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SOCIETY FOR INFORMATION DISPLAY

Information DISPLAY

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Display Industry Awards: A Look into the Future of Displays

Plus

Products on Display at Display Week 2013

A Quantitative Tool for Display Performance Prediction

Are Light-Field Displays the Future of 3-D?

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MAY/JUNE 2013
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ON THE COVER: *The 2013 Display Industry Award winners are, from top left, clockwise: Nokia Lumia 920, QD Vision's Color IQ optical component, Shenzhen China Star's 110-in. 4K x 2K 3-D TFT-LCD TV, Sharp's Moth-Eye Technology, Apple's iPad with Retina Display, and Sharp and Semiconductor Energy Laboratory for Sharp's IGZO LCD as used in the AQUOS PHONE ZETA SH-02E.*

Cover Design: Acapella Studios, Inc.

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

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- Tablet Shoot-Out
- Tablets in the Medical Field
- Optical Dry Bonding
- The Future of Touch and Interactivity

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editorial

Welcome to Vancouver and the Future of Displays

by Stephen Atwood

Welcome to Vancouver, British Columbia, for our 50th annual Display Week event. It feels like it was just yesterday when we were all in Boston for the last Symposium and Exhibition – not to mention the Market Focus Conferences, Business Conference, Investors Conference, Seminars, and the many other great happenings that are organized each year for your benefit and enjoyment. This year we're back on the West Coast of North America, in Canada for the first time. Vancouver is known to be a great destination city and one that promises lots of options for great food, sightseeing, and relaxing away from the demands of the office.

This year also continues our year-long celebration of the birth of SID, founded in September of 1962 by a small group of visionary people on the campus of the University of California in Los Angeles. The next year, 1963, marked the first annual SID Symposium, which quickly grew into the highly acclaimed Display Week program we have today. Now, 50 years later, it's amazing to see how much the Society has achieved and all that has happened in this time. Over the past year, we celebrated our anniversary with an outstanding one-day conference and banquet at UCLA organized by Larry Tannas and his fellow members of the SID LA Chapter.

As a veteran of Display Week myself for more years than I choose to count, I strongly encourage you to look beyond the world-class exhibition and consider everything going on during the week, including more than 400 paper presentations, short courses, seminars, the aforementioned conferences, the keynote addresses, the Honors & Awards dinner, and more. Now, take my advice: Getting the most out of your Display Week experience involves some serious planning. Take time to review the full program and mark off the things that are most important to you. Plan your days to see as many things as you can and coordinate with colleagues to make sure the stuff you cannot see is covered by others. Usually, there are dozens of presentations and exhibits that I know I want to attend, but I also find many surprises that I can only discover if I explore as much as possible.

This issue of *ID* can be particularly useful for your planning because it features our "Products on Display" coverage, which is assembled each year by our staff to help you get the most out of the exhibition. Also, as we do every year, we've invited a prestigious team of freelance technology enthusiasts to report on all the happenings in their subject areas, and they will be hard at work covering everything they can. We'll have daily blog updates on the newly redesigned *ID* web site (www.informationdisplay.org) and a full issue of post-show coverage later in the year. If you have a question about anything on the exhibit floor, just email us at press@sid.org and we'll get your question to the right reporter to see what we can find out.

Our cover story this month announces the recipients of the SID 2013 Display Industry Awards (for products that shipped in 2012). Each year the committee recognizes the most innovative display products and technologies from the wide array of nominations received. If you are around on Wednesday, consider making plans to attend the annual awards luncheon and see the winning companies receive their awards.

Our issue lineup continues this month with three Frontline Technology articles exploring the future of 3-D displays, beginning with author Jim Larimer, a human

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Changes Occur Among German Instrumentation Companies

Late last year, instrumentation companies around the world began consolidating at the speed of light, or so it seemed if you happened to be following the announcements. Most of the action occurred in Germany. In December 2012, Konica Minolta Optics (KMOP) in Japan announced that it had bought Instrument Systems, a lighting, LED, and display metrology company with facilities in Munich and Berlin, for an undisclosed sum. In January 2013, Instrument Systems disclosed that it had purchased all development and production rights from autronic–Melchers in the previous year. autronic–Melchers is a display measurement systems company formerly based in Karlsruhe, Germany. And in March, photometric test equipment maker Optronik Berlin announced that it had merged with parent company Instrument Systems.

In making the above moves, Instrument Systems, already an instrumentation leader, was seeking to expand its range of products into the measurement of lighting devices (that's why Optronik, with its product range of goniometers, was acquired) and to expand its expertise and range of products in the area of measuring displays, which it did by acquiring the IP of autronic–Melchers' DMS and ConoScope series of instruments).

KMOP, in turn, had begun reorganizing its optical businesses with the aim of evolving from a supplier of parts and components to limited industrial sectors into a group of business units focusing on growth markets. The company's recent acquisition of Instrument Systems should make KMOP a "power house" in the instrumentation industry, according to an e-mail interview with an industry source based in Germany.

Germany is still a power house on its own when it comes to instrumentation. The light and color measurement industry in this country has a rich history. Existing key companies include LMT Lichtmesstechnik Berlin GmbH, X-Rite (which had already acquired Optronik GmbH, retaining the color measurement IP and selling the light measurement part to Instrument Systems), BYK-Gardner, and, of course, Instrument Systems/KMOP.

In terms of ongoing operations, Instrument Systems, which employs 131 people and has R&D, production, and sales facilities in Munich and Berlin, will retain its own brand following the merger. Existing president and CEO Richard Distl, who started Instrument Systems 26 years ago, will remain with the company. autronic-Melchers GmbH has closed its operations in Karlsruhe. The Optronik location in Berlin will be retained, with all the employees working as a team of experts specializing in goniophotometry and in equipping turnkey photometric laboratories.

– Jenny Donelan

president's corner

SID, an International Society

by Brian Berkeley
President, Society for Information Display

Greetings and a warm welcome to all to Display Week 2013! As of this writing, final preparations are under way in earnest as SID heads to Vancouver, British Columbia, for its annual Display Week event. This year will mark the 50th meeting of Display Week, and it is the first time that it has been held outside of the United States. Considering that SID is very much an international society, it is fitting that Display Week be held at an international location. In fact, well over half of SID's membership is based outside of the U.S.

Vancouver was selected as the venue for Display Week 2013 for many reasons. It is a beautiful city that is well known for its diversity and international demographic. Less than half of its residents are native English speakers. Vancouver is accessible, with many daily non-stop flights from major cities throughout Asia, Europe, and the U.S. The most recent Winter Olympics, certainly an international event, were held in Vancouver. The conference center (or using local vernacular, "centre") where Display Week 2013 will be held has frequently received the #1 rating among all worldwide conference venues.

As is the case every year, Display Week 2013 promises to reveal many exciting technical developments in the field of information display. There are reports that very large 4K × 2K displays will be shown, and some as large as 110 inches will be reported in the technical sessions. Full high definition (FHD, or 1920 × 1080) resolution, which not too many years ago became available on TV-sized displays, can now fit in the palm of one's hand – driving pixel densities to well over the 400 ppi level in mainstream mobile devices that will ship this year. These and many other significant developments will be reported and shown at Display Week 2013. The Innovation Zone, or I-Zone for short, made its first appearance on the exhibit floor last year, and more emerging prototypes will be shown in this second year for the I-Zone. Display Week 2013 will certainly be ground-breaking and informative.

SID became an international society in 1976, when the Japan Chapter was officially instated. As of now, 17 of SID's 28 chapters are based outside of the U.S., and a majority of SID's student branches are also located outside of North America. Over time, as SID has broadened its reach to become a truly worldwide society, it has embraced a wide swath of cultural and style differences. It is probably not surprising that only two of SID's eight Executive Committee members are native English speakers. As one of the "two," I can relate to international immersion from personal experience, having lived in Korea for 8 out of the last 10 years. It was challenging and humbling to communicate in a very different language, to work in unfamiliar ways, and to accept many other differences. But it was also a rewarding life experience. Many times, I had to say, "천천히 다시 말해 주세요," which roughly means, "please say it again slowly." The experience taught me, when using English, to be just a little more patient and tolerant when communicating with non-native English speakers, and to try to explain things using the simplest possible terms and to stick to the essential points.

