LIGHT-FIELD ISSUE

Information DISPLAY

SID
SOCIETY FOR INFORMATION DISPLAY

Official Publication of the Society for Information Display • www.informationdisplay.org

Nov./Dec. 2017
Vol. 33, No. 6

Rendering Methods for Light-Field Displays

EXTREME MULTIVIEW: MAKING IT REAL

FOVEATED PIPELINE: THE EYE HAS IT

Plus

AR/VR Breakthroughs

Market Outlook for Stretchable/Flexible Technology

WILEY

SID
SOCIETY FOR INFORMATION DISPLAY

Information DISPLAY

NOVEMBER/DECEMBER 2017
VOL. 33, NO. 6

ON THE COVER: *Display hardware elements continue to advance, enabling us to make better light-field displays. The generation of the light-field radiance image remains a bottleneck, however. Solutions designed to tackle this challenge include foveal rendering, which is designed around the human visual system.*

Cover Design: Acapella Studios, Inc.

In the Next Issue of *Information Display*

Lighting Issue

- OLED Adoption in General and Automotive Lighting
- Biological Effects of Lighting
- Lighting Market Outlook
- Metrology of Curved Displays

INFORMATION DISPLAY (ISSN 0362-0972) is published 6 times a year for the Society for Information Display by Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; William Klein, President and CEO. EDITORIAL AND BUSINESS OFFICES: Jenny Donelan, Editor in Chief, Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; telephone 212/460-9700. Send manuscripts to the attention of the Editor, *ID*. SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008; telephone 408/879-3901, fax -3833. SUBSCRIPTIONS: *Information Display* is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues $100.00). Subscriptions to others: U.S. & Canada: $75.00 one year, $7.50 single copy; elsewhere: $100.00 one year, $7.50 single copy. PRINTED by Wiley & Sons. PERMISSIONS: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limits of the U.S. copyright law for private use of patrons, providing a fee of $2.00 per article is paid to the Copyright Clearance Center, 21 Congress Street, Salem, MA 01970 (reference serial code 0362-0972/17/$1.00 + $0.00). Instructors are permitted to photocopy isolated articles for noncommercial classroom use without fee. This permission does not apply to any special reports or lists published in this magazine. For other copying, reprint or republication permission, write to Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008.

contents

For Industry News, New Products, Current and Forthcoming Articles, see www.informationdisplay.org

editorial

Beginning to See the Light (Field)

by Stephen P. Atwood

Our attention this month is drawn to light-field technology and the promise of a high-resolution, true-3D display experience that includes occlusion and perspectives – just like in real life! Often dreamed about and frequently represented in science fiction movies, the real thing has proven elusive all these years, due to countless architectural problems that are just now beginning to yield themselves to relentless engineering efforts.

Guest editor Nikhil Balram is back this year to bring us two more excellent features on some practical advances in the field. With these advances, we seem to be marching ever closer to commercial viability. You should start by reading his guest editorial to learn his perspective on the current state of the field. And I just want to say thank you to Nikhil for all his effort and support while building this issue.

The Holy Grail, as they say, is a full-360º viewable display that can render any scene just as it would appear in real life. In our first Frontline Technology feature, author Thomas Burnett describes the various challenges facing light-field developers, including the total data volume that would be necessary to create this type of display. To overcome some of these challenges, he proposes a new graphics pipeline and a distributed-processing architecture that just might unsnag some of the bottlenecks with traditional approaches. Read the details in "Light-Field Displays and Extreme Multiview Rendering." Thomas analyzes this challenge from a number of different angles. Even with some very clever methods, the rendering times and total data requirements might seem onerous, but we're in a time when computing power is still growing exponentially and the cost of processing continues to fall, so the gap is closing.

Consider, for example, his proposal for arrays of multiview processing units (MvPUs) that can reduce the proposed approaches to silicon and can operate independent of any upstream information management hardware. Dedicated MvPUs, currently under development, can then directly drive assigned sections of the light-field optical array, and a massively parallel light-field image rendering system can be realized. This system would then run with an object-oriented graphics API Object GL language, also under development. This is promising work and well worth the effort and optimism invested in it.

While many people are working on the options for multiview displays, others are focused on single-view AR/VR headsets that also produce a lifelike real-world visual experience. But once again, the challenge of total data volume and bandwidth presents itself as a seemingly unyielding constraint. However, one of the advantages of a headset display is that there is only one observer and you can take special liberties with the presentation if you know exactly where that observer's eye gaze is focused. This is because, as authors Behnam Bastani *et al*. explain, "Primary image capture receptors in the retina are concentrated in a narrow central region called the fovea. The image that is acquired at each instant produces high information content only in the foveal region." In other words, only a very narrow region of your eye, and hence a very narrow field of view, can see high definition. Because of this unique characteristic, the authors propose a "Foveated Pipeline for AR/VR Head-Mounted Displays."

You might think of it as a round portal in the center of the image that is rendered at the highest possible resolution while the rest of the surrounding area can be rendered at much lower resolution without impacting the observer's perception of the image.

(continued on page 32)

Information DISPLAY

Executive Editor: Stephen P. Atwood
617/306-9729, satwood@azonix.com

Editor in Chief: Jenny Donelan
603/924-9628, jdonelan@pcm411.com

Global Ad Director:
Dan Nicholas, dnicholas@wiley.com

Senior Account Manager
Print & E-Advertising:
Roland Espinosa
201/748-6819, respinosa@wiley.com

industry news

By Jenny Donelan

United Technologies to Acquire Rockwell Collins for $30 Billion

Aircraft-parts suppliers United Technologies Corp. (UTC) and Rockwell Collins recently announced that UTC will acquire Rockwell Collins for $30 billion, or $140.00 per share in cash and UTC stock.[1] According to *Bloomberg Technology*, the combination of Boeing's second-largest supplier (UTC) with its ninth (Rockwell Collins) should give the new entity, Collins Aerospace Systems, considerable clout in negotiating with Boeing as well as with other customers, including Airbus SE.[2]

Bloomberg also noted that the new company will achieve near "one-stop-shop" status in terms of parts. Rockwell Collins is known for its avionic displays, flight controls, and aircraft interiors. Display products for avionics include "head-down" industrial-grade flight-deck displays with full-color-graphics video as well as night vision capability and sunlight compatibility. These displays are used in a majority of the world's commercial and military aircraft. Rockwell Collins also makes head-up displays used by international military tankers/transports, airlines, and flight-training companies, and it makes helmet-mounted displays for pilots, on-ground military personnel, and simulation and training applications.

UTC makes flight actuators, Pratt & Whitney jet engines, and much more. The deal is expected to close by the third quarter of 2018.

[1]https://rockwellcollins.com/Data/News/2017-Cal-Yr/RC/20170904-United-Technologies-to-Acquire-Rockwelll-Collins.aspx
[2]www.bloomberg.com/news/articles/2017-09-04/united-technologies-is-said-in-deal-to-buy-rockwell-collins

The Phones of Fall

As usual, Apple announced a new line of smartphones in September, including its first-ever OLED-based unit. Samsung and LG had new flagship offerings as well: the Galaxy Note 8 and the LG V30, respectively.

The most talked about of these phones may not end up being the one most bought, owing to its $999 price tag, which breaks new ground in terms of smartphone pricing. The iPhone X (Fig. 1), due to ship around press time, features a 5.8-in. screen with almost no bezel, except for a notch housing sensors, cameras, speakers, *etc*. at the top of the display. This notch has been variously described as a bug or a feature. Since it is theoretically possible to incorporate the sensors into the bezel, as other manufacturers have done, some reviewers, including *The Verge*,[3] surmise that the notch may be an intentional design meant to replace the circular home button (now gone) in visually differentiating the iPhone from other devices.

The OLED display, which Apple calls Super Retina HD, has a resolution of 2,436 × 1,125 and provides outstanding imagery. (Since Apple's OLED panels are produced by Samsung, they should be at least as impressive as those in the Galaxy Note 8 described below.) The phone also features facial ID and Apple's Animoji application, which allows users to create customized emojis using facial recognition software. There are also a new iOS, wireless charging, and Apple's all-new A11 bionic chipset.

Fig. 1: Apple's iPhone X features a minimal bezel with a distinctive and/or controversial notch at the top for the phone's cameras, sensors, and speakers. Image courtesy Apple.

Along with the iPhone X, Apple introduced the iPhone 8 and iPhone 8 Plus, which are LCD-based upgrades of the iPhone 7. The new phones have wireless charging, fast performance, and upgrades to the camera, screen, and speakers. Their starting storage size is 64GB, double that of the iPhone 7. The 4.7-in. iPhone 8 and the 5.5-in. iPhone 8 Plus start at $699 and $799, respectively.

The Galaxy Note 8 (Fig. 2) is another recently released big, beautiful, expensive phone. It arrives amid high expectations, as the comeback device for the well-regarded but ultimately recalled Note 7. (In the wake of the Note 7's battery problems, Samsung has established a multipoint battery safety check for these devices.) This phone has a 6.3-in. OLED-based, 1,440 × 2,690-pixel "Infinity Display," 6GB of RAM, two best-in-class rear cameras, and a price tag approximately $50 less than the iPhone X's.

LG Electronics began shipping its new LG V30 smartphone to customers in its home country of South Korea in September, with rollouts in America, Europe, and other key markets scheduled throughout fall of 2017.

LG's engineers fit its 6-in., 18:9, 1440 × 2880 FullVision (OLED) display into a bezel that is 8 mm shorter and 3 mm narrower than the phone's predecessor (Fig. 3).

Fig. 2: The Galaxy Note 8 comes with the S Pen, which enables freehand drawing, note-taking, highlighting, and more.

(continued on page 34)

guest editorial

Solving the Rendering Puzzle

by Nikhil Balram

The last special issue we did on light fields, back in July/August 2016, provided an overview and update on light-field displays. We divided these into two categories – displays for group viewing and displays for personal use (head-mounted displays, or HMDs) – because of the distinctly different challenges and trade-offs in a display meant for many users to view simultaneously, *vs*. just one. In either case, the objective was to present a representation of "the light field," the radiance that emanates from every point in the world and is visible to the human eye.

Display hardware elements continue to advance, with panels that have higher spatial resolution and faster response times, and with optics incorporating higher-quality lenses and fast-switching variable focus elements, enabling us to make better light-field displays. But there is another big bottleneck upstream – the generation of the light-field radiance image. In this special issue, we look at the state of the art in rendering for light-field displays, as well as major directions being followed to address the big challenges.

The first article in this issue, "Light-Field Displays and Extreme Multiview Rendering" by Thomas Burnett, provides an overview of the architecture of fully featured, group-viewable light-field displays, such as a light-field table that might be used by a roomful of generals to view a battlefield simulation, or a bar full of sports fans to watch a World Cup soccer match. Creating a rich and deep light-field volume requires a large number of views (pixels) per microlens element (hogel), possibly as many as 256 × 256 or even 512 × 512. Traditional graphics pipelines are not designed for such extreme multiview rendering and are extremely inefficient when thousands of render passes may be necessary to update a display.

Thomas's article explains the most suitable rendering algorithms for such extreme multiview light fields and the major bottlenecks they face. He proposes a new scalable processing architecture, the heterogeneous display environment (HDE), where the major portions of the graphics pipeline are separated into host and display-processing elements. The host is used to compute the scene geometry and send a high-level description of this to various displays using a newly proposed object graphics language (ObjGL) application programming interface (API). Each display is responsible for its own rendering using one or more newly defined multiview processing units (MvPUs) optimized for extreme multiview rendering.

In the case of HMDs, only a single viewpoint, the so-called "first-person perspective," needs to be generated. This enables a significant simplification of the light-field volume by approximating it with a discrete set of focal planes ("multifocal plane display") or even just one that is adjusted dynamically based on where the user is gazing ("varifocal display"). The big challenge in rendering lies in the limited compute and thermal budget available on a mobile system.

In his keynote speech at Display Week 2017, Clay Bavor, VP for VR and AR at Google, talked about the need for very high pixel counts to approximate human visual acuity in VR and AR displays and the challenges of driving these. He reminded us that despite the rich nature of the world image we perceive, the optic nerve that conducts a representation of the image captured by the retina to the visual cortex for processing only has a bandwidth of ~10 Mb/s. This elegant information-processing architecture

(continued on page 34)

SOCIETY FOR INFORMATION DISPLAY

1475 S. Bascom Ave., Ste. 114
Campbell, CA 95008
408/879-3901
e-mail: office@sid.org
www.sid.org

Light-Field Displays and Extreme Multiview Rendering

Light-field displays have moved beyond the realm of science fiction, with prototypes now existing in the real world. Light-field computation, however, is the barrier to deployment. The sheer number of pixels required to produce high-fidelity light-field content at a reasonable cost represents a daunting though not unsolvable problem.

by Thomas Burnett

If science fiction movies are any predictor of the future, then light-field displays are inevitable. In past years, rockets, moon landings, and self-driving cars were foretold in popular sci-fi media. In fact, it is hard to recall a recent sci-fi movie without a light-field visualization system at the center of a battle-space planning session or medical procedure visualization. And if battle-space and medical visualization become reality, then viewing of sports and other forms of entertainment in the home is also inevitable, since these visualization challenges are a subset of the aforementioned applications.

A light-field display produces 3D aerial imagery without head tracking and/or eyewear by reproducing the light that would reflect off an object if it were physically present in front of the viewers. A light-field display computes the synthetic light rays from a 3D model/scene in the form of pixels, which are subsequently converted to photons by a very high-density spatial light modulator (SLM). The projected photons/rays are then angularly distributed by a lensing system without regard to the number of viewers, viewer position, or viewer gaze direction.

There have been research studies highlighting the cognitive benefits of 3D light-field visualization. In 2013, Dr. Matthew Hackett at Army Research Labs in Orlando, FL, produced a study comparing medical anatomy training using traditional 2D photos *vs*. using 3D light-field holograms, and concluded there was a significant decrease in the cognitive load on the student and an increase in memory retention with the 3D holograms.[1] Similarly, a 2009 study investigating geospatial light-field holograms on SWAT team routing planning and wayfinding performance concluded that 3D holographic topographic maps increased mission performance within complex 3D operational environments.[2]

These kinds of studies highlight the key benefits of perspective-correct, full-parallax, 3D aerial light-field projections. With a projected 3D scene including the essential depth cues expected by the human visual system, such as occlusion, specular highlights, and gradient shading, a viewer can decompose a complex 3D scene into a more memorable experience or more actionable intelligence. By presenting a 3D aerial scene in a manner expected by the viewer, the cognitive load on the viewer is decreased, allowing him to make better decisions with greater confidence. In addition, since light-field displays project 3D aerial imagery without head-mounted glasses to interfere with natural communication, the level of collaboration among viewers increases (Fig. 1). This is why light-field displays are inevitable.

Light-Field Display Architecture

The light-field display architecture shown in Fig. 2 consists of four major subsystems:[3]

- ***Hogel optics*** refers to the array of micro-optics responsible for angularly distributing the light-field rays. The light-field display projection frustum is the union of all the micro-frustums of all the microlenses. From any position in the light field, a viewer sees a single ray projected from each microlens. The term "hogel," which stands for holographic element, is used to describe the 2D set of ray data projected through each microlens.
- The ***photonics subsystem*** is an array of SLMs whose function is to convert pixelized ray data (the hogel) into actual light rays. Pixel density at the combined SLM image plane is essential to projecting high-fidelity 3D aerial imagery, assuming the pixel-ray data can be preserved when angularly distributed by the hogel optics.

*As the software lead at Zebra Imaging, **Thomas Burnett** was a key contributor in the development of static light-field topographic maps for use by the Department of Defense in Iraq and Afghanistan. More recently, he launched a new light-field display development program at FoVI^{3D}, where he serves as CTO. He can be reached at tburnett@fovi3d.com.*

0362-0972/6/2017-006$1.00 + .00 © SID 2017

- The ***drive electronics subsystem*** manages the pixel hogel data delivery and synchronization across SLMs. In addition, the drive electronics perform spatial distortion and color corrections on a per-hogel basis.
- ***Radiance image computation*** is the subsystem responsible for rendering or computing the light-field rays from a 3D model/scene. The update rate of the light-field display is a function of the input model complexity (number of polygons, textures, materials, and their representation, *etc*.), the number of compute elements in the cluster, and the number of hogel views rendered to complete the radiance image.

The radiance image computation subsystem receives a 3D model from a host application. This differs from traditional display systems in which the host application dictates draw commands to a closely bound graphics processing unit (GPU) that in turn renders a video stream to the display. By passing the scene to the radiance image computation system, rendering the 3D aerial image becomes the responsibility of the light-field display.

Light-Field Rendering: In the context of the light-field display, light-field rendering is the process by which the synthetic light-field radiance image is rendered. The light-field radiance image is a raster description of a light field where pixels represent the origin, direction, and intensity of light rays within the light field as described by the plenoptic function in equation (1):[4]

$$L = P(\Theta, \varphi, \lambda, Vx, Vy, Vz) \quad (1)$$

Whereas a light-field camera captures the light-field radiance image by segmenting incoming light through a microlens array, thus preserving spatial and angular details of rays in the form of pixels, the light-field display computes a synthetic radiance image from a 3D scene/model and projects the radiance image through a microlens array to construct a 3D aerial image.[4] Binocular disparity, occlusion, specular highlights, gradient shading, and other expected depth cues within the 3D aerial image are correct from the viewer's perspective as in the natural, real-world light field.

The light-field display radiance image consists of a 2D array of hogels, each of which represents the direction and intensity of light rays passing through the hogel center (Fig. 3). Consequently, a hogel is a radiance microimage for a single microlens depicting the scene as projected onto the top plane of the microlens frustum.

The light-field display radiance image is similar to the radiance image as captured by a plenoptic camera; however, the hogel can represent light rays originating from either side of the light-field display hogel plane. This capability effectively doubles the projection depth potential of a light-field display. The light-field display radiance image is synthetically constructed by rendering hogel views from the perspectives of an array of microlenses defined in world space. As such, it requires not only a 3D model of a scene as input, but also a 3D model of the microlens array transformed into the world space of the radiance image rendering engine. Since the radiance image is composed of a microimage for each microlens, many hogel views are rendered to create one radiance image per update of the light-field display.

