LIGHT-FIELD DISPLAY SYSTEMS

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July/August 2016
Vol. 32, No. 4

Welcome to the Light Field

ROADMAP FOR LIGHT-FIELD SYSTEMS

HEAD-MOUNTED LIGHT-FIELD DISPLAYS FOR AR/VR

COLOR GAMUTS DEMYSTIFIED

ISSUES SHAPING THE DISPLAY INDUSTRY

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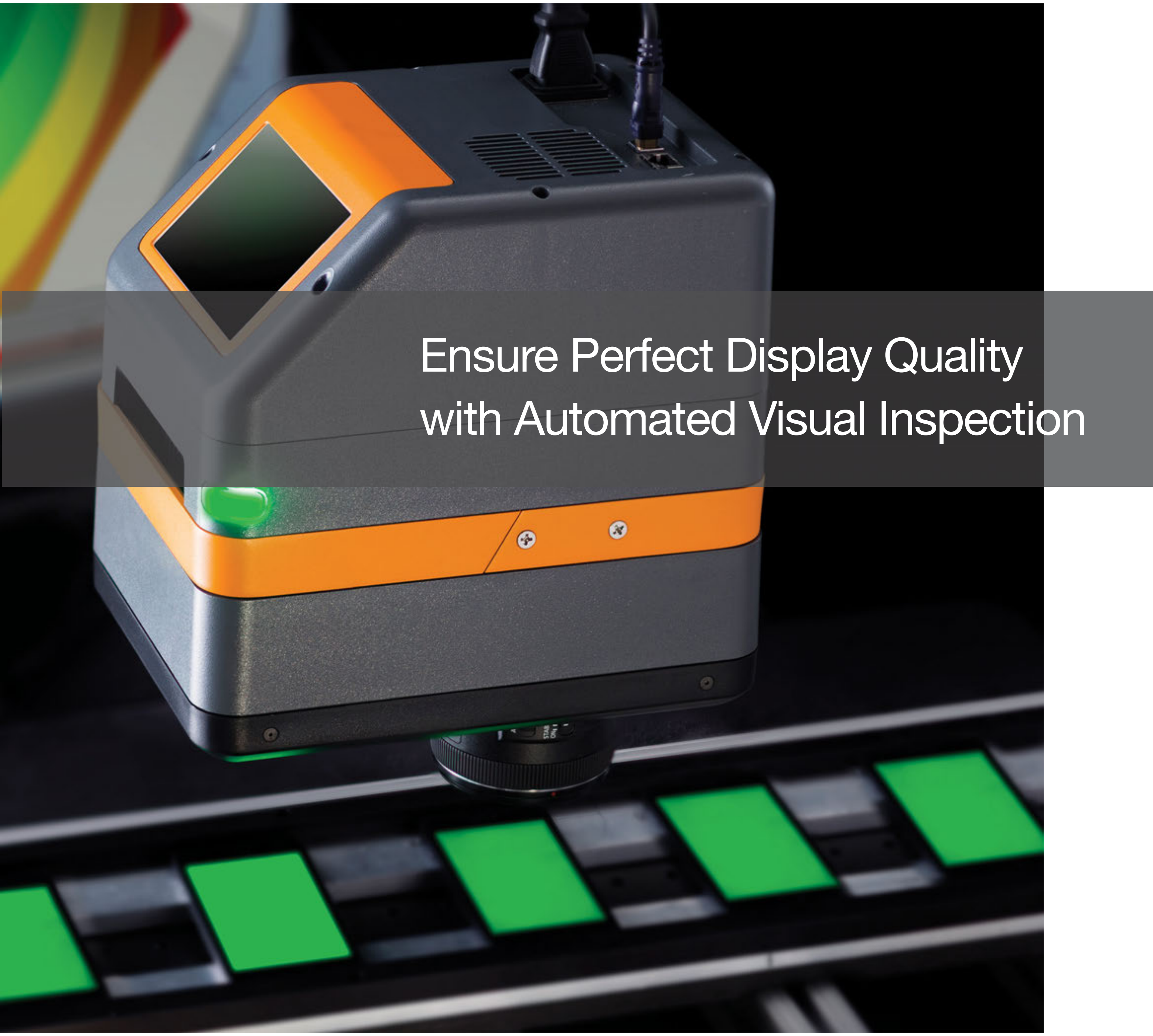
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editorial

A Mid-Summer Night's Dream

by Stephen Atwood

I woke this morning to the sound of my personal robotic assistant gently reminding me of the time. It was almost 7:30 and I had to be at my first meeting by 9:00. My assistant brought coffee to my room and replayed a brief summary of the overnight news headlines to let me know what was happening in the world. "Excellent!" I thought as he re-counted how many new medals the U.S. had picked up at the 2024 Olympic Games overnight. After getting dressed, I went downstairs and turned on the 3D projector to watch more sports coverage while I enjoyed my breakfast. I ruminated about how strange it must have been for people to watch television through little flat windows on the wall instead of having a holo-projection filling the entire room.

"Right on time" I thought as I checked my bio-feedback watch and moved from the kitchen to my studio office. Sitting down in my chair, I turned on my computer and started the virtual conferencing application that would carry me to the meeting room at the company headquarters in Portland. The projector in my office also came to life and an entire meeting room, including a conference-room table, appeared in front of me. I watched as other members of my team popped into view at various seats around the table. Thanks to the light-field camera array pointed at my chair, I also now appeared virtually in front of everyone else at the meeting. We could all see each other in full size and depth and look around the entire room, making it almost indistinguishable from really being there. But, in fact, we were all in different places including China, Europe, the U.K., and the U.S.

The meeting began with a holo-projection of the new product being assembled on the production line. I could see every detail of how the assembler was building the product and what issues he encountered. It was not going well enough and took too long to complete. We went around the room brainstorming about how to make the assembly easier and increase production to the critical target the GM wanted us to hit. After we collected the ideas, our animation artist used those ideas to re-build the original assembly sequence and then we could see exactly how the new assembly would flow based on our changes. A few more bugs needed to be worked out and then the final sequence was sent instantly to the factory floor, where the assembly team was waiting to watch the new projection. It took about 10 more minutes for all the assembly procedures to be electronically re-imaged and then we could see that we had solved the problem.

Just as the meeting was breaking up, my wife messaged to say that our son the gymnast was just starting his morning warm-ups. He had a meet later that day that I was going to attend but I needed to work that morning. So, she used her portable light-field camera to capture his routines and they appeared on my office holo-projector, replacing the conference room that was just there earlier. As I finished my morning reports, I could keep an eye on him and even message back some "helpful" suggestions that made him wave back in embarrassment.

The weekend before, our daughter played her first soccer game and the entire game was recorded with light-field cameras. After the game, the coach brought us all back to a holo-studio where we could replay all the critical moments of the game and literally walk onto the field in the projection and observe the plays from different angles. She could see and interpret her own foot work, understanding much better how to

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industry news

VESA Announces Early Certification Program for USB Type-C Devices

The Video Electronics Standards Association (VESA) recently announced the official launch of its early certification test program for products incorporating the new USB Type-C connector and the DisplayPort Alternate Mode standard. Using the DisplayPort Alt Mode standard, a USB Type-C connector and cable can deliver full DisplayPort audio/video performance (driving monitor resolutions of 4K and beyond), SuperSpeed USB data, and up to 100 W of power. DisplayPort is the only display interface alt mode natively supported by both standard USB-C connectors and cables. The new DisplayPort Alt Mode over USB-C Early Product Certification Program is intended to help ensure interoperability early on in development cycles.

"During new-technology development, products often are ready to ship before compliance test programs are complete. Conformance testing, however, is still vital to helping ensure a smooth roll-out and positive user experience with early products," said Jim Choate, compliance program manager for VESA. "To help USB Type-C product manufacturers address this challenge, VESA created the DisplayPort Alt Mode over USB-C Early Product Certification Program to help speed both the path to compliance and time to market for new products."

Nearly a dozen tablets, laptops, and monitors have been certified through the pilot phase of this early certification program, including products from Intel, Dell, Asus, HP, and LG Electronics. Several dozen more certified products are expected to be available by the end of the year.

NEW PRODUCT BRIEFS

Henkel Offers New Precise Edge-Control Liquid Optically Clear Adhesives

Henkel Adhesive Technologies' electronics business has developed and commercialized a novel suite of liquid optically clear adhesive (LOCA) materials that offer significant process and design enabling capabilities for touch screens including smartphone, notebook, all-in-one (AIO) PC, and large-format displays. The new Loctite brand materials are precise edge control (PEC) LOCA formulations that allow for the construction of displays with narrow-bezel and ultra-narrow-bezel architectures.

These adhesives have unique properties that allow them to remain at the edge of the touch panel without any overflow. For use with touch and large-format displays, Loctite PEC LOCA materials are available in pre-gel, high viscosity, and pressure-sensitive adhesive (PSA) formulations and deliver significant process benefits as compared to traditional LOCA materials.

Grauling Research Announces New Coating Technology for Improved Sensor Performance

Grauling Research, a North American research company and global supplier of coating materials, consumables, and equipment support for the thin-film optical-coating industry, is now offering IR-ISE (Infrared-Improved Sensor Efficiency), an improved photoconductive infrared sensor coating developed with new technology (Fig. 1). This IR thin-film coating greatly enhances performance and improves the efficiency of infrared sensors; in many applications, the coating also seals and protects the device, eliminating the need for glass encapsulation.

The novel thin-film coating was developed for use with lead sulfide (PbS) and lead selenide (PbSe) sensors. Due to the high index of refraction in current lead-salt sensor technology, around 40% of the incident IR radiation in today's common sensor materials is lost due to surface reflection. The advanced IR-ISE thin-film PbS and PbSe coating designs can reduce the surface reflection of incident radiation by utilizing environmentally rugged, single or multi-layered, thin-film coatings. In applications where glass encapsulation is no longer needed, the new IR-ISE reduces the size and weight of the photodetector and lessens the amount of time, materials, and labor costs needed for assembly.

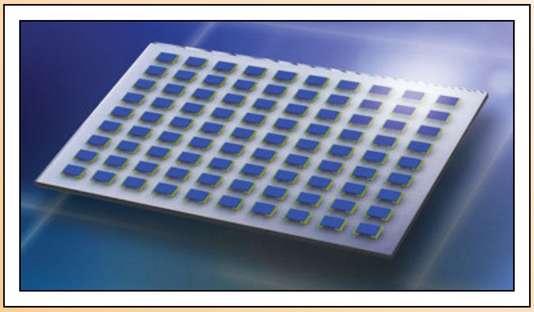

Fig. 1: This sensor array uses Grauling Research's new photoconductive infrared sensor coating.

CPT and Evonik Partner Create Metal-Oxide-Based Panel

At Display Week in San Francisco last month, German specialty chemical company Evonik Industries and Taiwanese display maker Chunghwa Picture Tubes (CPT) jointly presented an enhanced 5.8-in. LCD panel using iXsenic metal-oxide semiconductor material.

iXsenic is a solution-processable inorganic metal-oxide semiconductor for the display industry that is supplied by the Resource Efficiency segment of Evonik. It is applied under ambient conditions: no vacuum environment is needed, which results in a simplified process, high yield, and cost advantages. iXsenic is best applied via slot-die coating.

Chunghwa Picture Tubes (CPT) is dedicated to offering a full range of panel sizes, and positions itself as a leader for visual telecommunication products and an all-around innovator for optronic technology.

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guest editorial

Welcome to the Light Field

by Nikhil Balram

From the earliest days of history, humans have attempted to capture and display images. Cave paintings dating back 35,000 or more years show views of the world as seen by the ancient artist. The concept of photography as the capture of light using a recording medium is much younger, going back only to 1839, but the underlying concept of the camera obscura dates back to the sixth century. Paintings and photographs acted as static displays, showing various types of noteworthy images of the world. It was only 130 or so years ago that the idea of displaying the world in the form of moving pictures first took hold with the coming of films in the 1890s. The first commercial electronic displays, based on cathode-ray tubes (CRTs), only appeared as recently as 1922 and eventually enabled the concept of consumer television.

What is striking about this long history of capture and display is that almost all of it is based on two-dimensional imagery. The idea of enabling depth using stereoscopy was introduced by Charles Wheatstone in 1838. Since then, the notion of creating a perception of depth by presenting shifted images to the left and right eye has manifested itself many times – in the form of many generations of static stereoscopic viewers, printed images with lenticular layers creating distinct left and right views, 3D cinema using different color filters to separate left and right images, and, in the last decade, 3D cinemas and televisions using active or passive polarized glasses to enable separate shifted images for the two eyes. However, in each case the attempts at making three-dimensional viewing the norm failed to gain mass adoption — stereoscopic 3D has remained a niche. There may be many reasons for this failure but at least one prominent one is that presenting shifted left and right images on a single 2D image plane does not sufficiently approximate the way the human visual system sees the real three-dimensional world.

The continuous evolution of technology is once again presenting the dream of capturing and seeing three dimensions, this time using the light field, just like the human visual system does. But what is the light field, how is it captured and displayed, how does it take us from "flat land" to a true three-dimensional representation of the world, and when can we immerse ourselves in it? This special issue attempts to answer these questions through the two articles that follow.

The light field can be defined succinctly as the radiance that emanates from every point in the world and is visible to the human eye. The first article, "Light-Field Imaging and Display Systems," is a summary of the 4-hour Sunday Short Course I taught at Display Week 2016 in May. Written by my colleague Dr. Tošić and me, the article provides a definition of the light field and explains various imaging approaches for capturing it and display architectures for showing it. As we explain in the article, light-field imaging is reasonably well understood as the capture of a four-dimensional data set with two spatial and two angular dimensions with a well-defined methodology for designing systems tailored to specific applications such as factory automation, medical imaging, and cinematic virtual reality.

On the display side, the situation is much less clear. Given the propensity of the marketing side of the consumer-electronics industry to be creative in its use of terminology, one can expect "Light-Field TVs" coming to a holiday season in the not-too-distant future. From a display-technologist and vision-scientist point of view, a

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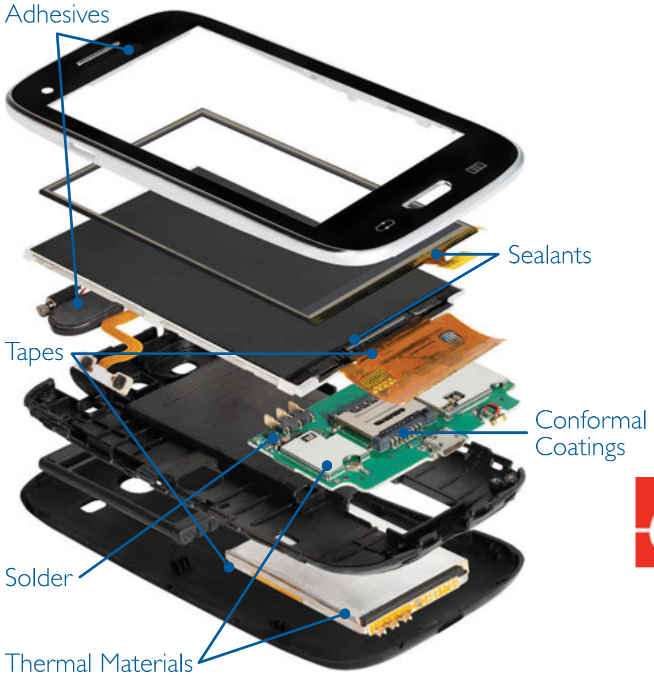
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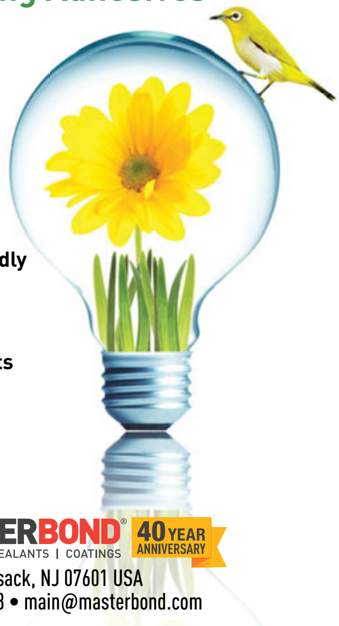

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Light-Field Imaging and Display Systems

Light-field imaging and display are often treated as separate areas, but at a conceptual level they are closely related. Display can be viewed as the reverse path of imaging, and this way of thinking can be helpful in the design of either type of system. This article offers a brief outline of both light-field imaging and display systems and a roadmap for their practical use going forward.

by Nikhil Balram and Ivana Tošić

THE light field is an old concept that has become increasingly relevant in recent times because of the advances made in digital and optical technologies and an improved understanding of how the human visual system perceives and interprets the world. This article provides a brief introduction to the concept and an overview of how light fields are captured (imaged) and displayed. Light-field imaging and display are often treated as separate areas because the approach, rigor of the design process, and clarity of possible applications and value propositions are quite different, with imaging being much further advanced in some respects. At the same time, at a conceptual level, one can view a light-field display as the reverse path of light-field imaging, and this way of thinking can be helpful in the design of either type of system, when practical trade-offs and limits have to be contemplated.

Introduction to Light Fields

Unlike a photograph that represents visual information as a projection of light on a 2D image plane, a light field represents the world around us through a set of light rays that fill up the 3D space. Even though not formally called the "light field," this concept dates back to the beginning of the 16th century and to Leonardo da Vinci, who referred to these sets of rays as "radiant pyramids." The introduction of the term "light fields" came four centuries later, in 1936 when Arun Gershun defined the light field as the amount of light traveling in every direction through every point in space. In 1991, Adelson and Bergen[1] formally defined the seven-dimensional "plenoptic function" to represent the visible radiance emanating from every object in the world to the human eye (Fig. 1, left image). This function is parametrized by the three-dimensional co-ordinates of the viewer (camera), the two dimensions (angular or cartesian) of the view direction, the wavelength, and the time. This function offers a complete representation of the light in a scene, but is too high dimensional to be of practical use. However, subsets of it can be used to represent and extract information.

The subset that provides the most generally useful representation for imaging and display is the 4D light field. The parametrization most commonly used today comes from Levoy and Hanrahan,[2] who represented the 4D light field as the coordinates of the two intersection points that any ray would have with two parallel planes (see Fig. 1, right image), producing a spatio-angular representation $L(u,v,s,t)$, with two dimensions (u,v) that are angular and two (s,t) that are spatial.

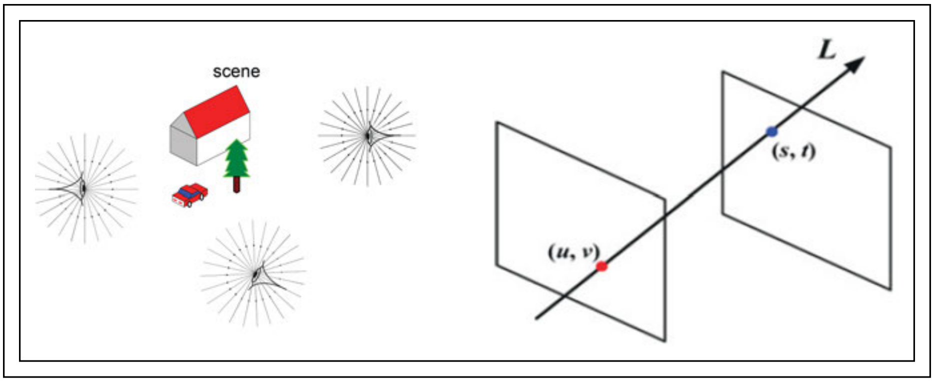

Fig. 1: *The plenoptic function represents all the radiance in the world (left). The 4D light field can be defined by the intersection of a ray with two parallel planes (right). (Information Display, Nov/Dec 2014)*

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Light-Field Imaging

The light field contains a wealth of useful information that can be acquired in its entirety or extracted in the form of application-specific subsets. Two fundamental approaches for acquisition of the light field use a two-dimensional array of synchronized cameras or a single camera with a two-dimensional array of microlenses between the main lens and the image sensor (see Figs. 2 and 3).

The early approaches to light-field acquisition used the concept of a camera array, either created temporally by moving a single camera[2] for static imaging or more generally with a physical $N \times N$ array.[3] The camera array approach provides high spatial resolution (since each camera has a $K \times K$ sensor, where K could be a large number), good image quality, and a broad range of distances at which object depths can be resolved (by constructing an appropriately wide baseline between the left/top versus the right/bottom views). The disadvantages are the significant bulk of the system, the difficulty in synchronizing and calibrating across many separate cameras, and the limited view resolution (since there is a physical limit to how closely together the cameras can be placed).