SID certainly is no stranger to international events. Although this year is the first for Display Week to be held outside of the U.S., in 2013 alone, SID is also sponsoring or co-sponsoring major events in Shanghai, Belgium, Korea, Taipei, London, Brazil, and Japan (in order). To increase worldwide access to the conference proceedings,

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TANNAS ELECTRONIC DISPLAYS INC.
LCD SOLUTIONS

guest editorial

Is 3-D Dead (Again)?

by Nikhil Balram

This is the question that came to mind for many attendees at the 2013 Consumer Electronics Show (CES) in January in Las Vegas. As usual, there were lots of interesting new consumer gadgets, with a special emphasis on networked and mobile ones. TVs were again a prominently featured item. But the main storylines for TVs were the connectivity and intelligence, and the step up to 4K resolution. A first-time visitor could easily think she was back in the pre-*Avatar* period of 2008 or earlier, when the big future themes were connectivity, smartness, and higher resolution.

The reality is that the second big coming, the "Renaissance" after the "Golden Age" of the 1950s, of stereoscopic 3-D (S3D) was probably overhyped in the euphoria around James Cameron's *Avatar*. Other factors were the film industry's need to raise ticket prices as an antidote to the shorter big screen life of movies, piracy, and other competitors for the consumer's time, as well as the always-urgent need of the consumer-electronics market for "the next big thing" to drive sales.

One can reasonably argue that S3D has settled into a steady state in which it is one of the options that certain segments of cinema and home viewers appreciate and seek out, while others ignore. A very big difference from the 1950s is that S3D today rides on top of the overall trend of adoption of digital technologies in cinema – from production to display – so even a modest adoption by consumers can make the economics work. However, as technologists and vision scientists, we (the experts) recognize another very important factor at work here – the S3D that is available today is fundamentally limited and flawed, and these limitations and flaws play a large role in the diminished interest that consumers are showing.

The work of well-known vision-science researchers like Professor Martin Banks at UC Berkeley has shown very clearly and conclusively that stereoscopic 3-D has some basic limitations. The most fundamental and arguably most important one is the so-called vergence-accommodation conflict created by the presentation of stereoscopic 3-D on the flat, single-plane screens used in cinema and home today. The July 2008 issue of *Information Display* has two articles – "Consequences of Incorrect Focus Cues in Stereo Displays" by Banks *et al*. and "Scanned Voxel Displays" by Schowengerdt *et al*. that explain the issue and provide insights into possible solutions. This fundamental conflict is caused by the fact that presentation of stereoscopic images on a single plane results in an unnatural decoupling of vergence (the point at which a person's eyes converge) and accommodation (the point at which the eyes focus), in contrast to real-world viewing where these two are always closely coupled. This conflict has been shown to cause viewer discomfort that manifests itself in different ways such as nausea, headaches, and tiredness.

The film industry has responded by moderating the amount of depth that is produced in S3D movies – the so-called "gentle 3-D". In particular, this approach avoids putting objects of interest (*i.e.*, objects the audience should be looking at) far behind or far in front of the screen. As a consequence, objects of interest are moved to the screen. This has reduced the possibility of viewer discomfort. But it has caused a different issue – a growing criticism from viewers that the 3-D effects are underwhelming and not worth the extra cost or inconvenience of wearing glasses. It is interesting to see letters to the editor in traditional home theater magazines in which

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SID 2013 Display Industry Award Winners

Once again, The Society for Information Display's Display Industry Awards Committee has selected six award winners that have advanced the state of the art of display products and technology in the categories of Display of the Year, Display Component of the Year, and Display Application of the Year.

Compiled by Jenny Donelan

THIS YEAR'S Display Industry Award winners (products that were commercially available in 2012) particularly exemplify the idea that it's what's inside that counts. Everyone knows that we judge the quality of displays primarily by what we see (though interactivity has become important as well). Yet, this year's achievements are characterized as much by what you *don't* see that makes them better displays.

A case in point is Sharp and SEL's IGZO technology, in which oxide semiconductors have been used to create a smartphone with exceptional battery life, high resolution, and touch capability. The result is a quality display you can enjoy much longer without running for the nearest electrical outlet. Another winner from Sharp uses nanotechnology inspired by the structure of a moth's eye to create a display that suppresses the reflection of ambient light and provides deeper blacks. QD Vision's light-emitting semiconductor nanocrystal products enable LCDs to achieve wider color gamuts than ever before. The Retina Display in Apple's latest iPad manages to fit 3 million pixels into a small area, producing a viewing experience that truly rivals printed paper and photographs. Nokia's Lumia 920 smartphone uses overdriving to create a display that is just plain fast. You can't actually see all the magic behind these devices, but it vastly improves the experience of using them in myriad ways.

There is one winner this year that turns heads even when it's off (though we suggest you turn it on): the 110-in. LCD TV from Shenzhen China Star Optoelectronics Company. As you can see in the photograph of this TV later on in this article, it's bigger than the person standing next to it.

According to Display Industry Awards Chair Robert Melcher, "The 2013 SID Display Industry Awards demonstrate the diversity of great achievements over the past year, and the results of ongoing investments into new R&D activities."

One of the exciting aspects of the display industry is that the underlying technology keeps evolving, even when we thought we might have reached a plateau. Please join us in saluting this year's inspiring Display Industry Award winners.

***Jenny Donelan** is the Managing Editor of* Information Display *Magazine. She can be reached at jdonelan@pcm411.com.*

Display of the Year

This award is granted for a display with novel and outstanding features such as new physical or chemical effects, or a new addressing method.

Gold Award: Sharp and Semiconductor Energy Laboratory for Sharp's IGZO LCD as used in the AQUOS PHONE ZETA SH-02E

The scope of connected applications for handheld devices is ever growing, as is the demand for information devices such as smartphones that enable us to see an enormous amount of rich content anytime, anywhere. The penalty we pay for this great performance has traditionally involved high-power demands and short battery life. In an effort to alleviate the need for this tradeoff, Sharp Corporation and Semiconductor Energy Laboratory (SEL) jointly developed a new IGZO technology that imparts crystallinity in an oxide semiconductor composed of indium (In), gallium (Ga), and zinc (Zn). This IGZO enables a display with both high resolution and ultra-low power consumption, characteristics that have in the past needed to be balanced against each other. In addition, the IGZO incorporates a touch panel, and represents the first time an IGZO panel has been integrated into a smartphone.

Sharp and SEL succeeded in aligning the crystallizing IGZO layer in the c-axial direction, which results in higher reliability of the device, in addition to enabling higher definition, lower power consumption (1/5–1/10), and high performance of the touch panel due to miniaturization and high performance of the thin-film transistor. The AQUOS PHONE ZETA SH-02E from Sharp can be used for 2 days without charging batteries because of its low power consumption and can be used 4.8 times longer than conventional units when displaying a static image, thanks to the IGZO. Improved recognition accuracy and response speed of the touch panel enable a better user interface as well. Pen input is also supported.

IGZO can also be applied to other, larger displays such as monitors, TVs, *etc.*, since it corresponds to the same manufacturing

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DISPLAY OF THE YEAR

***Gold Award:** Sharp and Semiconductor Energy Laboratory's IGZO LCD as used in the Sharp AQUOS PHONE ZETA SH-02E enables a display with high resolution, ultra-low power consumption, and touch.*

***Silver Award:** Shenzhen China Star's 110-in. 4K × 2K 3-D TFT-LCD TV is the largest of its kind in the world.*

processes of large motherglass substrates equivalent to a-Si. It can also be applied to displays other than LCDs; for example, organic electroluminescent displays. IGZO will also enable development of applications for non-display uses such as sensing devices. Sharp and SEL researchers believe that IGZO will become the core technology of displays in the future.

Silver Award: Shenzhen China Star's 110-in. 4K x 2K 3-D TFT-LCD TV

Shenzhen China Star Optoelectronics Technology Co., Ltd. (CSOT) has successfully developed a 110-in. LCD TV that is the largest of its kind in the world. The 110-in. TFT-LCD integrates many innovations in LCD technology. It has a reported dynamic ratio of 50000:1, an ultra-high brightness of 1000 nits while consuming less than 1100 W, and highly saturated color reproduction with a color gamut of about 92% of NTSC. Moreover, through the effective use of shutter glasses technology in 3-D mode, the left to right eye crosstalk ratio is less than 2.5%.

