6).



Twenty-four 17" Monitor, Flat and Curved (R=760mm)



Data analysis time between center and edge  
Flat : 75 ~ 160 sec ; Curved 90 ~ 120 sec



## opinion

investing a great deal of effort to overcome these issues.

### The Future of Curved Displays

As discussed in the previous section, the best curvature for a curved display might vary by viewing condition. As a result, there should be flat and curved transformable displays in real markets as shown in the CES 2014 demonstration. We also believe there is interest in curved monitors in the marketplace. We hope that in the near future not only television but also monitors will use the curved form factor. 2013 was the birth year of curved television products, and this innovation continued through 2014 and will continue to do so through 2015 and beyond.

### Reference

<sup>1</sup>[www.cnet.com/videos/reasons-not-to-buy-a-curved-tv/](http://www.cnet.com/videos/reasons-not-to-buy-a-curved-tv/)

<sup>2</sup>J. D. Prothero *et al.*, Human Interface Technology Laboratory Tech. Rep. R-95-4.

<sup>3</sup>H. B. L. Duh *et al.*, *IEEE Proceedings, Virtual Reality* (March 2001).

<sup>4</sup>M. Emoto *et al.*, *Presence*, 2004, NHK.

<sup>5</sup>K. Masaoka *et al.*, *Proc. SPIE, Image Quality and System Performance II*, 5688, 28.

<sup>6</sup>L. Shupp *et al.*, *Human-Computer Interaction*, "Shaping the Display of the Future: The Effects of Display Size and Curvature on User Performance and Insights," 24 (2009). ■

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**May 31–June 5, 2015**

**San Jose Convention Center  
San Jose, CA, USA**



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# Display Week 2015

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### Business Conference Reception, Monday:

Follows the Business Conference, please note conference attendance is required for admission.

### Annual Award Luncheon, Wednesday:

The annual Best in Show and Display Industry Awards Luncheon will take place at noon on Wednesday, June 3. Both awards are peer-reviewed, such that the luncheon is well-attended by captains of industry for high-level networking and recognition of the best in the industry over the last year.

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The IC will feature presentations from leading public and private companies in the display technology supply chain and encourage questions and discussion between presenters and participants. Concludes with Drinks & Displays: Networking Reception with Presenters and Investors

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# Display Week 2014 Review: Touch Technology

*Display Week is the single best place in the Western hemisphere to see and learn about touch technologies.*

by Geoff Walker

**E**MBEDDED TOUCH, touch controllers, the latest stylus technologies, and much more were to be found at Display Week 2014 in San Diego. As will be mentioned later in this article, some of the information was difficult to obtain, due to increasing secrecy on the part of display makers. But, all in all, the show was an excellent and, in fact, unparalleled place to learn about touch.

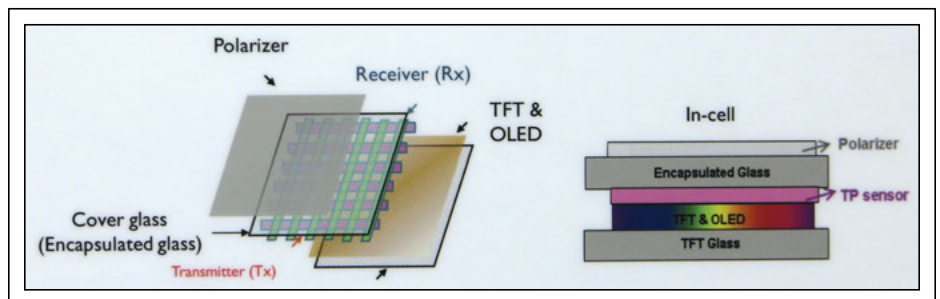
All of the six major display makers at Display Week 2014 either showed examples of embedded touch (AUO, JDI, LG Display, and Tianma) or acknowledged that they have developed embedded touch but chose not to show it this year (BOE and Samsung). Although high-volume shipments of embedded touch started only 2 years ago,<sup>1</sup> embedded touch has rapidly become a broadly accepted technology. In a conversation with the author, JDI Chief Strategy Officer and Deputy Chief Technology Officer Hiroyuki Ohshima expressed the opinion that *all* display makers are doing some form of embedded touch for revenue and profitability reasons.

While there were several interesting new disclosures of embedded touch on the show floor, in general the author has seen a steadily

decreasing flow of public information over the last year regarding what the display makers are actually doing with embedded touch. The author's opinion is that the competition between the display makers and the discrete touch-panel makers is intensifying, with the result that the display makers are becoming much less open about their new developments in embedded touch.

Probably the most interesting new embedded-touch exhibit was AUO's "in-cell OLED." The p-cap touch sensor in the two examples shown by AUO (1.6 and 5 in.) comprised two layers of ITO deposited on the *underside* of the OLED encapsulation glass (Fig. 1). The primary reason for this location (rather than on top of the glass, as with Samsung's technology) is to allow thinning of the glass. In theory, the glass could be thinned down to 100  $\mu\text{m}$ .

(Thinning the glass is done by mechanical abrasion or some form of chemical etching. If there are touch electrodes deposited on top of the encapsulation glass, the glass cannot be thinned.) The 10-point 120-Hz touch sensor is less than 1  $\mu\text{m}$  thick, and there is an air gap of a few microns between the touch sensor and the top of the OLED. The entire display is less than 0.6 mm thick. AUO acknowledged that the touch sensor could have just as well been constructed with a single layer of ITO with bridges. Actually, it is arguable whether this is truly "embedded touch" or not. Embedded touch is supposed to be something that only a display maker can do; the deposition of the touch sensor on the encapsulation glass can be done by a discrete touch-panel supplier. It's analogous to the way a discrete OGS touch panel is created on an LCD cover glass.



**Fig. 1:** AUO's in-cell OLED puts a p-cap touch sensor made up of two layers of ITO on the underside of the OLED encapsulation glass in order to allow thinning of the glass before attaching the polarizer. The thickness of the sensor layer is less than 1  $\mu\text{m}$ ; the thickness of the entire display is less than 0.6 mm. Artwork by AUO; photo courtesy Geoff Walker.