Subsequent approaches to light-field acquisition focused on a compact single camera that uses a $K \times K$ array of microlenses placed in between the image sensor and main lens of a conventional camera; an example of this approach is described in a 2005 Technical Report CSTR.[4] The microlens array (MLA) can be placed at different positions between the main lens and image sensor, but the most common and (computationally) convenient approach places the MLA at the focal plane of the main lens and the image sensor at the focal plane of the MLA. This results in the capturing of $N \times N$ views by the corresponding sensor elements under each microlens, and these sub-images can be processed to produce a set of $N \times N$ images in which each represents a unique view with a spatial resolution of K x K (see illustration in Fig. 4). This approach provides the advantages of a convenient portable form factor, high density of views (since N can be made reasonably large for a high-resolution image sensor), and the added option of capturing multi-spectral content by inserting a multi-spectral filter in front of the main lens.[5] The disadvantages are the reduced spatial resolution (which is defined by K, the number of elements in each dimension of the MLA), and the very small baseline between the left/top and right/bottom views, which limits depth imaging to nearby objects.

The camera-array approach was primarily used in research between 1995 and 2005, while various vertical application solutions were developed based on the single camera with the MLA approach, with, for example, Lytro introducing a consumer camera in 2011 and Raytrix and Ricoh introducing industrial cameras in 2010 and 2014, respectively (see Fig. 2). However, the recent resurgence of interest in consumer virtual-reality (VR) HMDs has motivated the development of spherical camera arrays as a means of capturing the 360° light field and processing it to provide cinematic VR content - see the examples of Jaunt ONE and Lytro Immerge in Fig. 2.

Figure 3 shows the duality between the camera array and the MLA + sensor approaches. It is interesting to note the reversal that occurs between the roles of the $N \times N$ and $K \times$ K parameters. A similar type of duality exists in the case of fundamental

Fig. 2: Light-field imaging can use an array of cameras arranged in a rectangular or spherical configuration (left) or a compact single camera that uses a microlens array (right).

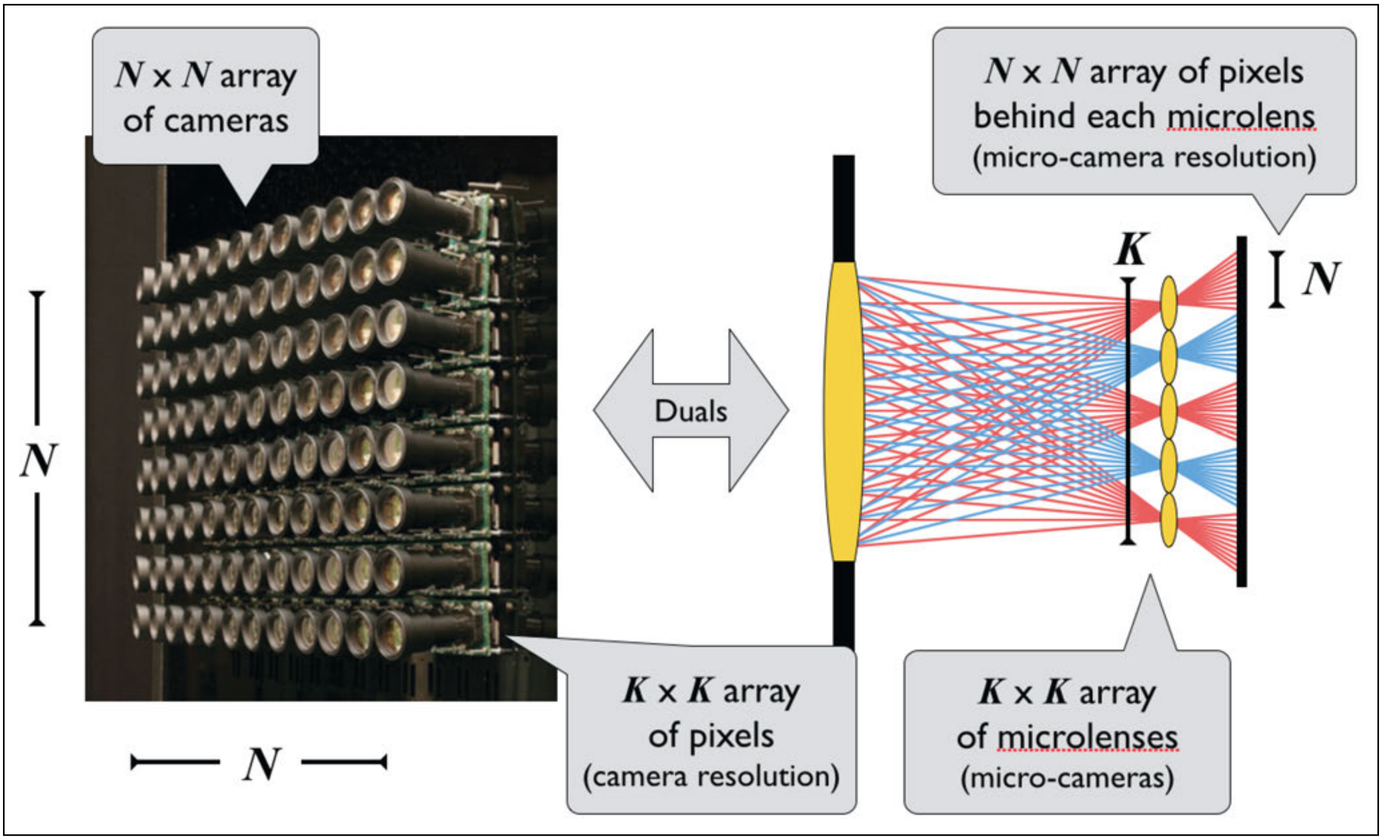

Fig. 3: *Depicted above is the duality between the array-of-cameras approach (left) and the single-camera-with-microlens-array approach (right) (Information Display, Nov/Dec 2015).*[6]

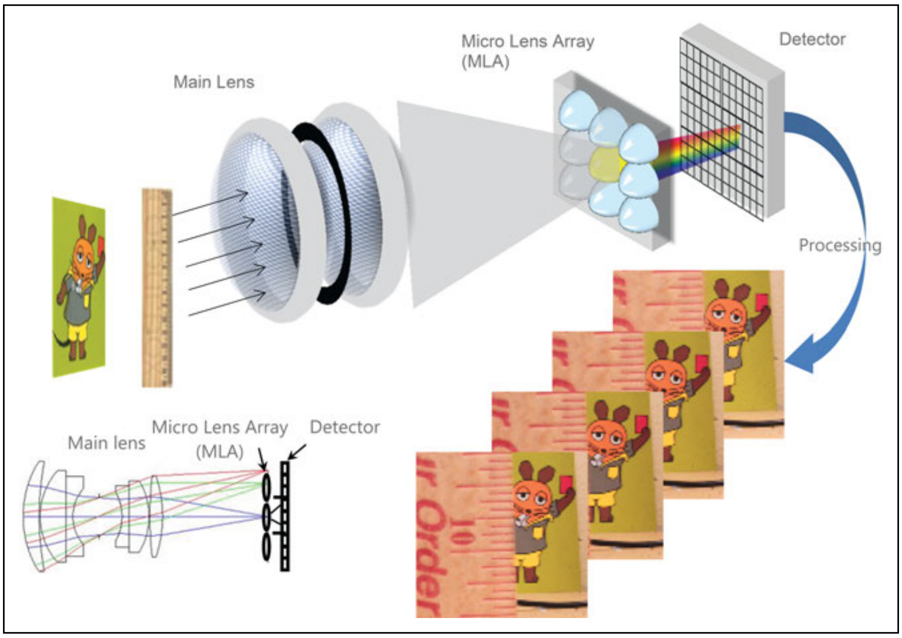

Fig. 4: *The light-field camera architecture includes the main lens, microlens array, and detector (sensor). The raw image has to be processed to produce sub-images representing the different views.*

light-field-display architectures, where the camera array is replaced by an array of displays such as projectors or microdisplays, and the MLA + sensor is replaced by the MLA + display.

As shown in Fig. 5, a robust system design methodology is used to design light-field imaging systems that are optimized for specific vertical applications; for example, as described in a 2013 paper by Berkner *et al*.[7] The major elements of the system are modeled and optimized through the use of performance metrics that are specific for each application. For example, in the case of a color inspection camera, the performance metric is the error between the computed and

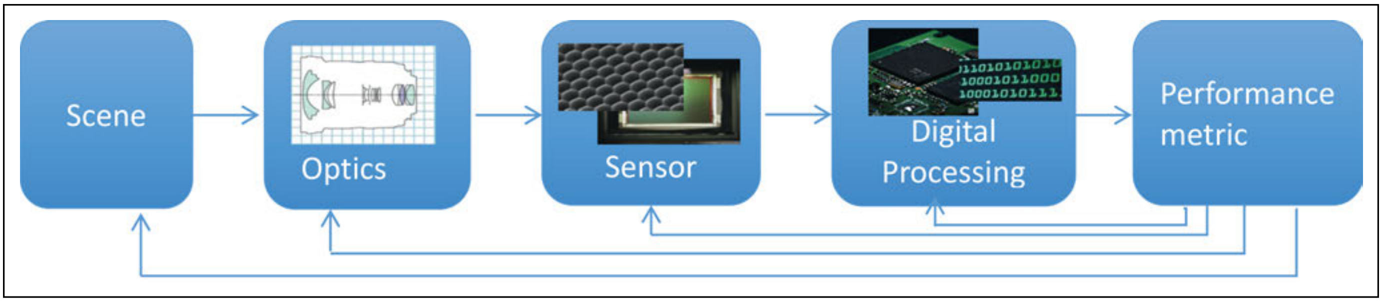

Fig. 5: In a system design model for light-field imaging, each major element of the system is modeled and the appropriate performance metric is chosen for each specific application. An iterative optimization process is used to design the optimal system for that application.[7]

known chromatic properties of a color calibration pattern.

The most important components of light-field imaging systems are:

- Calibration
- 3D (depth) estimation
- Resolution enhancement[a]
- Multi-spectral image processing[b]

We will briefly discuss the first three here. More detail can be found in the references.

Calibration: This refers to the process of taking raw data acquired by the sensor and converting it into a 4D (u,v,s,t) light-field representation. This involves a number of steps.[8] The first step, which has to be done only once for a given camera instance, includes locating lenslet image centers by using a white test image, estimating grid parameters, and building and saving the lenslet grid model. The additional steps, which have to be done for each acquired image, include some or all of the following: demosaicing to fill in complete R, G, B values from the Bayer pattern data; correcting vignetting by normalizing with the white image; resampling the image onto an integer grid using 1D or 2D interpolation; converting the grid from hexagonal to orthogonal (if hexagonal MLA is used); and slicing the results into a 4D light field $L(i,j,k,l)$ where (k,l) are the coordinates of each superpixel (representing one spatial point) and (i,j) are coordinates representing points (views) inside each superpixel. Thereafter, a system model needs to be estimated to allow conversion from homogenous coordinates to ray space coordinates (u,v,s,t), including adjustment for distortions in the real system.

3D (depth) estimation: This refers to the process of estimating the depth of a scene. Depending on the needs of the specific application, a generative model can be used to estimate the depth of planar scene layers[9] or, alternatively, a dense depth estimation approach can be used to assign depth to each spatial position[10,11] (see Fig. 6).

The latter uses 2D light-field slices called epipolar plane images (EPIs) that have one spatial and one angular dimension. Each EPI contains linear structures called "rays" that represent the radiance properties of a spatial point viewed from different angles. Points that lie on the focal plane of the main lens have negligible shifts across views and form vertical rays, whereas those that are in front or behind the focal plane show significant devia-

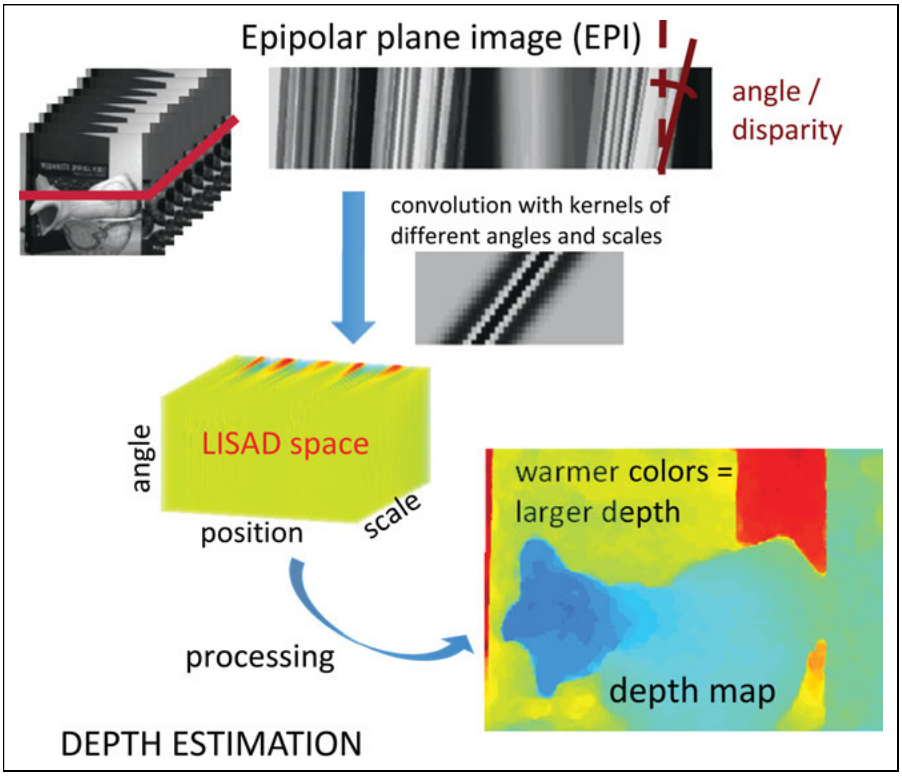

Fig. 6: A 3D estimation (dense depth-map generation) process using the LISAD approach.[10]

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[a] If more resolution is needed than provided by the native resolution of the MLA.

[b] If the application calls for the use of wavelengths that are different from the usual R, G, and B.

tion and form slanted rays. Consequently, the angle of a ray provides information about the depth of the corresponding point. In 2014, Tošić *et al.*[10] identified rays and their angles by localizing extrema in a novel scale-depth space representation of light fields, called LISAD (Light Field Scale And Depth), which is built upon the first and second derivatives of a Ray Gaussian kernel. Rays and their angles were further combined and processed to develop a dense depth map of a given 3D scene.

Enhanced resolution: Spatial resolution is a challenge for plenoptic systems because they trade it off to obtain a mixture of spatial and angular information. Higher resolution can be obtained physically by reducing the microlens diameter (and corresponding sensor pitch) and increasing the number of micro-lenses in the array or by increasing the sensor size to allow more micro-lenses of the same diameter. Either approach has tradeoffs – the former runs into diffraction limits and sensor noise issues; the latter makes the system larger and more expensive.

Resolution can also be increased algorithmically by using advanced super-resolution algorithms, but these provide limited improvements with the simple plenoptic architecture that is commonly used. A different architecture, sometimes called "focused plenoptic,"[12] that moves the MLA out of the focal plane of the main lens, thereby spreading rays from each object into adjacent superpixels, enables the use of super-resolution algorithms to provide significantly higher resolution, but at the cost of reduced angular resolution and additional complexity.

Figure 2 shows some prominent examples of light-field imaging systems currently being used in various vertical applications. We can expect a lot more systems to join this list in future.

Light-Field Displays

Light-field displays offer the promise of displaying realistic three-dimensional content in a way that appears natural to the human visual system. By applying the Turing test to displays, the ultimate goal would be a display that looks like a window through which the real world is visible. If a light field represents the radiance in a real scene that is visible to the human eye, then a display that provides a light field should create the same sensation and satisfy a Turing-like test. The display should provide the same type of depth cues that the human visual system gets from the real world. Most of these cues are monocular, falling into the categories of geometry, color, and focus, and are satisfied by properly captured or synthesized 2D images and video.

The two major binocular cues are vergence and retinal disparity. These can be provided by simple stereoscopic 3D systems that use single or dual 2D screens to show left- and right-eye images that are appropriately shifted according to their desired depth placement. But a fundamental, and now well known, problem occurs because of the coupling between the binocular cue of vergence (the two eyes rotating appropriately to make their lines of sight intersect at the 3D point at which the viewed object is placed) and the monocular cue of accommodation (the lens of each eye adjusting to focus on the same 3D point). This strong coupling is broken by the unnatural presentation of 3D content on a single display plane. Studies by researchers such as Banks et al.[13] have shown the significant discomfort and viewing problems caused by this cue conflict.

In order to offer natural viewing of 3D content, light-field displays can be used to create an accommodation response that is consistent with the vergence cues. Fundamentally, there are two ways of doing this: (i) the integral-imaging approach – creating parallax across each eye that produces the correct retinal blur corresponding to the 3D location of the object being viewed – by presenting multiple views per eye and (ii) multi-focal-plane approach – physically placing the object at the appropriate focal plane corresponding to its 3D location – by providing multiple focal planes. All real light-field displays use one of these two approaches.

The integral-imaging approach is the reverse path of the light-field imaging architectures we saw in Fig. 3 in the previous section. The same analogy of the array of cameras with each having its own sensor versus the array of micro-lenses sharing a single sensor applies here (but with light going in the reverse direction) – with the display equivalent of the former being an array of projectors or microdisplays and of the latter being a display with an array of micro-lenses on top of it. In either case, a natural accommodation response is created by providing correct retinal blur. Super multi-view (SMV) displays aim to provide a natural focus

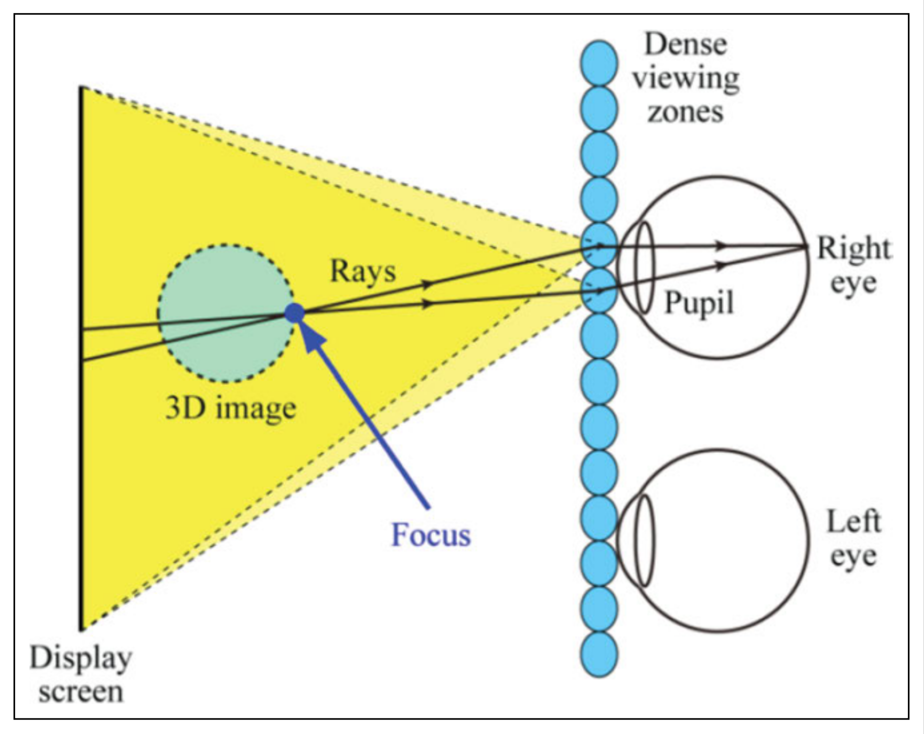


Fig. 7: Shown is a basic system model for a Super-Multi-View (SMV) display.[15]

cue by providing at least two views to each eye. The rationale for two views being sufficient is based on the simple trigonometric construction shown in Fig. 7 developed by Takaki *et al.*[14,15]

However, it is not clear how sensitive this two-view minimum is to viewing distance or whether it creates retinal blur that can provide appropriate size and distance cues. It is likely that a larger number of views per eye are needed and the true minimum number that provides natural retinal blur is not known yet, although there has been some work in modeling of parallax-barrier-based light-field displays[16] that suggests how a theoretical foundation could be developed to answer this question. There is a clear need for further user studies on this topic.