Fig. 1: *Light-field display use cases include battle-space planning (left) and gaming/sports visualization (right).*

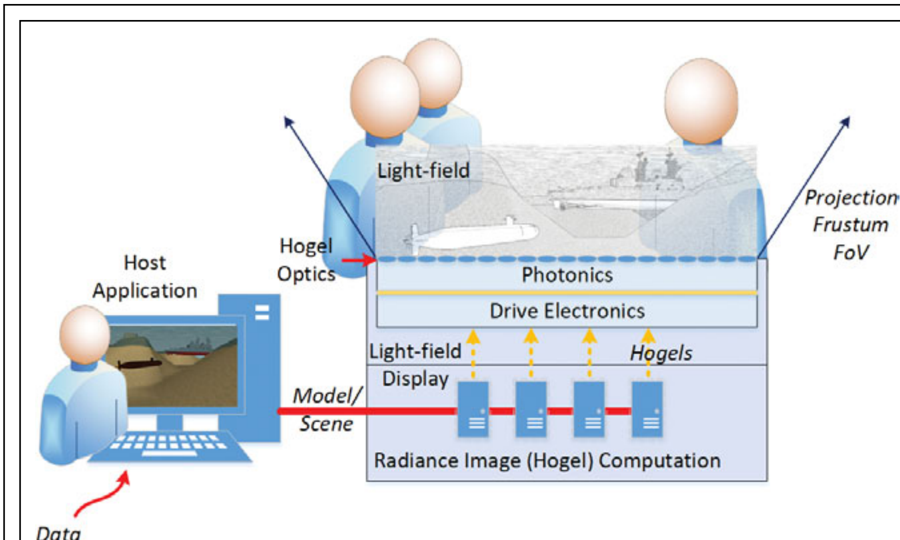


Fig. 2: *This light-field display architecture schematic highlights the four major subsystems of the display system: hogel optics, photonics, drive electronics, and radiance image computation.*

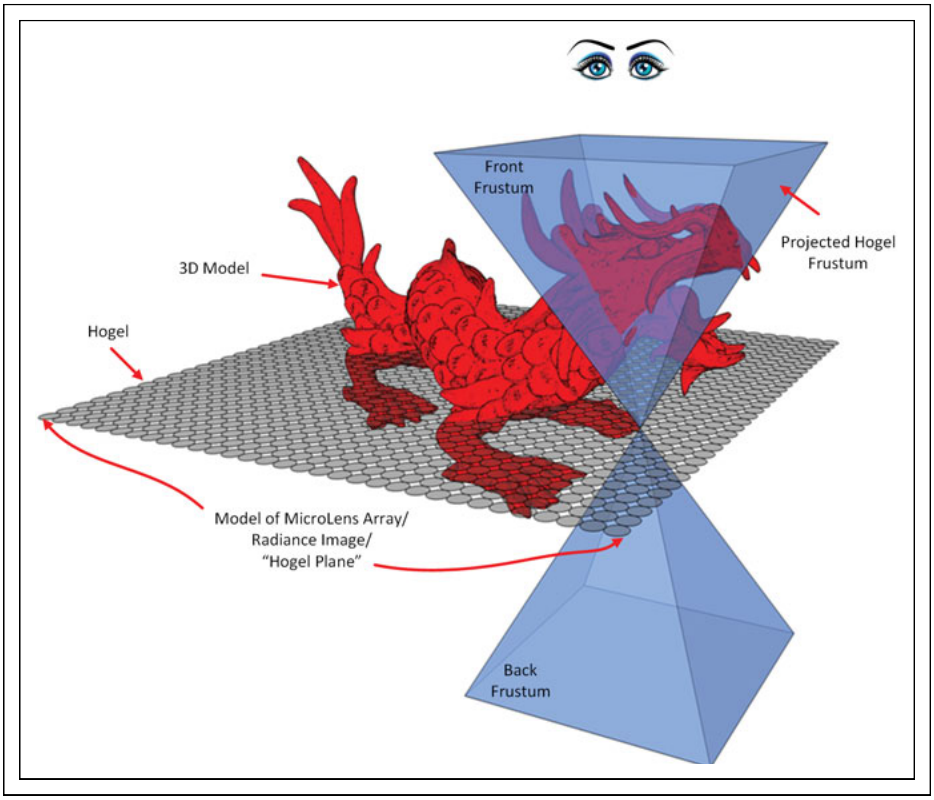


Fig. 3: *Above is a double-frustum hogel projection of a single hogel. The radiance image is a 2D array of these hogels.*

Light-Field 3D Aerial Fidelity: The radiance image is converted into light/photons by an array of SLMs, which project the light rays through an array of microlenses (hogel optics). The microlenses angularly distribute the radiance image light rays to construct a full-parallax 3D aerial image. As the pixels project through a microlens array, the resulting projected 3D image exhibits the classic light-field spatial/angular trade. In essence, the size, arrangement, and number of microlenses within the array defines the spatial resolution at the image plane of the light-field display. The number of pixels behind each microlens (the hogel size) determines the potential depth projection and resolution characteristics at height within the 3D aerial image.

The term directional resolution (Dr) is often used to describe the number of views that a hogel microlens can project along one axis. The total number of rays that are projected through a hogel is Dr × Dr. Angular pitch (Ap)[a] is a measure of the angular beam spread/divergence and is determined from the directional resolution and microlens field of view (FoV) by equation (2):

$$Ap = \frac{FoV}{Dr} \tag{2}$$

Increasing the pixel density behind each hogel can potentially increase 3D aerial image fidelity and achievable depth if the detail can be preserved when angularly distributed by the microlens array. Therefore, having small angular pitch is desirable and Ap can be used to describe a display's ability to project detail at height above the display plane. However, 3D spatial resolution, projection accuracy, color fidelity, and brightness degrade as the projection distance from the image plane increases.

Light-Field Rendering Algorithms

There are a few processes for generating hogel data (rendering the radiance image); the difference between the two most common rasterization approaches is the order in which they decompose the 4D light field (two dimensions of position, two dimensions of direction) into 2D rendering passes. The most direct rasterization method is by use of the double-frustum hogel-rendering algorithm, which processes all directions for a single hogel simultaneously.[5] A second algorithm, known as oblique slice and dice, processes all the rays for a single direction simultaneously and is better suited for small-area displays that can afford a huge pixel transform.

Double-Frustum Hogel Rendering: Double-frustum rasterization of the radiance image entails placing the virtual camera at the hogel center in world space and rendering the scene downward from the display plane; the camera is then flipped and rendered upward without clearing the depth buffer. The front camera is rendered preserving triangles farthest from the camera, thus closer to the viewer. When the two views are combined via their depth buffers, the hogel "bowtie" frustum is created (Fig. 3). The "bowtie" frustum represents the direction and intensity of light passing through the hogel center; thus, the rendered viewport is the hogel. This process is repeated for every hogel for every update of the scene.

The double-frustum algorithm has the advantage of rendering a hogel natively, in that the hogel can be subsequently projected with no further processing. However, the double-frustum algorithm does require two passes of the geometry to create the double frustum and there can be a mathematical singularity at the center of the bowtie.

At least within the fixed-function OpenGL render pipeline, the camera matrix cannot have a non-zero near plane. Any geometry that passes between the near planes of the front and back frustums is clipped. One way to resolve this issue is to offset the front and back frustums so that the near planes overlap. This negates the singularity in most cases, but is not a perfect solution in that the center of the bowtie becomes a small plane that can still exhibit mathematical anomalies that result in corrupted hogels.

Oblique Slice and Dice Hogel Rendering: The oblique slice and dice algorithm uses an orthographic camera projection with a shear applied to render all the pixels for a particular

[a]In a previous article, we had referred to this measurement as angular resolution. Angular Pitch is a better descriptor. Angular resolution would be better defined as *Dr/FoV*.

view direction during each pass of the geometry. The shear matrix is adjusted for each projection direction the light-field display can produce (Fig. 4). A display that has a 90° FoV with 256 × 256 pixels (rays) per hogel would require 256^2 render passes with a -45° to 45° shear applied in 2 dimensions in (90/256) increments.

Oblique rendering typically makes better use of the GPU in that the algorithm renders to larger framebuffers within GPU memory, and in some cases, requires fewer passes of the geometry than the double-frustum algorithm. However, the rendered pixels are not in a spatial form that can be projected through a microlens array and must undergo a pixel transform from oblique render space to hogel space (Fig. 4).

The pixel transform requires either a buffer that stores the entire rendered oblique data in advance of the pixel transform, which needs its own destination buffer of equal size; or a pixel transform engine that requests views that are rendered on demand and partially transformed depending on the available memory to store complete hogels. In the latter case, views are often re-rendered many times so that all the available memory is preserved for assembling as many hogels as possible per light-field display update. If the memory is not all co-located within a single computer and is spread across multiple machines, then the pixels must be pushed across an interconnect framework, which greatly increases the time to perform the pixel transform. As such, oblique slice and dice is not as usable in real-time solutions as double-frustum rasterization for large-area light-field displays.

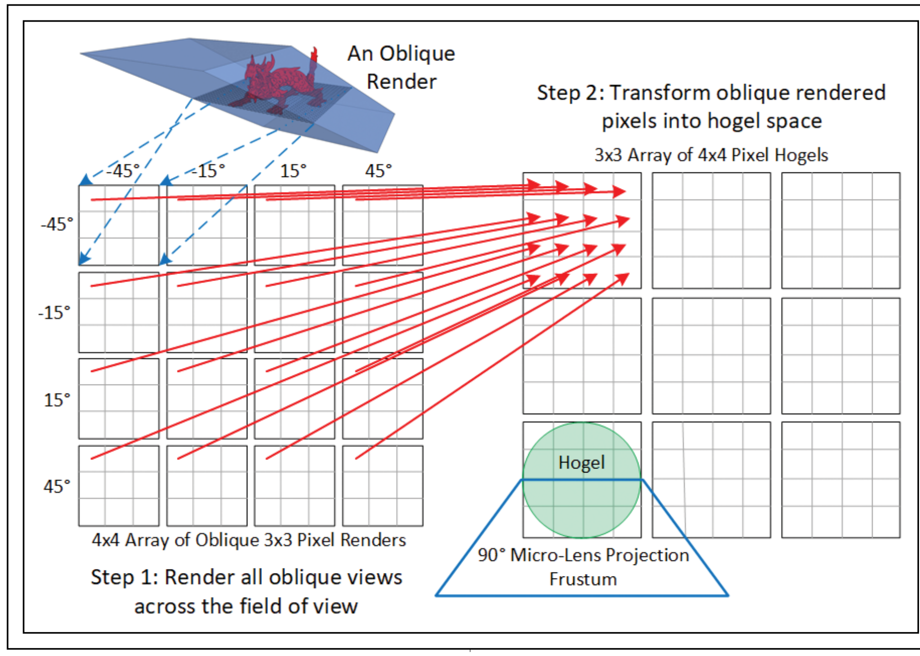


Fig. 4: *Oblique view projection incorporates pixel transform. Step 1 is rendering all the views; Step 2 transforms the pixels into a format for projection through a microlens array.*

Light-Field Radiance Image-Render Acceleration

There are several high-level processes by which the light-field display radiance image rendering can be accelerated. However, these optimizations are controlled by the central processing unit (CPU) side of multiview rendering and require implementation and management within the host application and/or render engine. In addition, their effect on the radiance image-render rate is different depending on the hogel-rendering algorithm.

Bounding Volumes: Bounding volumes are a standard mechanism used to accelerate rendering. Bounding volumes of geometric entities within the scene are checked for intersection with the virtual rendering camera; only geometries whose bounding volumes intersect the camera frustum are rendered. The double-frustum algorithm benefits significantly since the clipping frustum is tightly bound to a hogel's projection frustum, and only hogels whose frustums intersect the bounding volume of changed geometry need to be rendered. The oblique-view-clip frustum contains all the rays from each hogel in a particular direction; thus, oblique clip frustum is highly likely to intersect changed geometry whether or not an individual hogel frustum actually intersects that geometry. Therefore, bounding volumes have less impact (or no impact) on the oblique rendering rates.

Table 1 highlights an example of the effect of bounding volume rendering on a mountainous terrain model consisting of 1,340,190 triangles. The terrain mesh was batched into triangle strips with bounding volumes to enable intersection tests. The radiance image rendered consisted of 500 × 500 hogels, each having 256 × 256 pixels for a total of 16,384,000,000 pixels. When rasterizing the whole-terrain radiance image, the double-frustum algorithm benefited greatly from small batch size; the oblique algorithm render rates did not vary significantly with the batch size. Again, it bears mention that the oblique data would still need to undergo the pixel transform into hogel space before display.

Foreground/Background Segmentation: Since the collaborative light-field display is typically used to offer a top-down view into a scene, there are usually two modes in which the view-volume transform is used. Either the view-volume transform is related to a particular object transform by which the light-field projection follows an object, or the view-volume transform is independent of any object and in many cases rarely updated.

Consider that if the light-field display were used to project a football game, one mode of operation would be when the display-view volume is fixed to encompass the entire field and the other visualization mode follows a player. If the field, player, and ball geometry were separately defined as foreground and background objects, then triangles would only need to be rasterized when transformed. If the view-volume transform was set once, then the background geometry would only need to be rendered once. The geometry in motion (players and ball) would be rendered every cycle. This technique requires appropriate layer fusion capabilities within the display; however, the segmentation of geometry is defined within the host application.

Table 1: Below are render times for 500 × 500 hogel (256 × 256 pixels) radiance imagery.

Algorithm	~Batch Size (Triangles)	# Bounding Volumes	Hogels per second	Render Time (seconds)
Double Frustum	3,000	441	3,691	68
Double Frustum	20,000	64	1,839	136
Double Frustum	83,000	16	842	297
Double Frustum	1,330,745	1	432	579
			Frames per second	
Oblique: W/O Transform	3,000	441	689	95
Oblique: W/O Transform	20,000	64	829	79
Oblique: W/O Transform	83,000	16	842	78
Oblique: W/O Transform	1,330,745	1	848	77

Multiview (Hogel) Rendering

3D displays require the generation of more than one view per update of the display. At a minimum, stereo projection requires two views. Lenticular, multidepth plane, and volumetric displays are examples of multiview displays, while collaborative light-field displays that project radiance images could be classified as extreme multiview displays. With regard to display projection systems, there are two viewing perspectives to be considered for multiview 3D displays: first-person perspective and display-centric perspective.

First-Person Perspective: The first-person perspective renders the scene relative to a single viewer. The first-person view is the normal view users expect when viewing any 2D video source or 2D/3D game on a standard 2D monitor. In reality, any scene projected/rendered from a single reference point and orientation is in effect first-person. This includes stereo-rendered VR/AR (including multifocal plane) views for head-mounted displays (HMDs).

Display-Centric Perspective: The display-centric perspective defines a position and orientation of a view volume whereby the scene is rendered from the perspective of the display (as opposed to the viewer). The view-volume definition consists of the half-widths of a bounding rectangle and a model transform. A display that renders outward in a cylindrical or spherical sense from the center of a defined volume will require a display-centric volumetric definition. A light-field display, such as the LfD DK2 from the author's company, FoVI^{3D}, reduces the volumetric definition to a 2D image plane in 3D space from which the radiance image is rendered. Lenticular or similar displays that offer parallax viewing solely in one dimension still require a volumetric or image-plane definition, as a line segment defined in 3D space has no orientation.

Radiance-image rendering using the double-frustum algorithm requires the identification of a plane within the view-volume definition that can be used to calculate and describe the hogel transforms in world space from the point of view of the hogel. For example, equation (3) describes the transform from normalized hogel space to hogel camera position and orientation in world space.

$$vHPws = [mTws][mTms][2 * hWms][vHn] \quad (3)$$

Where $vHPws$ is the transformed hogel position (glm::vec3) as defined within the view volume in world space, vHn is the normalized (-0.5 to 0.5) hogel position (glm::vec3) within the display plane, $hWms$ is the halfwidth (glm::vec3) of the view volume defined in model space, $mTms$ is the model space view volume transform (glm::mat4), and $mTws$ is the world space view volume transform (glm::mat4).

To implement multiview rendering with a graphics processing unit (GPU) requires that the host application dispatch a render pass for each viewpoint required for the projection system. Therefore, the cost of radiance image rendering in terms of power and time is a function of the number of microlenses, the number of GPUs rendering the radiance image, and the complexity of the input model. Ultimately, the size, weight, and power (SWaP) requirements of a light-field display are largely a factor of radiance-image computation.

The radiance image in Fig. 5 contains 50 × 50 hogels, each with 40 × 40 pixels (rays). It was rendered to project through a 90° FoV microlens. Double-frustum rendering entails rendering 5,000 (50 × 50 × 2) views into 40 × 40 pixel viewports to update the display once. Oblique slice and dice rendering entails rendering 1,600 (40 × 40) views into 50 × 50 pixel viewports and then a 12MB (50 × 50 × 40 × 40 × 3) cache unfriendly byte transform from oblique space to hogel space.

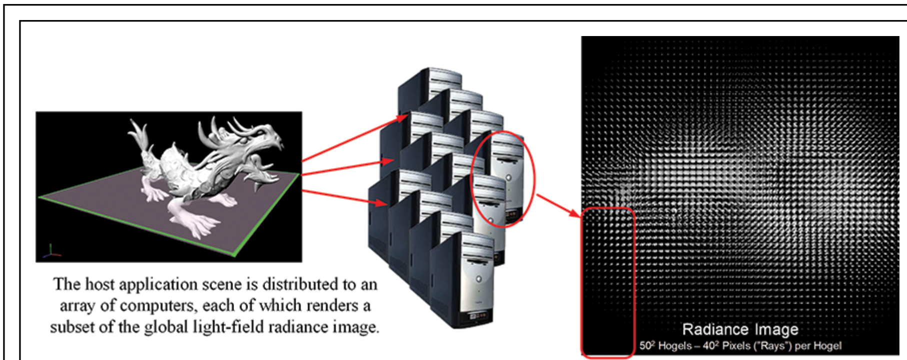


Fig. 5: *In this distributed radiance image rendering, each render box renders a subset of the global radiance image.*

Table 2 highlights the challenge of radiance image rendering for a 500 × 500 mm^2 display consisting of 1mm^2 hogels, comparing the number of render passes of both the double-frustum and oblique algorithms, and the number of red/green/blue (RGB) bytes rendered. While it is possible to reduce the rendering load by spatially and/or temporally subsampling rendered views or by tracking viewer head/eye position and orientation, these solutions can introduce additional artifacts into the light-field projection that degrade the visualization experience and, in some cases, inhibit collaboration. What should be obvious, though, is that light-field rendering is extremely parallelizable.

Table 2: Magnitude of radiance image rendering

	Width	Height				
Display Size (1mm hogels)	500	500				

	Directional Resolution		Single-Frustum Render Passes	Double-Frustum Render Passes	Oblique	Total RGB Bytes
Low Resolution	64	64	250,000	500,000	4,096	3,072,000,000
Medium Resolution	128	128	250,000	500,000	16,384	12,288,000,000
High Resolution	256	256	250,000	500,000	65,536	49,152,000,000
Very High Resolution	512	512	250,000	500,000	262,144	196,608,000,000
Extreme Resolution	1024	1024	250,000	500,000	1,048,576	786,432,000,000

Radiance Rendering Parallelization

There are two assumptions that preface the following discussion on radiance-rendering parallelization:

1. At the very least, the double-frustum render could be reduced to render both front and back frustums in a single pass of the geometry with a custom rasterizer. This results in a 2× hogels rendered per second (HPS) rate improvement (Table 2: SingleF column).
2. In a simple battle-space rendering test with a terrain mesh and Phong shading from a single light source, the render pipeline is either dispatch- or vertex-transform limited and not fragment-processing limited. This implies that the destination viewport size is not a primary factor for either double-frustum or oblique rendering rates.
   a. For this double-frustum rendering test, mesh-terrain files were loaded into batched triangle strips complete with bounding volumes to enable visualization tests; the render rates in terms of HPS did not change significantly when double-frustum rendering 128 × 128 pixel hogels or 1024 × 1024 pixel hogels.
   b. The majority of the light-field battle-space and medical applications depicted in movies have very simple lighting. While these scenes are currently fiction, they do foretell a use case/need where 3D spatial relationship is more important than rendering pixels with complex lighting and/or special effects.

Multi-GPU Parallelization: With Table 2 in mind, consider that if 20 GPUs are employed for radiance-image rendering, each owning render responsibility for an independent subset of the global radiance image, each GPU would have to render 12,500 (500 × 500/20) views in the optimized double-frustum render. The number of renders required by each of the 20 GPUs for oblique rendering would not change (each GPU would still have to render 500 × 500 views); only the size of the destination viewport would vary. As such, for example, the number of oblique-render views for the "medium resolution" radiance image in Table 2 exceeds the number of optimized double-frustum renders (16,384 > 12,500). In addition, the oblique-rendered radiance image would undergo a 614,400,000-(12,288,000,000/20) byte transform per GPU into hogel space before display.

Multiview Render Parallelization: The concept behind multiview render parallelism is to render as many views as possible per triangle dispatch. The ultimate goal is to responsibly relieve the host CPU from multiview rendering. This requires that a GPU-like device maintains a list of view transforms with corresponding viewports and applies any distortion corrections required by the optical system automatically within a specialized rendering pipeline.

One of the primary issues with multiview rendering across an array of GPUs is that the update rate of the host application becomes tied to the update rate of the multiview display. This occurs because the geometric definition of a scene cannot change during a display rendering cycle. If a multiview display rendering engine takes 10 seconds to render all views, then the host application rendering engine stalls for 10 seconds to preserve GPU cache integrity.

Once multiview rendering becomes the responsibility of the display using a GPU-like device, then the host CPU update rate is no longer dependent on the multiview renderer. In essence, the host application becomes loosely bound to the update rate of the display as long as the GPU-like device maintains a list of geometry cache updates to be applied between render cycles. Light-field (multiview) rendering then becomes the responsibility of the "display," and the host application has no knowledge or concern with regard to views being generated.