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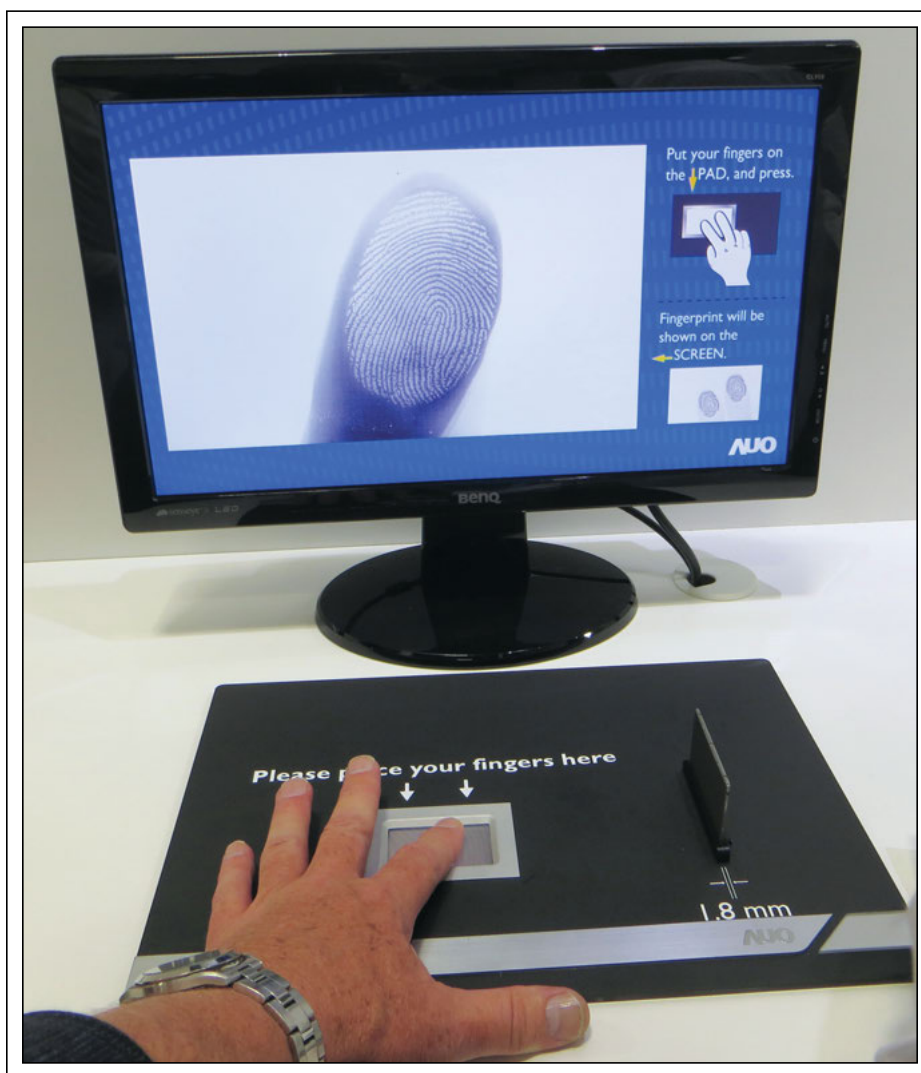
*Geoff Walker is a Senior Touch Technologist at Intel. He was also Information Display's Guest Editor for Touch & Interactivity for 2007 and 2010 through 2012. He can be contacted at [geoff.walker@intel.com](mailto:geoff.walker@intel.com); 408/765-0056 (office) or 408/506-7556 (mobile).*

However, this is the first time the author has seen a p-cap touch sensor positioned only a few microns away from an OLED. In discussing this, AUO pointed out that the electrodes on top of the OLED act as a shield for the OLED's TFT backplane, with the result that the touch sensor actually sees less noise than in an LCD. AUO also said that the large parasitic capacitance of the OLED top electrodes was not a problem due to "clever OLED driving that's optimized for touch-sensing" (sounds like a trade secret!).

Other AUO touch exhibits included a 5.5-in. in-cell FHD touch panel, a 6.1-in. on-cell touch panel, and a 7-in. direct-bonded discrete touch panel for automotive applications. Finally, AUO showed a very clever 2.4-in. (54 × 32 mm) fingerprint-sensing technology based on a-Si optical in-cell touch (Fig. 2). The sensor is basically a display backplane without pixel drive electronics, so the entire pixel (one TFT in each cell) can be used for optical sensing (the resolution is 508 ppi). AUO's initial target market is governments, which tend to require multiple-finger sensors. In the author's opinion, AUO was clearly the best touch exhibitor at Display Week 2014.

LG Display showed a 5-in. HD oxide display with in-cell touch with an accuracy of <1.0 mm and a reported rate of 120 Hz. The touch function was combined with the display driver function in a single touch display driver integration (TDDI) chip. Although it was not demonstrated, the touch function was also supposed to support hover and glove touch. The touch function was specified as having a "touch finger separation" of 1.0 mm, which is not really good enough. From the user's perspective, it is unreasonable to expect someone to hold their fingers at least 1 mm apart in order to register two distinct touches. More than half of the p-cap touch panels that the author has tried in the last year were able to reliably detect two fingers held tightly together as two distinct touches; in the author's opinion this is now the *de facto* standard. The performance of LG Display's in-cell touch with a rapidly circling passive stylus was decent, although it was clear that the controller was dropping some points and failing to meet its claimed 1-mm accuracy.

JDI showed two versions of "Pixel Eyes," its branded embedded-touch technology. One was exactly the same as shown at Display Week 2013,<sup>2</sup> even down to the 2013 date on



**Fig. 2:** AUO's 508-ppi fingerprint sensor shows the author's left index fingerprint. The sensor is basically a display backplane without pixel drive electronics, so the entire pixel can be used for optical sensing. Photo courtesy Geoff Walker.

the sign; the other had considerably improved performance – although it still dropped a few points during very rapid drawing with a 1-mm-tipped passive stylus (Fig. 3).