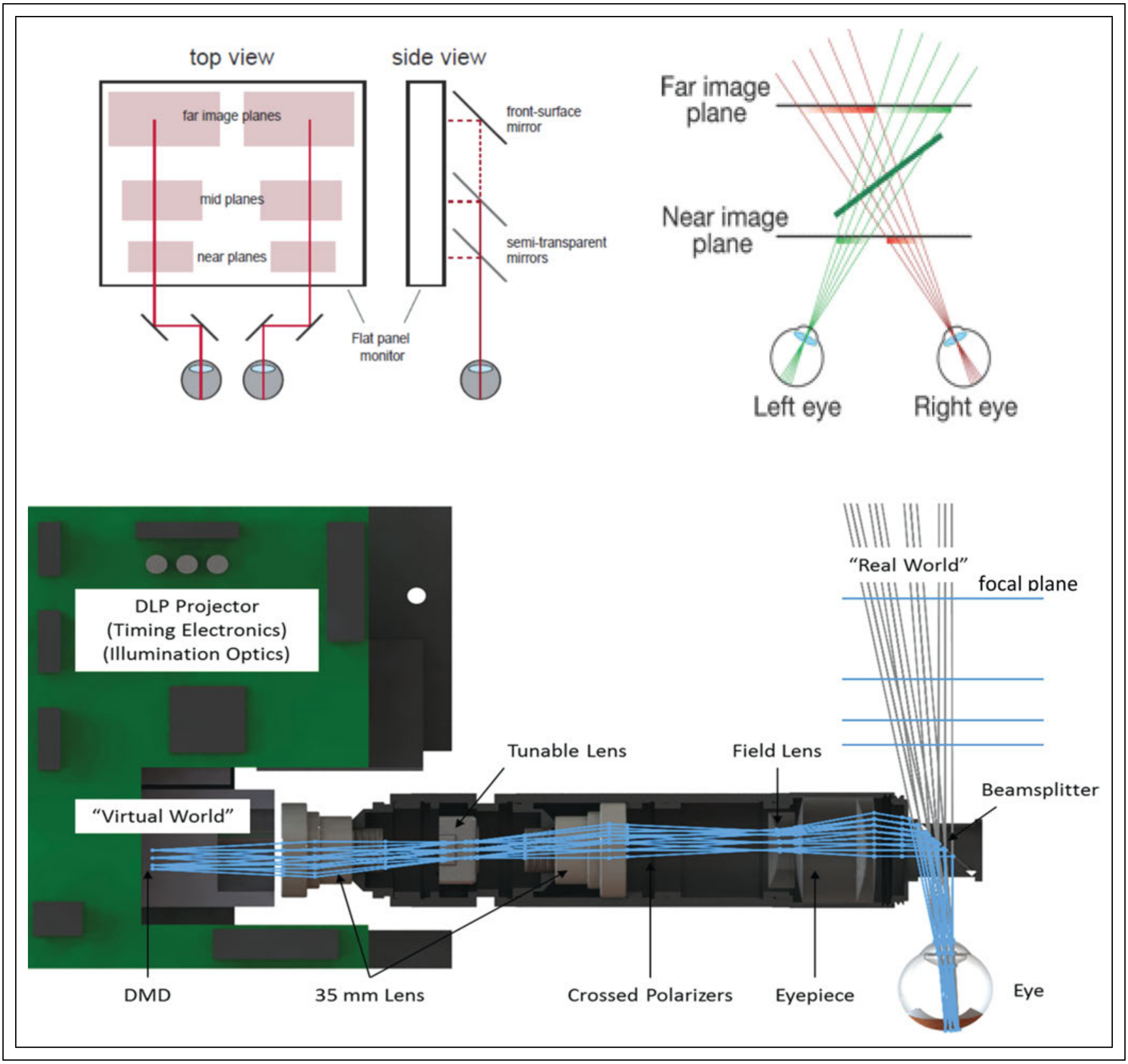
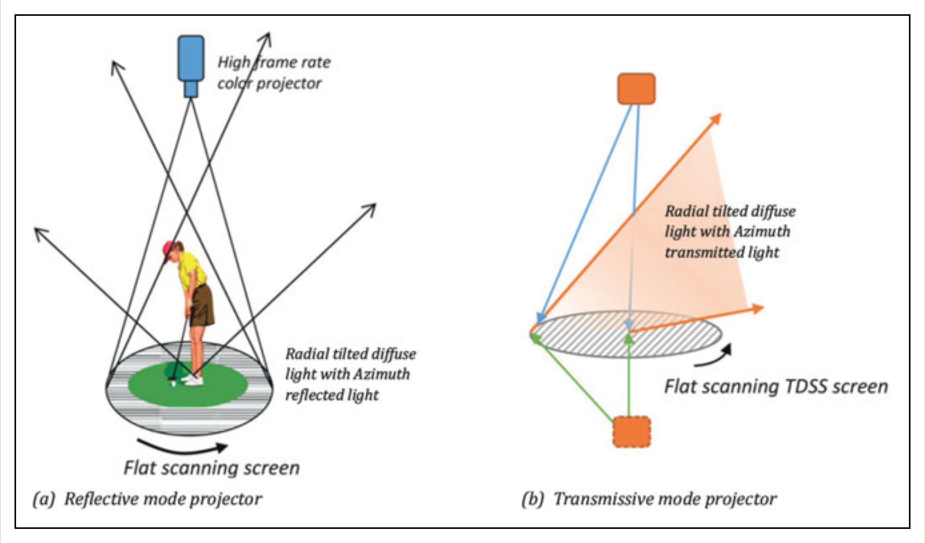


Fig. 8: *The multi-focal display systems shown above use spatial multiplexing (top left)*[13] *and temporal multiplexing (bottom image shows one eye; system is duplicated for two eyes).*[19] *Depth-weighted interpolation is used to produce a perception of continuous depth across the discrete planes (top right).*

The multi-focal-plane approach is a practical approximation of a light-field display that only works for a single viewpoint at a time. Spatial or temporal multiplexing can be used to create multiple focal planes that place objects at appropriate distances to be consistent with vergence. Akeley[17] built a three-plane system using spatial multiplexing of a single high-resolution display and demonstrated that it could provide consistent vergence and accommodation cues that enabled comfortable viewing of 3D content. He showed that depth-weighted linear interpolation could be used to place objects in between the display planes, and his work suggests that 16 or fewer planes might be sufficient to provide an appearance of continuous depth. Schowengerdt *et al.,*[18] Llull *et al.,*[19] and others have used temporal multiplexing instead to produce the effect of multiple planes. Figure 8 shows the spatial and temporal approaches used by Akeley and Llull *et al.*, respectively, and the linear interpolation used to provide continuous depth in between the planes.

More sophisticated and higher-performing depth-value generation approaches based on non-linear optimization of functions that consider the content and the visual system response have been developed recently.[20–22] As is often the case, there is a tradeoff between image quality and computational requirements.



(a) Reflective mode projector (b) Transmissive mode projector

Fig. 9: *This group light-field display uses the scanning type of approach with a high-frame-rate projector – using reflective diffuser screen (left) or transmissive diffuser screen (right)*[23] *(Information Display, Nov/Dec 2014).*

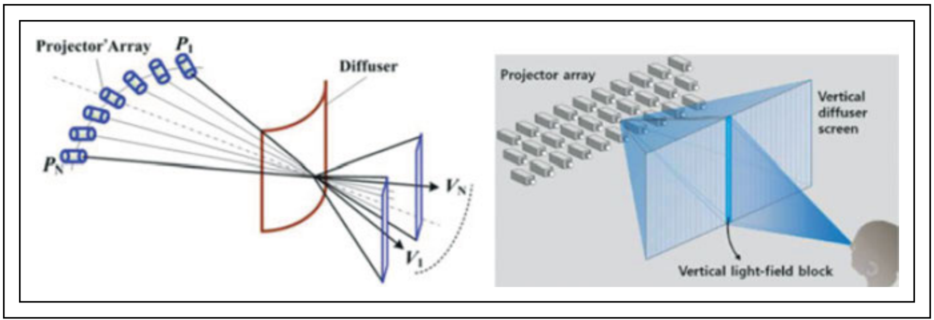


Fig. 10: *This group light-field display uses a multi-projector array approach with a vertical diffuser screen that provides horizontal parallax only.*[23] *(Information Display, Nov/Dec 2014.)*

Light-field displays can be divided into two different types based on fundamentally different use cases: group/multi-user displays and personal (near-to-eye/head-mounted) displays. Group displays are discussed briefly in this paper, while head-mounted displays for VR and AR are the subject of the article by Hong Hua that also appears in this issue.

Three major types of group/multi-user displays include scanning, multi-projector, and multi-layer. The first two are discussed in detail in Liu's overview paper,[23] and the third is discussed in articles such as one by Wetzstein[24] published in 2015.

The scanning type of group light-field displays uses a very high-frame-rate projector (usually DLP) with a rotating directional diffuser screen that could be transmissive or reflective (see Fig. 9).

Multi-projector systems use a tightly packed 2D array of projectors and a vertical diffuser screen to provide a light field with horizontal parallax (see Fig. 10).[23]

Multi-layer displays comprise a stack of programmable light modulators and refractive optical elements. The concept started over a century ago with the use of parallax barriers (Ives 1901) and lenslets (Lipmann 1908) and has expanded to the concept of an active stack using spatially and temporally modulated LCD panels and possibly a directional backlight based on a lenslet array (see Fig. 11).

In our opinion, because of the significant tradeoffs and system costs, group/multi-user light-field displays are likely to be focused on specific narrow vertical market applications such as museums, simulators, and high-end demo and conference rooms for the next several years and mainstream consumer usage (as replacements for TVs) will not occur before 2020. However, it is possible that high-resolution autostereoscopic TVs using Super-Multi-View could be marketed as "Light Field TVs," similar to the way LCD TVs with LED backlights have been marketed as "LED TVs."

On the other hand, single-user (personal) displays mounted on one's head significantly reduce the system requirements because they only need to present a high-quality viewpoint to one user. This reduction allows for practical architectures such as a multi-focal-plane[21] and dual-stack compressive[16] to be used for AR and VR, respectively. Such displays used for augmented or virtual reality can provide many types of compelling user experiences and are likely to see adoption in vertical mar-

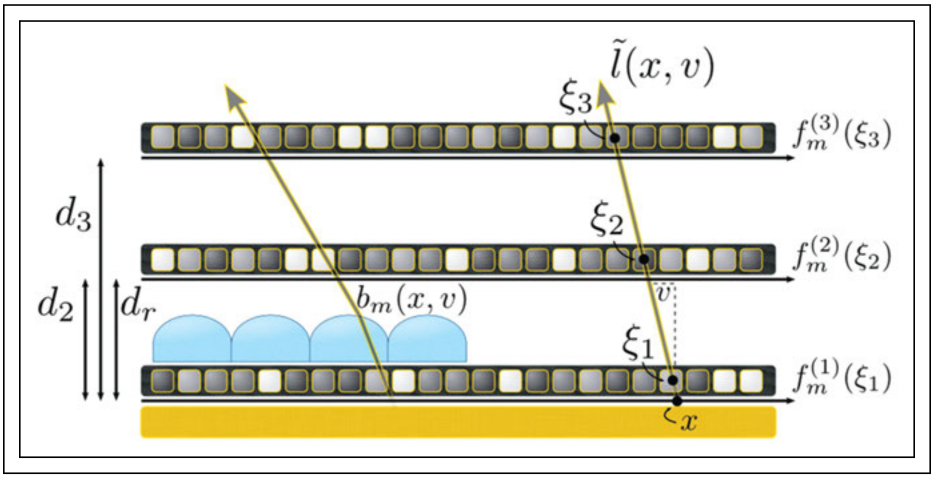


***Fig. 11:** This group light-field display uses a multi-layer approach – a compressive display employing a stack of LCD panels with directional (left side) or regular backlight.[25] A directional backlight is created by using a lenticular lens array on top of the bottom LCD panel, as shown on the left side of the figure.*

ket applications and broader consumer segments such as entertainment, gaming, and education within the next 5 years.[24,27] Since the quality of user experience will be of paramount importance in the successful and widespread adoption of these systems, light-field displays are likely to play a major role. For this reason, the next article in this issue, written by Hong Hua, is focused on recent advances in light-field displays for VR and AR HMDs.

Acknowledgments

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Advances in Head-Mounted Light-Field Displays for Virtual and Augmented Reality

Head-mounted light-field displays render a true 3D scene by sampling either the projections of the 3D scene at different depths or the directions of the light rays apparently emitted by the 3D scene and viewed from different eye positions. Head-mounted light-field displays are capable of rendering correct or nearly correct focus cues and addressing the well-known vergence–accommodation mismatch problems of conventional virtual- and augmented-reality displays.

by Hong Hua

HEAD-MOUNTED DISPLAYS (HMDs) have drawn significant interest in recent years for a broad range of consumer applications.[1,2] For instance, a lightweight optical see-through head-mounted display (OST-HMD), which enables optical superposition of two-dimensional (2D) or three-dimensional (3D) digital information onto a user's direct view of the physical world and maintains see-through vision to the real world, is one of the key enabling technologies for augmented-reality (AR) applications. HMDs are viewed as a transformative technology, enabling new ways of accessing and perceiving digital information essential to our daily lives. In recent years, significant advancements have been made toward the development of unobtrusive AR displays that integrate the functions of OST-HMDs, smart phones, and various mobile computing functions. A few commercial AR displays have demonstrated very compact and lightweight form factors with the potential of widespread public use. For instance, Google Glass[3] is a very compact lightweight monocular display that provides encumbrance-free instant access to digital information, while the Epson Moverio[4] and Microsoft Hololens[5] are binocular displays providing the benefits of stereoscopic viewing. On the virtual-reality (VR) side, several immersive HMD products are commercially deployed or close to commercial launch.

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Despite tremendous progress, minimizing visual discomfort involved in wearing HMDs remains an unsolved challenge. Most existing HMDs utilize 2D flat-image sources located at a fixed distance from the eye, and thus lack the ability to render correct focus cues (including accommodation and retinal image blurring effects) for digital information. The resulting well-known vergence–accommodation conflict (VAC) problem in both VR and AR systems is considered a key contributing factor to visual discomfort. Many studies have investigated the artifacts of the incorrectly rendered focus cues in conventional stereoscopic 3D displays.[6–9] Incorrect focus cues may contribute to the two commonly recognized issues: distorted depth perception and visual discomfort, including diplopic vision, visual fatigue, and degradation in oculomotor response.

Several methods have been explored in HMD designs to address the VAC problem and approximate the visual effects created by focus cues when viewing a real-world scene. Examples include a vari-focal-plane display that dynamically compensates the focal distance of a single-plane display based on a viewer's fixation point,[10,11] a multi-focal-plane (MFP) display method that creates a stack of focal planes in space- or time-multiplexing fashion,[12-17] a micro-integral imaging

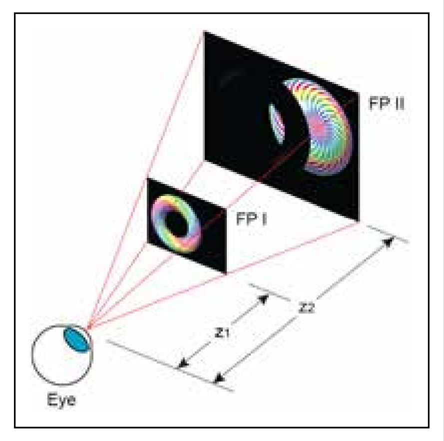

***Fig. 1:** This schematic shows the multi-focal-plane display method.*

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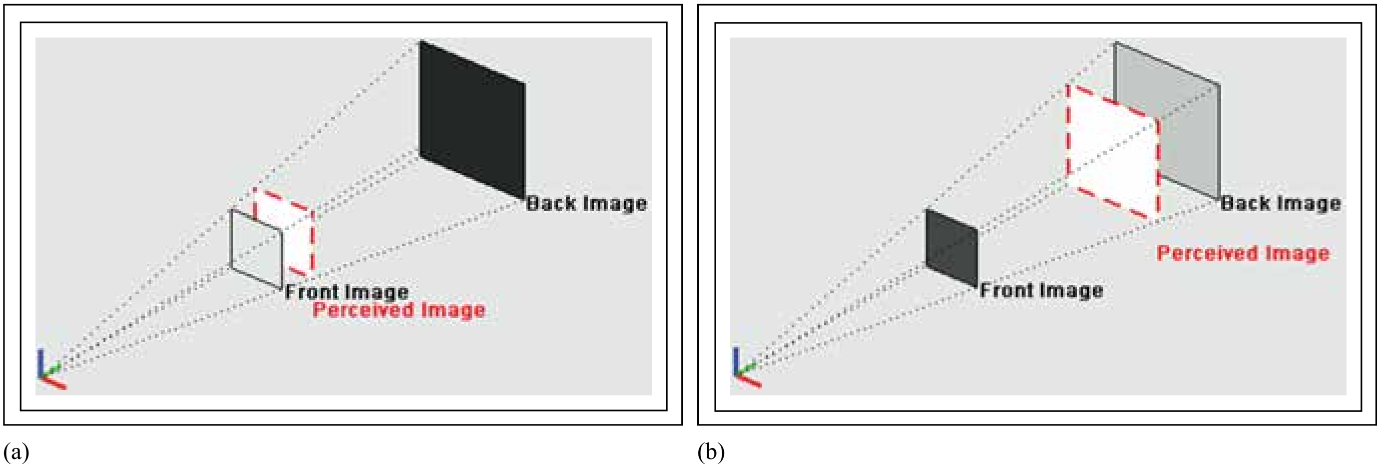
(micro-InI) method that reconstructs the full-parallax light fields of a 3D scene through pinhole or lenslet array[18,19] and a multi-layer method, which utilizes multi-layers of spatial light modulators (SLMs) to modulate a uniform backlight and render apparently directional light rays.[20,21] To some extent, these methods are able to overcome the VAC problem with different levels of limitations. In this article, we focus on reviewing recent advancements of head-mounted light-field displays for VR and AR applications, which incorporate some of these methods.

Multi-Focal-Plane Approach toward Head-Mounted Light-Field Displays

A multi-focal-plane (MFP) display creates a stack of discrete focal planes dividing an extended 3D scene volume into multiple zones along the visual axis, each of which only renders 3D objects nearby.[12–17] Figure 1 shows a schematic diagram of a dual-focal-plane example. An MFP-based display may be implemented either by spatially multiplexing a stack of 2D displays[12,13] or by fast switching the focal distance of a single 2D display sequentially using a high-speed vari-focal element (VFE) in synchronization with the frame rendering of multi-focal images.[14–17] For instance, Akeley *et al*. demonstrated a proof-of-concept bench prototype of a three-focal-plane display covering a fixed depth range from 0.311 to 0.536 m by dividing a flat-panel display into three focal planes through three beamsplitters placed at different distances from the viewer. McQuaide *et al*. demonstrated a dual-focal-plane retinal scanning display in which a 2D image is generated on a pixel-by-pixel basis by raster scanning a laser beam. The focus of the laser beam is varied through the use of a deformable membrane mirror device (DMMD), and the focus cues can be adjusted at every pixel if the DMMD operates at a high enough speed.[14] More recently, Schowengerdt *et al.* suggested a spatial-multiplexing retinal scanning display by replacing a single fiber source with a fiber array to produce a multi-focal bundle of beams.[22] By using a liquid lens as the VFE and an OLED microdisplay as the image source, Liu and Hua demonstrated the first prototype of a dual-focal-plane optical see-through AR display, which maintains a non-obstructive see-through view to the real world.[15] Love *et al*. demonstrated a prototype with four fixed focal planes generated through birefringent lenses as the VFEs and high-refresh-rate CRTs as the image sources.[16] Wu *et al*. recently demonstrated an MFP prototype by exploring dynamically variable planes adapted from contents.[23]

In these conventional MFP display methods, a large number of focal planes and small dioptric spacing are desirable for achieving accurate focus cues. It was suggested that the dioptric spacing between adjacent focal planes should be 1/7 diopters to achieve 1 arc-minute spatial resolution.[12] At this spacing, 28 focal planes are needed to cover the depth range from infinity to 4 diopters. A depth-fused 3D (DFD) multi-focal plane (DFD-MFP) display method was proposed (Fig. 2), through which the number of necessary focal planes is effectively reduced to an affordable level.[17,24–29] Liu and Hua,[17] Hu and Hua,[25] and Hu[26] presented a framework for a DFD-MFP system design in which the focal-plane spacing and the fusion functions are optimized to maximize the contrast magnitude and gradient of the retinal image fused by the two images overlapping along the visual axis. This framework avoids a conflict of focusing cues and creates a smooth contrast gradient that helps to stimulate and stabilize the eye accommodation response.

Figure 3 shows the optical layout of a monocular OST-HMD system based on the DFD-MFP method.[27] Each monocular setup consists of two parts: the composite optical see-though eyepiece and the image-generation subsystem (IGS). The composite eyepiece [Fig. 3(a)] consists of a wedge-shaped freeform eyepiece, a free-form see-through compensator lens, and a cylindrical lens.[27] The IGS [Fig. 3(b)] achieves the core function of generating the multi-focal-plane contents. It consists of a 0.7-in. high-speed digital-mirror-device (DMD) microdisplay, a deformable membrane mirror device (DMMD), and relay lens groups. The DMD display, illuminated by an RGB LED light source (not shown), is first magnified by two field lenses and then relayed by a double-pass double-telecentric lens group, forming an intermediate image between the IGS and the eyepiece. By changing



(a) (b)

Fig. 2: In this schematic model of a DFD-MFP display, the luminance ratio between the front and back images is modulated to change the perceived depth of the fused image to be near to the front image plane (a) and near the back image (b).