CSOT's goal was to develop an attractive display with an extraordinary visual quality that would enable entertainment applications such as gaming, movie, and multi-user communication. Such a TV will play an important role in bringing families together. Accordingly, the company wanted to develop a TV with a large LCD panel, high resolution, and 3-D functionality.

The 110-in. LCD was designed and fabricated in CSOT's Gen 8.5 facility. To meet the above visual reality and entertainment requirements, 4K × 2K resolution (3840 × 2160) and shutter glasses 3-D functionality were implemented. During development, the major challenges were panel uniformity, power consumption, visual quality, and the creation of an electric and optical and mechanical (OM) system for the ultra-high-definition LCD.

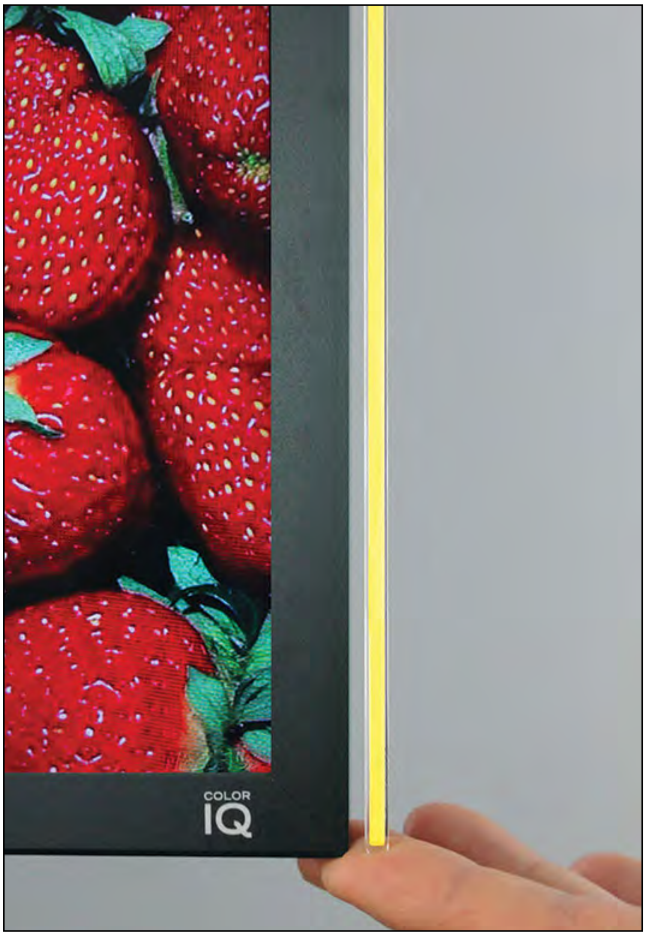
It is well-known that large-sized LCDs can suffer from a lack of panel uniformity when resolution and frame rate are upgraded for playing films or pictures. In order to suppress mura and to enhance panel uniformity, CSOT improved its manufacturing processes in several ways. High transmittance technology, high transmittance vertical alignment (HVA), and local dimming with a 288-area LED backlight were utilized to reduce power dissipation. To support the 3-D mode with 120 Hz, fine stereo performance (FSP) technology was implemented in the driving system, which greatly improved both 2-D and 3-D quality. Since the ultra-high-definition interface is not mature in the market, the image-process system was assembled with an FPGA-base unit by CSOT. This 110-in. panel can receive any format of 4K × 2K video and is compatible with commercial transmission interfaces such as HDMI and DP. In addition, the large-sized panel accommodates the entire viewing angle of the human eye.

Besides the TV application, this 110-in. TFT-LCD can be used for advertisements and educational and office displays. Another area of focus for the company is to replace the LED boards commonly found in public-information-display (PID) systems with a much more colorful, complex, and detailed messaging medium afforded by this new development.

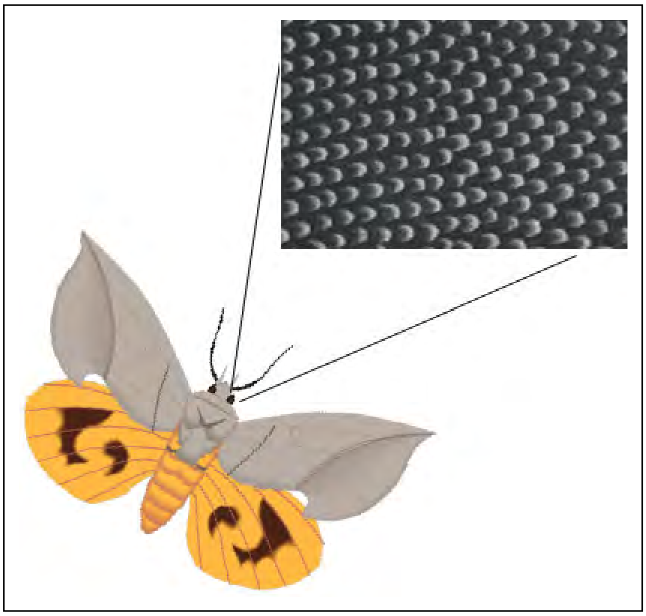
Display Component of the Year

This award is granted for a novel component that has significantly enhanced the performance of a display. A component is sold as a separate part destined to be incorporated into a display. A component may also include

DISPLAY COMPONENT OF THE YEAR



Gold Award: QD Vision's Color IQ optical component is the first product to utilize quantum dots for commercial displays.



Silver Award: Sharp's Moth-Eye Technology uses a nanoscale design inspired by the eyes of common night-flying moths to suppress the reflection of ambient light and realize deep black imagery.

display-enhancing materials and/or parts fabricated with new processes.

Gold Award: QD Vision's Color IQ Optical Component

Color IQ optical components are advanced light-emitting semiconductor nanocrystal products developed by QD Vision, Inc. They are the first product to utilize quantum dots for commercial displays. These breakthrough components enable LCDs such as TVs, monitors, and all-in-one computers to achieve significantly wider color gamut with a far more natural and vivid viewing experience than that of conventional white LED systems. While most LCDs offer color quality that might reach 60–70% of the 1953 NTSC standard, LCD products utilizing Color IQ optical components can achieve 100% of the NTSC, Adobe, and sRGB color performance standards.

Designed as a drop-in solution, Color IQ optical components may be easily integrated into conventional side-illumination LCD backlight systems. The components are delivered as a fully packaged, sealed solution, made of a glass optical tube containing red and green quantum dots (QDs) that are combined, tuned, and optimized to achieve a customer-specified on-screen white point. Designed for very-high-volume LCD applications, Color IQ products deliver color performance meeting or exceeding that of OLED and direct-lit RGB LED systems, while maintaining the cost structure of side-illumination systems for mainstream LCD TVs. After a number of years in development, Color IQ optical components have been rigorously qualified and tested to meet the stringent product reliability and lifetime requirements of mainstream consumer-electronics applications.

Systems with Color IQ optical components use highly efficient blue LEDs instead of white LEDs as the excitation source that stimulates the optical component to emit red and green and transmit blue light. Color IQ optical components harness the unique light-emitting properties of a new class of nano-materials called quantum dots to emit narrow bandwidth light, which is ideal for LCD systems, delivering pure saturated colors to the front of screen. QDs allow for independent control of emission color and composition, with their nanoscale dimensions controlling the semiconductor bandgap. Their combination of efficiency, reliability, saturated emission, and color tunability are unmatched in any known material set.

Sony is the first major TV manufacturer to incorporate Color IQ optical components into a series of new 2013 model LCD televisions.

Silver Award: Sharp's Moth-Eye Technology

Sharp's AQUOS Quattron 3D XL9 LCD TVs use "moth-eye panels" to suppress the reflection of ambient light and to realize deep black imagery. Moth-Eye technology incorporates a nanoscale design that is inspired by the eyes of the common night-flying moth. These Moth-Eye panels help to emphasize Sharp's "four primary colors technology," which enhances the quality of color displays, and also helps make imagery visible even in a bright room. These sets (AQUOS Quattron 3D, XL9 series, including 80-, 70-, 60-, 52- and 46-in. models) have a high contrast ratio to the level of 100 million:1 and images composed of approximately 8.3 million subpixels.