The JDI executive mentioned at the beginning of this section also made the following comments:

- JDI plans to stick with hybrid in-cell/on-cell construction rather than moving to on-cell or true in-cell. Hybrid construction has high sensitivity, it works well with a fine-tipped passive stylus, the manufacturing process has been perfected so that it can be produced with

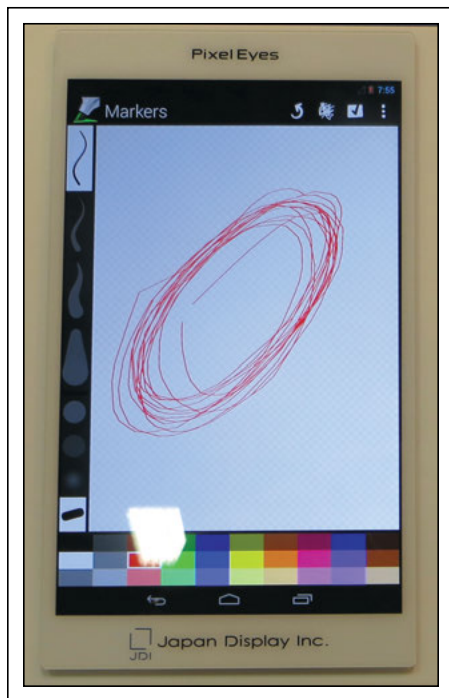
high yield, and it can be scaled easily. (This answer of "we're sticking with what we know" is the same reason that many discrete touch-panel manufacturers give for sticking with a particular stack-up such as GFF, G1F, or GG. Once one gets good at something, there is a lot to be said for continuing to leverage it even though other alternatives are available.)

- JDI is definitely going to use Pixel Eyes in a 10-in. tablet. There are no technical impediments; all the engineering and manufacturing problems have been solved, so it is just a matter of business

strategy. JDI is currently delaying introducing a product in order to make sure that it has a fully differentiated solution. In any case, the solution will definitely include a fine-tipped passive stylus.

- JDI believes that it could definitely produce a 13.3-in. display with Pixel Eyes (*i.e.*, for use in an Ultrabook), but it does not participate in that market and does not know the market requirements. Plus, JDI also views the touch-notebook market as being too small. So even though it is technically possible, it is unlikely that JDI will use its hybrid in-cell/on-cell embedded touch technology in displays larger than 10 in.

Tianma showed two prototypes of its latest two-layer in-cell touch (6.5 in. for phablets and 1.54 in. for wearables). Tianma's controller partners for in-cell are FocalTech and Synaptics. The smaller touch panel was rated



**Fig. 3:** JDI's "Pixel Eyes" hybrid in-cell/on-cell touch was demoed on a 7-in. 1200 × 1920 (323 ppi) LCD. The circles on the screen were drawn rapidly by the author with a passive stylus. The irregularities in the lines indicated some dropped points – although, overall, the performance seemed slightly better than that of LG Display's in-cell touch. Photo courtesy Geoff Walker.

for five points, which seems a bit like overkill on a screen that small. The great majority of Tianma's touch was shown as discrete p-cap touch panels, labeled "CTP" for "capacitive touch panel."

### Touch Controllers

The most pervasive touch trend on the Display Week floor can be summarized in four terms: water resistance, glove touch, hover, and passive stylus. The majority of all touch-panel and touch-controller exhibitors were showing one or more of these new characteristics. The entire touch industry has been doing development on these four characteristics for the last 18 months, and now it is done. All four are being rolled out into the real world. Because the touch portion of the Display Week exhibits had a strongly commercial-industrial slant, many of the demonstrations were in a commercial frame of reference. But there are consumer products on the market right now (mostly in Asia) that support one or more of these four characteristics.

The most "fun" demonstration of water resistance was in the UICO (duraTouch brand) booth (Fig. 4). A p-cap touch tablet running a software-based radio application was positioned under a shower head; with the water running, all of the touch controls on the tablet could be manipulated as though the water did not exist.

Most often, water resistance is achieved by operating a touch panel in two modes and switching back and forth between them. The modes are (1) self-capacitance (using only the top electrode layer) and (2) mutual capacitance (using both electrode layers). Self-capacitance is unaffected by water, while mutual capacitive sees water as a touch.

Solomon Systech, a Hong-Kong-based touch-controller supplier who sells mainly into the China white-box market, demonstrated water resistance using only algorithmic support on a 4-in. true single-layer ("caterpillar pattern") mutual-capacitance p-cap touch panel. This is a significant achievement because it is very difficult to distinguish water droplets from touches using only mutual capacitance. I asked if perhaps the Solomon Systech controller was using only a portion of the single-layer electrode in self-capacitance mode, and the booth representative insisted that the water resistance was accomplished purely via mutual-capacitance algorithms running on the touch controller.

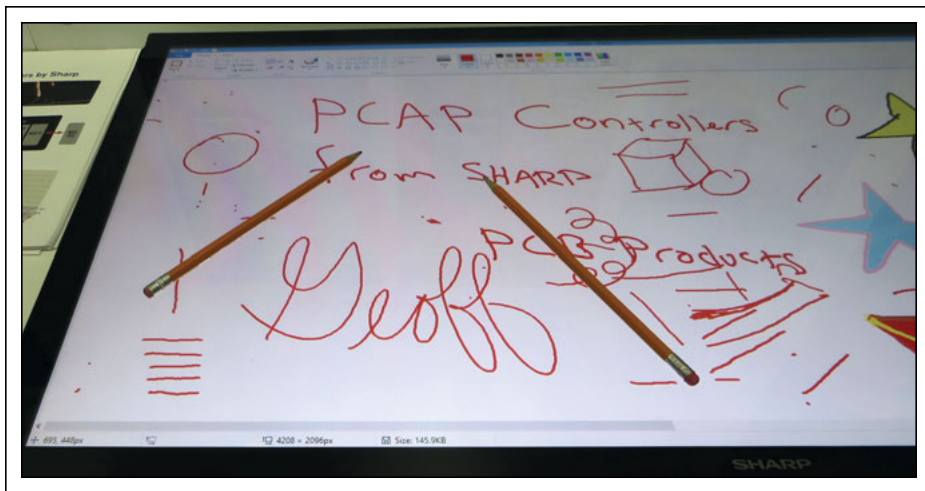
True single-layer mutual-capacitance touch panels have rapidly become the configuration of choice for low-end smartphones due to their low cost; Solomon Systech's ability to support more advanced functionality such as water resistance purely through mutual-capacitance firmware provides an interesting illustration of how the capability of p-cap touch is continuing to expand even at the very low end.