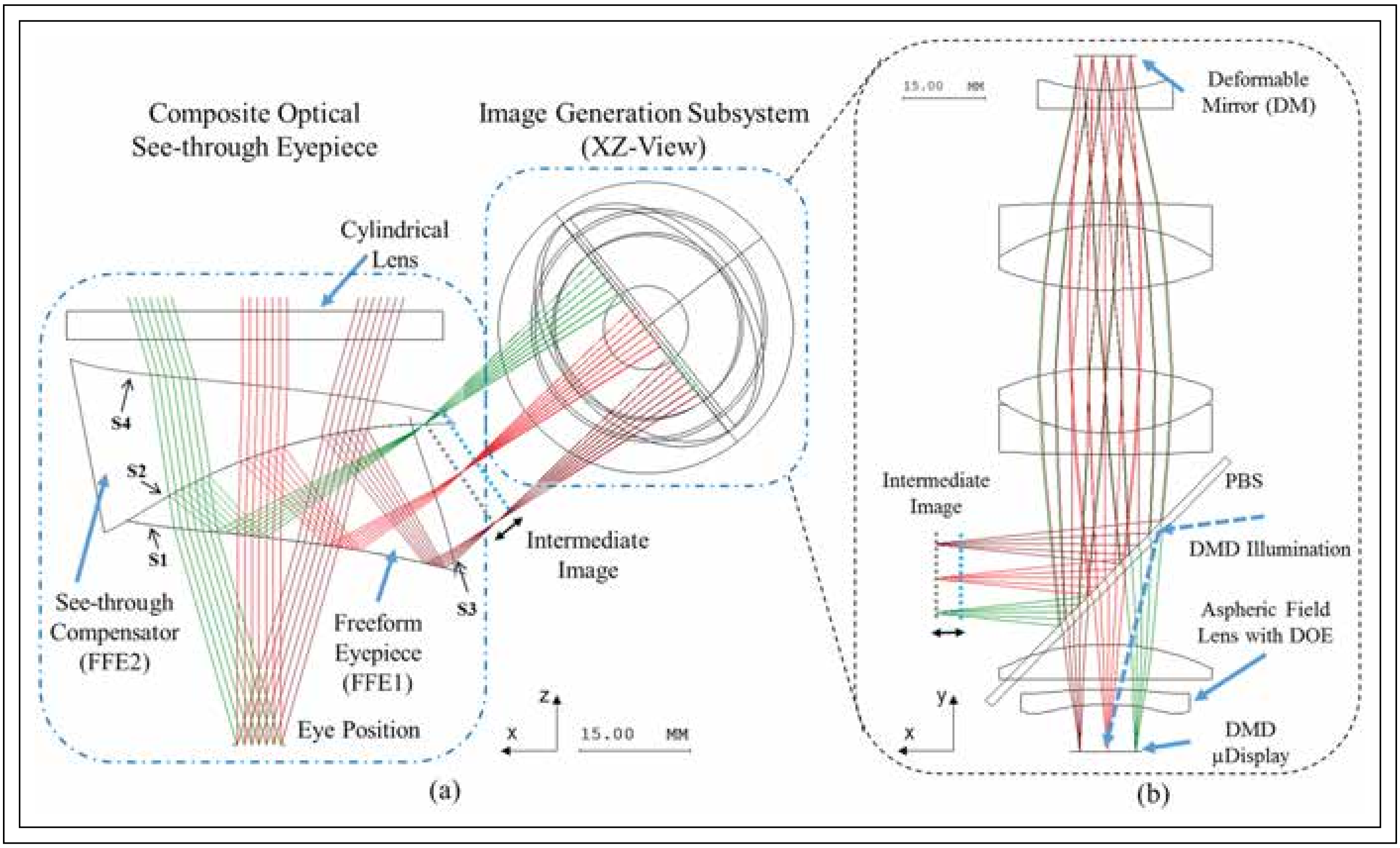


Fig. 3: (a) A top-view optical layout of the right-eye module of a DFD-MFP system includes (b) a detailed layout of the image-generation subsystem.[27]

the optical power of the DMMD, the intermediate image shifts axially with respect to the eyepiece without magnification change, while the accommodation cue of the HMD is varied from far to close. The optical power of the DMMD can change at a speed as fast as 1 kHz; thus, virtual images at multiple focal distances can be multiplexed by rapidly changing the optical power of the DMMD.

Figure 4(a) shows the actual setup built on an optical bench.[27] Figures 4(b) and 4(c) show photos of a 3D scene rendered by the virtual display and captured with a camera placed at the exit pupil position.[27] Six focal planes were dynamically formed at 3.0, 2.4, 1.8, 1.2, 0.6, and 0.0 diopters, respectively, at an overall refresh rate of 60 Hz. The 3D scene consists of a green floor grid extending from 3.0 to 0.6 diopters, a green wall grid at 0.6 diopters having a University of Arizona logo on it, and a grating target extending from 3.0 to 0.6 diopters, as well as a College of Optical Sciences logo placed at the 3.0 diopter end. Each focal plane displays a different part of the 3D scene. By incorporating non-linear depth-fusing functions,[25] this 3D scene was rendered continuously by five of the focal planes. Figure 4(b) shows the image with the camera focusing at a 3-diopter distance (near), and Fig. 4(c) shows the image focusing at a 0.6-diopter distance (far). Natural focus cues were clearly demonstrated, and high-contrast targets were correctly fused across focal planes, which visually validated the depth-fusion display method. The optical see-through path of the prototype also achieved superb performance.

Overall, the prototype adequately demonstrated the capability of the DFD-MFP display method for rendering nearly correct focus cues, with the potential for addressing the VAC. However, the technology suffers from several critical technical obstacles to becoming a viable solution for truly wearable light-field AR displays. The first major obstacle is miniaturization of the technology. Due to the limitations of several enabling technologies, including the high-speed displays and vari-focal element, the current prototype was implemented in the form of a bench prototype, occupying a volume of nearly 500 × 300 × 100 mm. The second major obstacle is real-time rendering and display. The prototype is limited by the current capabilities of high-speed display technology and display–computer interfaces and is unable to render and display six or more frames of high-resolution full-color images at a speed several times faster than a standard single-frame display. Transforming this display method into a compact wearable solution requires several technical innovations.

Integral-Imaging (InI) Based Head-Mounted Light-Field Displays

Instead of creating a stack of focal planes to sample the depth volume, an integral-imaging (InI) based display method reconstructs the full-parallax light fields of a 3D scene by densely sampling the different directions of

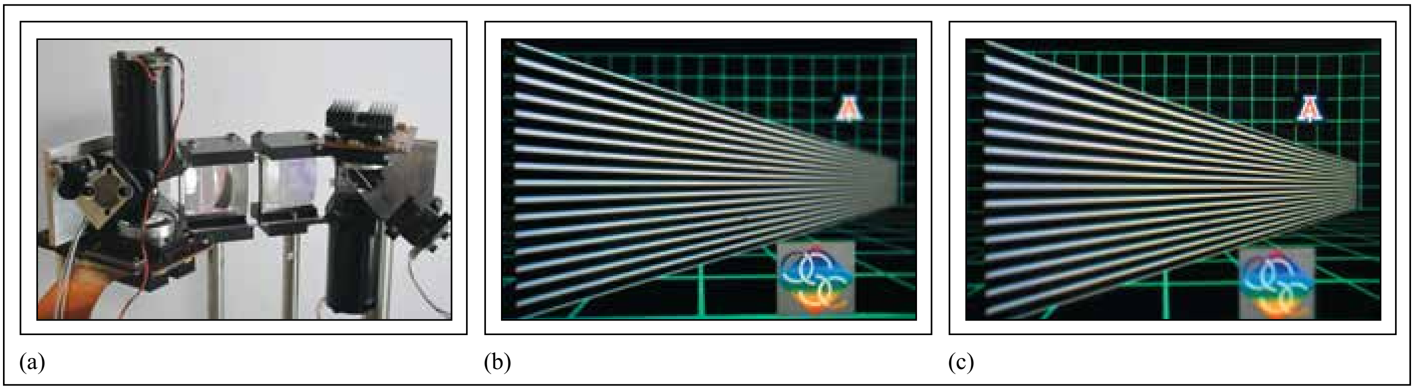


***Fig. 4:** A multi-focal-plane prototype system with freeform eyepiece (a) is shown with an example of 3D images rendered by the prototype for a camera at near focus (b) and at far focus (c).*[27]

the light rays apparently emitted by a 3D scene.[30] A simple InI display typically consists of a display panel and a microlens array (MLA). The display renders a set of 2D elemental images, each of which represents a different perspective of a 3D scene. The MLA creates the perception of a 3D scene that appears to emit light and occupy 3D space, through the intersection of the ray bundles emitted by the corresponding pixels in the elemental images. The InI-based display allows the reconstruction of a 3D shape with full-parallax information in both horizontal and vertical directions. The simple optical architecture of InI makes it attractive to integrate with an HMD optical system to create a wearable true 3D display.

Lanman *et al.* demonstrated a non-see-through light-field display by directly placing an MLA and an OLED microdisplay in front of the eyes to render the light field of a 3D scene for VR applications.[19] The prototype system, shown in Fig. 5, had a field of view of about 29° × 16° and a spatial resolution of 146 × 78 pixels. Hong *et al.* demonstrated a prototype of an integral floating display system using a convex half-mirror as the eyepiece.[31] The prototype system, however, had only a few degrees of FOV and did not demonstrate a useful see-through capability in a wearable device.

Hua and Javidi demonstrated the first practical implementation of an OST-HMD design that integrated a microscopic InI (micro-InI) method for full-parallax 3D scene visualization with free-form optical technology for OST-HMD eyepiece optics.[18] This approach enabled a compact 3D OST-HMD (InI-OST-HMD) with full-parallax light-field rendering

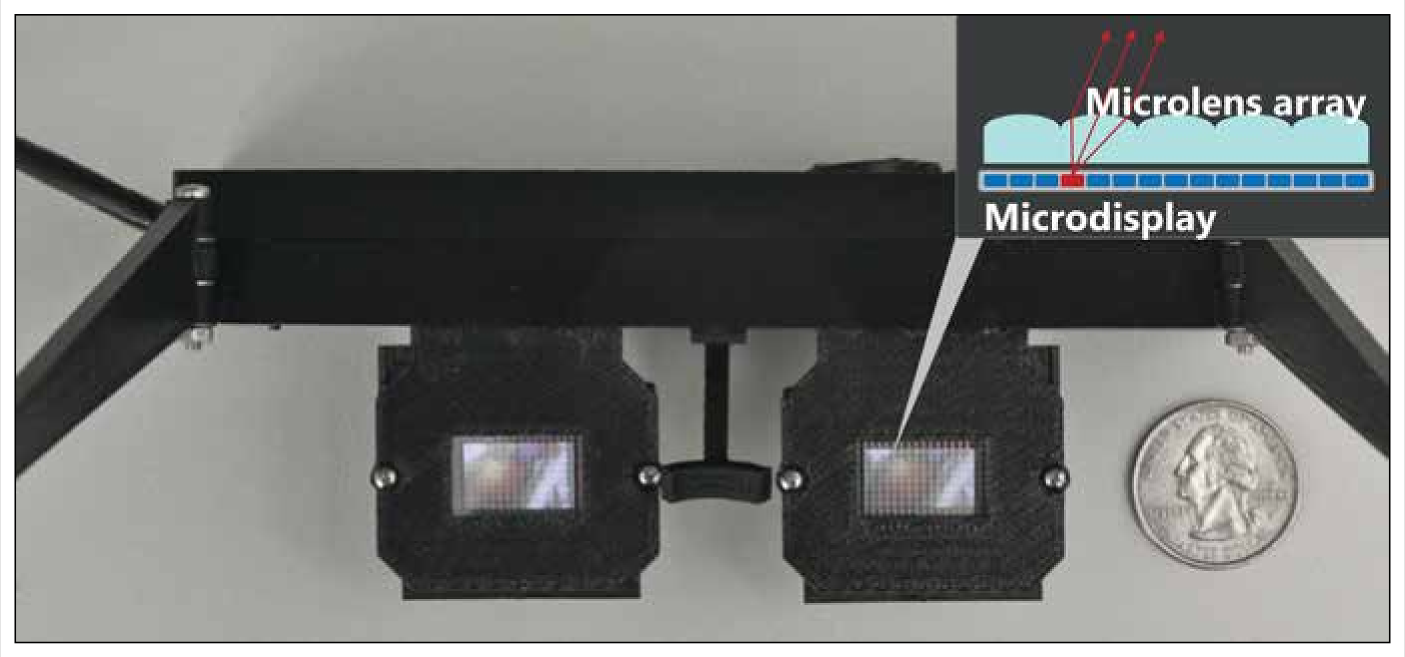


***Fig. 5:** This non-see-through head-mounted near-to-eye light-field-display prototype was demonstrated by Lanman in 2013.*[19]

capability. Figure 6(a) shows the schematic optical layout. The optics consist of a micro-InI unit, a wedge-shaped freeform eyepiece,[32] and a see-through freeform corrector lens. The micro-InI unit, consisting of a high-resolution microdisplay and an MLA, reproduces the full-parallax light fields of a 3D scene. which replaces a conventional 2D microdisplay as the image source. The freeform eyepiece optics directly relays the reconstructed 3D light fields into a viewer's eye for viewing, and the see-through lens cemented with the free-form prism optically enables non-obtrusive viewing of the real-world scene.

A prototype was demonstrated by utilizing a 0.8-in. OLED, an MLA with a 3.3-mm focal length and 0.985-mm pitch, a wedge-shaped freeform eyepiece with an equivalent focal length of 28 mm, and a see-through compensator. The gap between the microdisplay and MLA was about 4.3 mm, and the reference plane of the micro-InI unit was approximately 10 mm away from the MLA. After being magnified by the eyepiece, the virtual reference plane of the reconstructed 3D scene in the visual space was approximately 1 diopter away from the exit pupil of the eyepiece. An array of 12 × 11 elemental images was simulated, each of which consists of 102 × 102 color pixels. The FOV of the reconstructed 3D scene by the eyepiece was about 33.4° diagonally. The spatial resolution of the reconstructed 3D scene by the micro-InI unit was about 22.4 µm on the reference plane, which yielded an angular resolution of 2.7 arc-minutes on the virtual reference plane in the visual space.

Figures 6(b) and 6(c) show two views captured by a digital camera focusing at 0.25 diopters and 3 diopters, respectively. In the see-through view, two physical references, a Snellen eye chart and a resolution grating, were placed at a distance of 0.25 and 3 diopters, respectively, from the camera. In the virtual view, three columns of the letter "E" were rendered at a distance of 0.25, 1, and 3 diopters, respectively. The letters on the bottom, which were half the size of the letters on the top row, were about the same size as the largest letter on the Snellen chart, with a similar stroke width or gap. The gap or stroke of the largest letter on the Snellen chart represented an angular resolution of 15 minutes of arc at the distance of 4 m.

The results clearly demonstrate that an InI-based HMD method can produce correct focus cues and true 3D viewing in a large depth range. On the other hand, artifacts are visible in these images. Just like the InI-based autostereoscopic method for eyewear-free displays, the InI-HMD method is subject to the limitations of low lateral and longitudinal resolutions, shallow depth of field, narrow viewing angle, crosstalk due to the limited imaging capability and finite aperture of the MLAs, poor spatial resolution of the displays, and a trade-off relationship between wide viewing angle and high lateral and longitudinal resolutions. Further technological innovations are needed to improve the optical performance.

Computational Multi-Layer Light-Field Displays

Unlike the additive multi-focal-plane approach to light-field rendering, Wetzstein *et al.* described a multiplicative light-field-display technique utilizing a stack of time-multiplexed light-attenuating layers illuminated by either a uniform or directional backlight for autostereoscopic displays.[21] The modulation pattern of each layer was optimized to produce images for a desired viewing zone. Maimone *et al*. demonstrated the feasibility of stimulating correct eye accommodation by synthesizing dense samples of the light fields over the eye pupil.[33]

Maimone and Fuchs applied the multilayer computational light-field-display technique to HMDs and demonstrated a computational multilayer AR display.[20] A stack of transparent SLMs, a thin transparent backlight, and a high-speed shutter were sandwiched with a small spacing between the SLM layers. Figure 7(a) shows a schematic layout and Fig. 7(b) shows a prototype implementation. The sandwiched stack is placed directly in front of the eye, without any other focusing optics placed in between the display stack and the eye. The device operates in two modes: augmented image-rendering mode (shutter off) and the occluded real-world image-formation mode (shutter on). In the augmented view mode, the real-world view is blocked and a set of optimized patterns are rendered on the SLM layers to attenuate the light rays from the backlight and produce the final color of the rays entering the eye, which is the product of the attenuation values assigned to each of the intersected pixels across the layers. By reproducing a set of rays with adequate angular resolution over the eye pupil that appear to be emitted from a virtual object at an apparent location far from the device stack, the display is able to reconstruct the light field of a 3D virtual object and potentially provide correct focus cues. In the real-world image-formation mode, the backlight is turned off

(a) (b) (c)

Fig. 6: An optical see-through head-mounted near-to-eye light-field-display prototype uses free-form optical technology. Shown from left to right are a schematic layout (a) and a photograph captured with a camera focusing at 0.25 diopters (b) and at 3 diopters (c).[18]

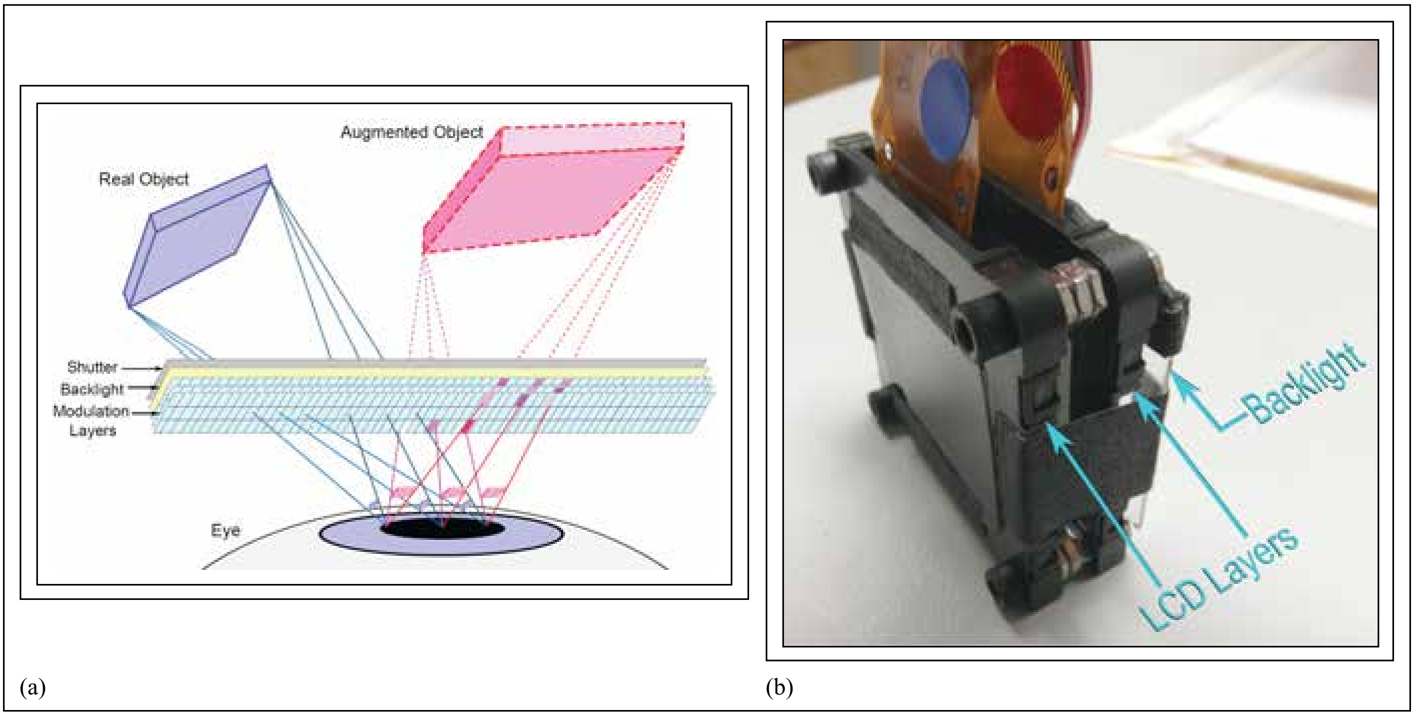


Fig. 7: A computational multi-layer optical see-through light-field display: (a) a schematic layout and (b) prototype implementation.[20]

and the shutter is turned off. Occlusion masks can be displayed on the SLM layers to allow selective transmission of the real-world rays, enabling mutual occlusion between virtual and real-world scenes.