Sharp Corporation succeeded in the first-ever mass production of Moth-Eye technology using a nano-imprint process incorporating a large-sized seamless drum stamper. In the field of the optical films, low-reflective (LR) films coated monolayer-on and anti-reflective (AR) films deposited multi-layer-on are popular. An LR film can be produced at a low cost, but does not provide a sufficiently low reflectance. An AR film can provide a low reflectance, but entails high costs for production. Therefore, there are strong demands to make both ends of optical properties and costs meet. The Moth-Eye technology is a solution because it has a single-layer film of UV curable acrylic resin on a base film, even though it works as a multi-layer film optically. A single-layer film has merits in terms of material and process costs. In the meantime, the drum stamper is also produced in a cost-effective and industrially easy way that utilizes a combination of anode oxidation and etching of aluminum. With this method, 100-nm-size structures are formed spontaneously in a large area by merely controlling anode oxidation voltage, rather than by an overly sensitive photolithography process that makes it difficult to achieve uniformity in a large area.

The biggest benefit obtained by Moth-Eye technology is that it provides users with clear and high-quality images in bright places both indoors and outdoors. In terms of power consumption, Moth-Eye technology can conserve electricity with no loss of image quality since it is not necessary to increase the brightness of the backlight as much as you would with a lower contrast panel. In the future, applications for Moth-Eye need not be limited to electronic displays. It can be used, for example, in the glass of a picture frame at a museum or for a showcase at a jewelry shop.

Display Application of the Year

This award is granted for a novel and outstanding application of a display, where the display itself is not necessarily a new device.

Gold Award: Apple's iPad with Retina Display

By using an organic passivation technology for the first time in a 9.7-in. display with an

DISPLAY APPLICATION OF THE YEAR

Gold Award: *Apple's iPad with Retina Display fits 3 million pixels into a 9.7-in. display area, producing a viewing experience that rivals printed paper and photographs.*

Silver Award: *The Nokia Lumia 920 smartphone features innovative imaging with greatly reduced motion blur, wireless charging, and advanced touch technology.*

amorphous-silicon TFT, Apple engineers and their technology partners were able to fit four times the number of pixels into the same 9.7-in. (diagonal) screen found on earlier iPad models. The resulting pixel density of the iPad Retina display – 264 ppi – makes text and graphics looks smooth and continuous at any size. This 2048 × 1536-pixel display has set a new standard for mobile-display resolution in a panel this size.

The third-generation iPad, as with each iPad since the original, uses technology called mobile in-plane switching (IPS) to achieve a viewing angle that has established the benchmark in the tablet category. It enables users to hold the iPad in almost any position they want and still see a high-fidelity image. The consistency of gamma over viewing angles provides an enhanced viewing experience to end users in consumer, business, and education applications; from web surfing, photo-sharing, and gaming to medical research, business analysis, and elementary and higher learning applications. The custom cell design is optimized for maximum transmittance, which, in combination with a custom driver IC and backlight, enables high resolution with industry-leading low power consumption.

Silver Award: Nokia Lumia 920

The Nokia Lumia 920 smartphone is known for innovative imaging, wireless charging, and advanced touch technology. The phone has a PureMotion HD+ screen that represents Nokia's latest innovation to radically improve display capabilities. The PureMotion HD+ 4.5 in. 332-ppi screen offers crisper graphics and less blurring while users are scrolling, navigating, and playing games. Nokia's PureMotion technology addresses the inadequate moving-image quality of other mobile displays, allowing it to better leverage the high-speed rendering capabilities of its internal graphics engine. One of the ways the Nokia Lumia 920 prevents blur on a screen is with a response time faster than 16.7 msec. On average, it takes about 9 msec for transitions on the screen of the Nokia Lumia 920. This phenomenal transition speed was achieved by boosting the voltage to each LCD pixel – overdriving the panel. With overdrive-enhanced LC response, PureMotion display pixels finish their transition well before the update of the next frame for any pixel needs to start, resulting in a less blurry image.

The Nokia Lumia 920 is the first Nokia smartphone to have a super-sensitive touch display that works with fingernails or even gloves. This new ability is the biggest leap forward for capacitive touch screens since multi-touch gestures were introduced. The technology is adaptive, reacting to any conductive object that is touching the screen. In practice, the screen will automatically adjust sensitivity to provide the best possible touch-screen experience, making touch usage faster, more natural, and accurate. Super-sensitive displays have also been featured in other Nokia Lumia smartphones like the Lumia 720 and 520.

The Nokia Lumia 920's PureMotion display also introduces a new level of outdoor viewing experience in mobile displays. In addition to the very low reflectance, which largely improves dark tone rendering in ambient light, PureMotion adds high luminance mode for backlight LED-driving and image contrast enhancement, on top of superb optical stack design. Together they improve the overall contrast and therefore sunlight readability. In an extremely bright environment, the Nokia Lumia 920 PureMotion display takes advantage of its backlight luminance reserve and becomes the smartphone WXGA (1280 × 768) display with highest peak luminance. This high-luminance mode works automatically, based on the data received from an ambient-light sensor. ■

The Road Ahead to the Holodeck: Light-Field Imaging and Display

Light-field displays represent the 3-D of our future.

by Jim Larimer

MODERN DISPLAYS can reconstruct 2-D and stereo-pair 3-D (s3D) imagery, but some important features of the natural visual environment are still missing; there remains a visible gap between natural imagery and its reconstruction on even today's most advanced display technologies. This gap can be closed as light-field technologies replace our current display systems. The light field is all of the information contained in light as it passes through a finite volume in space as we look in any direction from a vantage point within the volume. This article will describe the signals contained in the light field and captured by human vision that are missing with 2-D, s3D, and multi-view s3D displays. To understand what is missing, it is useful to understand the evolutionary context of biological vision.

A Brief History of Vision

Biological sensory systems evolved shortly after the Cambrian explosion, when predation became a part of life. Vision evolved so that creatures could find food and avoid being eaten. Vision plays a central role in cognition and our understanding of the world about us; it provides the basic information we use to orient in our immediate environment. Almost all ideas have images as correlates; a chair is a visual pattern, a tiger is a large cat. Even abstract concepts such as satisfaction can be imagined as a smile on a face. Visual cognition, understanding images, is not the mental equivalent of a photograph; our visual experience is more akin to Plato's concept of Ideals and Forms. We see people, objects, and actions — not their images as projected onto our retinas.

Human vision is object oriented. We use information extracted from the light field and neural signal processing based upon learning and memory to understand the environment we sense from the images projected onto our retinas. The image formed on the retina is the raw data for vision; it is not a sufficient signal for image understanding by itself. To understand what we see, we change eye positions and focus to de-clutter or segment a scene into whole objects.

Not all of the information embedded in the light field is accessible to vision. Reconstructing information we cannot see is wasteful, just as leaving out information we can see limits the veridicality of the virtual scene we experience on modern displays. Artists may wish to create non-veridical or distorted imagery in cinema and photography, but this is a choice the artist should make and not have made for them by the imaging technology.

Images exist because we have a chambered eye with an entrance pupil similar to a pinhole camera or the camera obscura (Fig. 1). Understanding how our eyes extract useful information from the light field and the physics of light both began with the camera obscura. The camera obscura's connection to sight was described by Mozi and Aristotle centuries ago and featured in da Vinci's notes on light and imaging.[1] The idea that light from a point on any surface can be considered as rays emanating in all directions external to the surface, a central idea in geometric optics, is based upon the pinhole camera. Evolution discovered the pinhole camera concept shortly after the Cambrian explosion almost 550 million years ago and a chambered complex eye like ours evolved over 500 million years ago.[2]

Michael Faraday in 1846[3] was the first to describe light as a field similar to the field theory he developed for electricity and magnetism. Almost 100 years later, Gershun[4]

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Note: Jim Bergen and David Hoffman made helpful suggestions to improve an early draft of this article. All remaining confusions and errors are mine, not theirs.