Probably the best of many demonstrations of passive stylus on the show floor was in the Sharp booth. In mid-2013, Sharp entered the merchant touch-controller business with a line of p-cap touch controllers that handles from 5 to 100 in. At Display Week 2014, Sharp was showing a 4K 32-in. LCD with a standard p-cap sensor and two #2 pencils (Fig. 5). The two pencils worked perfectly as styli, with the exception of the awkward and slow mode switch between stylus and finger touch (Sharp's firmware still needs some tuning.) In fact, the eraser on one of the pencils (the



**Fig. 4:** UICO's fun demonstration of water-resistance for p-cap touch was about as graphic and clear as it could be. UICO achieves this very high level of water resistance by writing its own touch-controller code, but similar results have been accomplished by the major suppliers. Photo courtesy Geoff Walker.





**Fig. 5:** Sharp demonstrated a 4K 32-in. LCD running its new touch controller with a standard p-cap sensor and two #2 pencils as passive styli. As the photo indicates, the pencils worked perfectly. In the last 18 months, the #2 pencil has become the de facto passive stylus that all the touch-controller makers use to prove that they have high SNR.

more worn-down one) even worked as a stylus. The touch controller for the 32-in. display consisted of one analog chip and one digital chip. For larger displays, additional analog chips are slaved in increments of 20 in.

Sharp is one of the few controller companies to explain at least one of the ways it achieves the very high SNR necessary to support a #2 pencil as a stylus.<sup>3</sup> The secret is “parallel drive.” It is commonly believed that a p-cap touch controller works by applying a signal to one drive electrode, and then reading the capacitance at each of the intersecting sense electrodes – *i.e.*, that it uses a sequential driving method. In reality, almost all touch-controller companies are driving multiple-drive electrodes at the same time and reading multiple intersections at the same time. In doing p-cap touch sensing, time and signal amplitude are critical. The more things that can be done in parallel, the more time is available for additional sensing cycles. And, when more electrodes are driven at the same time, the measured signal (output) increases. This effectively increases the SNR, which enables detection of very small touch objects such as the tip of a #2 pencil, even on larger screens. Most touch-controller suppliers keep the details of parallel drive as a trade secret and never talk about it. Apple published some details in a patent.<sup>4</sup>

Other touch-module and touch-controller suppliers who were demonstrating at least one

of the four new p-cap characteristics (but have not been mentioned yet) included AMT, Emerging Display Technologies, EETI, FocalTech, and SMK.

### Touch Sensors

The most significant trend in touch sensors is the move to true single-layer mutual-capacitance sensors. This trend is fundamentally driven by cost pressure and by the reality that very few products or applications require more than two touches, especially at the low end. This trend is most obvious in Asia, where more low-end phones are sold. Only a few touch suppliers were showing single-layer sensors at Display Week 2014 (*e.g.*, Solomon Systech) but several more acknowledged the trend in conversations with the author (*e.g.*, JDI).

Another touch-sensor trend that is growing but has not reached widespread consumer-electronics products yet is plastic (PMMA) cover lenses. Touch suppliers showing touch panels with PMMA top surfaces at Display Week included Dawar, Emerging Display Technologies, and Gunze. The primary issue that is keeping big consumer-electronics OEMs from using PMMA on phones and tablets is the deformability of the material. PMMA can be made very scratch resistant (up to 9H, as shown by Fujitsu), but it cannot be made so that a child with a ballpoint pen cannot damage it. The author believes that even-

tually one big OEM will switch to PMMA, then others will follow once someone’s broken the ground, and then everyone will become used to the dentability of the material. After all, we all lived with resistive touch panels on our pen computers, PDAs, GPSs, Microsoft tablet PCs, and other devices (PET top surface, easily damaged) for more than 20 years!

### Active Stylus

Hanvon was the only active-digitizer vendor exhibiting at Display Week. It was showing its standard battery-less Electromagnetic Resonance Touch (EMT-branded) product line, but it was a very low-profile exhibit. The most interesting statement made by a Hanvon representative was that the company has decided to take on the role of p-cap stylus ODM for suppliers such as Atmel, Synaptics, ELAN, *etc.* There is a distinct need for this in the market; none of the touch-controller suppliers (other than N-Trig, which was not exhibiting) want to be in the business of building active styli, and there are very few specialized manufacturers to whom these suppliers can turn.

The Hanvon representative told the author that although Hanvon suggested the possibility of a single stylus design that would work with all three brands of touch controllers, all three of the abovementioned suppliers rejected the idea (presumably because of revenue concerns because extra styli are a very high-margin accessory). Hanvon said that it is currently developing a “true battery-less stylus that derives its power from the touch-panel drive signal” – *i.e.*, no battery and no supercap. The frequency hopping that most touch-controller manufacturers use make this a little more challenging than it seems at first glance.

Hanvon was demonstrating one of its active styli that is designed to work with the FocalTech controller; the stylus was powered by a AAAA battery. If Hanvon wants to be successful as a stylus ODM, it is going to have to demonstrate a much better grasp of human factors than was evidenced in the FocalTech stylus – it was much too slippery, the button was too long and too close to the end of the stylus, and the writing experience did not replicate a pen-on-paper feeling.

The astute reader may notice that there are frequent mentions of passive stylus throughout this article, but this section contains the

only mention of active stylus. The reality is that passive stylus is getting so good (as a result of continuously increasing touch-controller SNRs) that it is approaching “good enough.” Stylus tips are now all in the range of 1.0–2.0 mm, and the tips are made of a harder material that produces a much more pleasant user experience than the old rubber-tipped styli.