The Heterogeneous Display Environment

Decoupling the host application from the display enables the heterogeneous display environment (HDE) (Fig. 6). Within the HDE, the host application executes blindly without knowledge of the number or architecture of attached displays. Consider the previously described football game scenario in which a server is broadcasting an "e-sport" football game. The viewer should be able to watch the game on any display device, whether head-mounted stereo, volumetric, or light field. This scenario implies a few key concepts.

The first is that the e-sport game broadcast consists of geometric model data and not prerendered pixels. Prerendered pixels imply a particular singular-view orientation that may not be conducive to all display architectures. For example, a prerendered view from the quarterback's perspective is not conducive to generating a god's-eye view for a light-field display. Likewise, the prerendered light-field field is way too many pixels (even com-

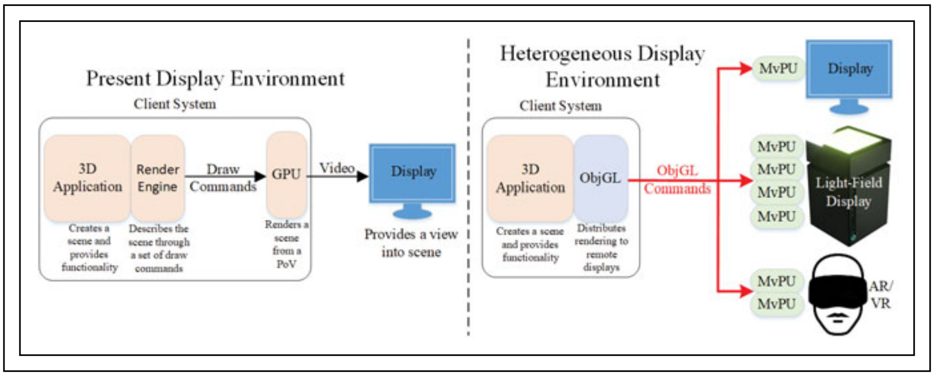


Fig. 6: The image on the left describes the traditional display environment in use today, while the right image shows a future Heterogeneous Display Environment where multiple displays/ architectures are connected to a single application simultaneously.

pressed) to transport over existing (or future) networks to facilitate a first-person view for an HMD at a reasonable frame rate. In addition, prerendered pixel data is likely to result in poorly sampled visualizations or visualizations with noticeable occlusion artifacts if not displayed on the intended device.

The second idea is that the visualization device is allowed to select the appropriate viewpoint or view volume. This allows the viewer with the HMD to select a vantage point to watch the e-game, whether from the quarterback's, receiver's, or coach's perspective. This implies that the geometric broadcast of the e-game is accompanied by a number of predefined interesting viewpoints/view volumes and that the viewer can switch between them at will.

The third concept is that the displays can connect to the host application broadcast at any time, which means that upon receiving geometric render commands, the display's geometric cache is likely to be stale. Therefore, out-of-band displays require a mechanism to request geometric updates from the host application's geometry server. These geometric "updates" are broadcast to requester and not globally to the HDE.

Multiview Processing Unit (MvPU): The primary technical objective of the multiview processing unit (MvPU) is to reduce the size, weight, power, and cost (SWaP-C) of multiview rendering by developing a processor capable of rendering multiple views in parallel without the need for a cluster of off-the-shelf (OTS) computers. By removing the OS, CPUs, and other PC system components, and refactoring the traditional graphics pipeline to render multiple views in parallel, a more efficient light-field/multiview rendering engine can be developed (Fig. 7).

Since many (possibly 10s to 100s) MvPUs may be required to drive a single light-field display, it is important that the MvPU be an independent processor, requiring minimal support logic and interconnect. Ideally, neither the host system nor the individual MvPUs would have knowledge of the interconnect topology or even the depth and breadth of the multiview system. The MvPU interconnect framework would provide scene, command, and sync buffering and relay throughout the topology.

The MvPU is physically located in close proximity to the photonics subsystem and has direct write access to the modulation driver back buffers. This reduces the complexity of the MvPU interconnect/support framework and eliminates the need to compress/transfer/decompress pixels from the render source to the destination driver over long traces/paths.

Each MvPU hosts multiple parallel independent render pipelines, which are fed viewpoints to be rendered simultaneously as triangles are dispatched. Dispatched triangles are transformed according to their unique viewpoints and are likewise shaded. Spatial distortion and color corrections complete the backside of each rendering pipeline.

Object Graphics Language (ObjGL): Object Graphics Language (ObjGL) is conceived by FoVI3D as an application- and display-agnostic API where rendering is the responsibility of the display. ObjGL draws heavily from the popular OpenGL graphics language yet is streamlined and optimized for fast rendering for remote multiview systems. The ObjGL API is simple and efficient, and it provides many geometric rendering clues that can be exploited by a well-implemented multiview rendering system.

The ObjGL application interface consists of three types of instructions: Control, Cache, and Render. Cache and Render instructions cannot be mixed and are delineated by Control commands. By strictly identifying Cache

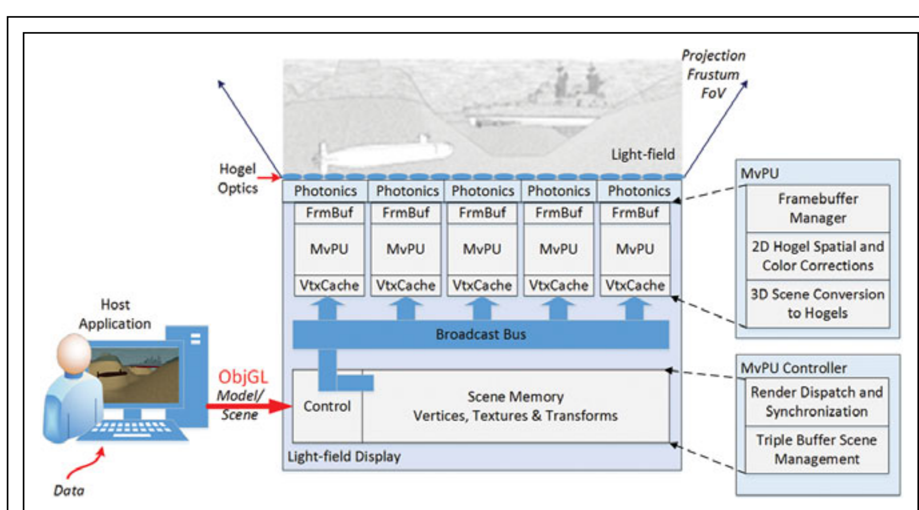


Fig. 7: MvPUs within the light-field display: An MvPU controller is responsible for managing the scene while the MvPU rasterizer converts triangles into pixels directly into the modulation framebuffers.

and Render commands, the multiview render system can accumulate Cache commands while executing its render cycle. After the multiview render cycle is complete, the Cache commands can be applied and the next complete render frame executed. This effectively allows for multiple displays to update independently while rendering the same content.

To support accelerated multiview rendering, a number of constructs and constraints are being developed to simplify the geometry definition yet provide efficient mechanisms for fast multiview rendering. These constructs/constraints are typical of the operations that intelligent rendering systems implement in software yet are propagated to the multiview display for implementation. In many cases, these constructs can't be applied within the host application, since the multiview rendering needs (points of view, display transform matrices, viewports, *etc.*) of the display are unknown to the host application. Some of these acceleration constructs include:

- Bounding volumes
- Foreground/background geometric segmentation
- Geometric level of detail
- Criticality of objects
- Frame packing
- Data phasing

ObjGL Thread Model: The ObjGL thread model is shown in Fig. 8 and consists of two primary threads, the application thread in which the application executes and the ObjGL manager thread. The ObjGL manager receives ObjGL commands from the host application, caches the geometry messages into a local message database, and formats the commands for global broadcast to all attached displays. In addition, the ObjGL manager receives out-of-band requests for late-joining displays and specifically updates those requestors.

ObjGL is currently in development at FoVI3D and has been demonstrated with multiple Oculus and Vive HMDs, and real and simulated light-field displays simultaneously viewing 3D imagery from multiple perspectives. FoVI3D intends to release ObjGL to the greater open-source community within the next year once the base architecture has been validated.

Computation Solutions Are in the Making

Light-field displays are no longer just a science fiction concept, and a few companies are producing impressive light-field display prototypes. While the focus has been primarily the development of light-field photonics and optical solutions to preserve 3D aerial image fidelity, ultimately light-field computation is the barrier to deployment. The sheer number of pixels required to produce high-fidelity light-field content for a reasonable SWaP cost is daunting; however, light-field computation is not an unsolvable problem. Light-field computation is highly parallelizable, and there are modes of operation and geometric model/scene properties that can greatly accelerate light-field rendering.

FoVI3D has developed a new system architecture to address the SWaP cost of light-field/multiview rendering. This architecture requires two major new elements that are in development at FoVI3D. The first is a multiview processing unit (MvPU), a GPU-like device designed to render multiple views in parallel without support from the host application. The second is an object-oriented graphics API Object GL (ObjGL) designed specifically to offload rendering to a heterogeneous display environment where rendering is the responsibility of the display. The successful completion of these two projects will enable graphical content to be remotely generated and transmitted for rendering at the display device whether it is a head-mounted stereo, volumetric display, or light-field display.

Eventually, this capability will enable a game to be captured (or generated, as in e-sports) and distributed to a home where a group of friends can enjoy a light-field 3D aerial projection of the game without headgear or eyewear inhibiting their personal interactions. This is a true 3D vision of the future.

Acknowledgements

FoVI3D would like to recognize the support that the Air Force, Navy, and Army SBIR programs have contributed to the advancement of light-field display technology. In particular, the Air Force HVD & FMHD[b] programs are advancing the LfD optics and photonics; the Air Force SMFoLD and the Navy ObjGL & LfPU (MvPU) programs address multiview rendering for Field of Light Displays (FoLDs); and the Army SCBV program advances the manner in which 3D aerial content is projected to reduce the cognitive load on the viewer.

References

[1]M. Hackett, "Medical Holography for Basic Anatomy Training," Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), 2013.

[b]With support from NavSea.

(continued on page 32)

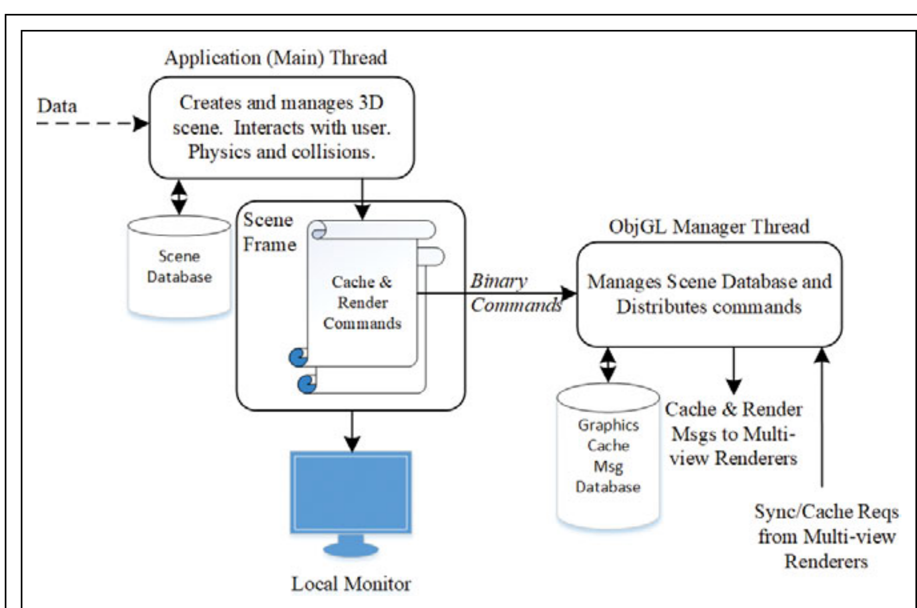


Fig. 8: *This ObjGL thread model highlights the separation of application and ObjGL scene-management responsibilities.*

Foveated Pipeline for AR/VR Head-Mounted Displays

In order to deliver a great visual experience with standalone augmented-reality or virtual-reality head-mounted displays (HMDs), the traditional display rendering pipeline needs to be re-thought to best leverage the unique attributes of human visual perception and the features available in a rendering ecosystem. The foveation pipeline introduced in this article considers a full integration of foveation techniques, including content creation, processing, transmission, and reconstruction on the display.

by Behnam Bastani, Eric Turner, Carlin Vieri, Haomiao Jiang, Brian Funt, and Nikhil Balram

THE visual experience that current augmented-reality/virtual-reality (AR/VR) headsets deliver is significantly below what we perceive in the real world, in every respect – resolution, dynamic range, field of view (FOV), and contrast. If we attempted to render content that was close to our visual system's capability of approximately 210 degrees horizontal and 150 degrees vertical FOV at 20:20 visual acuity, with a refresh rate well above the limit of flicker perception, we would need to deliver over 100 Gb/s to the display. The rendering rate becomes even larger when we consider generating a light field by using multiple focal planes per frame or multiple angular pixels per spatial element. These rates would be extremely difficult to achieve on mobile headsets with strict thermal limits restricting the available compute power of the system on chip (SoC) and the bandwidth of the link to the panels. In this article, mobile headsets are defined as systems that are self-contained in terms of computation and power, with all the compute being done by a main SoC similar to the application processor (AP) SoC used in a smartphone, and all the power coming from an on-board battery.

An elegant and practical solution is possible if we consider some core attributes of the human visual system when designing the pixel-generation pipeline. In particular, the primary image-capture receptors in the retina are concentrated in a narrow central region called the fovea. The image that is acquired at each instant produces high information content only in the foveal region. Using this attribute in the processing path enables the creation of a much more practical approach called the "foveation pipeline."

In this article we present a complete foveation pipeline for advanced VR and AR head-mounted displays. The pipeline comprises three components:

1. ***Foveated rendering*** with focus on reduction of compute per pixel.
2. ***Foveated image processing*** with focus on reduction of visual artifacts.
3. ***Foveated transmission*** with focus on reduction of bits transmitted to the display.

Figure 1 shows an overview of the foveated pipeline with these three major operations highlighted. The foveated rendering block includes a set of techniques with the aim of reducing operations per pixel. The foveated content is passed on to the foveated image-processing block, where operations focus on enhancing the visual perception of the overall system but in a foveated manner. These operations include correction for lens aberration or lighting estimation in augmented reality. The last block, foveated transmission, is where optimizations are done to transmit the minimum number of bits per pixel between the SoC and the display. Some of the transmission operations may benefit significantly when

__Behnam Bastani__ is an engineering manager for rendering investigation at Google's Daydream team. He can be reached at bbastani@google.com. __Eric Turner__ is a software engineer for Google's Daydream team. __Carlin Vieri__ has worked on various display projects as a hardware engineer at Google since 2013. __Haomiao Jiang__ is a software engineer for Daydream at Google. __Brian Funt__ is a professor of computing science at Simon Fraser University where he has been since 1980. __Nikhil Balram__ is head of display R&D for VR and AR at Google. He is an SID fellow and Otto Schade Prize winner.

0362-0972/6/2017-014$1.00 + .00 © SID 2017

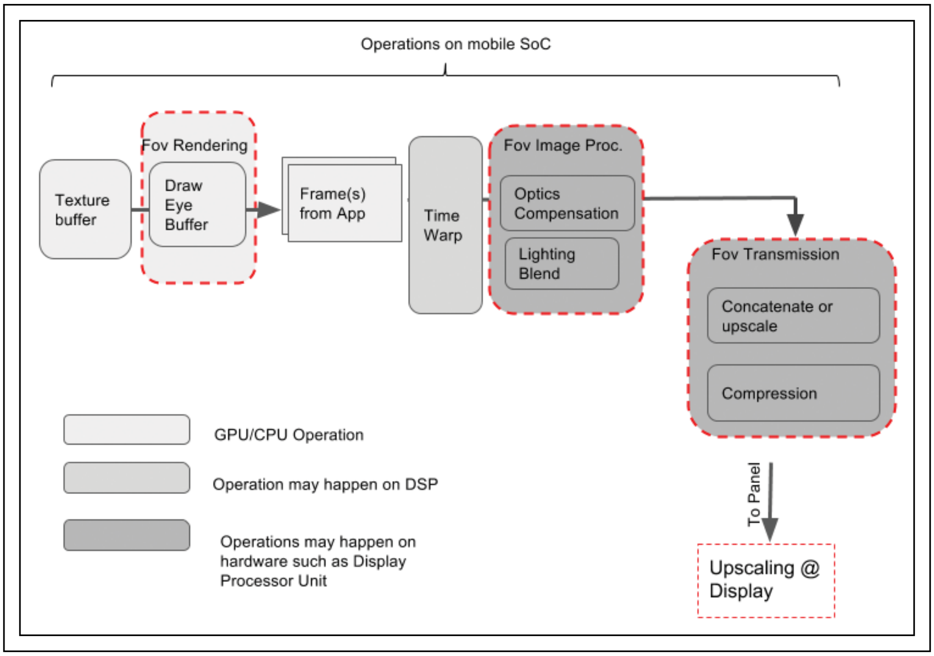


Fig. 1: The foveation pipeline for standalone AR/VR headsets shows operations performed on various compute subsystems of a mobile application processor SoC.

they are integrated with operations done at the display timing controller (TCON).

For each step, we have developed a set of techniques that consider both human visual perception and feasibility in current or upcoming mobile platforms.

Foveated Rendering

The human visual system has an elegant and efficient information-processing architecture. The eye's "image sensor," the retina, has two major types of receptors that capture light in the visible spectrum – rods and cones.[1] Rods are primarily used for vision in low light conditions and provide no color information. They are concentrated in the periphery and have limited spatial-discrimination abilities but are very sensitive to temporal changes. Cones are used for daylight viewing and provide fine spatial discrimination as well as a sense of color. They are present throughout the retina, but are concentrated in a narrow central region spanning only a few degrees, called the fovea. Figure 2 shows the distribution of rods and cones across the retina.

The sensation of having a high-resolution, full-scene representation like the one shown in Fig. 3 is produced by the eyes continuously scanning the scene through rapid eye movements called saccades.[2] At any specific instance, the front end of the human visual system is only capturing a high-resolution image over a few degrees of visual field. Hence, the optic nerve, the "information bus" that brings image data from the retina to the visual cortex for processing, is estimated to have a bandwidth of only ~10 Mb/s.[3]

This highly data-efficient "foveated" capture is the inspiration for efficient ways of rendering for head-mounted displays. Through the use of techniques called "foveated rendering," the user's eye movements are employed to deliver high resolution only for the specific region of interest.

Foveated rendering can take advantage of the radial drop-off in visual acuity to improve the performance of the rendering engine by reducing spatial, or bit-depth, resolution toward the periphery. The location of the high-acuity (HA) region needs to be updated to present high-resolution imagery to the fovea to preserve the perception of rendering a constant high-resolution image across the display. A delay between saccades and the updating of content on the display may result in perceptual artifacts.