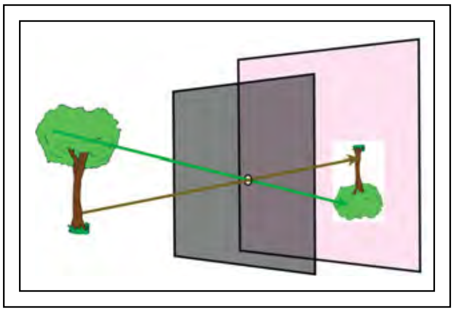

Fig. 1: *A camera obscura or pinhole camera is shown in this illustration. The discovery of the pinhole camera gave rise to early ideas about the nature of light, vision, and optics. That light can be thought of as traveling in straight lines comes directly from this discovery.*

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defined the light field as the uncountable infinity of points in three-space where each point can be characterized as a radiance function that depends upon the location of the point in space and the radiance traversing through it in every direction (Fig. 2).

Light traversing a point in the light field continues to move beyond the point until it encounters an impedance that can alter its course by reflection, refraction, or extinction. Every line passing through a point in the light field in terrestrial space will be terminated by two surfaces, one at each end. Every line segment defined this way contains two packets of information, each going in opposite directions. If the line segment is not very long and there is nothing to impede it, this information is almost entirely redundant at every point on the line. The information is unique to the surfaces and light sources creating the packets, and this is the information biological vision has evolved to sample and use.

Adelson and Bergen[5] called Gershun's radiance function the 5-D plenoptic function, indicating that everything that is visible from a point in free space is contained in it. They described how our visual system extracts information from the light field to discover properties of objects and actions in our visual environment. The plenoptic function contains information about every unobstructed surface in the lines of sight to the point in space and by adding time, the 6-D plenoptic function,

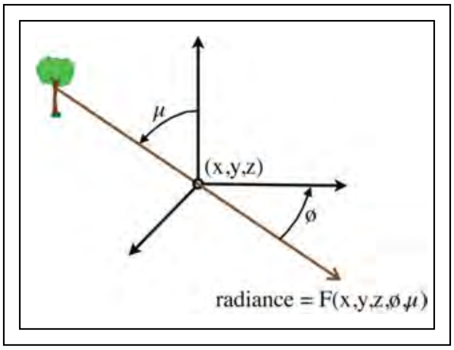

Fig. 2: *An arbitrary point in space is shown with a ray that originated on the trunk of a tree passing through it in a direction relative to the point at azimuth and elevation angles ø and μ, respectively. The radiance in this direction through the point is F(x,y,z,ø,μ). This is Gershun's definition of a point in the light field; Adelson and Bergen called this the 5-D plenoptic function.*

how these surfaces change. J. J. Gibson called the information we gather from the visual environment affordances[6] because it informs behavior; for example, when to duck when something is looming towards us. Information that is not useful in affording an action is not extracted from the light field.

A pinhole camera forms an image based upon the plenoptic function at the location of the pinhole. The image formed by the camera is based upon at most half of the plenoptic function at this point and is limited by camera size, blur, and diffraction. The image formed depends only upon the direction from which a ray travels through the pinhole. Images are therefore 2-D and flat. Information about depth in the visual field is missing in a single image. For example, image size is a function of both object size and the distance to the object from the entrance pupil of the camera. This information is ambiguous in a single image. Parallax produced by an object or camera motion or by the displacement of our two eyes and the resulting retinal image disparities provides the additional information required to disambiguate these two factors. Figure 3 illustrates how parallax is expressed in the relative location of the 2-D projections of objects on the projection plane of two cameras at different locations.

Our visual system has evolved neural mechanisms that use parallax to estimate the distance to objects and the closing rates of looming objects. These estimates are based upon data extracted from the light field sampled over a period of several milliseconds. Object recognition and identification, linear and aerial perspective, occlusion, familiarity, and other features of the imagery projected onto our retinas over time are all used by the visual system to augment our image understanding of the location, size, range, surface relief, *etc.,* of objects in the visual field.

Real pinhole cameras have entrance apertures or pupils that are larger than a point. The image formed by a pinhole camera is the sum of many points or plenoptic functions located within the entrance aperture. As the size of the aperture is enlarged to let in more light, the resulting image becomes blurry. The resolution limit of a real pinhole camera is limited by diffraction as the aperture size is reduced and by blur as it is enlarged. There is a tradeoff between image intensity and image clarity.

Evolution has overcome this tradeoff by evolving a lens located near the pupil that

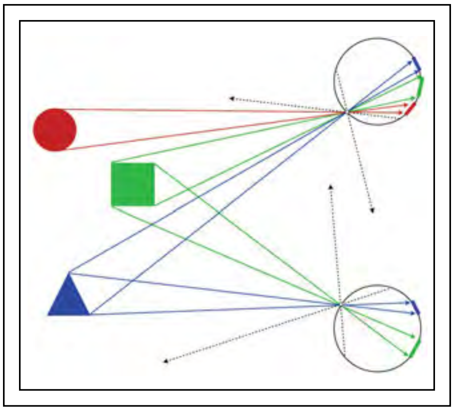

Fig. 3: *A top-down plan view of three figures in the visual field of two spherical pinhole cameras is shown in this drawing. The two cameras view the visual field from two different locations, and this results in changes in the relative locations and extents of the images of these objects on the projection surfaces. These differences are due to parallax. At the lower location, the red object is totally obscured by the green object, and there is no image of it visible on the projection surface. The relative change in location and rate of change as either objects or the camera move through space provides information about the range and size of objects in the visual field. To extract this information requires signal processing in the visual system.*

allows us to focus the light traversing the pupil, sharpening the images of some objects but not all objects in the field of view simultaneously. The depth of field[a] of the image is determined by the diameter of the entrance pupil and the eye's focus. Focus is determined by where we place our attention in the visual field. Blur is a cue used to estimate the size and the relative depth to objects.[7]

In and Out of Focus

The information in the light field passing through the pupil becomes more or less accessible to visual cognition depending upon the eye's focus. Focusing superimposes all of the rays passing through the pupil from many plenoptic functions that originated at single points on the surface of objects that are in focus onto single points in the image projected onto

[a]Depth of field is the distance between the nearest and farthest objects in the visual field that are sufficiently sharp to be characterized as in-focus.

the retina. Every in-focus point in the visual field will project to one point on the retina. Rays originating on out-of-focus points are spread over the retina in circles of blur whose size depend upon focus and pupil diameter. Figure 4 illustrates focus for a schematic eye showing four bundles of rays that originated from each of the ends of two arrows. The blue arrow is in focus and the green arrow is not.

Focusing the image on the projection surface aggregates information from all the rays passing through the pupil. When the information in these rays is correlated, *i.e.*, originated from the same point on an in-focus surface, the aggregate signal is strengthened. When the rays projected onto retinal locations come from several different surface points, and are therefore uncorrelated, information is mixed together and blurred, reducing the signal strength and image contrast. The information captured from the light field is not lost, but to see it we must focus on different surfaces.

Image-capture and reconstruction in traditional 2-D and s3D imaging systems do not support refocusing, and the only parallax information available in s3D is fixed by the location of the two cameras. When viewing natural scenes we move our eyes and translate and rotate our heads to obtain more parallax information from the light field. We can refocus our eyes to rearrange and sort the bundles of rays coming from all the points that traverse our pupils.

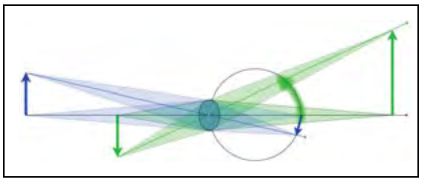

Fig. 4: This diagram shows a schematic eye focused on the blue arrow. The transparent blue and green bundles are the rays from the end points of both arrows that form images of the end points on the retina. The blue arrow's image is sharp on the retina and the bundles converge to a point on the retina. The green arrow would come to focus on a projection plane behind the retina. Rays emanating from the green arrow end points are spread or blurred over a wide area of the retina. When an out-of-focus object occludes an in-focus object, the blur reduces the image contrast of parts of the in-focus object.