Due to the close proximity of the SLM stack to the eye, this method could potentially achieve a compact OST-HMD with a wide FOV. Because of the light field's rendering nature, it can also potentially render correct focus cues and mutual occlusion capabilities. The researchers' early prototype demonstrated these capabilities to some extent. On the other hand, the limitations of this approach are also obvious and require significant innovations to enable improvements. For instance, both the rendered augmented views, although recognizable, suffer dramatic resolution loss due to diffraction effects through the SLM stack. The see-through view of the real world is blurry and low in contrast due to the diffraction effects of the SLMs as well as the partial transparency of the backlight. The technique is computationally intensive, which requires significant effort to reduce the optimization time to enable real-time use for AR displays. Finally, the prototype also suffers

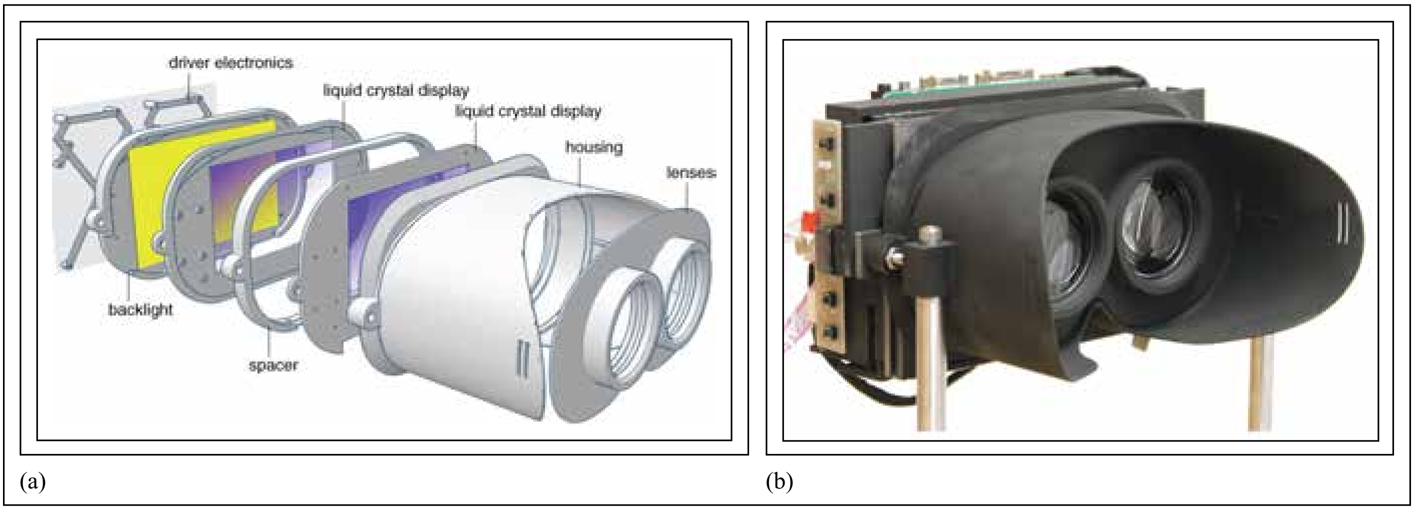


Fig. 8: A computational multi-layer light-field stereoscope appears in (a) the schematic layout and (b) prototype implementation.[34]

from high light loss due to the low transmittance of the SLM stack.

More recently, Wetzstein *et al.* extended their multi-layer factored light-field autostereoscopic display method and demonstrated a light-field stereoscope for immersive VR applications.[34] The schematic layout and the prototype implementation are shown in Figs. 8(a) and 8(b), respectively. The prototype consists of two stacked LCD panels with a gap of 53 cm in between and a pair of simple magnifier lenses with a focal length of 5 cm for each eye. Modulation patterns are computed using a rank-1 light-field factorization process to synthesize and render the light field of a 3D scene. Although their preliminary demonstration is promising, this approach is subject to a diffraction limit due to the fact that the virtual image pattern on the rear display panel is observed through the front panel.

Commercial Light-Field HMDs Are Still in the Future

Clearly, as outlined in this article, recent progress has been made in the development of head-mounted light-field displays for augmented- and virtual-reality applications. Despite the tremendous progress in past decades, all of the existing technical approaches are subject to different tradeoffs and limitations. The MFP display method is capable of rendering correct focus cues for a 3D scene across a large depth volume at high spatial resolution comparable to conventional non-light-field HMD methods, but it has to overcome several critical obstacles to become a compact wearable-display solution. The micro-InI-based light-field-display approach is able to render correct focus cues for a large depth volume, but its optical performances, including spatial resolution, depth of field, longitudinal resolution, and angular resolution, are relatively low compared to the MFP approach. The computational multi-layer approach is still in its preliminary development stage and requires significant innovations to overcome some fundamental limitations such as diffraction artifacts.

We still have a long way to go to engineer head-mounted displays with compact and portable form factors and high optical performance. However, based on the recent pace of development, I am confident that substantial progress and breakthroughs will be made over the next 5 years, making possible the commercial launch of head-mounted light-field displays for consumer applications.

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One Day, Sixteen Speakers, Innumerable Insights

The Bay Area chapter of SID recently brought together 16 experts for a fascinating, far-ranging look at issues that are shaping the display industry.

by Jenny Donelan, Sri Peruvemba, Paul Semenza, and John Wager

WE all know we should devote more time to learning about our industry, but the day-to-day demands of our jobs make it difficult to focus outside our respective academic or industrial silos. The SID Bay Area chapter (BA-SID), in collaboration with sponsor Honeywell, recently addressed this "education gap" with a fast-paced (16 speakers in 9 hours), one-day (March 24, 2016) conference designed to shed light on a wide range of technical and non-technical topics related to the display industry. These included the expected – OLEDs, QLEDs, and e-Paper – and the less expected – microdisplays and the brain, display data management, and changes in traditional environments for innovation.

"The thing I really liked about the conference is that it exposed me to such a wide variety of things I don't normally think much about," said Oregon State University's John Wager, who gave a presentation about backplanes. "I tend to stay in my very narrow field of specialized focus." The diversity of topics, including history, technology, markets, manufacturing, aerospace, business trends, data management, systems, and products, made it different from the ultra-specialized sessions he usually attends, added Wager.

For example: "I thought the Dolby presentation was amazing," he said. "Dolby does something other than sound. Who knew? The MIT Media Lab embedded interactivity was completely new to me and very interesting. And the resonant-frequency presentation [haptics] demonstrated to me that very clever and useful things can be accomplished using very simple ideas."

Market analyst Paul Semenza, who delivered the afternoon keynote, said, "The Bay Area SID conference provided examples of companies pursuing approaches that are aimed at differentiation and efficient production." These approaches are going to become increasingly important, he explained, as the hyper-competitive flat-panel-display industry continues to be dominated by increasingly high performance but otherwise undifferentiated products.

One example of this type of targeted approach came from speaker John Ho of QD Vision, who described the implications of the Rec.2020 standard for display development. While pixel densities are reaching the limits

Inventor Frederic Kahn, who has worked many years in the display business, explained how LCDs began fundamentally changing the display industry in the late 1960s.

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of the human visual system, the ability to display colors is relatively limited on most displays, and Rec.2020 specifies a broader color-gamut target than (for example) the NTSC standard.

A second example is flexible displays, a longstanding goal for the display industry. The ongoing development of curved OLED displays for smartphones and wearables represents progress toward this goal. However, these displays generally require the TFTs to be produced on glass substrates and then transferred to plastic because the processing temperature for the silicon devices is too high for plastic. The requirement of glass for TFT fabrication also means that inherently flexible-display technologies such as EPD are generally produced on rigid substrates. But as FlexEnable's Mike Banach described at this conference, his company has been developing organic TFTs that can be produced on plastic. Working with Merck, FlexEnable has been able to demonstrate plastic TFT-LCDs that are not only thinner and lighter than glass-based LCDs, but are flexible to a bend radius of 35 mm. FlexEnable has also demonstrated the ability to drive OLEDs with its organic TFTs.

"The display industry is hyper-competitive and driven by increasingly large investments – as currently exemplified by the multi-billion-dollar sums going into building OLED capacity," said Semenza. Despite the current phenomenon of new technologies being overlooked in favor of standardized TFT-LCD and OLED displays (which have already been heavily invested in), the above examples indicate that the display industry still harbors innovative approaches, he noted.

A Day of Display Technology

Dr. Russ Gruhlke, Chair of the BA-SID; Dr. Sudip Mukhopadhyay, Honeywell Fellow; and Sri Peruvemba, Director of the Bay Area chapter, kicked off the event with a welcome address and an introduction of the speakers. Short descriptions of these speakers and their topics follow:

Morning Keynote: "The Past, Present, and Future of LCDs – The Black Swan Matures and Prospers," *by Dr. Frederic J. Kahn, President, Kahn International.*

Kahn, an inventor, company founder, SID board member, editor, and recipient of some of SID's highest honors, described the Black Swan as a high-impact event that is hard to predict, similar to the LCD in 1967. (Some might also refer to this as disruptive technology.) Kahn traced the history of LCD development along with his own 49 years of experience, which included his invention of the vertically aligned nematic LCD still in use today.

"Flat-Panel Display Backplanes: Past, Present, and a Possible Future Option," *by Dr. John Wager, Chair, School of EECS, Oregon State University.*

Wager discussed a-Si products used in the past, the current crop of a-Si:H LTPS and IGZO technologies, and the possibilities of amorphous-metal non-linear resistors (AMNRs).

"OLED and QLED," *by Professor Poopathy Kathirgamanathan, Chair, Electronic Materials Engineering, Brunel University, UK.*

The focus of Kathirgamanathan's presentation was OLED and QLED devices, as well as the merits of quantum materials in achieving Rec.2020 specifications.

"Avionic Display Systems," *by Dr. Kalluri Sarma, Senior Fellow, Honeywell.*

Cockpit applications have specific display needs. Sarma described the work done by his team on the Boeing 777, the F16 fighter plane, various military and commercial planes, and the space station.

"Challenges and Opportunities in Display Data Management," *by Dr. Wei Xiong, Vice-President, Samsung Display.*

The display interface is highly important, but often overlooked, noted Xiong. While display resolution has increased significantly, panel interfaces have not. Data transmission via wires in the display has not kept up with pixel resolution, and Xiong expects tremendous demand in this area.

"Advances in Video," *by Ajit Ninan," Vice-President, Dolby.*

Humans can see a lot more dynamic range in color and luminance levels than what current displays offer, according to Ninan. We want 200x more brightness and 4000x more contrast. He talked about movie makers' desire to create more accurate renditions of their carefully orchestrated scenes, including more immersive colors and full dynamic range. Work in this area by Dolby has won the company both Emmy and Oscar awards.

"Beyond the Touch Screen: Embedded Interactivity for a Naturally Intelligent Environment," *by Dr. Munehiko Sato, Scientist, MIT Media Lab & University of Tokyo.*

Sato's research team has created interactive surfaces in everyday objects such as door knobs. Using bio impedance, his team has even been able to make plants touch-interactive. The team has built interfaces into chairs that can recognize individual users and accordingly create a custom environment for each occupant.

Afternoon Keynote: "Display Technology and Market Overview," *by Paul Semenza, Director of Commercialization, NextFlex.*

Semenza traced the history of display technologies and offered a panel roadmap, describing the "race to the bottom" with the creation of larger fabs and lower priced products. There has not been any killer app for display consumption since the tablet, and the newer apps in vehicles, wearables, *etc.*, use much less display by area. The industry is in a down cycle and there has been a culling of players and technologies. Hardly any Japanese players remain. Taiwan is not investing domestically; Korea has augmented vertical integration with a China strategy; and China continues to catch up. Materials and equipment companies are profitable, whereas panel makers continue to struggle.

"Haptics; It's All about Resonant Frequency," *by Francois Jeanneau, CEO, Novasentis.*

Jeanneau's talk about haptic technology identified the need for richer interactions. The current crop of products in the market using eccentric rotating mass (ERM) and linear resonant actuator (LRA) technologies leaves a gap in customer expectations. Newer technologies such as electromechanical polymers (EMPs) offer a range of pleasing sensations, are thin as paper, and enable new form factors. One smartphone has replaced some $3K worth of other electronic devices. As the smartphone continues to evolve, will it transform itself to a wearable device by 2020 and what will it look like? What are the enabling technologies?

"The Path to Rec.2020 Displays: Quantum Dots Versus Frickin' Lasers," *by John Ho, Product Marketing Manager, QD Vision.*

Display resolution is increasing, although eventually we will not be able to discern it. But there is lots of room for improvement in color. Lasers can achieve desired color specs but they are not practical – they are cost-prohibitive and susceptible to observer metameric failure (OMF), in which two viewers see the same source of light and perceive different hues. Quantum-dot technology offers the best path to achieving Rec.2020 spec. It is less expensive, and tunable primaries can reduce OMF and are easier to create through leveraging existing LCD fabs. Quantum dots do face challenges, including regulatory barriers due to the use of heavy metals such as cadmium.

"Flex Display Manufacturing," *by Mike Banach, Technical Director, FlexEnable.*

Banach's talk focused on organic-TFT-backplane LCDs (OLCDs), which enable flexible devices. His team has built devices using a number of frontplanes including OLED displays and e-Paper, but he believes that flexible-LCD technology offers a viable path forward through leveraging the existing infrastructure. He cited favorable trends for flexible displays, including the emerging Internet of Things and wearables markets, which are creating a desire for rollable, curved, and foldable devices.

"Flexible Transparent Barrier Films," *by Dr. Ravi Prasad, Chief Technology Officer, Vitriflex.*

Flexible transparent barrier films are being made by a roll-to-roll process for a variety of applications, including displays. Barrier films play a crucial role in the development of newer display technologies, including flexible displays and quantum dots. The goal is to create a film that has glass-like optical properties but is thinner, lighter, and unbreakable. Prasad's team has made great progress in addressing changing market needs through this technology.

"Delivering on the Promise of e-Paper," *by Luka Birsa, CTO, Visionect.*

Birsa has been working on e-Paper devices for 8 years, and his team has been able to deploy them in a variety of applications, including street signs in Sydney, Australia, on buses and at bus stops in Europe, and as conference room signs and e-Labels in museums and retail stores. He emphasized the value of low-power signage products that allow for the use of solar panels to power them in existing infrastructures without the need for digging or wiring power lines. In outdoor applications, the e-Paper's sunlight readability is a great enabler. Birsa's company has won numerous awards, including a CES Innovation award, for its conference-room signage.

"Sensors Integrated in Displays," *by Dr. Guillaume Chansin, Senior Technology Analyst, IDTechEx.*

Chansin's work comprises OLEDs, flexible sensors, and quantum dots. He began his presentation with the premise that a display tends to be a large part of most devices, so why not use it as the platform for sensors? These could be light sensors, motion sensors, touch sensors, *etc*. The trends he foresees in the market include the ability to embed sensors in displays, allowing for automatic adjustments to light and proximity sensing for interaction with objects and humans, biometric sensing, *etc.*

"Microdisplays and Interfacing with the Brain," *by Mina Hanna, Ph.D. student, Stanford University.*

Hanna explained some of the work going on in academia relating to microdisplays in brain stimulation; they offer great potential for treating brain-related illnesses such as Parkinson's disease. His team is working on microwire bundles that allow cellular- and circuit-level targeting; microdisplays allow them to control individual microwires.

Evening Keynote: "Mapping the U.S. Innovation System Today," *by Professor Fred Block, UC Davis.*

Block observed that the decline of large corporate labs in the past three decades, with many Ph.D.s moving to smaller firms, has led toward the trend of government-university-industry (GUI) collaboration. The current environment has its flaws – managing and coordinating is a big hurdle, the IP system can be dysfunctional, small firms are ignored by venture capitalists, and innovators have to build complex political alliances to scale. He called for more public awareness of this changed environment and highlighted the need for new rules and methods so as to encourage more innovators.

Beyond the Comfort Zone

Over 100 Bay Area display-industry enthusiasts attended this information-filled event in Sunnyvale. The evening reception allowed speakers and attendees to mingle – many continued informal discussions late into the evening. This knowledge transfer event, in which many of the speakers shared their life's work in a few minutes, will be held again. "The BA-SID was super excited by how the event turned out and plans to repeat this with a much larger audience next year," said Sri Peruvemba, one of the organizers.

Acknowledgments

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Display Color Gamuts: NTSC to Rec.2020

Modern color gamuts are one of the most misunderstood aspects of display metrology. Here, we will examine the usefulness of the still widely referenced 1953 NTSC gamut and also compare accurately colorized gamuts in the 1931 and 1976 CIE color spaces.

by Raymond M. Soneira

THE color gamut defines the palette of available colors that a display can produce – so it is the most important defining visual characteristic of any display. While color gamuts have changed over the years, in the past, virtually all displays needed just a single gamut to produce all of the content that a user wanted to see. But with the recent development of several wider-color-gamut standards for producing new content, including DCI-P3 for 4K UHD TVs and digital cinema, all future TVs, monitors, smartphones, tablets, and laptops will need to support at least two color gamuts.

So, there is a big learning curve for consumers, reviewers, content producers, and even manufacturers with regard to the proper use of the new color gamuts. In this article, we will examine and compare some of the most important display color gamuts that have been appearing in consumer products over the last 60-plus years, from the earliest NTSC gamut up through the latest DCI-P3 and Rec.2020 gamuts. In short, gamuts have been evolving and getting progressively larger.

Display Color Gamuts and Standards

Over the years, there have been an incredibly wide range of color gamuts that have been implemented for displays. Many are simply based on the particular native primary colors conveniently available at the time at low cost for different display technologies such as CRT, plasma, LCD, OLED, LED, quantum dots, phosphors, lasers, *etc*. Many applications just need any suitable range of colors to satisfy a user's needs. However, essentially all imaging-based applications need a specific well-defined color gamut in order to accurately reproduce the colors in the image content. Over the years, this has given rise to many different standard color gamuts for image content, and they have generally been based on what the current displays at the time could produce. So both the displays and content have evolved together over time, and many different gamuts have been defined, but they have not all been created equal.

What makes a color gamut important and a true standard is the existence of lots of content created specifically for that gamut: manufacturers then need to include that standard in their products. So, it is the content and content producers that define a true color-gamut standard – the displays then need to deliver it as accurately as possible on-screen. Every display needs to adapt its native color gamut for the content that it has to show. This is implemented using color management, which we discuss below.

While people primarily think of color gamuts in terms of their outermost saturated colors, most image content is generally found in the interior regions of the gamut, so it is particularly important that all of the interior less-saturated colors within the gamut be accurately reproduced.

And if you are not sure of the set of colors that the different gamuts actually produce, we will show you accurately colorized versions of the two most important standard gamuts being used today so you can evaluate them visually. In case you think you have already seen colorized gamuts before, the colors shown in essentially all published color gamuts are fictitious and wildly incorrect. We have accurately calculated them here.

Color Gamuts and Ambient Light

One very important point that applies to all displays is the color gamut that you actually see on-screen is reduced by any existing ambient light falling on the screen. Since very few users watch their displays in absolute darkness (0 lux), the color gamut that is actually seen is noticeably less than 100%. We examined this very important effect and its solution in an online DisplayMate article in 2014.[1]

NTSC Color Gamut

The first official color gamut standard for displays was the NTSC color gamut, which made its debut in 1953 for the beginning of U.S. color-television broadcasting. However, the NTSC primary colors were too saturated and could not be made bright enough for use in the consumer (CRT) TVs of that era, so the NTSC color gamut was never actually implemented for volume commercial production of color TVs. As a result, the NTSC gamut was never an actual standard color gamut, and there is essentially no consumer content based on the true NTSC color gamut. This is amus-

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ing (and annoying) because now, more than 60 years later, many manufacturers and reviewers are still quoting and referring to the NTSC gamut as if it were some sort of state-of-the-art standard, while in fact it has been obsolete and colorimetrically disjointed from most other standard gamuts for an incredibly long time.

Manufacturers of high-tech display products should be embarrassed for publishing their specifications in terms of NTSC, an obsolete technology more than 60 years old. So please everyone – let's stop referring to the very outdated NTSC and instead move on to the actual color gamuts that are being used in today's displays.

The Real Analog-TV and Standard-Definition-TV Color Gamuts

Instead of the official NTSC gamut colors, the practical phosphor colors that were actually used in early color TVs were developed by the Conrac Corporation. The result became the SMPTE-C color-gamut standard. TV production studios used Conrac color monitors to produce their broadcast TV content, so it was the Conrac color gamut rather than the NTSC gamut that was the real color-television standard gamut. The SMPTE-C gamut is not that different from today's sRGB/Rec.709 gamut, which is 13% larger than that of SMPTE-C. Many later gamut standards were based on SMPTE-C, including up to Rec.601 for Digital Standard-Definition TV. We are now going to skip over lots of history and get to the display color gamuts that are in use today.

sRGB/Rec.709 Color Gamut

For over 10 years, the main color gamut that has been used for producing virtually all current consumer content for digital cameras, HDTVs, the Internet, and computers, including photos, videos, and movies, is a dual standard called sRGB/Rec.709. If you want to see accurate colors for this content on just about any consumer product, then the display needs to match the sRGB/Rec.709 standard color gamut – not larger and not smaller. If your display does not faithfully render the content in this gamut, the colors will appear wrong and also be either too saturated or under-saturated.