An active stylus still provides three main advantages: (1) higher resolution, (2) pressure-sensing, and (3) hover. However, the author believes that the #1 advantage will disappear as touch-controller manufacturers continue to tune the algorithms that support passive stylus. Advantages #2 and #3 will both disappear if the touch industry finds a way to build high-quality pressure sensing into the p-cap sensor (rather than put it the stylus). Apple has started the ball rolling with the pressure-sensing technology in its Apple Watch; on its Web site<sup>5</sup> Apple claims that “[Force-sensing] is the most significant new sensing capability since multi-touch.” Hype aside, in the author’s opinion, Apple’s technology is best-suited for watch-sized displays and does not scale well to phones and tablets. The author recommends watching for an announcement from Cambridge Touch Technologies, a tiny UK start-up that has invented an elegant, scalable, and manufacturable method of adding high-quality pressure-sensing to any p-cap touch-panel stack-up, without changing any characteristic of p-cap.

### ITO Replacements

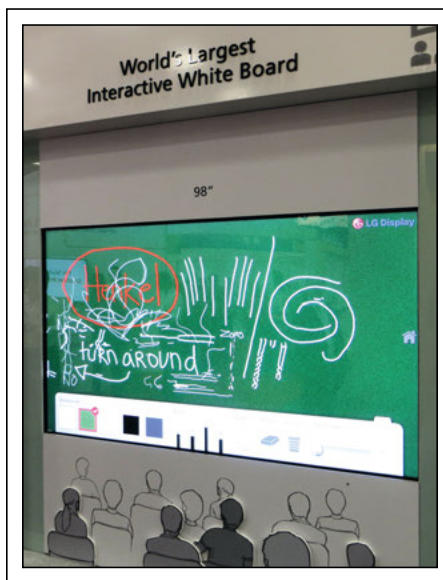
Transparent conductive material that can replace ITO in touch panels has been a very hot topic for at least the last year. However, the exhibits in this technology area at Display Week 2014 were surprisingly tame. Probably the most interesting was Cima NanoTech, which showed a 26-in. curved touch panel and what it claimed was the industry’s first 42-in. film-based non-ITO touch module. Actually, there have been film-based p-cap touch screens made with 10- $\mu\text{m}$  wire around for many years, but it is clear that Cima means “made from modern ITO-replacement materials,” which in this case means self-assembling silver mesh.

Other ITO-replacement material suppliers exhibiting included the following (in alphabetical order):

- **Canatu:** Roll-to-roll printed carbon nanotube (Carbon NanoBud brand) on PET film. This material won the SID

Display Component of the Year Silver Award at Display Week 2014.

- **Carestream Advanced Materials:** Roll-to-roll solution-processed silver nanowires on PET film (FLEXX brand). Films such as these are “drop-in” replacements for ITO, designed to fit the existing processes with minimum disruption. The problem is that disruption is what usually changes things (e.g., printed metal mesh where deposition and patterning of the transparent conductor are done simultaneously).
- **Oxford Advanced Conductors:** Silicon-doped zinc, similar to ITO but lower cost, solution-processed, more available, and greener. These are all good characteristics, but they are not focused on what the touch industry wants most: very low sheet resistivity and very high transparency.



**Fig. 6:** The touch response of LG Display’s 98-in. interactive whiteboard was slow at 0.5 sec. It handled 10 touches quite well; the 10 short lines just to the left of the long straight line were created by the author’s two hands. However, the touch system’s ability to separate two closely spaced fingers was not very good. The two sets of two parallel intertwined lines at the lower right of the long straight line were created by the author holding two fingers about 10 mm apart. The intertwining indicates that the touch system cannot decide if it is seeing one or two touches. Photo courtesy Geoff Walker.

- **Poly IC:** Roll-to-roll printed metal mesh on PET film. With a minimum conductor width of 8  $\mu\text{m}$ , the mesh is not competitive with the current 2–4- $\mu\text{m}$  range found in Asia.
- **Rolith:** Photolithography equipment capable of making metal mesh with < 1- $\mu\text{m}$  conductor width, < 5  $\Omega/\square$ , and > 95% transmission. Rolith’s estimation of mesh sensor cost (on its equipment) at the end of 2015 is \$15/m<sup>2</sup>; the author’s estimate of where the market will be is \$10–12/m<sup>2</sup>.

### Other Touch Technologies

There were three notable examples of non-p-cap touch on the Display Week show floor. The biggest was LG Display’s 98-in. UHD interactive whiteboard (Fig. 6). The touch technology was not labeled, but close inspection revealed it to be 10-point multi-touch infrared. The latency of this touch system was one of the worst that the author has seen – it was at least 0.5 sec. When the ink written on a whiteboard takes a half-second to appear, the lag is so disconcerting that it makes the whiteboard essentially unusable. It seemed fairly clear that the touch system was probably added as an afterthought, and that LG Display was mainly focused on showing off its 3840 × 2160 resolution and 98-in. diagonal. Note that the resolution calculates to only 42 ppi.

The second notable example of non-p-cap touch on the show floor was AD Metro’s 24-in. glass-film-glass (GFG) 5-wire resistive touch panel. Twenty-four inches is the largest resistive touch-panel the author has ever seen, and it looked great. An AD Metro booth representative said that the typical applications for this size included military and shipboard control panels.

The final notable example of non-p-cap touch was Panjit’s analog multi-touch resistive (AMR). This touch technology has become very rare (specialized) as a result of the onslaught of capacitive touch. The sensing element (square) of the sample on display was about 12 mm; this is just small enough that it is difficult to get two fingers onto one element, but not so small that the pinout count becomes unmanageable. A Panjit booth representative said that the typical applications for its AMR are military and industrial and that “healthcare that is not happy with all the characteristics of p-cap” (interesting!).

### More Touch Than Could Be Taken In at Display Week

As has been the case since at least 2010, there was a huge amount of touch-related technology to be seen on the show floor. Studying it all required more than one full day. And, as always, there were competing touch-related events such as the touch sessions in the Symposium on Tuesday and Thursday, the touch session of the Exhibitors' Forum on Tuesday, the Touch-Gesture-Motion Market Focus Conference on Wednesday, and the touch posters on Thursday. And that's not even mentioning the Touch Short Course on Sunday and the Touch Seminar on Monday. Display Week remains the single best place to see and learn about touch technologies in the Western hemisphere.