The signal for focusing is missing with traditional image technology as is a great deal of the parallax information, but our visual system evolved to use this information. The result can be annoying and uncomfortable. For example, when viewing a large displayed image the viewer might attempt to view an object on the screen that is out-of-focus or she may move her head to see around something in the scene. No effort on the viewer's part can bring an out-of-focus object in a displayed image into focus or allow her to see behind an occlusion.

A 2-D video sequence during which the camera moves, or in which objects are moving in the scene, can evoke the perception of depth in a scene, but as soon as the motion stops, these motion-parallax-driven cues, along with the sense of depth, are lost. The inability to see around occlusions and the fixed image focus in standard 2-D and s3D imagery are the missing and/or inaccessible light field data.

Light-Field Cameras

Cameras that can retain the perceptually relevant information in the light field have been developed. The idea for this camera has many sources: Lippmann or Ives,[8] and, more recently, Adelson and Wang[9] and Ng *et al.*[10] The company Lytro recently introduced a light-field camera into consumer markets and a commercial version of a light-field camera is available from Raytrix.[11] (For more about these cameras, see the article, "Communication through the Light Field: An Essay," in this issue.) Understanding how these cameras capture the light field reveals what is required to build a true light-field display capable of reconstructing parallax information appropriate for any head position and that supports attention-driven focusing.

A plenoptic camera is similar to an ordinary camera or to the eye in its basic design. To illustrate the principles of operation of a plenoptic camera, a spherical camera similar in geometry to the eye will be used. We will call the entrance aperture of the plenoptic camera the pupil and the projection surface where images are formed will be called the retina. The eye's lens is located very close to the eye's pupil and we will imply the same geometry for this plenoptic camera, although that is not a requirement. A plenoptic camera has an array of tiny pinhole cameras[b] located where the retina would be located in a real eye. These tiny cameras capture images of the rays passing through the pupil. Every pinhole camera has its own unique entrance aperture, its pinhole, located at uniformly spaced positions within this array of tiny cameras replacing the retina in our illustration. Two of these pinhole cameras are illustrated very much enlarged in Fig. 5; all of the other pinhole cameras are too small to be seen in this illustration.

Every tiny camera captures a slightly different image depending upon its location in the array. Where rays from points in the 3-D object space enter the plenoptic camera depends upon the location of these points in the visual field, the 3-D object space. Where rays traversing locations in the pupil of the plenoptic camera are projected onto the pinholes in the tiny camera array depends on the plenoptic camera's focus. A plenoptic camera does not require a lens that can change its focal length to make sharp images of any point in the visual field. It can bring any point into focus by rearranging the data captured by the array of tiny pinhole cameras. This requires some computation in addition to the array of tiny pinhole cameras.

Two rays from separate points in the 3-D object space entering the plenoptic camera at the same location in the pupil will generally be imaged to separate pinhole cameras. Two rays entering the plenoptic camera from the same point in 3-D object space will only be projected to the same pinhole in the tiny camera array if their point of origin is in focus. This is illustrated in Fig. 5.

Figure 5 traces four rays as they traverse the pupil and are projected onto the pinhole camera array. One ray from each of the blue and green arrow tips passes through the center of the pupil; these rays are shown as dashed lines in the figure. A second ray from each arrow's tip passes through the same peripheral location in the pupil; these rays are represented as solid lines.

The blue arrow is in focus, so the lens projects both the dashed and solid blue rays to the same pinhole camera location in the tiny camera array. The two rays are traced as they pass through the pinhole at this location and are projected onto the back surface of this tiny camera. The locations of the rays on the pinhole camera's back surface are correlated with the entrance pupil locations of the rays, which are correlated with the location of the point in

[b]The tiny camera array does not necessarily have to be made of pinhole cameras; these tiny cameras could have lenses. The principles of operation of the plenoptic camera would be the same in either case.

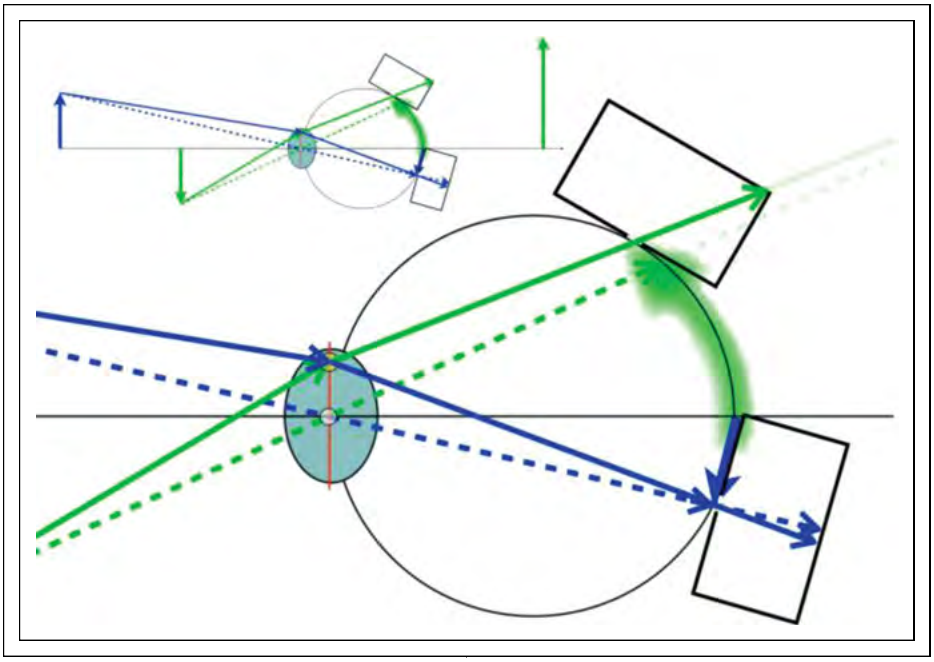

Fig. 5: *Ray tracings for two rays originating at the tip of the green arrow and two rays originating at the tip of the blue arrow are followed as they come to focus at different depths in the upper small illustration. The blue arrow is in focus on the retina whereas the green arrow comes to focus behind the arrow. The enlarged illustration traces the rays as they are captured by or miss the apertures in the case of the green dashed ray of two pinhole cameras located on the retina.*

the 3-D object space at which both of these rays originated. This is the directional information that is lost in ordinary cameras. Most or even all of the rays projected onto this pinhole will have originated at the same point on the blue arrow's tip. The image projected on the back surface of this pinhole camera records each ray's location in the pupil.

The dashed and solid green lines tracing the path of rays from the green arrow tip are projected to different locations on the pinhole array because this arrow is not in focus. Different pinhole cameras will record the directional information contained in these two rays. The plenoptic camera nonetheless captures all of the directional information contained in these rays, so no directional information is lost.

In summary, rays originating at points in focus in the scene will be captured by a single pinhole camera in the array and rays originating from out-of-focus points will be captured by different pinhole cameras. Capturing the directional information is the key to capturing the light field in a small region in free space, *i.e.*, where the plenoptic camera's entrance aperture is located.

Figure 6 illustrates what happens in a plenoptic camera when two points in 3-D object space are located along the same direction from the eye and one point is nearer to the eye than the other. This is illustrated with points on the base of the two arrows illustrated in Fig. 5. The green arrow is out of focus and its base occludes some of the rays from a point on the base of the in-focus blue arrow. The entire bundle of rays originating at a point on the base of the green arrow will be projected onto the pinhole camera array of the plenoptic camera as a small circle of blur, *i.e.*, different rays going to different locations on the retina. In this illustration only the non-occluded half of the bundle of rays that originates at a point at the base of the blue arrow passes through the plenoptic camera's pupil. The base of the green arrow occludes the other half of this bundle of rays. Therefore, only one-half of the blue rays in this bundle are sharply focused on the pinhole camera at this retinal location. These rays from the blue arrow are imaged on the pinhole camera's back surface, covering half of it. In the middle of the image formed by this pinhole camera is a small portion of the green rays from the out-of-focus green arrow base. The image formed by this pinhole camera from rays originating at these two points is shown as an inset in Fig. 6.