Figure 4 shows an example of the results produced by a foveated rendering system, where content in the fovea, usually around 5 degrees as shown in the yellow circle, is

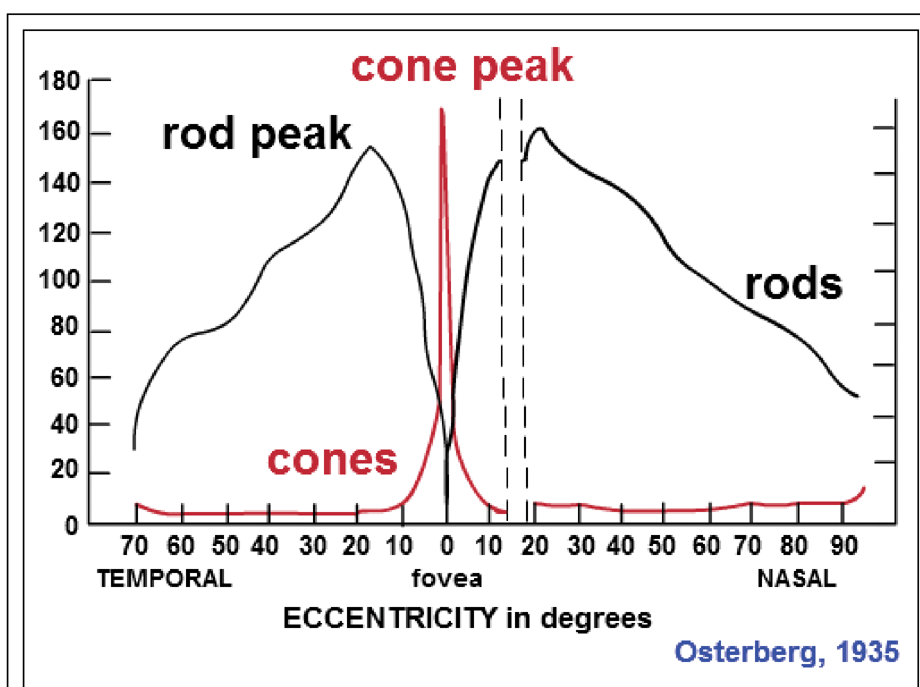


Fig. 2: Rods and cones are distributed across the retina.[1] The receptors (cones) used for daylight viewing and the sensation of color are concentrated in a narrow region called the fovea.

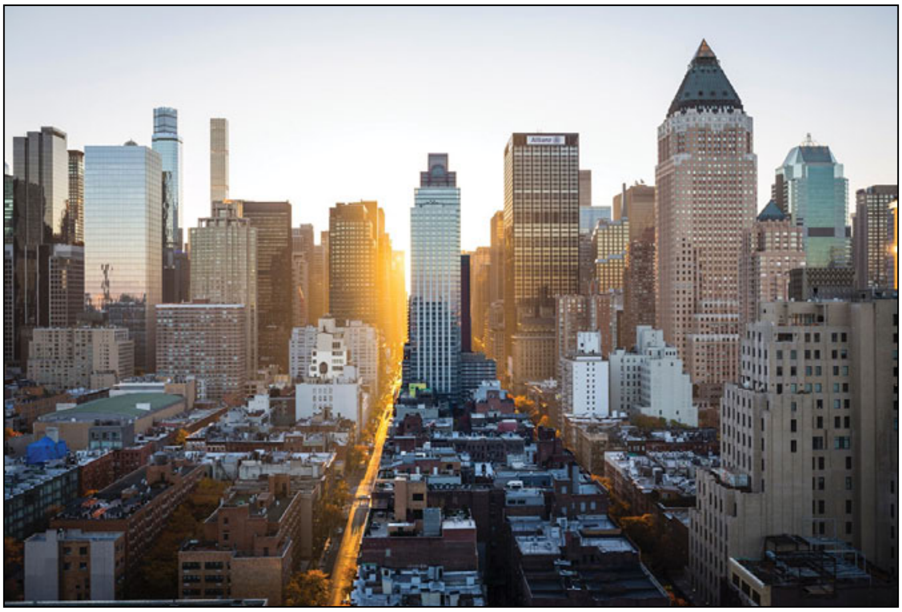


Fig. 3: This example of high-resolution content was rendered at constant high-spatial resolution.

rendered at high-spatial resolution, and content in the periphery is rendered at low resolution. Since the spatial acuity of human perception drops continuously outward from the fovea, one can represent the gradual drop in resolution using multiple low-acuity regions.

There are two approaches to address the requirements of saccades in foveated rendering –"dynamic foveation" and "fixed foveation."

Dynamic foveation uses eye tracking to measure gaze location and then adjusts the location of the HA region accordingly. Higher accuracy and lower latency in the eye-tracking sensor allows for the same visual quality to be achieved with a smaller HA region. The smaller the HA region, the greater the reduction in overall rendering computational costs.

Fixed foveation considers the optical performance of the HMD lenses and their impact on perception of HMD display acuity. For the fixed-foveation method, the rendered spatial resolution tries to match the optical performance of the HMD lens. For this method, the HA region is typically larger than in the case of dynamic foveation, and its rendering cost is higher. By not requiring an eye-tracking sensor, this approach is compatible with all existing devices. Application developers may select a more aggressive foveation region than what the HMD acuity is, thus resulting in smaller HA regions and better compute savings. Heuristics such as a foveation heat map over time may be used to adjust the foveation region and the resolution of the peripheral region.

In practice, existing dynamic foveation techniques tend to be more conservative in their foveation than our human visual system. Part of the issue is that current headsets aren't starting out as a perfect visual system to begin with. Current commercial headsets are resolution-limited and present details comparable to 20:90 acuity on a standard eye chart. From such a reduced starting point, aggressive foveated rendering in the periphery is easily noticeable. Additionally, these headsets have an FOV much narrower than the human visual system, typically delivering 90 degrees horizontal, whereas humans can see in excess of 200 degrees horizontal.

However, the long-term trend for HMDs is to improve display resolution and increase FOV, with the goal of matching the limits of the human visual system. This means we can expect foveated rendering to become much more important. We expect the high-acuity regions to get relatively small compared to the rest of the display, and the spatially downsampling factor in the periphery to get more and more extreme.

Another parameter that significantly affects the performance of specific foveated-rendering techniques is the approach to foveation. As Guenter *et al.*[4] have shown, there may be perceptible artifacts that get introduced from different foveation techniques. These artifacts become more perceptible when a temporal change occurs in the scene due to viewer

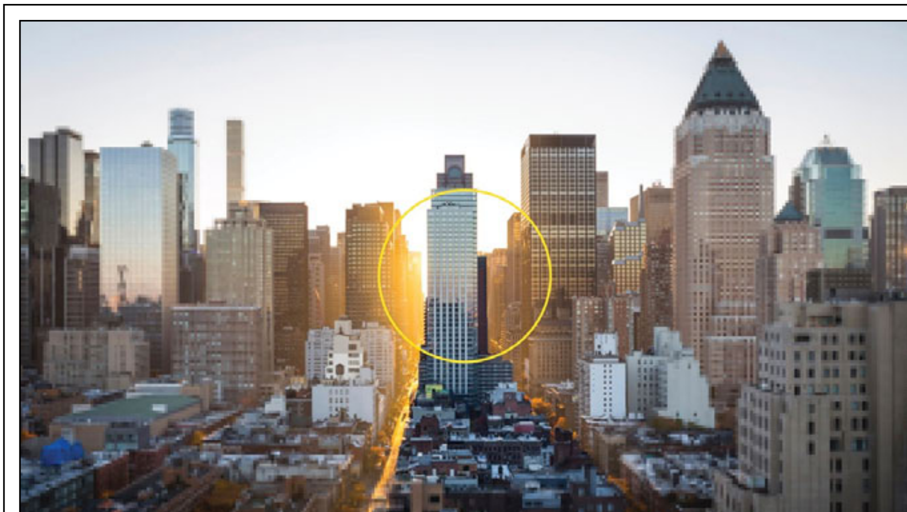


Fig. 4: This example uses two layers of foveation -- one rendered at high resolution (inside the yellow circle) and one at lower resolution (outside the circle).

movement or scene content. The next section reviews some of the general artifacts one has to be aware of when designing a foveation algorithm.

Human Visual System and Visibility of Artifacts: *Local Contrast:* To simulate lower visual acuity in peripheral vision, one may apply a blur across the frame that scales with the radial position from the fovea. Our visual system perceives a sense of tunnel vision when viewing the peripherally filtered content due to loss of local contrast in the blurred region. This sensation is perceptible even though the blurred output has the same spatial bandwidth as the periphery of the human eye. Patney *et al*.[5] have shown that despite having lower visual acuity in the periphery, the human visual system preserves perception of local contrast. Thus, loss of local contrast needs to be avoided, or the local contrast has to be recovered. Contrast enhancement techniques exist that have been shown to significantly reduce the sensation of tunnel vision.[5] However, these techniques may come with additional challenges:

1) a more sophisticated up-sampling technique that may be more expensive, and
2) techniques that do not address temporal artifacts and may require more sophisticated post-processing.

Bit depth: Although the local contrast-sensitivity of the human visual system is fairly stable in the periphery, gray-level discrimination (which is analogous to bit depth) drops quickly, and one can take advantage of this phenomenon. However, it is important to make sure that lower bit-depth rendering does not result in any quantization banding or other spatial artifacts, or any changes in color.

Temporal sensitivity: The human visual system is quite sensitive to temporal phenomena in the periphery. Thus, when designing any foveation technique, we need to be careful not to introduce what appear as temporal artifacts when there is a change in the content. Change in content may be due to animation, head motion, eye motion, or even body motion.

There are several techniques for rendering content for foveal and peripheral regions, but generally they fall into two categories:

(1) techniques that try to hide artifacts that are created in the periphery, and
(2) techniques that try to prevent the creation of artifacts.

Foveated Rendering and Artifact Correction: This category of foveated rendering techniques aims to simulate a drop in acuity in the visual system from fovea to periphery by rendering peripheral content to a smaller framebuffer resolution and then resampling it using a range of temporal and spatial upscaling algorithms. If the upscaling algorithm does not take into account aliasing artifacts, unintended motion artifacts may be introduced when the viewer moves her head and the aliasing moves in position with respect to the original contents.

In this category of foveated rendering, one may attempt to blur aliasing, reducing the perceptibility of introduced temporal artifacts. As mentioned earlier, the anti-aliasing techniques should be aware of local contrast loss during the operation. Patney *et al*.[5] have proposed an edge-enhancement process in the periphery to recover loss of local contrast. They have shown the proposed solution reduces perception of tunnel vision noticeably. However, the algorithm may not map efficiently to existing mobile SoC hardware architecture and would therefore require more compute cost.

Another technique is based on simulating gradual reduction in resolution by breaking down the rendering buffer into smaller regions. By introducing spatial downsampling in a piecewise-linear manner, each block of foveated regions can have constant spatially downsampled content. In addition, the multiregion process enables a gradual introduction of the artifacts related to foveation by pushing more aggressive foveation to farther out in the peripheral region. Figure 5 shows an example of a multiregion-rendered foveation buffer.

There are several challenges to this approach, including a need to draw content at multiple steps, causing a resource-intensive operation through the graphics API. Another point to consider is the transition between the boundaries and how one may try to blend them both temporally and spatially.

Another approach is to use previously rendered frames to predict and reduce introduced motion artifacts with minimum loss in local contrast.

Temporal anti-aliasing (TAA) is a common method for smoothing the animation in a scene by averaging the pixel colors of the current frame with that of the previous frame. However, since VR head movement causes extreme rotations, this method produces ghosting artifacts. To reduce ghosting, the previous frame's output image is reprojected to correct for the net head rotation that occurred from the previous frame. Karis *et al*.[6] proposed a reprojection method with reduced space complexity cost. Figure 6 shows the general structure of the algorithm.

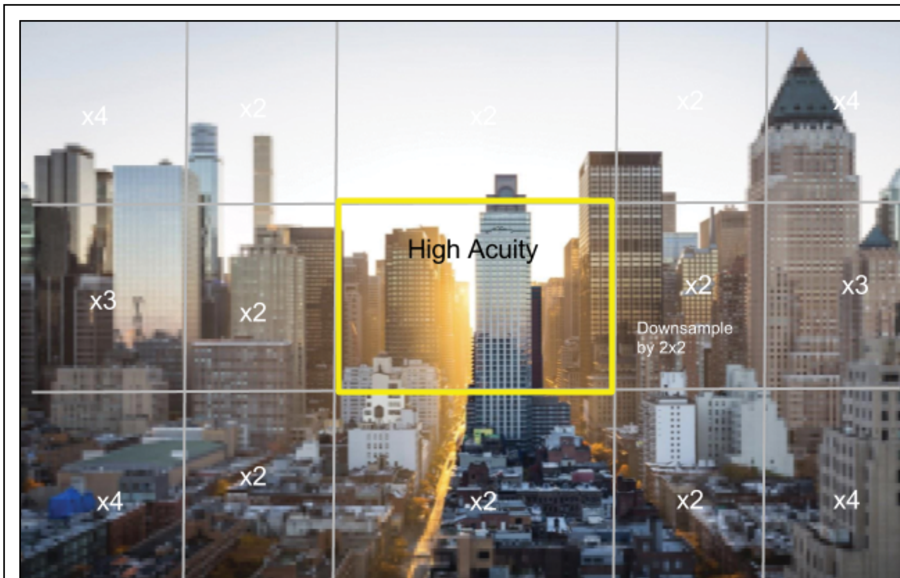


Fig. 5: *The above example of multi-region foveation shows the highest-resolution sector in the area of high acuity (center).*

Some ghosting artifacts still exist, since this reprojection does not correct for 6 degrees of freedom (6-DoF) movement by the user or animation in the scene. The remaining ghosting artifacts are reduced by clamping outlier color values.

The clamping operation works as follows: For each pixel <*i,j*>, before blending the previous frame's color $Cij[N-1]$ with the current frame's color $Cij[N]$, we check how close $Cij[N-1]$ is in value to the neighborhood around $Cij[N]$.

If $Cij[N-1]$ is more than StdDev[Neighborhood$ij[N]$] from Mean[Neighborhood$ij[N]$], then the blending is aborted, and only the current frame's color is used for this pixel.

This threshold is applied in each component of the YCoCg[7] color space of the pixels.

Foveated Rendering and Artifact Prevention: The general techniques used in this category spring from understanding the root cause for perceptibility of an artifact and then attempting to remove what makes the artifact perceptible.

Phase-Aligned Rendering: One general approach in this category focuses on interaction between motion and aliases generated by rendering content in the periphery at lower resolution. One may consider this algorithm by looking at how information is presented in the real world. If we look at a real-world object with high-frequency edges, we do not perceive temporal information other than what exists in the subject. The proposed method looks at why high-frequency content in the world does not introduce a temporal artifact and applies the learning to rendering techniques.

With traditional foveated rendering, the frustums of both the low-acuity and high-acuity regions are updated with head-tracking information (and the high-acuity region can be further updated if eye tracking is available). Any artifacts generated by aliasing due to upsampling the low-acuity region will be aligned to the display coordinate system. Since the display is moving with respect to the virtual world content, aliasing artifacts will be moving relative to the content, causing artifacts that move independently of the content.

Instead, we want to enforce the low-acuity regions to be world-aligned. Then these world-aligned screens are reprojected and resampled onto the final display surface. This method means the phase offset between the low-acuity pixels and the native-resolution pixels are dynamic from frame-to-frame, always ensuring each low-acuity pixel is phase-aligned with the virtual world content (hence the name). In other words, the low-resolution sampling occurs in world space, and the artifacts are mostly invariant to head pose.

With this method, both aliases and original high-frequency content continue to exist in the scene but do not produce motion artifacts. This technique may take advantage of presenting the world in a projected space such as a cube map,[8] which makes it simpler for rendering and reprojection of certain features in the scene. This kind of representation may have an additional cost due to re-rendering the world at multiple viewports, which results in multiple draw calls. Draw calls are often resource-intensive, causing performance overhead on both the central processing unit (CPU) and general processing unit (GPU). Multiview projections are typically used to reduce CPU cost for multiple draw calls per frame. Several multiview operations have been developed, with some fully supported on mobile SoCs.

Conformal Rendering: Another approach for foveated rendering is to render the content in a space that matches our visual acuity and thus not introduce artifacts related to existing rendering pipelines to start with. Such techniques can be fast, single-pass methods that could be used for both photographic and computer-generated imagery. An important feature of such techniques is that they are based on a smoothly varying reduction in resolution based on a nonlinear mapping of the distance from the fixation point. This avoids the tunnel-vision effect that has plagued previous foveated-rendering methods. The single-pass method relies on standard computer graphics GPU-based rendering techniques; hence, it is computationally very efficient and requires less time than would be required to render a standard full-resolution image.

The proposed foveated-rendering method is based on:

(i) performing a 2D warp on projected vertex positions,

(ii) rasterizing the warped image at a reduced resolution, and

(iii) unwarping the result. All these operations are carried out on the GPU of the SoC. The unwarping step can be combined with other fragment operations into a single pass operation and thus be inexpensive.

In addition to reducing image storage requirements, such foveated rendering also reduces the computational load. Less computation is required because the reduced resolution used for the warped image means that fewer pixels need to be processed by the expensive rendering shaders that compute lighting and texturing. Speed-up ratios of at least 4:1 have been obtained for standard FOV images where the content does not have many vertices. Since this method may require

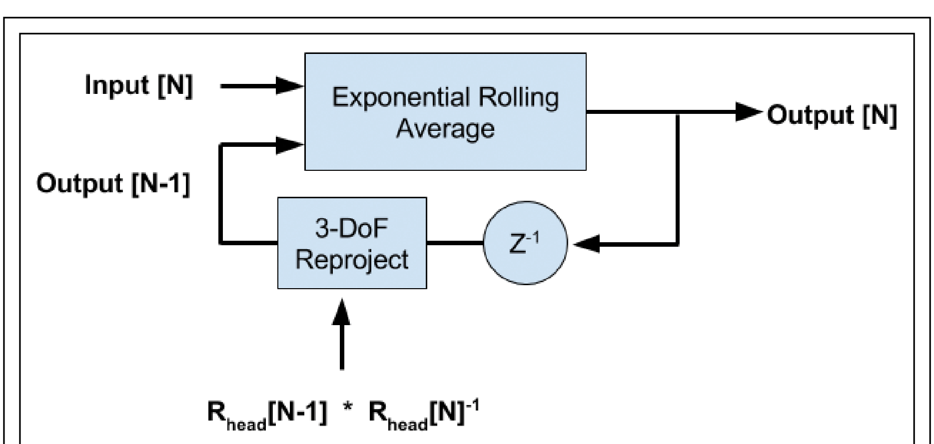


Fig. 6: *This temporal anti-aliasing uses 3-degree-of-freedom (3-DoF) reprojection.*

additional vertex creation in order to run warp operation accurately, it may not have the desired performance gain on small FOV displays with vertex-heavy content.

Steps Toward a Standard API for Foveated Rendering: Several different techniques exist for foveated rendering. Some of these methods take advantage of specific hardware features, and some take advantage of knowing how the rendering application presents content. Hence, the effort around foveated rendering has been fragmented.

To make the process more unified, a technique may need to know information about the content coming in and should have access to manipulate certain parameters in rendering, such as viewing angle or FOV of the content. The unified effort should also consider how foveated rendering interacts with the rest of the pipeline, including foveated image processing and foveated transmission (Fig. 7).

It is desirable to have a standard API for foveated rendering. One effort led by the Khronos[9] OpenXR committee aims to bring a standard extension for foveation techniques, thus enabling a language where a set of techniques can work together.

Foveated Image Processing

Foveated image-processing techniques include processes that improve visual quality of the rendered image. Operations that fall in this category include local tone mapping, HMD lens distortion correction, and lighting blending for mixed-reality applications.

The traditional image-processing operations run the same set of kernels on all pixels. A foveated image-processing algorithm may have different kernels for different foveation regions and thus reduce computational complexity of the operations significantly.

As an example, lens distortion correction, including chromatic aberration correction, may not require the same spatial accuracy for optical corrections. One can run such operations on foveated content before upscaling, as shown in Fig. 8.

The lens-correction operation is applied in a foveated space and then the foveated buffers are merged together as a single operation. Since lens distortion is another stage that operates on rendered pixels with a given spatial discretization, it can add inaccuracy in values. The merge operation can play an important role, and for certain foveated rendering techniques, this merge operation may combine several operations into a single step, thus reducing both compute and inaccuracy in the pipeline. The result can be perceptible for high-frequency content such as text.

Another point worth highlighting is the ability to access intermediate content of foveated rendering before upscaling. One advantage, as previously mentioned, is foveated lens distortion. In the next section we present another gain for such operations.

Foveated Transmission

In a standalone HMD system, one non-trivial but sometimes ignored source of power consumption is the data transmission over certain physical layers (PHY) between the SoC and the display module. Based on a conservative estimate, each payload bit takes around 10 pico joles to be transmitted through a mobile industry processor interface (MIPI) PHY[10] to the display. This means that even for a relatively low-resolution system with QHD resolution (2,560 × 1,440 pixels), transmission of bits can cost around 50 mW, which could represent up to 10 percent of the power consumption of the HMD's display subsystem.