There are still widely held beliefs by many reviewers and consumers that viewing content on a display with a larger color gamut is actually better, but it is definitely worse because the display will produce colors that were not actually present in the original content, creating an oversaturated or generally incorrect rendering. Below, in Figs. 1–4, we will show both visually and quantitatively what the sRGB/Rec.709 color gamut looks like in both the 1976 and 1931 CIE diagrams.

Accurately Matching the Color-Gamut Standard

For reasons similar to what occurred long ago with the NTSC gamut, up until recently a reasonable fraction of all displays could not produce 100% of the sRGB/Rec.709 color gamut. This was especially true for mobile displays, which in many cases provided less than 70% of the sRGB/Rec.709 gamut due to luminance and efficiency issues similar to those that had plagued the NTSC gamut. As a result, their on-screen images appeared somewhat bland and under-saturated. But today, most good-quality products have displays that produce close to 100% of the sRGB/Rec.709 color gamut.

Similar issues also apply to the newest and largest color gamuts, DCI-P3 and Rec.2020, which we examine in detail below. 4K UHD TVs only need to provide 90% of the DCI-P3 color-gamut standard to receive a 4K UHD Alliance certification, and the currently available Rec.2020 displays typically only provide 90% of the Rec.2020 color-gamut standard. It has always taken some time for displays to fully and properly implement the latest color-gamut standards. However, this delay introduces color errors that reduce the absolute color accuracy of the displayed content, which we discuss below.

Adobe RGB Color Gamut

Most high-end digital cameras have an option to use the standard Adobe RGB color gamut, which is 17% larger than the standard sRGB/Rec.709 color gamut that is used in consumer cameras. The Adobe RGB gamut is also used in many other advanced and professional imaging applications. For consumers, Samsung's Galaxy smartphone and Galaxy tablet OLED displays accurately produce the Adobe RGB gamut as covered in DisplayMate's Mobile Display Technology Shoot-Out article series.[2]

DCI-P3 Color Gamut

The newest standard color gamut that has significant content is DCI-P3, which is 26% larger than the sRGB/Rec.709 gamut. It is being used in 4K UHD TVs and in digital cinema for the movie industry, so while the amount of existing DCI-P3 content is still relatively small compared to that for sRGB/Rec.709, it is now starting to grow rapidly. DCI-P3 is also being adopted in many other new displays and applications that need to provide a wider color gamut with a wider range of more saturated colors. DisplayMate recently tested the new Apple iPad Pro 9.7, which has a very accurate native 100% DCI-P3 gamut and also produces a very accurate 100% sRGB/Rec.709 gamut by using color management.[3]

Rec.2020 Color Gamut

The next-generation standard color gamut will be the impressively large Rec.2020 standard, shown in Fig. 1. In fact, it is 72% larger than the sRGB/Rec.709 and 37% larger than the DCI-P3. The color gamut is extremely wide and the color saturation extremely high. However, there is almost no current existing content for Rec.2020. And there are very few existing displays that come close to providing Rec.2020, which requires quantum dots for LCDs. Of course, continuing progress is being made in extending the color gamuts for both LCD and OLED panels, so Rec.2020 will become an important new standard gamut within the next several years.

Comparing the Standard Color Gamuts

Figure 1 shows the color gamuts for most of the standards that we have been discussing. They are all plotted on a CIE 1976 uniform chromaticity (color) diagram that quantitatively evaluates color in a perceptually uniform manner for human color vision with (*u'*,*v'*) color coordinates. All of the color regions and visual differences among colors remain consistent throughout the entire 1976 CIE color space, so it provides an excellent and accurate method for specifying, manufacturing, marketing, comparing, measuring, and calibrating displays.

Note that the older 1931 CIE diagrams with (*x*,*y*) color coordinates that are published by many manufacturers and reviewers are very non-uniform and distorted, so they are effectively meaningless for quantitatively evaluating color gamuts and their color accuracy. The color gamuts shown in Fig. 1 would appear very differently in the 1931 CIE

Check These Figures Online

A note regarding the color accuracy in the printed figures: Due to the limitations in printing the accurately colorized display color gamuts, readers should also view them on a display in the online version of this article at www.informationdisplay.org.

Furthermore, to make sure that you are seeing the colorized gamuts accurately, your display must support active color management or be set in Figs. 2 and 3 to the sRGB/Rec.709 standard found on most recent smartphones, tablets, laptops, monitors, and full-HD TVs, and in Fig. 4 to the DCI-P3 standard found on UHD TVs and on some new displays such as the Apple iPad Pro 9.7 as discussed in the article. Otherwise, the colors will be incorrect and either undersaturated or too saturated.

diagram. We will examine this in detail for the sRGB/Rec.709 gamut below.

In all of the CIE diagram figures, the outermost white curve is the limit of human color vision – the horseshoe is the pure spectral colors and the diagonal is the *line of purples* connecting red and blue at the extreme ends of human color vision. Green is between red and blue in the spectrum and is on the extreme left in the CIE diagrams.

A given display can only reproduce the colors that lie inside of the triangle formed by its three primary colors, which are always based on red, green, and blue, following the eye's own spectral color response. The wider the color gamut, the greater the range of colors that can be produced. Some displays have more than three primary colors. In such cases the color gamut is then defined by a polygon. Sharp's Quattron, for example, includes a fourth yellow (non-standard) primary color that actually improves the display's brightness and efficiency more than enlarging the gamut as can be seen in Fig. 1.

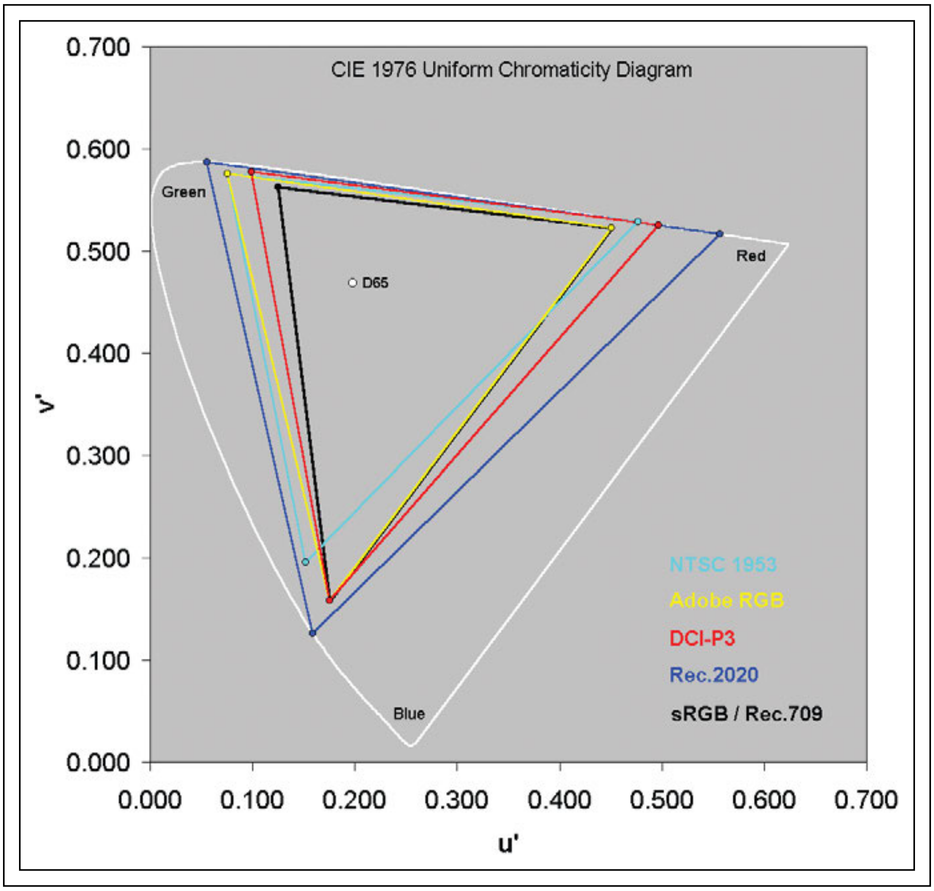


Fig. 1: Shown are the standard color gamuts plotted on a CIE 1976 uniform chromaticity diagram.

When content is being produced, colors that are outside of the content's color gamut move automatically to the closest available color and no longer exist and cannot be recovered later by using a wider color gamut. So, the highly saturated colors outside of the color gamut are still reproduced but with lower color saturation.

The standard color of white for almost all current color-gamut standards is called D65, which is the color of outdoor natural daylight at noon with a color temperature close to 6500K and is marked in the figures as a white circle near the middle. To deliver accurate image colors, a display must match the same color gamut and also the same color of white that was used to create the content. Unfortunately, many displays accurately reproduce the color gamut, but then use an inaccurate (typically too blue) white point, which then introduces color-accuracy errors throughout the entire inner regions of the gamut.

Color-Gamut Size Comparisons in Terms of Area

A common metric for comparing the relative sizes of the color gamuts is by using their relative areas within the Uniform 1976 CIE diagram. The relative gamut sizes that are calculated from the non-uniform 1931 CIE diagram are significantly different and are compared in a later section below.

- The Adobe RGB color gamut is 17% larger than that for sRGB/Rec.709.
- The DCI-P3 color gamut is 26% larger than that for sRGB/Rec.709.
- The Rec.2020 color gamut is 72% larger than that for sRGB/Rec.709 and 37% larger than that for DCI-P3.

And for those of you still interested in NTSC-gamut statistics: The NTSC color gamut is 98% of the Adobe RGB color gamut. So while they are both very close in gamut area and size, note how very different their triangular gamut shapes and color regions are in Fig. 1, proving that the still current practice of using NTSC for gamut specifications, and comparisons has little colorimetric meaning or useful quantitative value for the current gamuts and displays (and is doubly incorrect when combined with the non-uniform 1931 CIE color space).

Accurately Colorized sRGB/Rec.709 Color Gamut

Figures 2 and 3 show an accurately colorized sRGB/Rec.709 color gamut. For displays this can only be done for a single color gamut at a time. The colors in the figure have been accurately calculated to show the real colors within the sRGB/Rec.709 gamut – the colors shown in most published color gamuts are fictitious and wildly incorrect. Also included are 41 reference colors that we use for measuring absolute color accuracy throughout the entire gamut, which is discussed below.

Note that printed versions of the colorized gamuts depend on the particular inks being used and also their spectral absorption of the particular ambient light you are viewing them in, so they cannot be as accurate as when viewed on an emissive display, and they also generally provide smaller gamuts than most displays. (See sidebar on previous page.)

Note that every color within the gamut is shown at its maximum brightness (luminance). White is the brightest color near the middle because it is the sum of the peak red, green, and blue primary colors. The secondary colors of cyan, magenta, and yellow radiate from the white point as ridges because they are the sums of two primary colors.

One particularly interesting result seen in Fig. 2 is how relatively small the green region of the sRGB/Rec.709 color gamut is in the accurate 1976 CIE uniform color space. However, the green region appears considerably larger in the distorted and non-uniform 1931 CIE chromaticity diagram, as shown in Fig. 3. The newer color gamuts – Adobe RGB, DCI-P3, and Rec.2020 – all significantly enlarge the green region of their color space within the uniform 1976 CIE diagram.

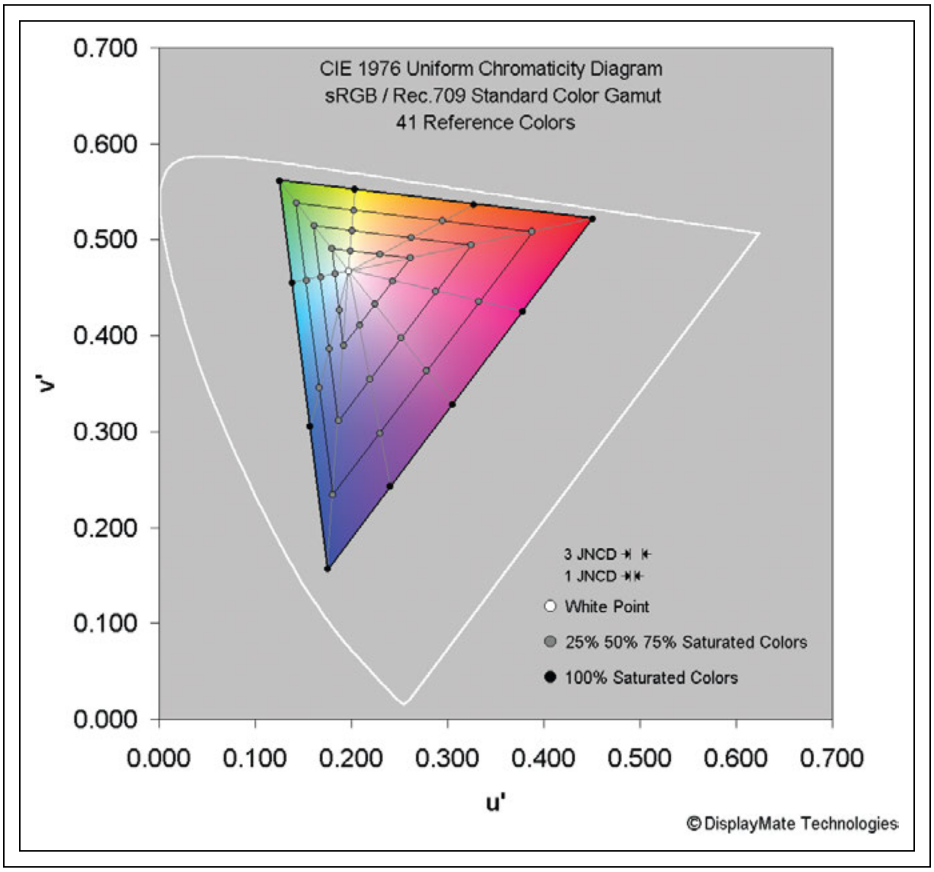


Fig. 2: An accurately colorized sRGB/Rec.709 color gamut appears with reference colors.

Absolute Color Accuracy and Just Noticeable Color Differences (JNCD)

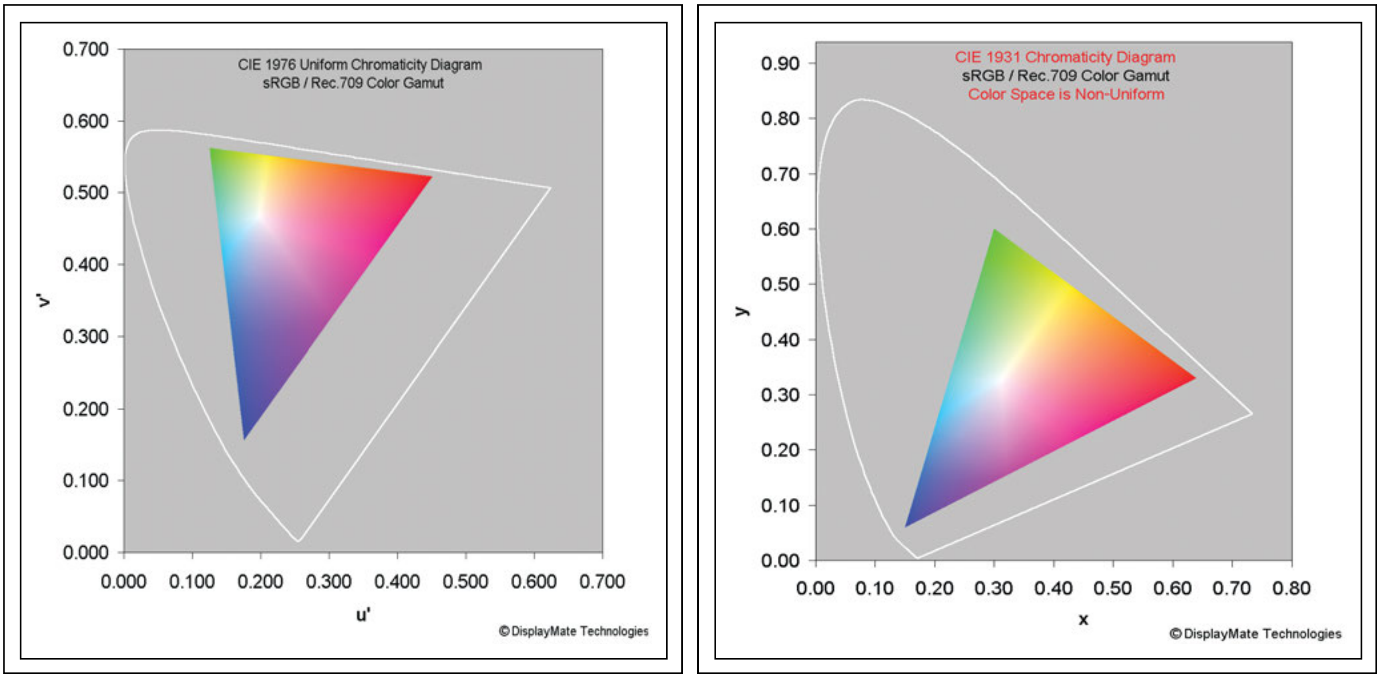
One very important issue is the accuracy of each display's color gamuts, and the absolute color accuracy for all of the colors within the entire color gamut. One vital reason for accurately colorizing and rendering each color gamut in the 1976 CIE uniform color space is that the display's color accuracy and color calibration can be accurately analyzed uniformly, and then the true color errors uniformly minimized for all of the colors within the color gamut. The errors are expressed in terms of Just Noticeable Color Differences (JNCD), which correspond to fixed linear distances within the CIE diagram. Figure 2 shows distances corresponding to 1 JNCD and 3 JNCD, with 1 JNCD = 0.0040 in the (u', v') 1976 color space.

For each display we test, we measure the absolute color accuracy of 41 reference colors, which are shown for sRGB/Rec.709 in Fig. 2. See this color accuracy analysis for both the DCI-P3 and sRGB/Rec.709 color gamuts in the DisplayMate article on the Apple iPad Pro 9.7, which includes a more detailed discussion of JNCD.[4] In the Absolute Color-Accuracy Shoot-Out online article, we show the colors for a wide range of facial skin tones and fruits and vegetables so that you can get a good idea of where these important colors fall within the 1976 CIE diagram.[5]

Accurately Colorized 1931 CIE Diagram for the sRGB/Rec.709 Color Gamut

The best way to demonstrate the large differences between the 1976 uniform and the older 1931 non-uniform CIE diagrams is to show an accurately colorized sRGB/Rec.709 color gamut for both side-by-side in Fig. 3. Note that for comparison, both of the color triangles have been scaled to have the same geometric area in the figures.

Note how differently the colors are distributed within each color space. The obsolete but still widely used 1931 CIE diagram has a very non-uniform color space that significantly expands the green region and significantly compresses the blue region, providing a very distorted representation of human color perception. Specifying and analyzing displays



(a) 1976 CIE Uniform Diagram for sRGB/Rec.709

(b) 1931 CIE Non-Uniform Diagram for sRGB/Rec.709

Fig. 3: *Accurately colorized comparisons of the 1976 Uniform and 1931 Non-Uniform CIE color spaces. For the comparison, both color triangles have been scaled to have the same geometric area in the figures.*

in terms of the very non-uniform and distorted 1931 CIE color space introduces significant performance, calibration, and color-accuracy errors. Many manufacturers also specify their guaranteed display color accuracy in terms of the non-uniform *(x,y)* 1931 CIE coordinates, which results in large variations and differences in color accuracy throughout the color space.

The 1976 CIE diagram transforms and corrects the distortions in the original 1931 version to produce a uniform color space that accurately renders human color perception and color accuracy. It's about time that manufacturers and reviewers abandon the obsolete 1931 CIE color space for all of the above reasons!

The color-gamut size comparisons that are calculated and specified by many manufacturers using the 1931 CIE diagram are also inaccurate and misleading. For example, in the non-uniform 1931 CIE color space, the Adobe RGB color gamut is 35% larger than that for sRGB/Rec.709, more than double the accurate 17% value listed above from the 1976 CIE uniform color space. And in the 1931 CIE color space, the DCI-P3 color gamut is 36% larger than that for sRGB/Rec.709, a 38% size exaggeration compared to the accurate 1976 CIE value of 26% larger. Manufacturers should be embarrassed for specifying their products in terms of the obsolete and very misleading non-uniform 1931 color space.