This is an example of how blur can mix rays from different objects together, reducing the contrast of portions of sharp images formed on the retina when two objects at different depths are near the same direction on a line of sight from the eye. This is an example of the how the parallax information contained in two distinct plenoptic functions whose xyz locations in 3-D space are separated by less than the diameter of the pupil is lost in ordinary image capture by a camera or the eye. A plenoptic camera retains this information in the pattern of images formed on the array of tiny pinhole cameras replacing the retina.

These off-pupil-center rays from all of the points in 3-D object space are the signal that our eyes use to focus. Without direct access to these signals we cannot focus. These rays contain some information regarding what is behind an occluding object, but nothing compared to the information we obtain by moving our heads or from the separation between our two eyes. In a light-field camera instead of the eye, the entrance aperture can be very large. As this aperture gets bigger the camera can look farther behind occluding objects. A light-field or plenoptic display must reconstruct this information and it must perform this reconstruction for every head location and orientation within the viewing space where the eyes might be located. This is the inverse of the sampling operation performed by the plenoptic camera, with the caveat that the samples must also include a wide variety of locations within the visual field corresponding to any pair of eye locations from which a display user might view the plenoptic or light-field display.

There are fundamental resolution limits to be considered now that the operational principles of light-field imaging have been described. Sampling is a quantization and a windowing problem. The volume of space to be reconstructed and the volume of real space from which it can be viewed determine the number of rays that must be reconstructed for a light-field display to operate. The larger these

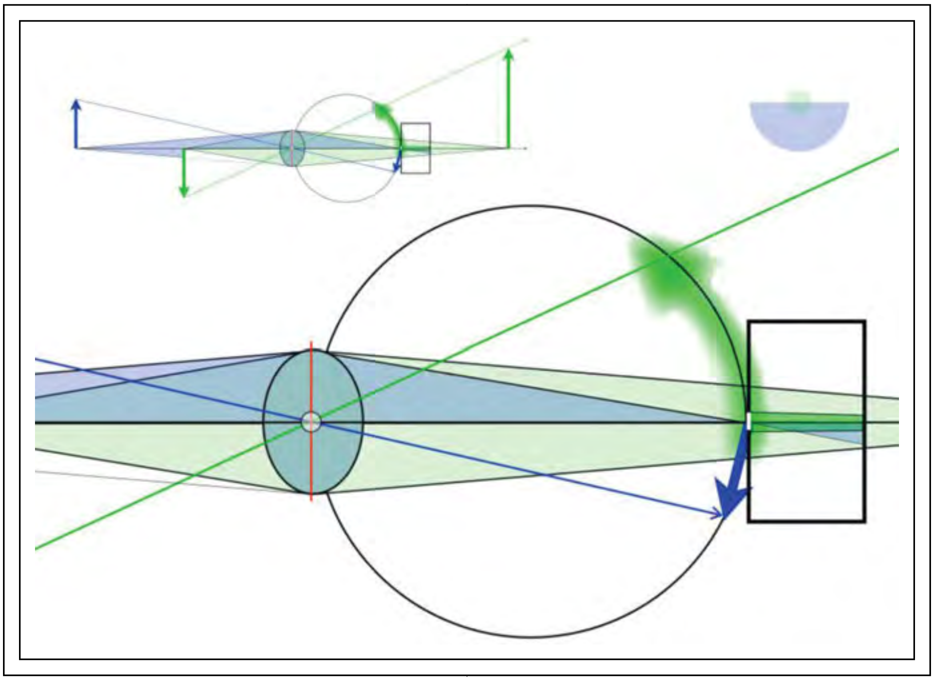

Fig. 6: *The small upper-left illustration traces two bundles of rays originating from the base of two arrows as they are traced to their conjugate points on the images formed by the lens. A pinhole camera placed at the location where the blue bundle of rays comes to focus captures an image of the bundle as it passes through the lens. The bundle of rays from the green arrow would form a circle of blur at this image depth, so the pinhole camera captures a fraction of the rays in this bundle as a small spot on the pinhole camera's projection surface. The image of the rays from both bundles as captured by the pinhole camera is shown as the insert in the upper right of the illustration.*

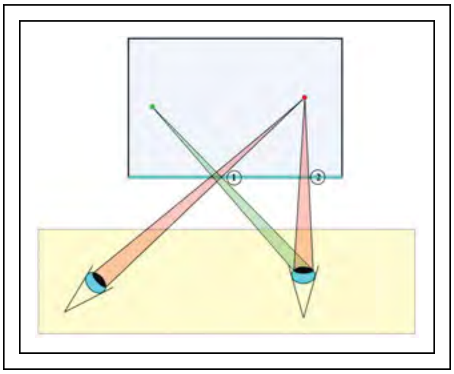

Fig. 7: *A hypothetical light-field display is illustrated in a top-down plan view. The blue edge at the bottom of the blue rectangle represents the front surface of the display. The light-blue area in the rectangle is the reconstructed light-field volume and the yellow rectangle represents the viewing window in which viewers can correctly view the space. The screen surface at the point labeled 1 must be able to send rays corresponding to the green dot in the viewed volume to the eye on the right while simultaneously sending rays corresponding to the red dot to the eye on the left. This is the task of the plenoptic display.*

spaces become, the more rays will be required. This is a standard clipping or windowing issue; how much of the space can be clipped away before the volume is too small to be useful? That is a task-dependent question.

The same spatial and temporal resolution requirements apply to a light-field display that apply to ordinary displays. At half-a-meter viewing distance, a 100-dpi display produces about 15 line-pairs per degree of visual angle, adequate for many display tasks at this viewing distance. For a handheld display that will be viewed closer to the eye, 200 dpi or more is appropriate. Temporal-resolution requirements are the same as in current displays. Avoiding or controlling temporal artifacts such as flicker, judder, motion blur, and a recently documented temporal artifact in s3D imaging[12] must be considered to determine the frame rates required for any specific task.

Figure 7 depicts a light-field display in top-down plan view. The front surface of the display is the light-blue side of the rectangle with the blue fill. The blue fill represents the light-field volume that can be reconstructed on this display. This volume can be viewed only from locations within the yellow fill. Two individuals, each with a single eye, are looking at the red dot. It must appear at locations 1 and 2 on the front surface of the display. For the eye on the right, the green dot is also visible on the screen at the same location the red dot is visible to the left eye, *i.e.*, location 1. This illustrates the requirement that a light-field display must be capable of reconstructing directional views to objects that appear at different front-screen locations depending upon where the viewer is located. A light-field display reconstructs parallax information for any head location or rotation relative to the display screen within the viewing window.

The light-green and light-pink pyramids represent the bundles of rays from each dot that are traversing the pupils of these two eyes. Multiple rays within these bundles are required if observers are to be able to arbitrarily focus on any object within the reconstructed light-field volume. This would be possible if the front surface of the display was an array of micro-projectors that could project independent rays at each location of the front surface of the display towards every location where the viewer's eyes might be located. A video display produced by Zebra Imaging based upon this architecture will be the described at the SID Display Week Technical Conference in May in Vancouver.[13]

To focus the eye at any arbitrary depth within the reconstructed volume, more than a single ray from every surface point in the virtual volume must be included in the bundles of rays passing through the viewer's pupil for every possible eye location within the viewing space. This is the data that is captured by the plenoptic camera. The reconstruction of this data is slightly more complicated than its capture because the eye's optics must be considered again. It is these bundles of rays traversing the display viewer's pupil that allow the eye to focus at any arbitrary depth within this volume. The Zebra Imaging light-field video display described in Ref. 13 provides parallax and unique s3D information for every viewer location, but lacks sufficient rays to support arbitrary focusing.

In the camera discussion, the number of rays captured at any pinhole camera location in the plenoptic camera corresponded to the number of independent locations or pixels on the sensor on the back surfaces of the pinhole camera. This resolution determines the depth of field in which the data can be rearranged through image processing to bring an object into focus or the number of stereo pairs for s3D viewing that can be reconstructed from the captured data.

How many rays are needed at each location, or correspondingly, how many rays from every surface point in the virtual space must pass through the eye's pupil at any arbitrary location in the viewing space? The answer is the angular ray resolution requirement for a light-field display. This requirement is related to the ability of the human eye to see a change in blur and this is related to pupil diameter and the point-spread function of the eye.