### References

<sup>1</sup><http://informationdisplay.org/IDArchive/2012/September/DisplayWeek2012Review-TouchTechnology.aspx>

<sup>2</sup><http://informationdisplay.org/IDArchive/2013/SeptemberOctober/Touch.aspx>

<sup>3</sup>[http://techon.nikkeibp.co.jp/english/NEWS\\_EN/20130315/271452/](http://techon.nikkeibp.co.jp/english/NEWS_EN/20130315/271452/)

<sup>4</sup><http://www.freepatentsonline.com/y2009/0009483.html>

<sup>5</sup><http://www.apple.com/watch/technology/> ■

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## Rolling Out the Red Carpet



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Competition of live demonstrations regarding emerging information-display technologies, such as not-yet-commercialized prototypes and proof of concepts.

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The Society for Information Display highlights the most significant new products and technologies shown on the exhibit floor during Display Week.

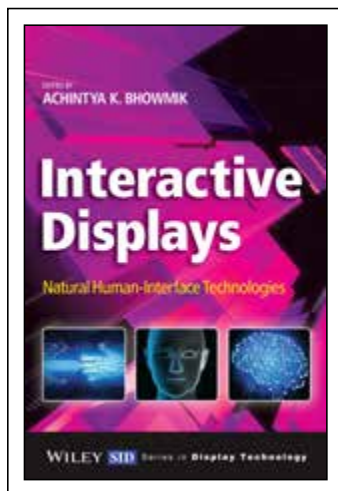
### *Journal of the Society for Information Display (JSID)* Outstanding Student Paper of the Year Award

Each year a sub-committee of the Editorial Board of *JSID* selects one paper for this award which consists of a plaque and a \$2000 prize.



## ***Interactive Displays: Natural Human-Interface Technologies*, Achintya Bhowmik (ed.), Wiley, 2015.**

Reviewed by Jyrki Kimmel



The latest addition to the SID–Wiley Series in Display Technology books is *Interactive Displays*, a volume edited by Achintya Bhowmik from Intel. *Interactive Displays* is of particular interest because it expounds on topics rarely dealt with in display literature.

It opens with an overview of the basic principles of vision and the history of human–computer interaction paradigms. The heart of the book deals with touch interaction, voice interaction, various technologies for the three-dimensional sensing of the proximity of a flat-panel display, gaze interaction, and multimodal

paradigms for interaction and biometrics. The volume concludes with a look forward to the ultimate displays of the future, which will be able to sense the entire 3-D visual field.

The writers of the individual chapters have been recruited from among the top researchers in the fields of interaction technology and information displays. Geoff Walker from Intel gives an excellent and comprehensive overview of touch; the way voice is employed in the user interface receives an expert treatment by Andrew Breen and colleagues from Nuance; gaze tracking is clearly explained by Heiko Drewes from Ludwig-Maximilians-Universität; and multimodal input technologies are clearly classified by Joseph J. LaViola and co-workers (University of Central Florida), to cite just several examples.

The topic of interactive displays is increasingly relevant to today's display-centric human–machine interaction paradigm. For developers charged with creating intuitive user interfaces, this book will provide a wide breadth of information. Many of the chapters can be treated as reviews of the state of the art in their respective fields, and the reference lists are extensive, providing the reader with a great starting point to become familiar with any particular interaction modality that might be focused upon. The treatment of individual topics is a bit uneven among chapters, with some having been written in a more concise and cursory way and others focusing on just a single application field. Altogether, however, the reader is presented with a body of knowledge that has been thus far missing from the literature in information displays.

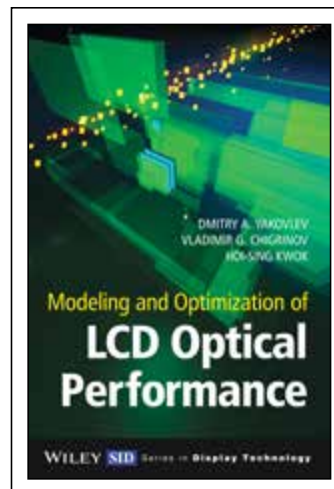
The editor, along with colleagues well known in the field of displays, Jim Larimer (ImageMetrics) and Philip Bos (Kent State University), conclude *Interactive Displays* with a section on the display technology of the future. This chapter describes how difficult it is to realize a display that utilizes the plenoptic function of the visual field. The interaction paradigms with this “display technology of the future”

are presented only with regard to the 3-D visual field. This can hardly be regarded as a gross omission, as such technology is the grand challenge of display technology, but this topic might have provided an opportunity to bring together the various themes of the book in a kind of closure. In all, however, I recommend *Interactive Displays* as a welcome addition to the SID–Wiley Series in Display Technology.

*Jyrki Kimmel* is with Nokia Technologies located in Tampere, Finland. He can be reached at [jyrki.kimmel@nokia.com](mailto:jyrki.kimmel@nokia.com).

## ***Modeling and Optimization of LCD Optical Performance*, by Dmitry A. Yakovlev, Vladimir G. Chigrinov, and Hoi-Sing Kwok. Wiley, 2015.**

Reviewed by Sally Day



*Modeling and Optimization of LCD Optical Performance* is one of the latest books in the SID–Wiley Series on Display Technology. It is written by Dmitry A. Yakovlev, Vladimir G. Chigrinov, and Hoi-Sing Kwok. The book is a detailed treatise on the methods of modeling the optical properties of the classic liquid-crystal (LC) modes: twisted nematic (TN), supertwisted nematic (STN), and ferroelectric LC (SSFLC). The chapters tend to alternate between detailed descriptions of theory, starting from how Maxwell's equations are used to provide the matrix

methods for accurate modeling and practical examples in which the models are applied. The theories are described thoroughly, leading into discussions of the most important aspects that must be included in order to obtain precise simulation of the optical performance of displays. The book assumes a working knowledge of liquid-crystal physics and device structures.