Accurately Colorized DCI-P3 Color Gamut

Figure 4 shows an accurately colorized DCI-P3 color gamut with an inscribed sRGB/Rec.709 gamut in order to demonstrate the differences between the two gamuts. DCI-P3 is being used in 4K UHD TVs and in digital cinema for the movie industry, so while the amount of existing DCI-P3 content is still relatively small compared to that for sRGB/Rec.709, it is starting to grow rapidly.

Note how much larger the green region in the DCI-P3 color space is in comparison to sRGB/Rec.709. The extreme reds have also been significantly expanded. Based on the measurements in DisplayMate's Absolute Color Accuracy Shoot-Out, most fruits and vegetables are found in the most saturated red-to-orange-to-yellow-to-green regions of the color space (so they visually attract animals who will eat them and spread their seeds), and the most highly saturated colors are also heavily utilized in a great deal of human-generated content in order to get people's visual attention. Therefore, the enlarged red-to-green sliver in the DCI-P3 color space is actually very important.

Color Management for Multiple Color Gamuts

When a display needs to support one or more additional color gamuts such as sRGB/Rec.709, which is smaller than its native color gamut, it can accomplish this with digital color management performed by the firmware, CPU, or GPU for the display. The digital RGB values for each pixel in an image being displayed are first mathematically transformed so they colorimetrically move to the appropriate lower saturation colors closer to the white point. The available color gamuts can either be selected manually by the user or automatically switched if the content being displayed has an internal tag that identifies its

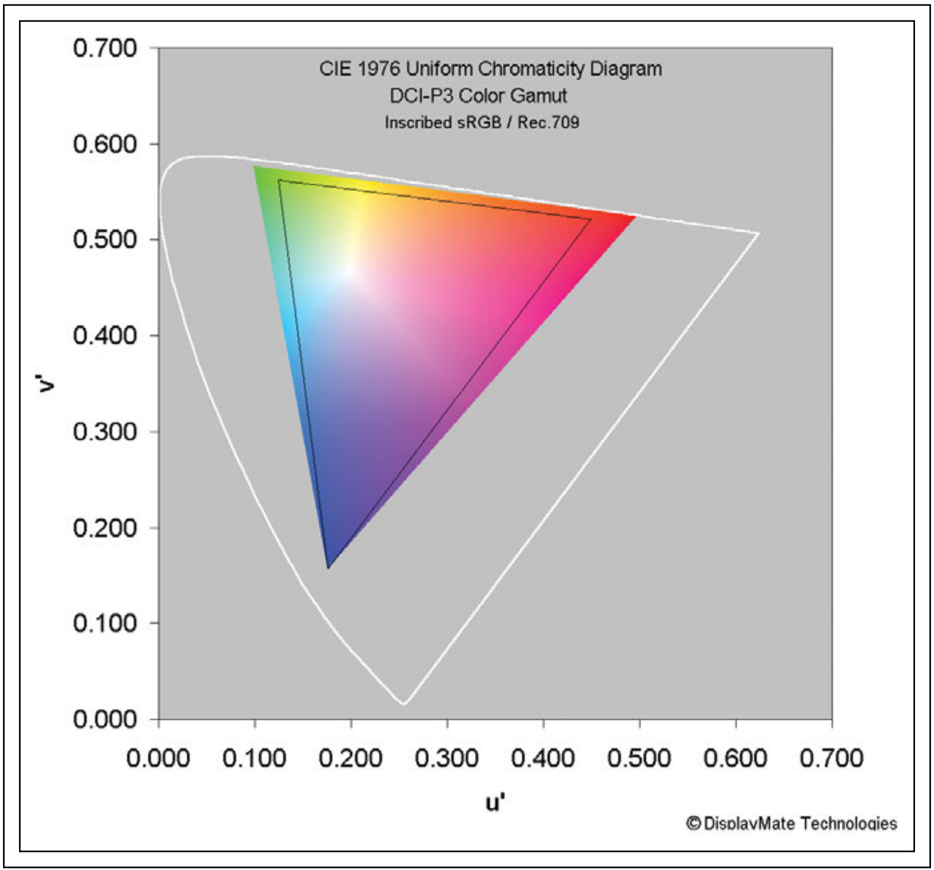


Fig. 4: An accurately colorized DCI-P3 color gamut is shown with an inscribed sRGB/Rec.709 gamut.

native color gamut, and that tag is recognized by the display's operating system or firmware. The Apple iPad Pro 9.7 implements color management that automatically switches between the DCI-P3 and sRGB/Rec.709 gamuts.

Another, more advanced color-management approach is for the content to include a detailed specification for the colorimetry of the content, and then it is up to the display to implement it as accurately as possible using its native color gamut.

Out With the Old, in With the New

This overview from the earliest NTSC gamut to the latest DCI-P3 and Rec.2020 gamuts demonstrates the importance of eliminating the widespread use of the obsolete 1953 NTSC gamut and the obsolete 1931 CIE diagram in the display industry.

The 1953 NTSC gamut was never actually used for production displays and is colorimetrically different from current standard gamuts, so it is misleading to use it as a reference gamut. The 1976 CIE diagram transforms and corrects the large distortions in the original 1931 diagram to produce a uniform color space that accurately renders human color perception and color accuracy.

Switching to current display technology and colorimetry standards is tremendously overdue. It is essential not only for properly specifying, measuring, manufacturing, and accurately calibrating displays, but also for comparing and marketing them to both product manufacturers and consumers.

The display industry and manufacturers of high-tech products should be embarrassed for using obsolete 63-85 year old standards and colorimetry! At Display Week 2017, I am really hoping not to see any obsolete NTSC gamut specifications and obsolete 1931 CIE diagrams.

References

[1] http://www.displaymate.com/Display_Technology_2014.htm#Ambient_Light

[2] http://www.displaymate.com/mobile.html

[3] http://www.displaymate.com/iPad_Pro9_ShootOut_1.htm

[4] http://www.displaymate.com/Colors_35.html

[5] http://www.displaymate.com/Color_Accuracy_ShootOut_1.htm ■

Display Week 2016 Show Daily Highlights

Color e-ink, augmented reality's relationship with human evolution, and displays for smartwatches that really resemble a watch were only a few of the great discoveries that Information Display's roving reporters made at Display Week 2016 in San Francisco.

by Information Display Staff

ENGINEERS, developers, analysts, CEOs, investment bankers, and many others headed to San Francisco last May for Display Week 2016. With a technical symposium, seminars, short courses, business and marketing conferences, and a three-day exhibition that included the always-popular Innovation Zone, Display Week offered more than one person could possibly see.

Fortunately, our team of ace reporters – Achin Bhowmik, Jyrki Kimmel, Steve Sechrist, and Ken Werner – were on the job, homing in on specific areas of technology and sharing their discoveries via blogs throughout the show. (They are also writing longer articles that will appear in our September/October post-show issue.)

We think the blogs are a fun way to get a taste of the really novel things from the show, so we decided to share several of them in print. If you want to read more, please visit www.informationdisplay.org.

Augmented and Virtual Reality at Display Week: Game On!

by Achin Bhowmik

In recent years, virtual reality has moved from science-fiction movies, to academic research labs, to product development in the industry, and, finally, into the hands of consumers in the real world. A number of marquee devices have been launched into the marketplace, along with some compelling immersive applications. Some cool augmented-reality devices and developer kits have been released as well. The recent pace of progress in both virtual- and augmented-reality technologies has been rapid.

In line with this fast-emerging trend in the ecosystem, SID decided to create a special track on Augmented and Virtual Reality for Display Week 2016. The rich lineup included a short course, a seminar, a number of invited and contributed presentations in the symposium, and demonstrations on the exhibit floor.

Displays are the face of some of the most-used electronic devices in our daily lives – the smartphone, tablet, laptop, monitor, and TV, among other examples. As such, the health of the display industry rises and falls with the growth and saturation of these devices. Take the exciting phase of innovation in LCD TV technology as an example. The screen size went from 24 in. to 32 in. to 40 in. to 55 in. to 80 in. and above. The resolution went from 720*p* to full HD to QHD and beyond, whereas the frame rates went from 60 to 120 fps. And there were many more advances – contrast, brightness, color, *etc*. However, it has gotten to the point where further advances in display technology are providing only incremental benefits to the consumer. This situation often leads to a reduced demand for new features and a slowdown in development, and it is to some degree what those of us in the display industry have been facing.

Let's now turn to virtual reality. It's a completely different story at the moment. The displays on the best state-of-the-art VR devices today fall way short of the specifications required for truly immersive and responsive experiences, despite the dizzying pace of development. The pixel density needs to increase significantly and latencies must be reduced drastically, along with many other improvements such as increased field of view, reduced pixel persistence, higher frame rates, *etc*. Besides the display, the systems also require the integration of accurate sensing and tracking technologies. Augmented-reality devices impose additional requirements.

So this is exciting for the researchers and engineers in the industry, who must go back to solving some difficult challenges, with the potential for big returns. Judging by the excellent quality of the papers, presentations, and exhibitions at the Display Week, it's obvious the display ecosystem is all geared up. AR and VR technology is just what the display industry needs for a massive rejuvenation. Game on!

Wearable Displays Sport Classic Designs

by Jyrki Kimmel

There was a time when watches seemed to go out of fashion. Everyone could find out what time it was by looking at their mobile-phone screen. But in the last couple of years, "connected watches" have become a wearable part of the mobile ecosystem and their design has approached that of classic wristwatches (Fig. 1). The intuitive round-faced hand-dial interface has pulled through, once again.

How has this development come about? Weren't we satisfied with the function of the square-screen Android devices that appeared in the marketplace about 5 years ago? Apparently not.

The wearables being demonstrated on the exhibition show floor featured many round-faced watch-sized displays. The Withings

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Fig. 1: *JDI's Memory-in-Pixel reflective connected watch display offers a traditional rounded watch-face shape. (Photo by Jyrki Kimmel)*

activity monitor, for instance, was featured in the E Ink booth, sporting a reflective e-Paper display in a round design in a futuristic setting and band.

Assuming that customer demand drives the adoption of consumer devices, once the technology to realize these is available, we can infer from the exhibits shown that there is a demand to minimize the bezel and dead space in a watch form-factor display. Companies are striving to provide a bezelless design similar to what has become possible in mobile-phone displays. This is much more difficult with a round shape. AUO has made some progress and explained during two symposium presentations how this can be done using a plastic substrate display. Instead of placing the driver chip on the face of the display, in a ledge, or using a TAB lead, AUO bends the flexible substrate itself to place the driver at the backside of the display. In this way, a bezel of 2.2 mm can be achieved, with clever gate-driver placement and by bringing the power lines into the active area from the opposite side of the display face.

Another direction in the development of wearables is a band form-factor display that wraps around the user's wrist. Canatu, the Finnish touch-panel maker, was showing an e-ink-based display device from Wove at its booth. (For more on this device, see "Enabling Wearable and Other Novel Applications through Flexible TFTs" in the March/April 2016 issue.) The touch panel was assembled in an "on-screen" touch fashion to make a complete integral structure without any separate outside encapsulation. According to Canatu, the entire module thickness is only 0.162 mm.

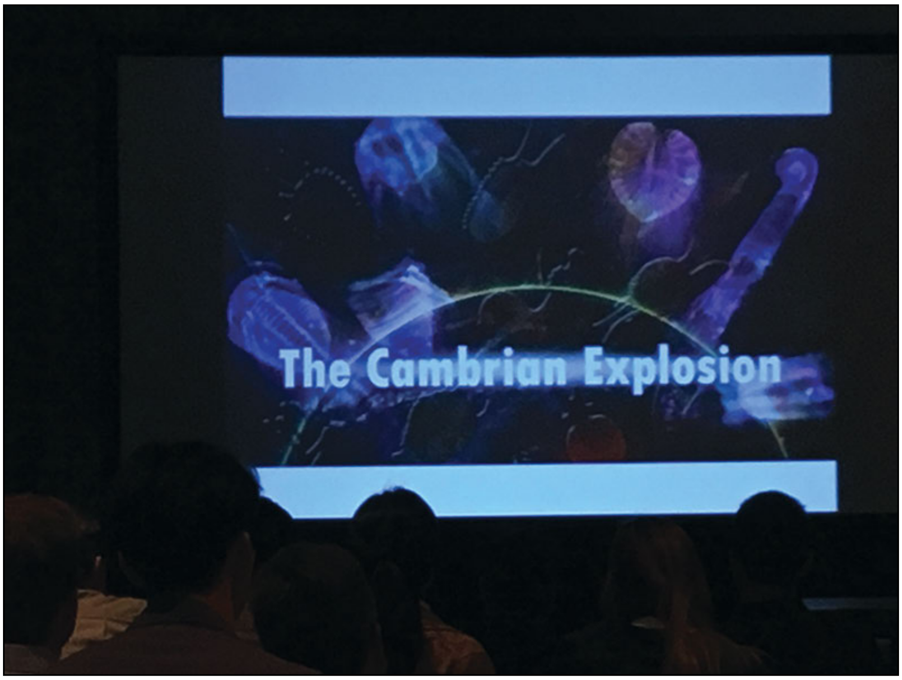

Fig. 2: *About 540 million years ago, most of the types of animals that exist on earth today appeared rather suddenly, during a period that is called The Cambrian Explosion.*

So, it seems like the technical capabilities in displays are beginning to satisfy user needs in wearable devices. With the round-faced and band-shaped form factors making it possible to wear a watch again, the "Internet of Designs" can begin.

The Convergence of Human and Display Evolution

by Steve Sechrist

The seminars that are presented on the Monday before Display Week officially begins are invaluable ways to gain knowledge in a particular area in a brief period of time. One of these courses, "Augmented and Virtual Reality: Towards Life-like Immersive and Interactive Experiences," given by Intel's Achin Bhowmik (also one of *ID*'s roving reporters), treated session attendees to a most unexpected perspective.

The discussion began with the Cambrian Explosion, which Bhowmik explained directly led to the evolution of the human visual system and the basis of key issues those of us in the display industry need to consider today (Fig. 2).

It was interesting to observe the overflow crowd of electrical and computer engineers suddenly confronted with the cold hard fact that biology, based on the distribution of photoreceptors in the human eye (yes, rods and cones), is driving key display requirements. Bhowmik explained that the human fovia consists of only cones (color receptors) and rods. Cones make up the periphery, with far more (orders of magnitude more) rods than cones in that space.

Resolution and field of view (FOV) were also discussed, with the assertion that we should be talking about pixels per degree (ppd) rather than pixels per inch (ppi) specifications in HMD applications. Bhowmik said the human eye has an angular resolution of 1/60 of a degree, with each eye's horizontal field of view (FOV) at 160° and a vertical FOV of 175°.

What all this portends is that the direction of display development is finally moving beyond speeds and feeds. For significant development to continue, serious consideration needs to be given to how the eye sees

Fig. 3: E Ink's full-color electrophoretic display has four colors of particle and no matrix color filter. (Photo: Ken Werner)

images and particularly color. Maybe it's time to take a refresher course in Biology 101.

E Ink Shows a Color Electrophoretic Display that Pops

by Ken Werner

The E Ink Carta reflective electrophoretic display (EPD) is a near-perfect device for reading black text on a white background. But there are applications, such as various types of signage, that demand vibrant color. Until now, the only way to get "full" color from an EPD – at least the only way that E Ink has shown us – is by placing a matrix color filter in front of the monochrome display.

The problem with this approach for a reflective display is that the 40% of light reflected from a good EPD is brought down to 10–15% by the filter. This results in a limited gamut of rather dark muddy colors. E Ink showed the way forward a few years ago with a black, white, and red display, which managed to control particles of three different colors using differences in mobility and a cleverly designed controlling waveform.

At Display Week 2016, E Ink introduced an impressive expansion of this approach, in which particles of four different colors are included within each microcapsule, given different mobilities through different sizing and driven with a pulsed controlling wave movement that permits the creation of thousands of colors, as explained by E Ink's Giovanni Mancini.

The resulting display showed impressively bright and saturated colors and drew crowds (Fig. 3). When a new image was written, the display would flash several times. It took about 10 sec for a new image to build to its final colors. One possible application Mancini mentioned is a color e-ink sign powered by photocells.

This is a significant development that will definitely expand the range of applications EPD can address. ■

SOCIETY FOR INFORMATION DISPLAY NEWS

SID 2017 honors and awards nominations

On behalf of the SID Honors and Awards Committee (H&AC), I am appealing for your active participation in the nomination of deserving individuals for the various SID honors and awards. The SID Board of Directors, based on recommendations made by the H&AC, grants all the awards. These awards include five major prizes awarded to individuals, not necessarily members of SID, based upon their outstanding achievements. The **Karl Ferdinand Braun prize** is awarded for ***"Outstanding Technical Achievement in, or Contribution to, Display Technology."*** The prize is named in honor of the German physicist and Nobel Laureate Karl Ferdinand Braun who, in 1897, invented the cathode-ray tube (CRT). Scientific and technical achievements that cover either a wide range of display technologies or the fundamental principles of a specific technology are the prime reasons for awarding this prize to a nominee. The **Jan Rajchman prize** is awarded for ***"Outstanding Scientific and Technical Achievement or Research in the Field of Flat-Panel Displays."*** This prize is specifically dedicated to those individuals who have made major contributions to one of the flat-panel-display technologies or, through their research activities, have advanced the state of understanding of one of those technologies. The **Otto Schade prize** is awarded for ***"Outstanding Scientific or Technical Achievement in the Advancement of Functional Performance and/or Image Quality of Information Displays."*** This prize is named in honor of the pioneering RCA engineer Otto Schade, who invented the concept of the Modulation Transfer Function (MTF) and who used it to characterize the entire display system, including the human observer. The advancement for this prize may be achieved in any display technology or display system or may be of a more general or theoretical nature. The scope of eligible advancement is broadly envisioned to encompass the areas of display systems, display electronics, applied vision and display human factors, image processing, and display metrology. The nature of eligible advancements may be in the form of theoretical or mathematical models, algorithms, software, hardware, or innovative methods of display-performance measurement and image-quality characterization. Each of these above-mentioned prizes carries a $2000

SID honors and awards nominations

Nominations are now being solicited from SID members for candidates who qualify for SID Honors and Awards.

- KARL FERDINAND BRAUN PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, display technology.
- JAN RAJCHMAN PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, research on flat-panel displays.
- OTTO SCHADE PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.
- SLOTTOW–OWAKI PRIZE. Awarded for outstanding contributions to the education and training of students and professionals in the field of information display.
- LEWIS & BEATRICE WINNER AWARD. Awarded for exceptional and sustained service to SID.
- FELLOW. The membership grade of Fellow is one of unusual professional distinction and is conferred annually upon a SID member of outstanding qualifications and experience as a scientist or engineer in the field of information display who has made widely recognized and significant contribution to the advancement of the display field.
- SPECIAL RECOGNITION AWARDS. Presented to members of the technical, scientific, and business community (not necessarily SID members) for distinguished and valued contributions to the information-display field. These awards may be made for contributions in one or more of the following categories: (a) outstanding technical accomplishments; (b) outstanding contributions to the literature; (c) outstanding service to the Society; (d) outstanding entrepreneurial accomplishments; and (e) outstanding achievements in education.

Nominations for SID Honors and Awards must include the following information, preferably in the order given below. Nomination Templates and Samples are provided at *www.sid.org/awards/nomination.html.*

1. Name, Present Occupation, Business and Home Address, Phone and Fax Numbers, and SID Grade (Member or Fellow) of Nominee.

2. Award being recommended:
   Jan Rajchman Prize
   Karl Ferdinand Braun Prize
   Otto Schade Prize
   Slottow–Owaki Prize
   Lewis & Beatrice Winner Award
   Fellow*
   Special Recognition Award
*Nominations for election to the Grade of Fellow must be supported in writing by at least five SID members.

3. Proposed Citation. This should not exceed 30 words.

4. Name, Address, Telephone Number, and SID Membership Grade of Nominator.

5. Education and Professional History of Candidate. Include college and/or university degrees, positions and responsibilities of each professional employment.

6. Professional Awards and Other Professional Society Affiliations and Grades of Membership.

7. Specific statement by the nominator concerning the most significant achievement or achievements or outstanding technical leadership that qualifies the candidate for the award. This is the most important consideration for the Honors and Awards committee, and it should be specific (citing references when necessary) and concise.

8. Supportive material. Cite evidence of technical achievements and creativity, such as patents and publications, or other evidence of success and peer recognition. Cite material that specifically supports the citation and statement in (7) above. (Note: the nominee may be asked by the nominator to supply information for his candidacy where this may be useful to establish or complete the list of qualifications).

9. Endorsements. Fellow nominations must be supported by the endorsements indicated in (2) above. Supportive letters of endorser will strengthen the nominations for any award.

E-mail the complete nomination – including all the above material by **October 15, 2016** – to swu@ucf.edu with cc to office@sid.org or by regular mail to:
Shin-Tson Wu, Honors and Awards Chair, Society for Information Display,
1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008, U.S.A.

stipend sponsored by AU Optronics Corp., Sharp Corporation, and Samsung Display, respectively.