This cost can become a noticeable portion of the overall power consumption of the display system and the cost increases proportionally with display resolution and frame rate. As the bits/second that need to be transmitted increase, more MIPI lanes need to be allocated to the system, which may introduce other constraints such as in the overall mechanical design of a headset.

Foveated rendering saves compute by rendering most of the displayed image at a low spatial resolution (the LA region). This region has to be upscaled to the spatial resolution of the display and blended with the small high-acuity foveal region (the HA region) to form the final image for the display. Foveated transmission sends the native LA and HA data across the link and does the upscaling and blending operations on the display side. This saves power and bandwidth by minimizing the amount of data sent across the PHY.

Under this foveated transmission scheme, the transmitted data rate is greatly reduced. In most foveation systems, the foveated data package (high acuity + low acuity) saves a considerable number of the bits for a full-resolution framebuffer. This corresponds to 60 to 90 percent power reduction in the transmission process. In addition, we expect the

(continued on page 35)

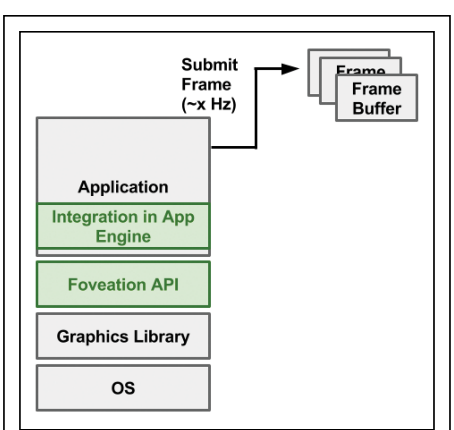


Fig. 7: In a system architecture for standard API for foveation, a unified API is presented to the application or 3D engine, and thus the complexity of the foveation techniques is abstracted out. Green areas represent the expected changes, where an API abstracts out the foveation techniques and application engines opt-in to use the API.

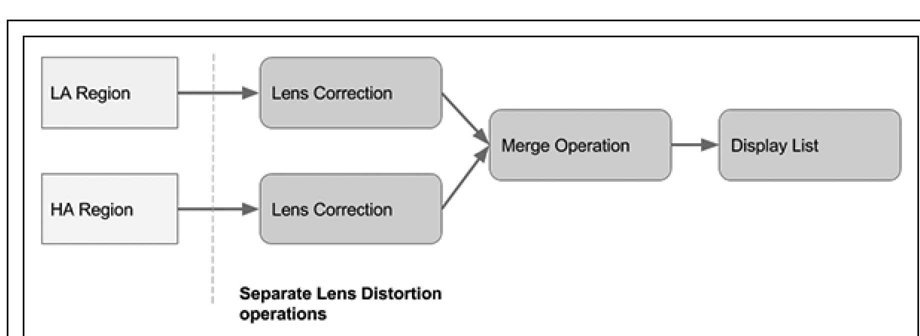


Fig. 8: In foveated image processing, various operations run separately in the low-acuity (LA) and high-acuity (HA) regions.

Recent Developments in Virtual-Reality and Augmented-Reality Technologies

Along with the advances in virtual-reality (VR) and augmented-reality (AR) technologies, many challenges remain. This is therefore an exciting time for the display industry and its engineers. In this article, we present a summary of select new developments reported at Display Week.

by Achintya K. Bhowmik

Virtual- and augmented-reality technologies, along with the increasingly numerous variants referred to as mixed- and merged-reality platforms, represent the next frontier of visual and interactive applications. These devices free us from the confines of conventional screens for immersive viewing experiences, and promise to seamlessly blend digital objects with the physical world. While these concepts have been pioneered over many decades, rapid developments in displays, sensors, and computing technologies in recent years are now pushing this dream toward reality. The applications are endless, including gaming, media, education, virtual tourism, e-commerce, *etc*.

This article provides a synopsis of some of the key new developments in the field as presented at Display Week 2017.

Dr. Achintya Bhowmik *is the chief technology officer and executive vice president of engineering at Starkey, the largest hearing technology company in the US. In this role, he is responsible for leading the company's research and engineering efforts. Prior to joining Starkey, Bhowmik was vice president and general manager of the Perceptual Computing Group at Intel Corp. He can be reached at achintya.k.bhowmik@gmail.com.*

All the 'Realities'

"What is real?" asks the character Morpheus in the acclaimed 1999 science fiction movie, *The Matrix*. Then he rhetorically asks, "How do you define 'real'?" He goes on to answer his own question: "If you're talking about what you can feel, what you can smell, what you can taste and see, then 'real' is simply electrical signals interpreted by your brain."

Well … this is a profound definition of reality – one that engineers can readily accept! If we can understand the electrical signals that zip around the neurons in the cerebral cortex of our brain as we sense and perceive the world, then we may be able to artificially stimulate the neurons in someone's brain with similar signals. This would create the illusion of seeing something, or being somewhere, that is completely different from "actual" reality and yet indistinguishable from the physical world. That, precisely, is the goal that virtual-reality engineers around the world are striving to achieve.

There exists some confusion over the terms "virtual" reality and "augmented" reality, not to mention "mixed" reality, "merged" reality, and "extended" reality. The short course on virtual and augmented reality at Display Week 2017 presented by this author made an attempt at defining these terms.[1] Virtual reality (VR) places the user in a virtual environment, generating sensory stimuli (visual, vestibular, auditory, haptic, *etc.*) that provide the sensation of presence and immersion. Augmented and mixed reality (AR and MR) place virtual objects in the real world while providing sensory cues to the user that are consistent between the physical and digital elements. Merged reality blends real-world elements within the virtual environment with consistent perceptual cues, scene understanding, and natural human interactions.

Augmented- and Mixed-Reality Devices

While the research and development of virtual- and augmented-reality technologies have a rich history going back several decades, recent advances in some of the key areas are now starting to make it possible to design and commercialize practical products with compelling new applications. These include significant progress in displays and optics, miniaturized and high-accuracy sensors with low latencies, high-performance and low-power graphics and computer vision processing, ergonomic system designs, understanding of the important human factors and their related issues and mitigations, and more.

The technical symposium at Display Week included several papers and demonstrations that narrated the state-of-the-art results in

0362-0972/6/2017-020$1.00 + .00 © SID 2017

these key technologies and how they're being implemented in devices. The product development efforts in the industry that were presented at the event included Microsoft HoloLens, the Meta 2 Augmented Reality headset, Intel Project Alloy, Google Tango, and various other projects. A key enabling technology incorporated in all these devices is a new technique called simultaneous localization and mapping (SLAM), which is based on sensor-fusion approaches including computer vision and inertial measurement units,[2] along with high-fidelity and immersive graphics and display technologies. The devices also included depth sensors for 3D spatial learning and gesture interactions for natural human interfaces. The system-design variants included all-in-one untethered mobile devices as well as head-worn displays connected to a computer.

B. C. Kress *et al.* detailed the display architectures for the Microsoft HoloLens mixed-reality headset,[3] presenting a review of the key display requirements for the untethered system and the optical hardware module selections that were made for the device. The paper described the optical subsystem architecture consisting of the display engine, imaging optics, waveguide modules including diffractive optical elements, and the overall optical module assembly. Figure 1 shows the pupil-forming optics and the display module assemblies for the HoloLens device. The authors also described the user experience considerations that drove the technology selections, with a focus on viewing comfort and immersion.

The second-generation immersive optical see-through AR system from Meta was presented by K. Pulli.[4] Consisting of an optical engine based on a freeform visor display with a relatively large (90°) field of view and integrated sensor modules for 3D tracking and gesture interactions, the device is designed to connect with a computer that runs the applications, as depicted in Fig. 2.

Among other presentations describing approaches to creating augmented imagery via head-worn display devices were the Lumus optical technology presented by A. Frommer,[5] Avegant direct-view optics for near-eye displays presented by A. Gross *et al.*,[6] and a complex amplitude-modulation technique presented by Q. K. Gao *et al*. from the Beijing Institute of Technology.[7]

D. Diakopoulos *et al*. presented the system architecture of the Intel Project Alloy platform,[8] an all-in-one merged-reality device incorporating inside-out visual-inertial tracking, depth sensing and 3D spatial-capture technologies, integrated application and graphics processors, and hardware for accelerating computer-vision algorithms. The paper also detailed prototype applications based on scanning the 3D environment and blending real-world elements into the virtually rendered world, as demonstrated in Fig. 3.

The technical details and applications for the Google Tango project were presented by J. Lee. This project integrates motion tracking, depth sensing, and area-learning capabilities into a smartphone platform to provide augmented-reality experiences.[9] Figure 4 shows demonstrations for two of the applications, including real-time measurements and annotation, as well as augmentation of the real-world scenes with virtually created characters.

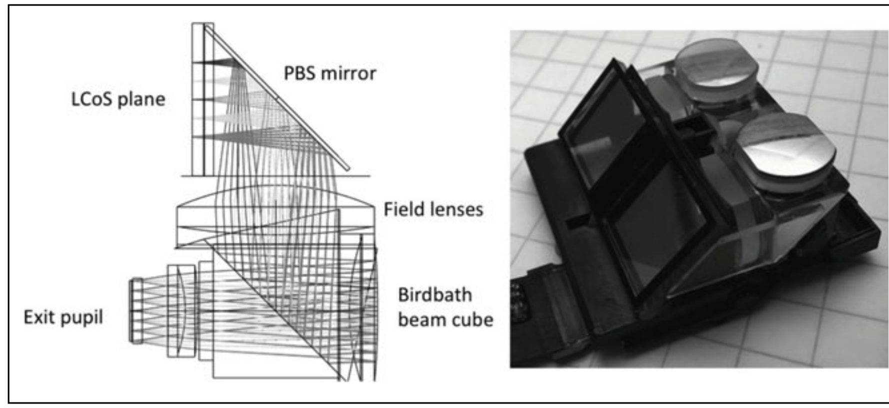


Fig. 1: *On the left, the Microsoft HoloLens display architecture[3] incorporates a display module assembly consisting of a liquid-crystal-on-silicon (LCoS) microdisplay and pupil-forming optics. The right image shows the dual-display module assemblies with the shared optics for both eyes.*

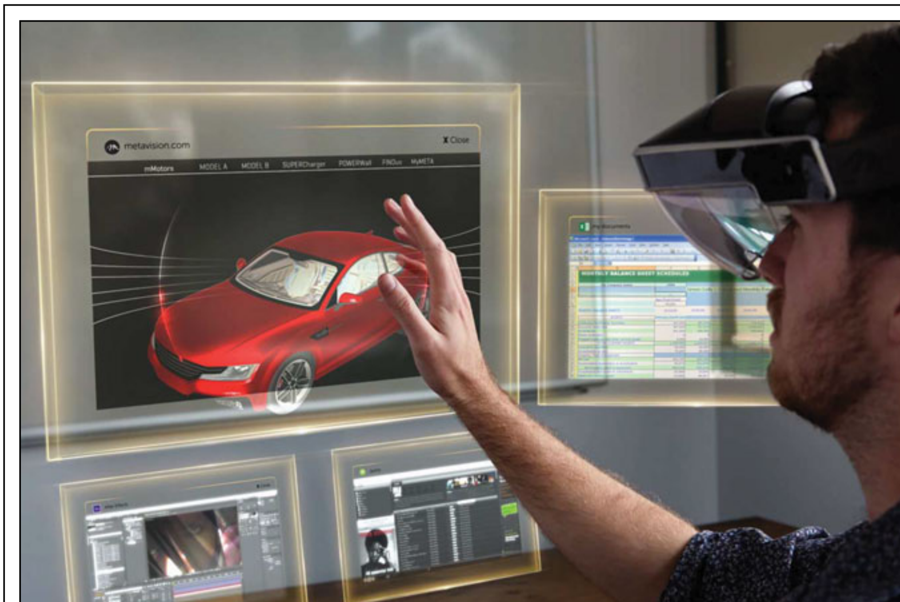


Fig. 2: *Meta has developed an optical see-through interactive AR display system.[4]*

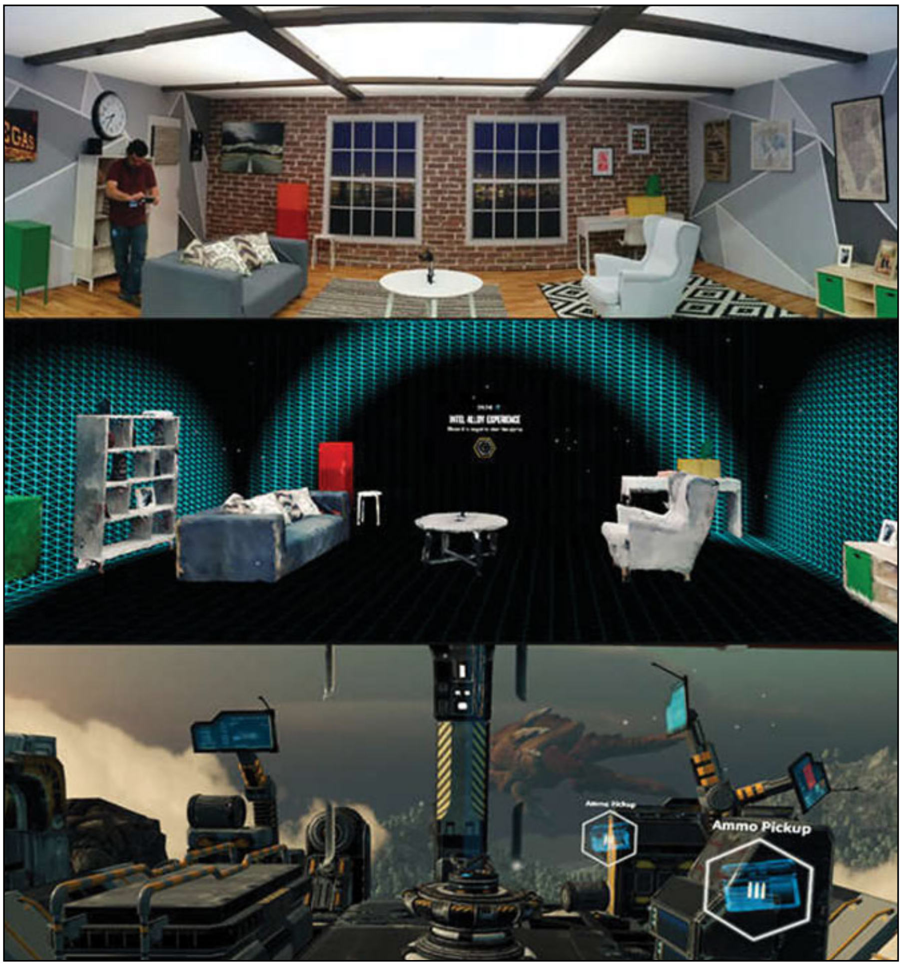


Fig. 3: Intel's Project Alloy all-in-one device merges real-world elements into the virtual world. The top image shows the real-world scene; the middle shows the 3D scanned version of the scene; and the bottom shows the merged-reality environment where the real-world elements have been transformed and blended into the virtually rendered world.[8]

Improving Visual Acuity for VR

"How many pixels are really needed for immersive visual experiences with a virtual-reality head-mounted display?" was one of the most common questions raised during and after the short course this author taught at Display Week. So here we reflect on this a bit, and point to some recent developments and trends in the display industry as gleaned from the presentations and demonstrations at this year's event.

First, let's consider some basic, back-of-the-envelope math and calculations. Here are some facts related to the human visual system: An ideal human eye has an angular resolution of about 1/60th of a degree at the central vision. Each eye has a horizontal field of view (FOV) of ~160° and a vertical FOV of ~175°. The two eyes work together for stereoscopic depth perception over ~120° wide and ~135° high FOV.[1] Since current manufacturing processes for both liquid-crystal displays (LCDs) and organic light-emitting diode (OLED) displays produce a uniform pixel density across the entire surface of the spatial light modulators, the numbers above yield a whopping ~100 megapixels for each eye and ~60 megapixels for stereo vision.

While this would provide perfect 20/20 visual acuity, packing such a high number of pixels into the small screens of a VR head-mounted display (HMD) is obviously not feasible with current technologies. To put this into context, the two displays in the HTC Vive HMD consist of a total of 2.6 megapixels, resulting in quite visible pixilation artifacts. Most people in the short course raised hands in affirmative answer to a question about whether pixel densities in current VR HMDs are unacceptable.

Even if it were possible to make VR displays with 60 to 100 million pixels, there are other system-level constraints that make this impractical. One involves the graphics and computation resources necessary to create enough polygons to render the visual richness to match such high pixel density on the screens. Next, the current bandwidth capabilities cannot support transporting such enormous amounts of data between the computation engines, memory devices, and display screens, and at the same time meet the stringent latency requirements for VR.

So … is this a dead end? The answer is a resounding "no!" Challenges such as these are

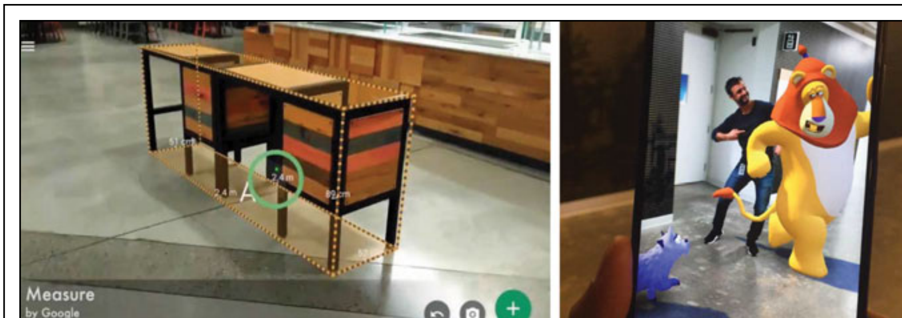


Fig. 4: These demonstrations of AR experiences on a smartphone platform are delivered by the Google Tango project. The left image shows real-time measurements and annotation with dimensions, while the right one shows virtual objects blended into a real-world scene.[9]

what innovators and engineers live for! Let's look at biology for some clues. How does the human visual system address this dilemma? It turns out that high human visual acuity is limited to a very small visual field – about +/- 1° around the optical axis of the eye, centered on the fovea. So, if we could track the user's eye gaze in real time, we could render a high number of polygons in a small area around the viewing direction and drop it exponentially as we move away from it. Graphics engineers have a term for such technologies already in exploration – "foveated" or "foveal" rendering. (See the article on foveated rendering in this issue.) This would drastically reduce the graphics workload and associated power consumption problems.

Due to the severe limitation in pixel densities in the displays that can be made with current manufacturing technologies, there is a significant ongoing effort to reduce the "screen-door" effects resulting from the visible pixelation artifacts. As an example, B. Sitter *et al*. from 3M presented a technique to incorporate a diffractive film to reduce the screen-door effect and improve the visual quality of a virtual-reality display.[10] As shown in Fig. 5, the diffractive film is made with 3M's precision micro-replication process. The authors also presented a method to measure the effect that they used to demonstrate the efficacy of their technique. In another paper, J. Cho *et al*. from Samsung presented the results from their work on reducing pixelation artifacts by inserting an optical film that acts as a low-pass filter.[11] The technique is illustrated in Fig. 6.

Toward Matching Convergence and Accommodation

The optics and mechanics of human eyes allow us to "accommodate," *i.e.*, adjust the shapes of our lenses dynamically to focus on the objects in the physical space that we "converge" our two eyes on in order to dedicate our visual attention to them. As we look at an object that is located at a close distance, we rotate our eyes inward such that the optical axes of both eyes converge on it. At the same time, the lenses of the eyes are made thicker by adjusting the tension in the muscles that hold the lenses in order to bring the light from the object to focus on the retina to form a sharp image. On the other hand, as we shift our visual attention to an object that is located farther away, we rotate our eyes outward so that the optical axes now converge at that distance. In parallel, the lenses are made thinner to adjust the focal lengths accordingly.