For example, the authors apply the Jones matrices to some LC layers and investigate different parameter spaces, thereby anticipating the different polarization modes and states for a number of different LC modes. This is followed by a discussion of the modes and an analysis of the case for reflective modes, explaining how mode analysis can aid in the choice of LC structure in display design. An example is given for the design of bistable displays. This is presented along with an interesting analogy that includes Smith charts, a section that is likely to be interesting to electronic engineers in particular.

Different liquid-crystal modes are described, along with a theory that can be used to predict some of the liquid-crystal director structure and visco-elastic behaviors. Examples are given of modeled results, with a discussion of viewing-angle properties provided before the modeling methods have been fully explored. Necessarily, the modes that are

described are those for uniform pixels, thereby excluding the modes now commonly found in high-performance LCDs.

From these more practical aspects, the authors return to the mathematics of matrices, radiometric quantities, and how these are represented in Jones matrices. A subsequent chapter discusses the simulation of TN and STN, *i.e.*, distorted chiral structures, and explains the analysis that is needed to understand fully the experimental results required for the exact design of high-performance displays. This chapter also has a discussion of compensation films.

Real displays will have scattering elements, may diffract light, and use light that is not monochromatic, and these issues are considered, together with information about some of the common additional layers in LCDs, such as ITO, alignment layers, and glass. An ensuing discussion goes back to Maxwell's equations and discusses the so-called Berreman method, well known to those who model LC optics. The use of eigenwave representation is described, and there is a discussion of the methods together with detailed descriptions of modeling of interfaces, again an important consideration for displays where high brightness, energy efficiency, and excellent contrast ratios are required.

A library of codes is provided online with the book, and two chapters provide details on this. There is a discussion of some of the shortcomings of the various Jones-matrix methods and an analysis of when these shortcomings are significant, together with applicable numerical methods. Some of the less-accurate methods are nonetheless useful because of the insight that they offer. There is a discussion of the comparison of modeling and experiment and how parameters of the LC layer can be obtained from the inverse problem. Only in the final chapter is there mention of the now commonly used LC modes – IPS, FFS, PVA, and MVA; however, as is said, the rigorous methods described in this book cannot easily be applied for accurate modeling over the whole pixel area. Example results are given using director simulation software available to the authors.

Overall the book should be useful to researchers and engineers who have a working knowledge of LCDs and are interested in the detailed theory of the methods for precise and accurate modeling of the optics and optical performance of LCDs. A slight shortcoming of the book is that some of the figures are not fully labeled, but they can be understood from reading the relevant text. This work is a useful addition to the book series as a thorough exploration of the modeling of the optics of LCDs *via* Jones and other matrix modeling methods. ■

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## LA Chapter Sponsors Flat-Panel Conference

The Society for Information Display's Los Angeles Chapter is sponsoring a special one-day technical and business conference, "Advances in Flat-Panel Displays," on February 6, 2015, in Costa Mesa, California. This is an excellent opportunity to learn about and discuss key flat-panel issues such as spatial and temporal resolution, image processing, quantization, contrast, color gamut, and more. Topics and speakers will include:

- IGZO/LTPS Metal Oxide Transistor and Electron Mobility, *Dick McCartney*
- Carbon Nanobud Technology and Contrast Improvements to Displays, *Bob Senior*
- The Business Future for AMLCD and AMOLED Displays, *David Barnes*
- Touch Developments, *Jennifer Colegrove*

In addition, there will be presentations on Quantum Dots, Improvements in Flat-Panel Display Parameters, and more.

The program runs from 8:00 am to 4:00 pm, with registration and breakfast at 7:00 am. It takes place at the Costa Mesa Country Club in Costa Mesa, California. Register by January 12, 2015 to receive the early bird discount.

Visit [www.sid.org/Chapters/Americas/LosAngelesChapter.aspx](http://www.sid.org/Chapters/Americas/LosAngelesChapter.aspx) for more information and to register. If you have any questions, contact Conference Chairman Larry Iboshi at [iboshi@pacbell.net](mailto:iboshi@pacbell.net) or the Program Chair Mike Moyer at [mike@mosci.com](mailto:mike@mosci.com). ■

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## Display Week 2015

Innovation Zone (I-Zone)

June 2–3, 2014

The prototypes on display in the Innovation Zone at Display Week 2015 will be among the most exciting things you see at this year's show. These exhibits were chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. Programmable shoes, interactive holograms, the latest head-up displays, and much more will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

SID created the I-Zone as a forum for live demonstrations of emerging information display technologies. This special exhibit offers researchers space to demonstrate their prototypes or other hardware demos during Display Week, and encourages participation by small companies, startups, universities, government labs, and independent research labs.

Don't miss the 2015 I-Zone, taking place two days only: Tuesday June 2, and Wednesday June 3, on the show floor at Display Week.

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*continued from page 2*

light-field methods. Exciting work in the form of prototypes is already under way and carefully described in detail by the authors. Some additional introduction of both articles is provided by Nikhil in his guest editor's note, where he observes that "These two articles remind us of the rich diversity and potential that light-field displays offer."

While true 3-D is the future of TV, UHD is part of the present landscape, and the best way to understand what it means to the marketplace is to read our Display Marketplace feature, "UHD TV Strives for Consumer Recognition," by IHS analysts Jusy Hong and Veronica Thayer. Here, they discuss some critical issues with regard to increased consumer adoption – such as general awareness of the advantages, content availability, and price compression. These are familiar themes to any of us who have followed the market, but more complex and promising this time because of the diversity of content delivery methods and the motivations of various content providers as well as set manufacturers.

However, for UHD to roll out smoothly, the various members of the industry need to get together and embrace a uniform set of standards that provide for content creation, encoding, and delivery in a way that takes full advantage of these new UHD TVs. This is the subject tackled by our next Frontline Technology feature, "UHD Calls for New TV Infrastructure" by author Wade Wan. Wade explores the current efforts and proposals under way and provides a detailed view of some of the technical challenges, such as encoding schemes, bandwidth, and content protection. This is a timely subject that has been getting treatment in several other sources and on-line publications, so we are pleased to have this coverage in *ID* as well. This topical coverage of UHD technology was developed for us by our Guest Editor Steve Sechrist, who provides some additional color on the subject in his guest editor's note.