The **Slottow–Owaki prize** is awarded for ***"Outstanding Contributions to the Education and Training of Students and Professionals in the Field of Information Display."*** This prize is named in honor of Professor H. Gene Slottow, University of Illinois, an inventor of the plasma display and Professor Kenichi Owaki from the Hiroshima Institute of Technology and an early leader of the pioneering Fujitsu Plasma Display program. The oustanding education and training contributions recognized by this prize is not limited to those of a professor in a formal university, but may also include training given by researchers, engineers, and managers in industry who have done an outstanding job developing information-display professionals. The Slottow–Owaki prize carries a $2000 stipend made possible by a generous gift from Fujitsu, Ltd., and Professor Tsutae Shinoda.

The fifth major SID award, the **Lewis and Beatrice Winner Award,** is awarded for ***"Exceptional and Sustained Service to the Society."*** This award is granted exclusively to those who have worked hard over many years to further the goals of the Society.

The membership grade of **SID Fellow** is one of unusual professional distinction. Each year the SID Board of Directors elects a limited number (up to 0.1% of the membership in that year) of **SID members** in good standing to the grade of **Fellow.** To be eligible, candidates must have been members at the time of nomination for at least 5 years, with the last 3 years consecutive. A candidate for election to Fellow is a member with ***"Outstanding Qualifications and Experience as a Scientist or Engineer in the Field of Information Display who has made Widely Recognized and Significant Contributions to the Advancement of the Display Field"*** over a sustained period of time. SID members practicing in the field recognize the nominee's work as providing significant technical contributions to knowledge in their area(s) of expertise. For this reason, five endorsements from SID members are required to accompany each Fellow nomination. Each Fellow nomination is evaluated by the H&AC, based on a weighted set of five criteria. These criteria and their assigned weights are creativity and patents, 30%; technical accomplishments and publications, 30%; technical leadership, 20%; service to SID, 15%; and other accomplishments, 5%. When submitting a Fellow award nomination, please keep these criteria with their weights in mind.

The **Special Recognition Award** is given annually to a number of individuals (membership in the SID is not required) of the scientific and business community for distinguished and valued contribution in the information-display field. These awards are given for contributions in one or more of the following categories: (a) ***Outstanding Technical Accomplishments,*** (b) ***Outstanding Contributions to the Literature,*** (c) ***Outstanding Service to the Society,*** (d) ***Outstanding Entrepreneurial Accomplishments,*** and (e) ***Outstanding Achievements in Education.*** When evaluating the Special Recognition Award nominations, the H&AC uses a five-level rating scale in each of the above-listed five categories, and these categories have equal weight. Nominators should indicate the category in which a Special Recognition Award nomination is to be considered by the H&AC. More than one category may be indicated. The nomination should, of course, stress accomplishments in the category or categories selected by the nominator.

While an individual nominated for an award or election to Fellow may not submit his/her own nomination, nominators may, if necessary, ask a nominee for information that will be useful in preparing the nomination. The nomination process is relatively simple, but requires that the nominator and perhaps some colleagues devote a little time to preparation of the supporting material that the H&AC needs in order to evaluate each nomination for its merit. It is not necessary to submit a complete publication record with a nomination. Just list the titles of the most significant half a dozen or less papers and patents authored by the nominee, and list the total number of papers and patents he/she has authored.

Determination of the winners for SID honors and awards is a highly selective process. On average, less than 30% of the nominations are selected to receive awards. Some of the major prizes are not awarded every year due to the lack of sufficiently qualified nominees. On the other hand, once a nomination is submitted, it will stay active for three consecutive years and will be considered three times by the H&AC. The nominator of such a nomination may improve the chances of the nomination by submitting additional material for the second or third year that it is considered, but such changes are not required.

Descriptions of each award and the lists of previous award winners can be found at *www.sid.org/Awards/IndividualHonorsandAwards.aspx*. Nomination forms can be downloaded by clicking on "click here" at the bottom of the text box on the above site where you will find Nomination Templates in both MS Word (preferred) and Text formats. Please use the links to find the Sample Nominations, which are useful for composing your nomination since these are the actual successful nominations for some previous SID awards. Nominations should preferably be submitted by e-mail. However, you can also submit nominations by ordinary mail if necessary.

Please note that with each Fellow nomination, only five written endorsements by five SID members are required. These brief endorsements – *a minimum of 2–3 sentences* to a maximum of one-half page in length – *must state why clearly and succinctly, in the opinion of the endorser, the nominee deserves to be elected to a Fellow of the Society. Identical endorsements by two or more endorsers will be automatically rejected* (no form letters, please). Please send these endorsements to me either by e-mail (preferred) or by hardcopy to the address stated in the accompanying text box. Only the Fellow nominations are required to have these endorsements. However, I encourage you to submit at least a few endorsements for all nominations since they will frequently add further support to your nomination.

All 2017 award nominations are to be submitted by October 15, 2016. E-mail your nominations directly to swu@ucf.edu with cc to office@sid.org. If that is not possible, then please send your hardcopy nomination by regular mail.

As I state each year: "In our professional lives, there are few greater rewards than recognition by our peers. For an individual in the field of displays, an award or prize from the SID, which represents his or her peers worldwide, is a most significant, happy, and satisfying experience. In addition, the overall reputation of the society depends on the individuals who are in its 'Hall of Fame.'

When you nominate someone for an award or prize, you are bringing happiness to an individual and his or her family and friends, and you are also benefiting the society as a whole."

Thank you for your nomination in advance.

— Shin-Tson Wu
Chair, SID Honors & Awards Committee

Society for Information Display Announces New Executive Leadership Team

The Society for Information Display (SID) recently announced the members of its new leadership team, all of whom are distinguished experts in the display industry. Professor Yong-Seog Kim has become the new SID president, while Dr. Helge Seetzen moves into the role of president-elect. Takatoshi Tsujimura will serve as the new treasurer and Dr. Achin Bhowmik is the executive committee's new secretary. Three new regional vice-presidents were also selected: Sriram Peruvemba (Americas), P. Kathirgamanathan (Europe), and Xiaolin Yan (Asia).

Kim has been an active member of SID for the past 15 years and is a distinguished professor in the Department of Materials Science and Engineering at Hongik University in Seoul, Korea. He is regarded as one of the leading researchers throughout the world in materials development and processing for information displays.

President-elect Seetzen is a multi-media technology entrepreneur with particular expertise in the university tech transfer space. He is currently the General Partner of TandemLaunch Ventures – a consumer-electronics investment fund – and has held executive roles at Dolby Laboratories and at BrightSide Technologies, which he co-founded.

With more than 20 years of LCD and OLED industry experience, newly appointed treasurer Tsujimura also serves as the general manager and department head of Konica-Minolta's OLED business.

Bhowmik, the new SID secretary, has been with Intel Corporation for more than 16 years. He currently serves as vice-president and general manager of the perceptual computing group at Intel.

Dr. Amal Ghosh, outgoing SID president, stated, "It's been a great honor to serve as president for the world's premier display-technology organization over the past 2 years. SID both attracts the very best display technologists and fosters leading-edge R&D. My predecessors on the board, through their dedicated service, have led SID to this rank, and I have no doubt that Professor Kim will succeed in taking it to new levels of excellence."

Noted Kim, "I would like to thank Amal for all he has done over the past 2 years to advance the organization's goals and visibility as more new cutting-edge displays enter our lives. I am truly honored to assume this responsibility, and I look forward to helping usher in the next generation of dynamic technologies and products that are being developed. It will be an exciting challenge to help ensure that SID keeps pace, while continuing to advance its reputation as the display industry's leading organization. I've enjoyed working with the current executive team, and as we all move into our new roles, I look forward to a dynamic and progressive next 2 years."

(*ID* magazine acknowledges MCA Public Relations, on whose announcement this article is based.) ■

Journal of the
SOCIETY FOR
INFORMATION
DISPLAY

Call for Papers on
Vehicle Displays

The Journal of the SID is soliciting original contributed papers on Vehicle Display, to be published in a Special Section in the Journal of the SID in the first quarter of 2017.

Topics of interest include, but are not limited to:
-Automotive displays
-Head-up displays
-Cockpit displays
-Rugged displays
-New concepts for vehicle displays

Papers can deal with technological aspects of manufacturing, image quality and reliability issues, form factors, deformability, power consumption, human factors related to the use of vehicle displays, etc.

Authors are invited to submit manuscripts online in electronic files to the JSID at:
http://mc.manuscriptcentral.com/sid

Authors submitting their manuscript must identify their manuscripts as being submitted for the Special Section by selecting "Special Section Paper" as the paper type in Step 1 of the submission process and by subsequently entering the special issue title 'Vehicle Displays' in Step 5 of the submission process. The Information for Authors document provides a complete set of guidelines and requirements required for the preparation and submission of a manuscript, including a discussion of the formatting requirements and the journal page charge policy.

The deadline for the submission of manuscripts is **September 15th, 2016**

The Guest Editors for this Special Section will be:

- Rashmi Rao, rao.rashmi@gmail.com
- Haruhiko Okumura, haruhiko.okumura@toshiba.co.jp

Please direct any questions about this special issue to the Editor-in-Chief of JSID at editor@sid.org or to one of the Guest Editors

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improve her game. We're hoping for a championship season this year.

It was about noon, and I was getting ready to leave for the meet. I thought I would take the self-driving car we had just bought so I could work some more during the long drive. It was a little extravagant for our budget, but since they added the light-field array cameras to the technology package its been practically fool-proof and really much safer than my own driving anyway. The combination of full situational awareness in these cars and the neural network deployed on all major U.S. highways had really transformed driving and vehicle safety. The kids love it because the holo-projection turns the inside of the cabin into a virtual movie studio and they even forget they are riding in a car.

As I slid into the seat, I felt something wet on my cheek. Wet? Huh? It's not raining. It feels like dog slobber … hey where am I? Ugh, I'm in bed and the dog wants to go outside. It's 2016 and I do not have a robot, or a studio, or a holo-projector. And I have a 60-mile commute in my human-driven car and I need to get going … Sigh.

OK, so my imagination might have gotten a bit ahead of the technology, but as you will see in our issue this month the light field is the place to be, and we really are heading for a radical transformation in how we capture, view, and interact with images in the real and virtual worlds. As our hard-working guest editor for this month, Dr. Nikhil Balram, says in his guest editorial, "From the earliest days of history, humans have attempted to capture and display images ... . What is striking about this long history of capture and display is that almost all of it is based on two-dimensional imagery." We have been trying to capture and render the world in three dimensions, the way we experience it in real life, but each attempt failed to gain mass adoption. Well, finally we can start to make this dream real, using the light field the way our human visual system does. It will not happen overnight, but given the recent advances in the field artfully described by Nikhil in his Frontline Technology article, "Light-Field Imaging and Display Systems," maybe my dream of a life in 2024 might be a bit optimistic but the science and technology already being developed gives me a lot of hope.

Even without holographic projectors we can begin to imagine creating virtual worlds for a single observer using head-mounted displays. In our second Frontline Technology feature on this topic, titled "Recent Advances in Head-Mounted Light-Field Displays for Virtual and Augmented Reality," by Professor Hong Hua, we learn about the several methods beyond stereoscopic imaging that can be employed to create a true sense of depth and parallax for the observer. With this and the earlier mentioned article by Dr. Balram, I hope this issue becomes a go-to reference for you on this topic for a long time to come.

Closely aligned with the topic of light fields is the world of augmented and virtual reality, which has been more the stuff of science fiction than fact. But things are progressing rapidly, and that's why SID chose to make it a special topic focus track at Display Week this year. This AR/VR progress, along with other interesting information, is compiled for you in our "Display Week 2016 Show Daily Highlights" article this month. Contributing authors Achin Bhowmik, Jyrki Kimmel, Steve Sechrist, and Ken Werner give you a taste of the highlights ahead of the full show-issue coverage coming next month in *Information Display.*

Ahead of Display Week this year, the Bay Area SID chapter held a one-day marathon technical conference for people looking to catch themselves up on important topics within the field. Topics ranging from OLEDs, QLEDs, lasers, and e-Paper – all the way to black swans and microdisplays — filled the day with information, opinions, and creative ways of looking at our field. It sounds like such a great event, and one that I am sorry I missed, so we sought inputs from Sri Peruvemba, Paul Semenza, and John Wager, who along with our own Jenny Donelan put together this innovative conference review titled "One Day, Sixteen Speakers, Innumerable Insights." Both the event itself and the way we tried to cover it are different than what you may be used to, so I hope you enjoy this article.

Ray Soneira is well-known in our industry and a great supporter of both display measurement technology and the things that can be done with it – as evidenced by the work he has done through his company DisplayMate Technologies Corporation. We always appreciate Ray's insight and balanced opinions. He works hard to gather objective data on the performance of so many sizes, brands, and types of displays. This month, we welcome Ray back to the lineup with a Frontline Technology article on the subject of color gamuts titled "Display Color Gamuts: NTSC to Rec.2020." In this article, Ray describes the history of color gamuts as they have been created and adopted, along with the role they play in producing high-performance display products. It's a tricky subject because almost anyone close to the field has an opinion and those opinions can differ significantly. However, regardless of your point of view, I think we can all agree that the subject can be confusing, and it is rarely presented accurately and in the correct context by the commercial world. So, we welcome Ray back with his thorough treatment of this topic and thank him for his efforts to help clear the fog a little.

Along these lines, I will make one editorial comment of my own. Having been personally involved in developing color-matching programs for displays and dealing at length with the challenges of incorrect color rendering caused by the variations in display hardware, I would love to see the day when the entire concept of encoding RGB gray-level pixel values is set aside in favor of native methods such as those being proposed by Dolby and others. If the display itself knows what color gamut it can render and the video content arrives with each pixel encoded by *x, y* or *u', v'* and absolute luminance, then we have a better chance of the display device being able to render the content as close to its original intent as possible – provided, of course, the gamut of the display is suitably large enough. But regardless of what encoding scheme is used, color gamuts are fundamental to displays. Understanding what they mean and how they are used is crucial to designing a suitable display information system.

And so with that I'll sign off and wish you a great summer season. Oh, and about that personal-assistant robot – the last time I saw him he was visiting San Francisco and we snapped a picture of him for the cover of our July 2015 issue. After that he said he was going to tour the world and he has not come home yet. If you see him, ask him to call or write – he has my credit card. ■

THE DISPLAY INDUSTRY'S SOURCE FOR NEWS AND TECHNICAL INFORMATION

Event Date	Event Description	Closing Date
January/February	**Digital Signage, Materials** **Special Features:** Digital Signage Technology Overview, Digital Signage Market Trends, Oxide TFT Progress Report, Alternate Display Materials, Top 10 Display Trends from CES, Chinese Business Environment **Markets:** Large-area digital signage, in-store electronic labeling, advertising and entertainment, market research, consumer products, deposition equipment manufacturers, fabs	**December 28**
March/April	**Display Week Preview, Flexible Technology** **Special Features:** SID Honors and Awards, Symposium Preview, Display Week at a Glance, Flexible Technology Overview, Wearables Update **Markets:** Research and academic institutions, OLED process and materials manufacturers, consumer products (electronic watches, exercise monitors, biosensors), medical equipment manufacturers	**February 29**
May/June	**Display Week Special, Automotive Displays** **Special Features:** Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Insider's Guide to the Automotive Display Industry **Markets:** Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies	**April 21**
July/August	**Light Fields and Advanced Displays** **Special Features:** Overview of Light-field Display Technology, Next-generation Displays, Market Outlook for Commercial Light-field Applications **Markets:** Research institutions, market analysts, game developers, camera manufacturers, software developers	**June 20**
September/ October	**Display Week Wrap-up, Emissive Technologies** **Special Features:** Display Week Technology Reviews, Best in Show and Innovation Awards, Quantum Dot Update, A Look Forward at Micro-LEDs **Markets:** OEMs, panel makers, component makers, TV and mobile phone companies	**August 25**
November/ December	**Applied Vision** **Special Features:** Advanced Imaging Technology Overview, Current Key Issues in Applied Vision, Real-World Applied Vision Applications **Markets:** Medical equipment manufacturers, game developers, research institutions, OEMs, software developers	**October 24**

guest editorial

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light-field display is one that presents a light field to the viewer and enables natural and comfortable viewing of three-dimensional scenes. As explained in the article, for comfortable viewing a display needs to create a natural accommodation response for each eye that matches the convergence response in the human visual system, where these two are tightly coupled. There are two fundamental ways of doing this – either (1) by creating parallax across each eye that produces the appropriate retinal blur corresponding to the 3D location of the object being viewed (presenting multiple views per eye) or (2) by placing the object on the appropriate focal plane corresponding to its 3D location (providing multiple focal planes per eye).

Implementing either of these approaches, or a hybrid of them, requires tradeoffs that need to be made very carefully with the target application in mind. The most fundamental application choice is whether a display system is designed for group (multi-user) or personal (single-user) viewing. While many multi-user autostereoscopic displays may well be marketed as "light-field displays," light-field displays satisfying the above-mentioned definition will probably not be in mainstream use for a number of years. On the other hand, the significant simplification enabled by the single viewpoint design of a head-mounted (near-to-eye) display makes the use of light fields for virtual- and augmented-reality head-mounted displays a much likelier scenario in the next few years.

So, we focus on head-mounted displays in the second article of this issue, written by Professor Hong Hua of the University of Arizona, called "Recent Advances in Head-Mounted Light-Field Displays for Virtual and Augmented Reality." It describes the state of the art in three major approaches to achieving light fields with head-mounted displays – multiple focal planes, integral imaging, and multiple optical layers. Each of these approaches shows the promise of enabling a real product. At the same time, each approach clearly has tradeoffs and that means, for the foreseeable future, successful market entry will require careful design optimization for specific target segments, such as gaming, entertainment, education, training, healthcare, logistics, and banking. Even if a general consumer product that is the equivalent of the large UHD flat-panel TV is still some ways off, we can all expect to see light-field systems in different spheres of our lives in the next few years.

Goodbye, Flat World. Welcome to the Light Field!

__Dr. Nikhil Balram__ is President and CEO of Ricoh Innovations Corp. He can be reached at nbalram1@hotmail.com. ■

industry news

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LG Innotek Unveils Fingerprint Sensor Module without Button

LG Innotek recently announced an under-glass fingerprint sensor module, a departure from 'button-type' modules that require users to press a raised square or circular button for the fingerprint to be read accurately. To effect this, LG Innotek cut a shallow furrow of 0.01 in. (0.3 mm) thick on the lower back side of the cover glass and installed the fingerprint sensor inside it (Fig. 2).

With this module, the sensor is not exposed to the outside of the device, so the manufacturer can produce a sleekly designed smartphone. The fingerprint recognition area can be indicated by various patterns, according to the design of the product. The new module has a false acceptance rate (FAR) of 0.002%. ■

Fig. 2: LG Innotek's new fingerprint sensor is implemented under the display glass.

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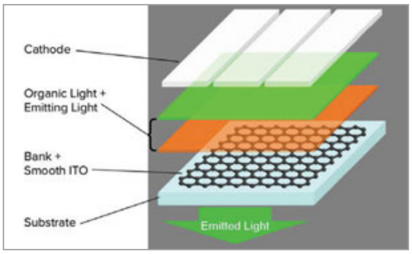

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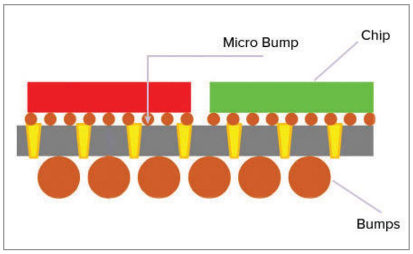

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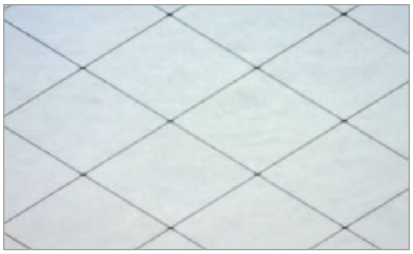

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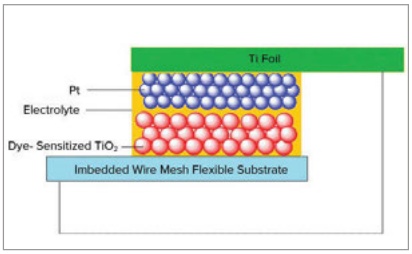

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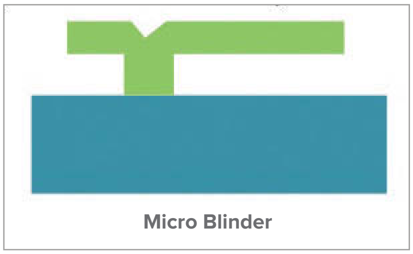

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