For natural viewing conditions in the real world, these convergence and accommodation mechanisms are in sync. In other words, there is a consistent correspondence between where our eyes converge to and the lenses adjust to focus on. However, in currently available VR and AR devices, such a correspondence is not afforded, thereby causing visual fatigue and discomfort. The displays in a conventional headset are located at a fixed distance, whereas the virtual objects are rendered at different distances to create a stereoscopic 3D visual environment. This creates a mismatch between the convergence and accommodation mechanisms, as illustrated in the top image of Fig. 7.[12]

There is significant ongoing research to address this human factors issue. For example, N. Padmanaban *et al*. from Stanford University reported their work on combining eye-gaze-tracking technology with adaptive-focus displays to minimize the mismatch between the convergence and accommodation points,

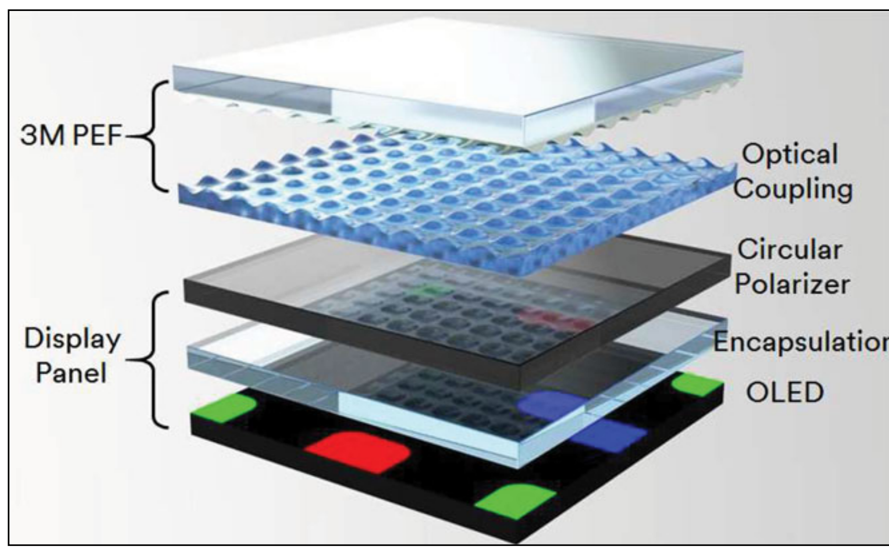


Fig. 5: *Researchers from 3M demonstrated a technique to reduce the screen-door effect in virtual- and augmented-reality displays by incorporating diffractive films.*[10]

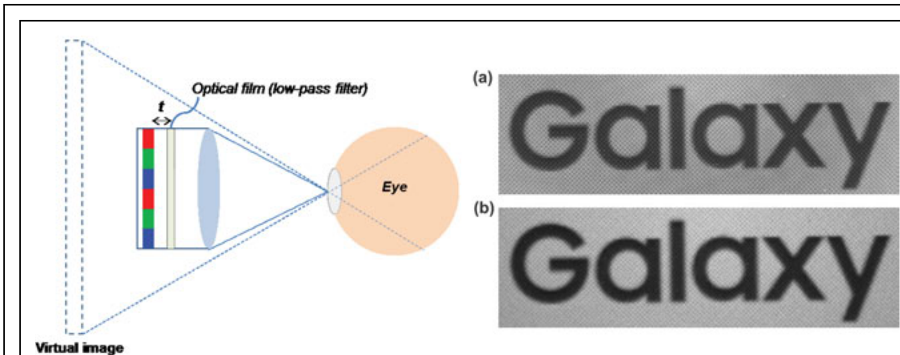


Fig. 6: *A paper from Samsung described the insertion of an optical film in the displays of a VR device that acts as a low-pass filter (left), with demonstrated reduction in the pixilation artifacts (right).*[11]

as depicted in the bottom image of Fig. 7. The authors demonstrated prototypes with both focus-tunable lenses and mechanically actuated displays to dynamically adjust the accommodation points and provide natural focus cues. Demonstrations of technologies designed to solve this problem also included a tunable liquid-crystal lens by A. Jamali *et al.*,[13] and a switchable lens based on cycloidal diffractive waveplate by Y. H. Lee *et al.*[14]

VR/AR Challenges/Opportunities

Clearly, we are still in the early days of VR and AR technologies, with many challenges remaining to be solved, including presenting adequate visual acuity and truly immersive experiences on the displays. So, this is an exciting time for the display industry and its engineers, reminiscent of the days at the onset of display technology advances toward HDTVs and smartphones. The special track on VR and AR technologies at Display Week 2017 consisted of papers and demonstrations of new developments in this burgeoning field, including both commercially available products and results from ongoing research toward understanding and resolving key technical issues on the way to achieving compelling user experiences. There is much to look forward to at the next Display Week!

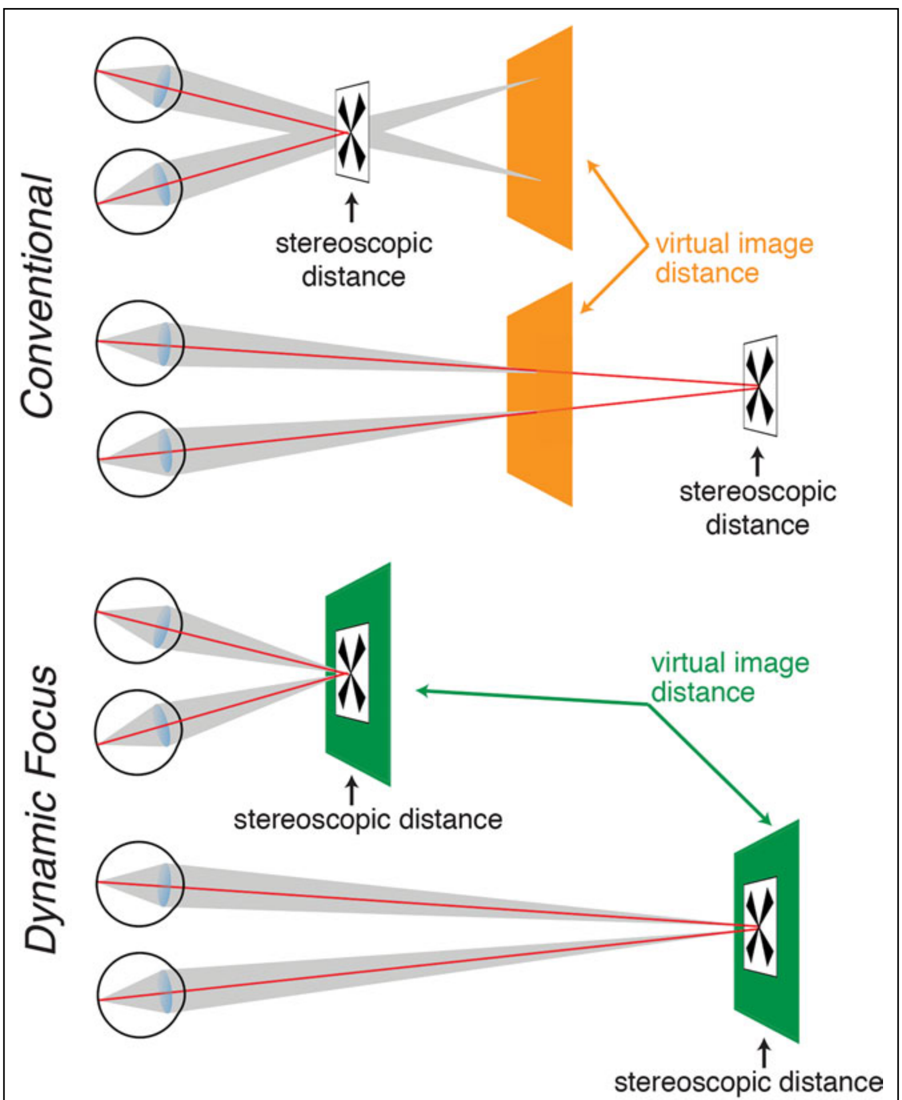


Fig. 7: *An accommodation-convergence mismatch occurs in conventional VR and AR displays where the convergence points at the stereoscopic distances do not match the virtual image distances (top figure). Dynamic focus displays provide focus cues that are consistent with the convergence cues (bottom figure).*[12]

References

[1]A. K. Bhowmik, "Virtual & Augmented Reality: Towards Life-Like Immersive and Interactive Experiences," Short Course S-2, Display Week 2017.

[2]A. K. Bhowmik, "Sensification of Computing: Adding Natural Sensing and Perception Capabilities to Machines,"*APSIPA Transactions on Signal and Information Processing,* **6**, 1, 2017.

[3]B. C. Kress and W. J. Cummings, "Towards the Ultimate Mixed Reality Experience: HoloLens Display Architecture Choices," Paper 11.1, Display Week 2017.

[4]K. Pulli, "Meta 2: Immersive Optical-See-Through Augmented Reality," Paper 11.2, Display Week 2017.

[5]A. Frommer, "Lumus Optical Technology for AR," Paper 11.3, Display Week 2017.

[6]A. Gross, E. Tang, N. Welch, and S. Dewald, "Direct View Optics for Near-Eye Displays," Paper 11.4, Display Week 2017.

[7]Q. K. Gao, J. Liu, J. Han, X. Li, T. Zhao, and H. Ma, "True 3D Realization in the See-Through Head-Mounted Display with Complex Amplitude Modulation," Paper 51.1, Display Week 2017.

[8]D. Diakopoulos and A. K. Bhowmik, "Project Alloy: An All-in-One Virtual and Merged Reality Platform," Paper 4.2, Display Week 2017.

[9]J. Lee, "Mobile AR in Your Pocket with Google Tango," Paper 4.1, Display Week 2017.

[10]B. Sitter, J. Yang, J. Thielen, N. Naismith, and J. Lonergan, "Screen Door Effect Reduction with Diffractive Film for Virtual Reality and Augmented Reality Displays," Paper 78.3, Display Week 2017.

[11]J. Cho, Y. Kim, S. Jung, H. Shin, and T. Kim, "Screen Door Effect Mitigation and Its Quantitative Evaluation in VR Display," Paper 78.4, Display Week 2017.

[12]N. Padmanaban, R. Konrad, T. Stramer, E. Cooper, and G. Wetzstein, "Optimizing Virtual Reality User Experience through Adaptive Focus Displays and Gaze Tracking Technology," Paper 4.3, Display Week 2017.

(continued on page 32)

Journal of the
SOCIETY FOR
INFORMATION
DISPLAY

Invitation to submit review papers

The Journal is presently soliciting review papers on any display-related topic. If you have a great idea for a review paper, please contact the editor at editor@sid.org.

Page charges for review papers will be waived.

Herbert DeSmet
Editor-in-Chief

Announcements

Expanded Papers from the International Display Workshops in conjunction with Asia Display 2016 (IDW/AD '16)

Selected papers from the **IDW/AD '16** conference have been expanded and published in the July and August issues and in a virtual online issue of JSID. A total of 6 papers were accepted after peer review. **tinyurl.com/jsidhome**
The 20 Expanded Distinguished Papers from Display Week 2017 are still **openly accessible** until December 31st via **http://tinyurl.com/edpdw17**.

JSID social media presence

Follow JSID via Twitter hashtag **#JSOCINFDISP**, and Facebook "News at Journal of the Society for Information Display" or **http://tinyurl.com/jsidfb.**

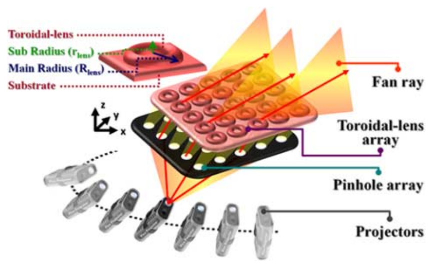
Highlighted recent papers

Editors' pick of the month:
Single-layered retardation films with negative wavelength dispersion birefringence made from liquid-crystalline monomers | Mika Yamamoto *et al.*| DOI: 10.1002/jsid.564

Sample Name	Sample A	Sample C	Sample O
Alignment	Homogeneous (+A-plate) Nx>Ny=Nz	Homeotropic (+C-plate) Nx=Ny<Nz	Hybrid (O-plate)
Re(450nm) / Re(550nm)	0.826	0.803	0.850
Re(650nm) / Re(550nm)	1.030	1.074	1.029

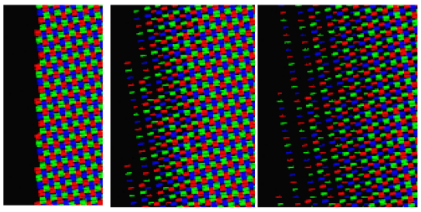
For the purpose of suppressing reflection of external light on the OLED displays, new liquid-crystalline monomers, exhibiting excellent solubility and alignment characteristics, have been developed, and the retardation films showing excellent negative wavelength dispersion (NWD) and high thermal stability were obtained. Three types of retardation films with NWD with homogeneous, homeotropic, and hybrid alignments have also been obtained.

A toroidal-lens designed structure for static type table-top floating image system with horizontal parallax function | Ping-Yen Chou *et al.*| DOI: 10.1002/jsid.570



A new structure of horizontal parallax table-top floating image system, which consists of circularly arranged pico-projectors, pinhole, and toroidal-lens layers, was developed. In the design, the light field could be controlled as a fan ray, which has a widely scattered angle in latitude and high directivity in longitude. Based on inverse light tracking method, displaying floating image with circular viewing zones would be achieved.

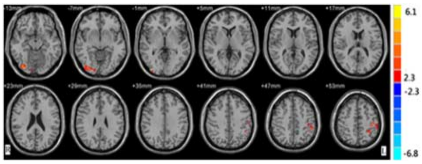
Influence of depth and 3D crosstalk on blur in multi-view 3D displays | Hyungki Hong | DOI: 10.1002/jsid.568



(a) (b) (c)

Blur occurs in autostereoscopic multi-view 3D due to incomplete image separation between views. Blur width depends on the depth condition.

Analyzing fatigue in prolonged watching of 3DTV with ReHo approachs | Chunxiao Chen *et al.*| DOI: 10.1002/jsid.601



Significant differences of ReHo map in the 3D-Post as compared with the 3D-Pre. An R-value scale was shown on the right. Red indicates that 3D-Post showed significantly greater increases than 3D-Pre, which can be seen in the right occipital gyrus, left parietal lobe, and frontal lobe.

Adjustable beam lighting with LED matrix and lens array | Yuning Zhang *et al.* | DOI: 10.1002/jsid.597

A Matrix Lighting configuration, which mainly consists of a light-emitting diode matrix and a lens array, is proposed as a promising adjustable beam lighting solution. It easily builds up the source-target mapping based on the integral imaging principle and could adjust the light beam and shape freely and timely. It shows a nice possibility for the convergence of lighting and display.

Information about the Journal

JSID is published monthly by Wiley. Subscription fees apply, but SID members and student-members have free online access via **sid.org/Publications.aspx**
Many universities also have an institutional subscription.
JSID is indexed in the Web of Science.
Submit your original manuscript online via **mc.manuscriptcentral.com/sid**
Author guidelines can be found on the Journal's homepage at Wiley Online: **tinyurl.com/jsidhome**.
Editorial board: **tinyurl.com/jsideb.**
Please direct any questions about the journal to the Editor-in-Chief of JSID at **editor@sid.org**
EarlyView: accepted papers about to be published can be accessed online via **tinyurl.com/jsidev**

#JSOCINFDISP tinyurl.com/jsidfb

ID Interviews Edward Tang, Co-Founder and CTO of Avegant

Edward Tang oversees the strategic direction of Avegant, which develops head-mounted mixed-reality technology. He also drives the company's business development and fundraising activities. Prior to Avegant, Tang started Tang Engineering Consulting LLC, a consulting and design firm for the MEMS community. He received his B.S. in electrical engineering from the University of Michigan.

Conducted by Jenny Donelan

Information Display:
Tell us about Avegant.

Edward Tang:
Before I started the company about five years ago, several of us were working on new display technologies with the Department of Defense. At the time, the [DoD] guys were saying, "We need better displays for mission-critical type applications. We need stuff that's higher resolution, higher color fidelity, lower latency, higher performance." So we ended up forming Avegant to develop a new display technology – which I would describe as bio-inspired – to meet that demand.

When we look at the world, we're seeing light reflected off of objects. We're not looking at flat panels. So we got rid of the usual display panels and pixels, because those cause a lot of eye strain. And we built a retinal projection system that used digital micro-mirror displays. This system reflects light onto your retina, and is getting closer to how we actually see. With this technology, which we call retinal imaging, users were experiencing higher perceived resolution, higher framerates, better color, and also much lower eye fatigue. That's what motivated us to start this company. We had developed some prototypes of our retinal projection technology, and were pleasantly surprised by how well they worked.

ID: Those prototypes became the Glyph, is that right?

ET: Yes. About two years ago, we started shipping a consumer product based on this technology called the Glyph. It was designed for general consumers. Most people used it as a personal theater. It looks like a set of headphones [that projects a 720p HD screen in front of your eyes]. You plug it into your smartphone and you can watch anything you want – Netflix, Hulu, games. We found that roughly two thirds of our customers were using it for travel. The other one third, unexpectedly, was the drone market. People were using these things to fly drones. Instead of looking down at your phone or tablet while flying your drone a mile away, you could put on your headset, and feel like you were up in the sky – a really incredible experience.

ID: The Glyph was received positively. Are you still selling it?

ET: We are still selling the Glyph. You can find it on Amazon in the US, and it's also available in Europe and China. However, we're focused on the future and that is around mixed-reality technologies.

ID: The focus is on mixed reality via light-field technology?

ET: About two and a half years ago, we started seeing an increased interest in VR [virtual reality] and after that we started seeing transparent AR [augmented reality] devices, so we decided that we needed to focus a lot of our research efforts on transparent displays. We found that it was not hard to build a transparent display, but it was hard to build the kind of mixed-reality experiences that people wanted.

One of the first things we tried to do was create an object overlaid onto a table that you could reach out and touch. The problem is in the way our eyes perceive how far away an object is. There are a lot of different depth cues. One of the most important cues is focus; your eye works a lot like a camera lens. It can actually change its focus and you can focus on something far away or up close.

So if I want to have a [virtual] object sitting on a table or in my palm, the focus of that object needs to be the same as my hand. Otherwise it doesn't look right.

Jenny Donelan *is the editor in chief of* Information Display *magazine. She can be reached at jdonelan@pcm411.com.*

0362-0972/6/2017-026$1.00 + .00 © SID 2017

What light field does is allows us to display objects at the correct focal distance and multiple objects at different distances. So I can now have multiple objects in a scene with one close and one far away, and have it all happen at the same time.

What's interesting is that even people who understand the light-field space really well and understand the approach that we're taking are wowed by the experience when they put on one of our headsets. There's something very human and experiential about it. When I open up my hand and see an object that's in my palm, and it looks like a real object, there's something about that experience that is indescribable. I do demos all year and I never get tired of seeing people, even people who are very technical, having these visceral reactions.

For another demo, we put a virtual person in the room, a woman standing there talking to you. You can walk up to her, but 99 percent of people stop about three or four feet away from her because they start feeling like they don't want to invade her comfort zone. We encourage them to get closer and they start feeling very uncomfortable. You don't have these kinds of reactions with regular computer imagery.

Edward Tang

ID: Do you find yourself having to explain to a lot of people what the light field is?

ET: I do. It's hard. It's a very technical term. In fact what we do here is a little bit different from what a typical light-field display is. Our technology uses a multi-focal optical element, and, similarly to the Glyph, it projects light from a three-color LED through a chip filled with tiny mirrors and then onto your retina, where an image is formed.

ID: What about rendering? That seems to be the bottleneck for light-field displays at this time.

ET: I'm looking at a TV on the wall right now. If that TV were a light-field display, it would actually behave a lot like a window. I could see through it, and see depth, and if two different people were looking at the window from two different vantage points, they would see two different views. This is what I would call a full 4D light-field display, which means it has to send all the different angles of light, all the different data points, and all the different angles, all the time.