Another topic that comes up frequently in conversation is the debate between the merits of LCD and OLED screens, and especially with the added variable of curved screens. This month we welcome David Choi from LG Display, who presents his perspective in a guest opinion article titled "OLED TV Provides Superior Viewability." In David's view, there are a myriad of benefits to OLED technology, and when combined with the purported advantages of curved screens, the combination yields a truly impressive platform for future

TV viewing. To be honest, I was a believer in OLED technology already, and now I am saving my pennies in hopes of bringing one of these OLED TV sets home soon myself.

From the LCD curved-TV camp, we have another opinion piece, "The Curved Display Makes an Impression," by Samsung's Nam-Seok Roh. This article delves further into the benefits of curved TVs, making a case for why they are more than a fad and how they offer a truly optimal immersive viewing experience.

In case you think we forgot, in the last issue we promised the final element of our comprehensive review of Display Week 2014, and thanks to the great efforts of author Geoff Walker, we have this month the review of touch technology for you. As Geoff explains, Display Week has become the leading show in the industry for exhibition of new touch technology, and the depth and breadth of presentations on touch were amazing this year. Geoff, along with his colleagues on the program committee, work tirelessly to help organize all of this content, and his coverage of this year's new offerings is thorough and highly valuable to all of us who help deliver touch-enabled products to the marketplace.

Before I close, I just want to thank everyone who works so hard to put *ID* magazine together throughout the year. Our team of guest editors and contributing editors helped us create a great lineup of articles for 2014 and I cannot thank them enough for their hard work. Our editorial staff, consisting of Jenny Donelan and Jay Morreale, did an outstanding job managing the production process and producing our in-house articles. Our cover designs this year continued to amaze, thanks to both Jody Robertson-Schramm, who has worked with us for many years, and Jodi Buckley, who joined us this year to produce several covers as well. It is an honor to work with this outstanding team and I truly hope you enjoyed reading the results throughout the year. As we all approach the holidays, I hope you find time to reflect on the many things that make your lives special, including family and friends that you hold dear. Life is much more than just the great work we do in this display industry. Cherish those things that are most important to you and nurture them so they enrich your life in return. I wish you all a healthy and prosperous New Year! ■

*continued from page 4*

approaches can be separated into those that use temporal multiplexing (time sequential) and those that use spatial multiplexing. Each type of approach has some advantages and disadvantages, and it appears that the best choice depends on the attributes of the target application.

These two articles remind us of the rich diversity and potential that light-field displays offer, with parallel paths taking us toward group/multi-user and personal/portable systems. In my opinion, the prospect of developing useful real (natural) 3-D displays within the next 5 years is very bright. I confidently predict that these will first see use in a set of applications before the year 2020. ■

*Nikhil Balram is President and CEO of Ricoh Innovations Corp. He can be reached at [nbalram1@hotmail.com](mailto:nbalram1@hotmail.com).*

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# Information DISPLAY

Official Monthly Publication of the Society for Information Display

## 2015 EDITORIAL CALENDAR

### ■ January/February

**Flexible Technology, e-Paper, Wearables**

Special Features: Wearables Update, Flexible Technology Market Overview

Related Technologies and Markets: e-Paper, substrates, films, coatings, OLEDs, manufacturing, wearables

**Sept 1:** Editorial content proposals due

**Jan 5:** Ad closing

### ■ March/April

**Display Week Preview, Topics in Applied Vision**

Special Features: SID Honors & Awards, Symposium Preview, Display Week at a Glance

Related Technologies and Markets: Projection, LCDs, OLEDs, metrology, wearables

**Nov 3:** Editorial content proposals due

**Mar 6:** Ad closing

### ■ May/June

**Display Week Show Issue, Automotive**

Special Features: Display of the Year Awards, Products on Display, Market Overview of Automotive Trends

Related Technologies and Markets: LCDs, OLEDs, projection, ruggedization, manufacturing, automotive, marine

**Jan 5:** Editorial content proposals due

**May 1:** Ad closing

**Special Distribution:** Display Week 2015 in San Jose and IMID in Korea

### ■ July/August

**Interactivity/Touch/Tracking, Portable Technology**

Special Features: Portable Devices Study, Touch Market Update

Related Technologies and Markets: Materials, ITO, ITO replacements, backplanes, glass, films, tablets, smartphones

**Mar 2:** Editorial content proposals due

**June 30:** Ad closing

**Special Distribution:** Vehicle 2015 and EuroDisplay in Belgium

### ■ September/October

**Display Week Wrap-up, Metrology**

Special Features: Display Week Technology Reviews, Best in Show and Innovation Awards, Metrology Update

Related Technologies and Markets: Measurement, spectrometers, LCDs, OLEDs, quantum dots, manufacturing

**May 4:** Editorial Content Proposals due

**Sept 2:** Ad closing

**Special Distribution:** IDW in Japan

### ■ November/December

**3D/Holography, Television**

Special Features: Consumer TV Roundup, State-of-the-Art 3D Survey

Related Technologies and Markets: OLEDs, LCDs, TVs, Retail Electronics

**July 1:** Editorial content proposals due

**Nov 3:** Ad closing



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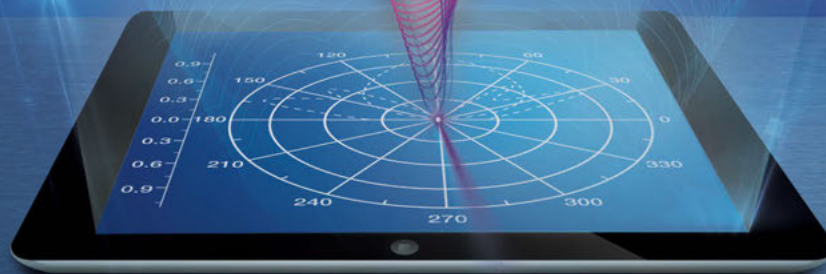
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