For a head-mounted display [HMD], this would be overkill. You're never going to look at this display from a different direction; you're only going to look at it from a fixed vantage point, where your eyes are. Because of that, we actually don't need to use all that data. Our light-field displays today run on regular computers, and we actually have them running on mobile chipsets as well.

ID: What about light-field content? That's another bottleneck you hear about.

ET: We created plug-ins for graphics engines such as Unity, which is the most popular [VR/AR] graphics engine these days. The plug-in allows Unity to output the light-field information that we need in real time for all the objects. All the content that people already have and have already created, thus works — on very low-compute power.

ID: Regarding the light-field technology, are you creating the HMD or are you creating the optics and outsourcing it to people who make the HMDs?

ET: The latter. We are providing our technology to the companies that make the HMDs.

ID: Let's move to the business side of things. What has been your experience of working at a startup? Do you have advice for others?

ET: Startups are a rollercoaster. You have the extremes of emotion and experience at both ends – the highs and the lows – and those happen almost simultaneously. There are things that are going on that are so exciting that you can't believe it. At the same time, the things that you worry about are incredibly stressful as well. Working at a [non-startup] company, you just don't expose yourself to that dynamic range of emotions.

Another thing that's amazing about being at a startup is when you're not huge, you have this camaraderie and team involvement, and the impact that every single individual has at the company is something that makes people excited to come to work. Every single person knows that what they do has a tangible effect.

ID: Is there anything you look for that makes somebody a particularly successful startup team member?

ET: When you're a small company, you need to make sure that people jibe with each other, that personality-wise, people have the right mentality to approach problems. That's really important. Something else you must learn in a startup is you have to be very flexible. You can't step into a role and say, "This is what I do and it's all I'm gonna do and anything else is not my

(continued on page 35)

> **"When you're an engineer you think that technology is the most important thing. And really it's only a piece of the puzzle."**

Stretchable and Conformable Electronics: Heading Toward Market Reality

Stretchable and conformal electronics are more than just novelties. This article describes how many of the simpler and less glamorous aspects of stretchable and conformable devices have already been commercialized or are very close to being commercialized.

by Khasha Ghaffarzadeh and James Hayward

MOST people still believe that stretchable and conformal electronics (SCEs) are academic curiosities with no particular market. This belief appears to be based on proof-of-concept studies that are occasionally published, based on the results of those rare devices that happen to work well. Even when companies demonstrate prototypes, it is easy to dismiss them as mere marketing exercises devised to make their inventors look like R&D leaders.

However, with regard to the SCE industry, there is much more than meets the eye. At IDTechEx (the market research firm at which we are based), we have been researching this technological frontier for several years. In this article, we will describe how many of the simpler and less glamorous aspects of SCE have already been commercialized or are on the cusp of being commercialized. And we will discuss two major trends underpinning interest in SCE: (1) wearables going truly wearable and (2) structural electronics. Furthermore, we will argue that viewing SCE as a single entity is grossly misleading. SCE is an umbrella term under which exist many different technologies and applications. It is appropriate to view SCE as a collection of disparate niche applications and solutions.

***Khasha Ghaffarzadeh** and **James Hayward** are analysts for IDTechEx, a market research and technology consulting firm with headquarters in the UK. They can be reached at khasha@idtechex.com and j.hayward@idtechex.com, respectively.*

Wearable Technology Is Becoming Truly Wearable

Interest in wearable technology rose exponentially starting in late 2013. This was accompanied by the emergence of several new product categories that helped define the new wearable tech *vs*. the old wearable tech (pocket and wrist watches, dating back centuries). These new categories included smart connected watches, smart eyewear, virtual- and augmented-reality glasses, and more.

Each of these categories is very different in terms of underlying technology, readiness level, target markets, and current and future earning potential. In fact, in a recent market forecast, our team tracked 42 separate categories of wearable devices, with an overall growth from a current base of around $US35 billion to more than $US155 billion by 2027.

There is often little unifying these disparate technologies. Indeed, there is a real possibility that the divergent fortunes of these categories will render the umbrella term of wearable technology irrelevant in the not-so-distant future.

Despite this pending divergence, a common trend across nearly all devices is a change in form factor. If you scan the current landscape of products you will soon find that they are simply old, rigid components assembled into a new "box" that can be worn somewhere on the body. Nearly all these components are borrowed from existing industries such as the consumer electronics, medical, or automotive sectors. There exists relatively little hardware innovation for creating truly wearable devices.

This is changing. As shown in Fig. 1, companies large and small are beginning to make wearable devices truly wearable. Often, these are early-stage exploratory products that have been developed to test the waters and are not yet mature, tried-and-tested, finished articles.

Stretchable Electronics for Wearable Technology

Work toward creating truly wearable devices includes all required parts of the system. There is progress in stretchable and/or conformable batteries, transistors/memories, displays, sensors, PCBs, and interconnects (stretchable connections). Most SCE components are, however, still at a very early stage of technological readiness. Here, therefore, we focus on stretchable interconnects and sensors as two examples of SCEs that are already commercial or on the edge of being commercialized.

Interconnects may seem like simple elements, but they are crucial in enabling truly wearable textile-based applications. Currently, there are several approaches for creating textile-based interconnects, including fine metal wire and metal-coated fiber/yarn.

0362-0972/6/2017-028$1.00 + .00 © SID 2017

Fig. 1: Wearable devices are beginning to transition from rigid components in boxes toward truly wearable devices. So far, nearly this entire market is served by existing sensors borrowed from other industries. However, we now see the rise of new sensors made with wearability in mind. Image sources: Fitbit, Apple, Samsung/Oculus and Google, and IDTechEx photos of Clothing+/Myontec, Bainisha, Toyobo, Parker Hannifin, EMS/Nagase and others.

Stretchable conductive inks are also emerging as a serious contender to fulfill this role. This is because conductive ink technology is highly adaptive, enabling custom products to be developed to satisfy different price and performance (conductivity, stretchability, *etc.*) requirements. This is critical at this exploratory stage of the market when the customer requirements are not fully known and can be very divergent.

Inks have a further advantage in that they are a post-production step that can be universally applied once a textile is made using existing unmodified processes. Indeed, ink technology has the potential to piggyback onto existing infrastructure and know-how for screen printing graphics on textiles.

As shown in Fig. 2, there are already many electronic textile (e-textile) prototypes and products that use flexible and/or stretchable conductive inks. These examples range from heart-rate monitors for humans and animals (*e.g.*, horses), shoe in-sole pressure sensors, interconnects, and so on. In general, our statistics, shown in Fig. 2, demonstrate that interest in stretchable inks is on the rise. The number of ink-based e-textile products/projects is significantly up year-on-year.

Despite this interest, stretchable inks are not yet a finished commodity-like article. There is much room for continued improvement and customization. In the current approach, the printed layer is sandwiched between a plastic substrate and an encapsulation layer, and is then laminated onto the textile. This is not a sufficiently elegant solution in that it requires two additional layers. The substrate is used essentially to create a common surface in an industry in which numerous textiles exist, each offering a widely different surface characteristic. The commonplace encapsulation materials are also not yet perfect in that they are not very breathable or even comfortable. The performance of stretchable inks can also be further improved, even though the latest generation is better at suppressing resistivity changes with elongation and at withstanding washing conditions, compared to earlier versions. All this suggests that there is opportunity for material innovations and improved formulations to enable more stretchable inks that can be applied directly onto various textiles with strong adhesion.

This trend has so far been characterized by a push from material/ink suppliers, and not every company is experiencing commercial success. In fact, we are still in early days and the value chain for e-textile is still being shaped, with active involvement from traditional textile makers, large contract manufacturers, and major brand owners.

Many examples of SCE sensors are either commercialized or close to commercialization. For example, piezoresistive sensors are already commercially used to measure pressure distribution over uneven topographies. One use case involves measuring the topography of a patient's teeth. The patient bites on the piezoresistive sensor, and by doing so, changes the sensor's thickness, and thus its resistivity, at various locations, allowing for a reading. In such applications, the degree of stretching is often low, whereas surface conformity is excellent and essential.

Many other types of stretchable sensors are also being developed. One example involves stretchable strain sensors that measure large (>100 percent) displacements, well beyond the capabilities of standard strain gauges. The device architecture can be relatively simple; for example, a dielectric-polymer can be sandwiched between two printed electrodes to create a capacitive strain sensor. These sensors are being aggressively commercialized by several suppliers around the world. The target application space is potentially very broad, spanning e-textiles, robotics, industrial machinery, and so on.

Although it may seem that there is a sudden commercial interest in and progress on SCE, these technologies are not overnight wonders. For example, consider the simple dielectric-based stretchable strain sensors. Working examples have been developed, but companies have been trying to commercialize these for more than 13 years. During this time, the IP and commercialization rights for this technology have changed hands at least three times, and numerous potential markets have

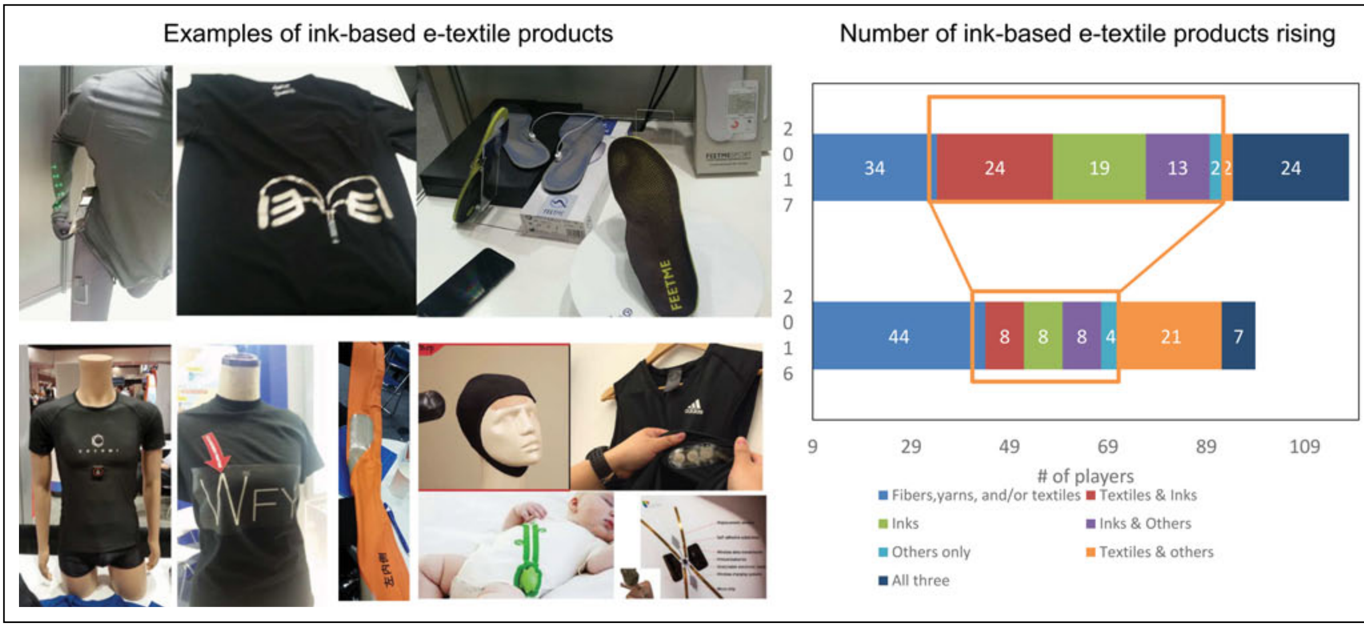


Fig. 2: At left are ink-based e-textile prototypes and products. Image sources: Holst Centre/DuPont (Wearable Expo Japan 2017), FEETME/DuPont (Wearable Expo Japan), Bebop impact sensors, Mimo breathing sensor, stretch sensor by Bainisha, activity sensors by Clothing +, Toyobo (Japan 2017), Jujo Chemical (FineTech 2016), Maxim Integrated, Toyobo (Japan 2017). (The information in parentheses indicates where/when IDTechEx analysts took the photos.) At right are statistics showing that the popularity of ink-based solutions is on the rise in e-textiles. Source: IDTechEx.

been tested, creating a large accumulation of commercial experience.

Structural Electronics Are a Potential Endgame for Electronic Devices

Structural electronics represent a megatrend that will transform traditional electronics from being components-in-a-box into truly invisible electronics that form part of the structure itself. This is a major, long-term innovation that will lead to a root-and-branch change of the electronic industry, including its value chain, materials, and components (Fig. 3). Stretchable and conformable electronics are giving shape to this megatrend. Indeed, they enable it.

In one manifestation of SCE in structural electronics, electrodes/antennas are deposited on the surface of 3D-shaped objects, eliminating the need for a separate printed circuit board. Here, as in piezoresistive sensors, stretchability is important in the form of ready 3D surface conformity rather than elasticity or high-strain capabilities. In another manifestation, in-mold electronics (IME) is helping to structurally embed electronic functionality into 3D objects made using high-throughput processes such as thermoforming.

In IME, electronic materials, together with graphics inks, are deposited (printed or coated) onto a flat sheet before being thermoformed into a 3D shape. This causes the materials to experience a one-off major stretching event. If standard materials are employed, this stretching will cause layer cracking and failure. The materials used therefore need to be specially made or formulated to become IME compatible.

Herein lies an opportunity for material suppliers. The first material to respond to this

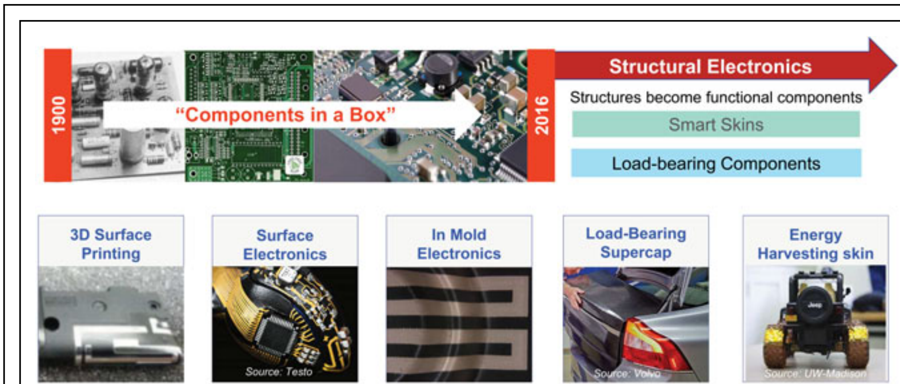


Fig. 3: Structural electronics represent a trend that will see electronic functionality become a part of the structure itself.

need has been conductive ink, partly because of its technological adaptability in terms of custom formulations. This flexibility has helped it become IME compatible. Indeed, as in the development of commercial stretchable conductive inks, IME-compatible material experiences a one-off stretching event. There were only two or three suppliers two years ago or so, but now many ink suppliers have demonstrated capability or commercially launched their products, often with aggressive pricing strategies.

The materials menu is of course not limited to conductive inks. Another major component that is becoming IME compatible is transparent conductive films (TCFs), which form the basis of capacitive touch-sensing technology. These stretchable TCF technologies, including those based on carbon nanotubes (or nanobuds), silver nanowires, and PEDOT, can enable 3D-shaped touch surfaces made using molding processes.

As shown in Fig. 4, there are already numerous IME prototypes aimed at high-volume white-good (home) appliances and automotive applications. Many such prototypes are in late-stage qualification. Interestingly, IME had previously had a false start in that an IME overhead console had been adopted into a car before malfunction (attributed to process simplification going from prototyping to mass production) caused the product to be recalled. This cautionary tale further underscores the fact that SCE did not appear overnight and has in fact been in the making for years. Note that despite that recall, commitment has remained strong behind the scenes and we expect commercial product launches soon.

A Slow and Profitable Path to Innovation

There will be much more innovation in SCE in years to come, because all electronic components, to various degrees, are becoming stretchable and conformable. As described above, most are still years away from commercialization. This is partly due to technological immaturity but also because SCE components are often very different from their rigid counterparts in terms of performance and application. Consequently, they cannot just be considered a substitute for the next generation of existing components/materials.

Indeed, SCE components must find and create new markets and new product categories. This requires extensive time-consuming exploration of many niche markets. We currently see that several SCE components are exactly in this phase: the market is experiencing many divergent application ideas. This phase will inevitably end as hit products are found, causing the industry to consolidate around them. This period of convergence will then continue until competition erodes margins, forcing players to seek new markets and unleash the next phase of divergence.

The high level of diversity, however, both in terms of technologies and target applications, will ultimately offer resilience to the SCE market. While every application won't succeed, it would be unreasonable to assume that every application will fail. In our forecasts, we can see a $US600 million market by 2027 for SCE. For further details please refer to our report, Stretchable and Conformal Electronics 2017–2027, available at www.idtechex.com/stretchable. ■

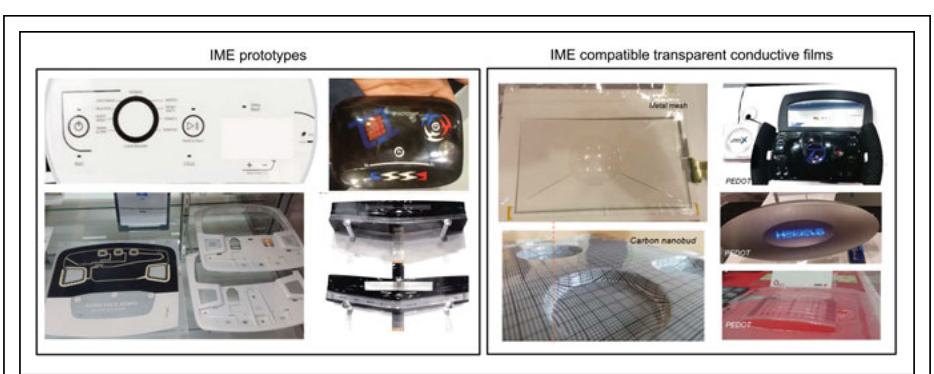


Fig. 4: There are many examples of IME prototypes that are aimed at white-good appliance applications, such as washing machine human-machine interfaces, as well as at automotive applications, such as overhead or heating control consoles. Sources: In box at left, clockwise from top left: Jabil, Tactotek (Printed Electronics Europe 2016), DuPont (Wearable Expo Japan 2017), DuPont (IDTechEx Show! 2016), Jujo Chemical (FineTech Japan 2017). In box at right are examples of various thermoformed transparent conductive films. Sources: clockwise from top left: Fujifilm (IDTechEx Show! USA 2016), Negase (Nepcon Japan 2017), Heraeus (IDTechEx Show! USA 2016), Aga (FineTech 2014), Canatu. (Information in brackets indicates where/when IDTechEx analysts took the photo.)

continued from page 2

It sounded to me like a bit of a trick at first, but after reading this article and taking in the associated excitement around the concept at Display Week this year, I'm convinced this is a very promising approach. It's somewhat analogous to the early days of color TV, when we took advantage of the observer's lower sensitivity to resolution in certain colors to achieve the lowest possible total channel requirements. Behnam and his coauthors (including Nikhil) take this concept all the way through a practical system architecture and full image-processing and data-management design to show how this can be implemented with existing technology, including silicon. This is very significant work, and actual images with great promise have already been demonstrated.

VR and AR Developments

Staying with a similar theme, we offer the next installment in our review coverage of Display Week 2017, "Recent Developments in Virtual-Reality and Augmented-Reality Technologies." Frequent contributor Achintya Bhowmik was at the hub of many of the new developments revealed this year as a teacher, developer, and observer. It's been a busy year, with so many new concepts being shown, including a whole range of new augmented- and mixed-reality devices. In fact, even the vocabulary is getting complicated. For example, where is the boundary between virtual reality and augmented reality? Is it at the intersection of transparent optics that merge simulated scenes with real scenes or is it something else? Well, whatever it is, what really matters is the rapid pace at which we're seeing creative solutions and new ideas, including new ways to address the classic accommodation-vergence problems. Achintya's review covers several critical areas of this field, including the hardware innovations in the displays themselves and the methods for achieving acceptable visual acuity (including foveated rendering). It's a great summary of the state of the field from one of its foremost experts.

One of the companies that is working hard to bring a new type of light-field display technology to market is Avegant. Led by cofounder and CTO Edward Tang, Avegant is designing a new generation of transparent headset displays that can render light-field images in a virtual space in front of the observer with technology the company calls "retinal imaging." Of interest to us was not just Avegant's innovation but how far the company has gotten and what it was like to develop this technology in a startup environment. Our own Jenny Donelan took the challenge and produced this month's Business of Displays Q & A feature for your enjoyment. At one point during the conversation, Ed describes the experience: "Startups are a rollercoaster. You have the extremes of emotion and experience at both ends – the highs and the lows – and those happen almost simultaneously. There are things going on that are so exciting that you can't believe it. At the same time, the things that you worry about are incredibly stressful as well."

Having been in several startup environments myself over the years, I could not have said it better. A cool idea and a new product are exciting, but getting the entire business over the goal line and into the marketplace is a far greater and more stressful challenge than developing the technology alone. I tip my hat to Ed and everyone else in our great industry who risk so much for their entrepreneurial achievements.

Market Realities for Stretchable Technology

Another area that has seen a lot of activity this year is stretchable displays and electronics. We've covered some interesting highlights recently in *ID*, and there were some very notable demonstrations at Display Week this year as well. However, there has been a lot more to talk about than we could cover ourselves, so we asked our friends Khasha Ghaffarzadeh and James Hayward from IDTechEx to write this month's Display Marketplace feature, "Stretchable and Conformable Electronics: Heading Toward Market Reality." As the title implies, the advances we see are just the tip of the iceberg, with all the underlying innovations lining up to bring some really interesting concepts to market. And while a lot of this work does produce visual items like clothing that can change color and displays that can be applied in countless ways, there is also a whole field of devices that can be integrated into fabrics to monitor health and wellness, and to protect users from dangers in the environment. Imagine, for example, clothing that can detect heat or dangerous vapors before the wearers are actually exposed. But this is not yet a mature space by any measure and the supply chain, market needs, and other business aspects are far from being well defined yet. With their great efforts, where we are now and where we will need to go is the picture the IDTechEx authors want you to appreciate.

As we move into the end of 2017, I want to wish everyone safe and happy holidays. I also want to acknowledge the people who may be struggling with loss due to recent events and extend my heartfelt sympathies to you. May you find peace, comfort, and security during this season. Cheers and best wishes! ■

frontline technology

continued from page 13

[2]S. Fuhrmann *et al.*, "Investigating Geospatial Holograms for Special Weapons and Tactics Teams," *Cartographic Perspectives,* 2009.
[3]M. Klug *et al.*, "A Scalable, Collaborative, Interactive Light-Field Display System," *SID Symposium Digest of Technical Paper, 2013.*
[4]N. Balram, "Fundamentals of Light-Field Imaging and Display Systems," Short Course, Display Week 2016.
[5]M. Halle and A. Kropp, "Fast Computer Graphics Rendering for Full Parallax Spatial Displays," Massachusetts Institute of Technology, Media Laboratory, Cambridge. ■

show review

continued from page 24

[13]A. Jamali, D. Bryant, Y. Zhang, A. Grunnet-Jepsen, A. Bhowmik, and P. Bos, "Design Investigation of Tunable Liquid Crystal Lens for Virtual Reality Displays," Paper 72.3, Display Week 2017.
[14]Y. H. Lee, G. Tan, Y. Weng, and S. T. Wu, "Switchable Lens based on Cycloidal Diffractive Waveplate for AR and VR Applications," Paper 72.4, Display Week 2017. ■

UCF Students Earn Outstanding Student Paper Award from SID

By Ruidong Zhu with Jenny Donelan

The growing popularity of augmented-reality (AR) applications, coupled with the challenges posed by creating optimal displays for these devices, prompted a student research team at the University of Central Florida to develop new materials to support AR technology. In order to improve the ambient contrast of AR systems, and also to reduce their size, the students created a "smart" liquid-crystal film and polarizer that can potentially be used in automotive head-up displays (HUDs) as well as AR head-mounted devices (HMDs). At Display Week 2017, authors Ruidong Zhu, Haiwei Chen, Guanjun Tan, and Professor Shin-Tson Wu from the University of Central Florida, as well as collaborators Tamas Kosa and Pedro Coutino of AlphaMicron, Inc., in Kent, OH, received the Best Student Paper Award from SID for their 2016 paper "High-Ambient-Contrast Augmented Reality with a Tunable-Transmittance Liquid-Crystal Film and a Functional Reflective Polarizer." See Fig. 1.

Seeking Solutions in Ambient Light

Sunlight readability is an obvious problem for mobile displays and head-up display devices. The displayed images can easily be washed out by strong ambient light. Researchers at UCF have been tackling this problem for decades, and the issues have become even more challenging with the emergence of AR and automotive displays.

Zhu's team of graduate students at UCF, under the direction of Wu, decided to tackle this problem with a "smart dimmer" and a functional reflective polarizer. Wrote Zhu: "Our LC film (we call it a smart dimmer) works similarly to transition sunglasses (the kind that automatically darken in response to light). To develop it, we doped some dichroic black dyes to our LC host. Without voltage, the transmittance for unpolarized light is about 76 percent. As the voltage increases, the transmittance decreases gradually. At 8 volts, the transmittance reaches ~26 percent."

The new film's transition time is only a few milliseconds – much faster than that of transition glasses. For practical applications, Zhu explained, a sensor can be added to the LC smart dimmer. When the ambient light is strong, the voltage will be turned on so that the film darkens, reducing the transmission of the high ambient light. If the ambient light is weak, then no voltage is applied and the LC smart dimmer will become highly transparent.

The team also developed a functional reflective polarizer, which works to optically combine the ambient light and the display images. Similar to a polarizing beam splitter (PBS), it transmits one polarization and reflects the other. However, compared to a PBS, it is smaller and its design process is truly flexible. These features will help minimize the thickness and weight of the optical systems. Wrote Zhu: "We can design the transmittance and reflection band of the functional reflective polarizer for other alternative applications; one example we showed in our paper is to help people with color-vision deficiency."

Overcoming Challenges

The most challenging aspect of this project was to achieve a wider tunable transmittance range, which required dye materials with a higher dichroic ratio. With help from their industrial collaborator, AlphaMicron, the UCF researchers say they were able to get "the best dichroic dye material on the market" and incorporate it into their device. "However," wrote Zhu, "we still need to increase the transparency state to above 80 percent and the dark state to below 10 percent. We need to develop better materials and device approaches, especially lightweight and conformal smart dimmers."

As for developing the functional reflective polarizer, the biggest challenge was tuning the reflection band to mitigate color-vision deficiency. The UCF group spent a great deal of time evaluating commercially available products and comparing their performances to provide direction and inspiration. They also performed a number of simulations to determine the optimal reflection band. They are still looking for an industrial company to manufacture the functional reflective polarizer.

Zhu said his team realized it was making potentially important discoveries when it measured the transmittance and response time of the smart dimmer and found out it had the leading tunable transmittance range on the market and was 100 times faster than commercial transition glasses.

Real-World Applications

In the real world, the smart dimmer can be used for all scenarios in which high ambient contrast is required; for example, transparent displays, smart watches, pilot goggles, *etc.* Collaborator AlphaMicron is already commercializing this technology for ski goggles. As for the (functional) reflective polarizer, it can be used for scenarios in which polarization recycling is required, such as display backlighting. At the same time, the reflective polarizer can be used as an optical combiner for optical see-through systems. Moreover, by carefully designing the transmittance curve of the functional reflective polarizer, the sensor can help people with color-vision deficiency.

When these two components are combined, they should be an excellent match for augmented-reality systems, wrote Zhu. He added that the team is also trying to incorporate the technologies in other applications, such as transparent displays.

Another future direction involves dividing the smart dimmer, a single-pixel device, into several segments so that it can be used to selectively dim a bright area locally without affecting the see-through aspect of surrounding or adjacent areas. For example, when a user is driving into the sun, just the bright area of the automotive see-through display could be dimmed while the high transmittance is retained for the rest of the field of view.

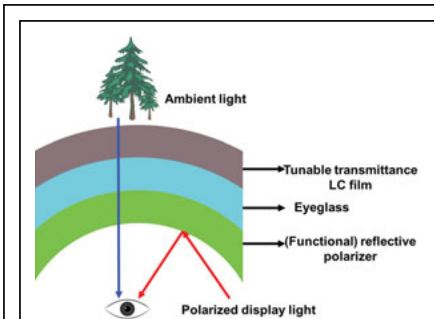


Fig. 1: A tunable transmittance LC film and reflective polarizer work together to create a display that can react quickly to changes in ambient light.

***Ruidong Zhu** received his B.S. in electronics science and technology (optoelectronics) from Harbin Institute of Technology, Harbin, China, in 2012. He is currently working toward a Ph.D. at the College of Optics and Photonics at the University of Central Florida. From 2014 to 2015, he served as the president of the IEEE Photonics Society Orlando student chapter.* ■

continued from page 3

The V30 is sheathed front and back in tempered glass that curls around its edges. It weighs only 158 grams, which LG claims makes it the lightest smartphone in existence in the 6-inches-and-over category.

[3]www.theverge.com/2017/9/14/16306244/apple-iphone-x-design-notch

Fig. 3: *The LG V30 incorporates LG's own plastic OLED (P-OLED) touchscreen display.*

LG and Samsung Invest €25 Million in CYNORA

CYNORA, a developer of organic emitting materials for OLED displays based on thermally activated delayed fluorescence (TADF) technology, recently announced that LG Display and Samsung Venture Investment Corp. were investing a combined €25 million in a Series-B financing round to support the German company in the development of a full-color portfolio of organic-emitting materials for AMOLED displays. (This is not the first time both display powerhouses have invested in the same TADF technology; in 2016, both companies, as well as Japan Display/JOLED and several Japanese venture capital funds, participated in a $13.5 million Series A round of funding for TADF developer Kyulux.)[4] Going forward with CYNORA, LG and Samsung will establish separate development efforts to assist with CYNORA's R&D, according to OLED-Info.[5]

With its TADF technology, CYNORA claims it will be able to commercialize the first high-efficiency blue-emitting material on the market. Blue is currently an elusive and sought-after material among OLED display makers. High-performance blue materials will enable a significant reduction of power consumption and allow higher display resolution.

According to Gildas Sorin, CYNORA's CEO, these investments validate the importance of his company's materials to the OLED display industry. Said Sorin in a press statement: "CYNORA will work in close collaboration with LG and Samsung to support their respective activities. The cash injection will also be used to strengthen our worldwide presence as a supplier of high-efficiency emitting materials. We will commercialize our first blue product by the end of 2017, followed by green and red." (*Information Display* interviewed CYNORA CMO Andreas Haldi for the November/December 2016 issue.)

[4]www.prnewswire.com/news-releases/kyulux-inc-announces-135-million-series-a-financing-and-acquisition-of-large-oled-patent-portfolio-from-kyushu-university-300247016.html
[5]www.oled-info.com/tags/cynora

LG Invests in OLED Fabs

LG Display is wagering heavily on OLEDs, as underscored by its recent investment of KRW2.8 trillion into a Gen 10.5 (2,940 mm × 3,370 mm) OLED production line at its P10 plant in Paju, Korea. The obvious use for a Gen 10.5 line is OLED-based TVs. The company will also invest KRW5 trillion in a new Gen 6 (1,500 mm × 1,850 mm) plastic OLED (P-OLED) production line in Paju.

According to LG, its Gen 10.5 OLED production line will be the first of its kind in the world. The size of mother glass produced in 10.5-generation production lines is 1.8 times larger than that in Gen 8 generation production lines.

LG does note that it will only begin mass production of OLED TVs after stabilizing the technology for producing extra-large panels and oxide backplanes for the mother glass, and determining which size large-TV panels are most desired in the marketplace. ■

continued from page 4

is based on the retina's primary daylight viewing receptors (cones) being densely concentrated in a very narrow region, called the fovea. From the fovea, the cones continuously scan the scene through rapid eye movements called saccades to build a full-scene representation over time. So, at any particular moment, the front end of the human visual system is only capturing a small high-resolution image spanning a few degrees of visual field.

This foveated capture is the inspiration for efficient ways to render a rich world image to the single user of an HMD through the use of a set of techniques called foveated rendering. These techniques employ knowledge of the user's eye movements to deliver high-resolution imagery for only the specific region of interest.

The second article in this issue, "Foveated Pipeline for AR/VR Head-Mounted Displays" by Behnam Bastani *et al.*, provides an overview of the foveated rendering and display processing algorithms and architecture needed to deliver perceived high-fidelity images to the viewer using knowledge of where she is looking. These algorithms and architecture need to efficiently align with the compute and thermal constraints of mobile processing to enable the goal of delivering great virtual and augmented experiences to the user as she roams freely.

With efficient and practical light-field display architectures and the associated rendering pipelines coming together, we can anticipate the beginning of the era of light-field display systems. Perhaps there is an Olympics or World Cup in the not-too-distant future that will be experienced by billions of users all over the world as if they are actually there.

Nikhil Balram *is head of display R&D for VR and AR at Google. He is an SID fellow and Otto Schade Prize winner. He can be reached at nbalram1@hotmail.com.* ■

Submit Your News Releases

Please send all press releases and new product announcements to:

Jenny Donelan
Information Display Magazine
411 Lafayette Street, Suite 201
New York, NY 10003
Fax: 212.460.5460
e-mail: jdonelan@pcm411.com

frontline technology

continued from page 19

hardware upscaling and blending to be more efficient on the display side compared to performing these operations on the GPU in the mobile AP SoC.

There are compression techniques such as stream compression (DSC)[11] that are widely adopted in the display industry. Such in-line compression methods can further reduce the data transmission rate. DSC is a visually lossless compression method that saves up to 67 percent (75 percent for ADSC) of data to be transmitted. With a carefully engineered design, one may combine DSC operation with foveated transmission and further reduce the transmission data to 2.5 percent of the original, potentially saving close to 95 percent of transmission power. Special bit manipulation may be required to maintain the visual quality of DSC while transmitting content in a foveated manner.

Toward a New Pipeline

In summary, the traditional rendering pipeline used in today's common HMD architectures needs to be re-architected to take advantage of the unique attributes of the human visual system and deliver a great visual experience for VR and AR standalone HMDs at the low compute and power budgets available in mobile systems. The solution is a "foveated pipeline" that delivers a perceptually full-resolution image to the viewer by sending native resolution image data to the specific portion of the display at which the eyes are looking and low-resolution elsewhere, thereby saving on processing, storage, and power. In this article, we discussed three parts of the full content-creation-to-final-display pipeline that can be foveated. The pipeline can be made very efficient if the main elements of the system, *i.e.*, the processing, optics, electronics, and panel, are optimized together. This has been an active area of research for many years and it seems reasonable to expect the appearance of VR and AR headsets with foveated pipelines in the next few years.

References

[1]G. Osterberg, "Topography of the layer of rods and cones in the human retina." *Acta Ophthalmologica Supplement* **6,** 1–103, 1935.

[2]D. Purves, G.L. Augustine, D. Fitzpatrick, *et al.*, editors, "Types of eye movements and their functions," *Neuroscience*, 2nd edition, Sinauer Associates, 2001.

[3]K. Koch, J. McLean, R. Segev, M. Freed, M. Berry, *et al*., "Calculate how much the eye tells the brain," *Current Biology*, **16**(14), 1428–1434, 2006.

[4]B. Guenter, M. Finch, S. Drucker, D. Tan, J. Snyder, "Foveated 3D graphics," *ACM Transaction of Graphics,* 2012.

[5]A. Patney, M. Salvi, A. Kim, A. Kaplanyan, C. Wyman, *et al*., "Towards foveated rendering for gaze-tracked virtual reality," Proceedings of ACM SIGGRAPH Asia 2016.

[6]B. Karis, "High-quality temporal supersampling," *Advances in Real-Time Rendering in Games*, SIGGRAPH Courses 2014.

[7]"YCoCg," Wikipedia, https://en.wikipedia.org/wiki/YCoCg

[8]"Cube mapping," Wikipedia, https://en.wikipedia.org/wiki/Cube_mapping

[9]www.khronos.org

[10]www.mipi.org

[11]F. Walls, A. MacInnis, "VESA Display Stream Compression: an overview," SID International Symposium, 360–363, 2014. ■

business of displays: Q&A

continued from page 27

problem." That's not the right attitude to have. You can get away with that probably at a large company, but at a small company you need a lot of flexibility because there are always small fires that you're putting out.

Right now we have about 45 to 50 people at Avegant. I'm sad that there will come a day when I walk in here and don't know everybody's names, but that will probably happen.

ID: Can you describe the transition from being an R&D enterprise to one that is at least equally focused on marketing?

ET: There are a couple of big hurdles to clear when you go from being a technology company to one that actually ships something. A very large hurdle, which many technologists don't get, is that having something work as a prototype is very different from being able to make 100,000 of something that is manufacturable and passes quality control and works according to yield, cost, and scale, And then there are the logistics – working with third parties, copyrighting in foreign countries, managing time zones. How do we build an inventory? How do we get this distributed all over the world? How do we do the sales, the marketing that we need? Dealing with Amazon is very different from dealing with, say, Best Buy. It is a massive effort. The devil is in the details, but some of those details will kill your company. I know multiple companies that have gone out of business because of poor distribution terms, or payment terms.

ID: Companies with great products?

ET: Oh absolutely. When you're an engineer you think that technology is the most important thing. And really it's only a piece of the puzzle. If you don't have a good management team, if you don't have good sales, good operations – any one of these things will conquer you.

ID: What is the biggest lesson learned from your experience? Is there something you would definitely do differently next time and why?

ET: Every day is a humbling learning experience for me. Looking back, there are always small mistakes that you wish you could go back and do differently. Most of these are startup-related growing pains that everyone goes through. Being a serial entrepreneur, I just focus on moving fast and try not to get hung up about breaking things.

ID: When will we see commercial products incorporating your technology?

ET: We are not in a position to release exact dates, but you can expect products with our technology within the next year. Light field is what we are ready to have on the market and we're very excited about it. We'll be first. But we're always working on the next thing. There are other display developments that we are working on that we look forward to sharing with you. ■

corporate members

GOLD CORPORATE MEMBERS

admesy — ADVANCED MEASUREMENT SYSTEMS

Google

Instrument Systems — KONICA MINOLTA Group

RADIANT VISION SYSTEMS

intel REALSENSE TECHNOLOGY

TechnoTeam Bildverarbeitung GmbH

SILVER CORPORATE MEMBERS

AGC ASAHI GLASS

CHIPONE

ELDIM

INCOM — Bright Ideas in Fiberoptics

RAVITEK

SILVACO

TIANMA

NLT Technologies

index to advertisers

Corporate Members

Abrisa Technologies
Apple, Inc.
Applied Materials, Inc.
AU Optronics Corp.
ChromaATE
CLEARink
Coretronic
CYNORA
Display Link
Dontech
E Ink Holdings
Earth LCD
eMagin Corp.
Europtec USA, Inc.
Flectrode Technology Limited
FocalTech Systems
FUJIFILM Dimatix, Inc.
Galloping Technology
ITRI
I-PEX
Japan Display, Inc.
Japan Patent Office
Jiangsu Sunera Technology Co., Ltd.
KMTC
Kyulux
LXD Research & Display, LLC
MegaChips Corp.
Mindfire Solutions
Mitsui Chemicals
NANOSYS
NLT Technologies
Noritake Itron Corp.
Nvidia
Oculus
Panasonic
POLOMO
Rolic Technologies
Sakai Display Products
Sharp Corp.
SpectraTek
TDMDA
Teijin Films Solutions Ltd.
TFD, Inc.
Thine
TLC International
Tokyo Ohka Kogyo Co.
UICO
Universal Display Corp.
US Micro Products
Vestel Electronics
Vigor Gas Purification Technologies
Visionox
WaveOptics
Westar Display Technologies, Inc.
Yazaki Europe Limited
YUASA SYSTEM Co., Ltd.