Akeley *et al.*[14] constructed a prototype display for a single eye position that allows viewers to focus arbitrarily within a finite volume, but only from a fixed-eye location and only with some important cheats. Occlusion is not supported in this quasi-light field display. To understand how they did this, imagine looking at a point on a plane in space that is perpendicular to your line of sight. How far in front or behind this plane would another point have to be placed before you noticed it was blurry? This distance defines planes of just perceptible blur and measured in diopters, they are equally far apart.

Suppose a viewer is focused on a point on a plane and a second point is either one blur distance in front or behind it. Suppose the number of rays being reconstructed from the second point is finite and that some number of them, say n, traverse the viewer's pupil. Because this point is out of focus, these n rays will be imaged within the blur circle of the eye for real points on a surface this far removed from an in-focus point in the field of view. If those n rays form n perceptually distinct points, then the viewer could discern that these are different from a real blur circle. The real blur area would not be completely covered in this case, so it would be noticeably different from real blur. If, on the other hand, there is no noticeable difference between the n points created by the n rays from this light-field reconstruction and the blur created by real objects, then the observer would have no way of knowing that this reconstruction is different from a real light field created by a real object. This is the key to figuring out how many rays are required. At this point in time, this number has not been determined in the lab. Nor is it known at what number of rays a sufficient signal for focus is produced. It could be that we could focus with fewer or more points than are required to match all possible blur circles. Figure 8 illustrates the case where the number of rays from an out-of-focus object is inadequate and the individual rays would be visible to the observer and therefore inadequate to reconstruct the light field.

The lab apparatus built by Akeley *et al.* employed three planes spaced between 0.5 and 1 diopter apart. With this apparatus, a volume roughly 25 cm deep close to the eye was reconstructed. Their cheats allowed them to trick the eye into focusing at any depth within this volume by approximating the blur circles and by avoiding scenes where this scheme would produce conflicting signals.

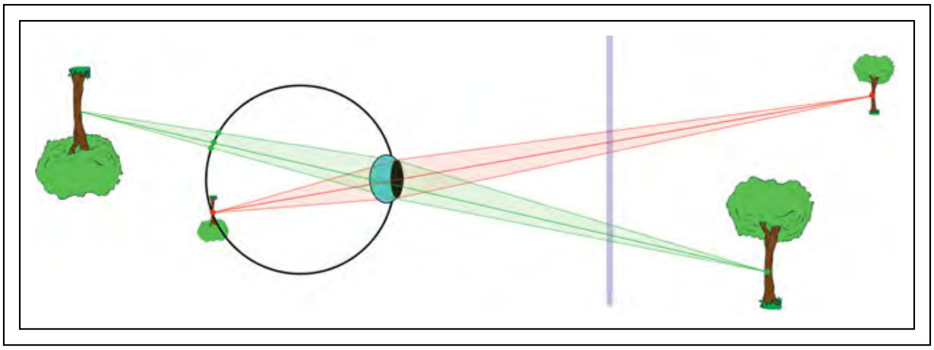

Fig. 8: *The vertical blue line represents the surface of a plenoptic display and the two trees depicted to the right of it are in the virtual space of the display. The pink and green bundles represent the trajectories of all the rays from two points on the trunks of these two virtual trees that might traverse the observer's pupil. The screen must reconstruct an adequate number of these rays. Suppose from each virtual tree trunk location only three rays reconstructed on the screen traverse the pupil. For the in focus pink bundle these three rays are superimposed on the retina, but for the out of focus green bundle these rays are projected onto the retina with large gaps between the rays. The observer would detect the sparse reconstruction as a series of distinct dots instead of a blur circle, so this display would not adequately reconstruct the light field. More rays would be required to traverse the observer's pupil from every screen location.*

Light-Field Displays

Many display architectures for light-field displays are possible. Schowengerdt *et al.*[15] described a head-mounted light-field display at Display Week 2010 based upon a novel fiber-optic projector. Most recently, Fattal *et. al.,* described a light-field display based upon diffractive optics and light guiding, where images are created by turning on and off light sources. The spatial, temporal, tone-scale, and angular resolution of these future light-field displays will depend upon individual application requirements. The additional angular resolution requirement will determine the amount of arbitrary user-unique focusing a specific display device will support. We can expect these parameters to be traded off like any other engineering trade-off, to suit the application requirements. No display, including the light-field display, needs to exactly match nature; it only needs to be veridical enough for an observer to not see or care about the difference.

The challenges for light-field displays will involve developing display architectures that can be manufactured reliably and inexpensively, developing signal processing and addressing bandwidth schemes that are consistent with the capabilities of electronic components, and discovering the engineering trade-offs most appropriate for each application. Once these hardware challenges are overcome, only a light-field communications infrastructure that includes capture, transmission, and reconstruction will be the remaining barriers to realizing light-field imaging. It was only 20 years ago that some people doubted that the CRT could ever be completely replaced as the backbone of video technology; it would be difficult to speculate on how rapidly light-field technology will roll out.

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Communication through the Light Field: An Essay

In the foregoing article, "The Road Ahead to the Holodeck: Light-Field Imaging and Display," James Larimer discusses the evolution of vision and the nature of light-field displays. This article looks at the physical, economic, and social factors that influence the success of information technology applications in terms that could apply to light-field systems.

by Stephen R. Ellis

THE development of technology has greatly transformed the media used for all our communications, providing waves of new electronic information that amuse, inform, entertain, and often aggravate. Some of these media technologies, though they may initially seem solely frivolous, ultimately become so integrated that they become indistinguishable from the environment itself. A perfect example is the personal computer, initially seen as a toy of no practical use. Its key component, the micro-processor (or the modern day micro-controller), is now in myriad forms practically invisible in our watches, books, home appliances, cars, cash registers, telephones, address books, and flower pots.

The recent advances in light-field[a] displays, and in light-field capture in particular (Fig. 1), put a new twist into the process of integration because the idealized light-field display in a sense actually disappears, leaving only the light field emitted from a volume of space.[1–4] Viewers of an idealized display are thus left with a window into a world seen as a volume with all its physical features. When fully developed, this view could be indistinguishable from what they would see if they were looking through a physical window. What would such a capture and display system be good for?

By analogy with previously developed technology we can be sure such displays will also amuse, inform, entertain, and aggravate us. But it seems to me hubris to claim to know what the first "killer app" for such displays will be. They may have scientific applications. They may have medical applications. They seem to be natural visual formats for home and theater entertainment, a kind of ultimate autostereoscopic display. Indeed, since they do not have specific eye points for image rendering, they are really beyond stereoscopic display. But to assert with any reasonable degree of confidence how, where, or why light-field technology will change the world seems premature, especially since there are not many established systems that include both capture and light-field display, and the constraints on their use are not well known. (Figure 1 illustrates two currently available products that are designed to capture light-field data.) However, whatever applications ultimately succeed, they will succeed because they communicate information to their users.

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Communication through the Ambient Optic Array

The physical essence of the light field is the plenoptic function, which is discussed in this issue's article, "The Road Ahead to the Holodeck: Light-Field Imaging and Display," by James Larimer. Interestingly, the plenoptic function has a psychological/semantic aspect that Gibson[5] called the ambient optic array. This array may be thought of as the structured light, contour, shading, gradients, and shapes that the human visual system detects in that part of the light field that enters the eye. The features of the ambient optic array are primarily semantic rather than physical and relate to the array of behavior possibilities the light field opens to the viewer.

These features are in a sense the natural semantics of our environment to which we have become sensitive through the processes of evolution. The array was considered important by Gibson because it presents the viewer with information about the environment that is invariant with respect to many specific viewing parameters, *e.g.*, direction of view, motion, and egocentric position. The array thus allows viewers to determine environmental properties such as distance, slope, roughness, manual reachability of objects, or the accessibility of openings such as doors.

[a]The light field, considered primarily in terms of the light rays of geometrical optics, is defined as radiance as a function of all possible positions and directions in regions of a space free of occluders. Since rays in space can be parameterized by three spatial coordinates, *x*, *y*, and *z* ,and two angles, the light field, therefore, is a five-dimensional function. (See the article by Larimer in this issue.)

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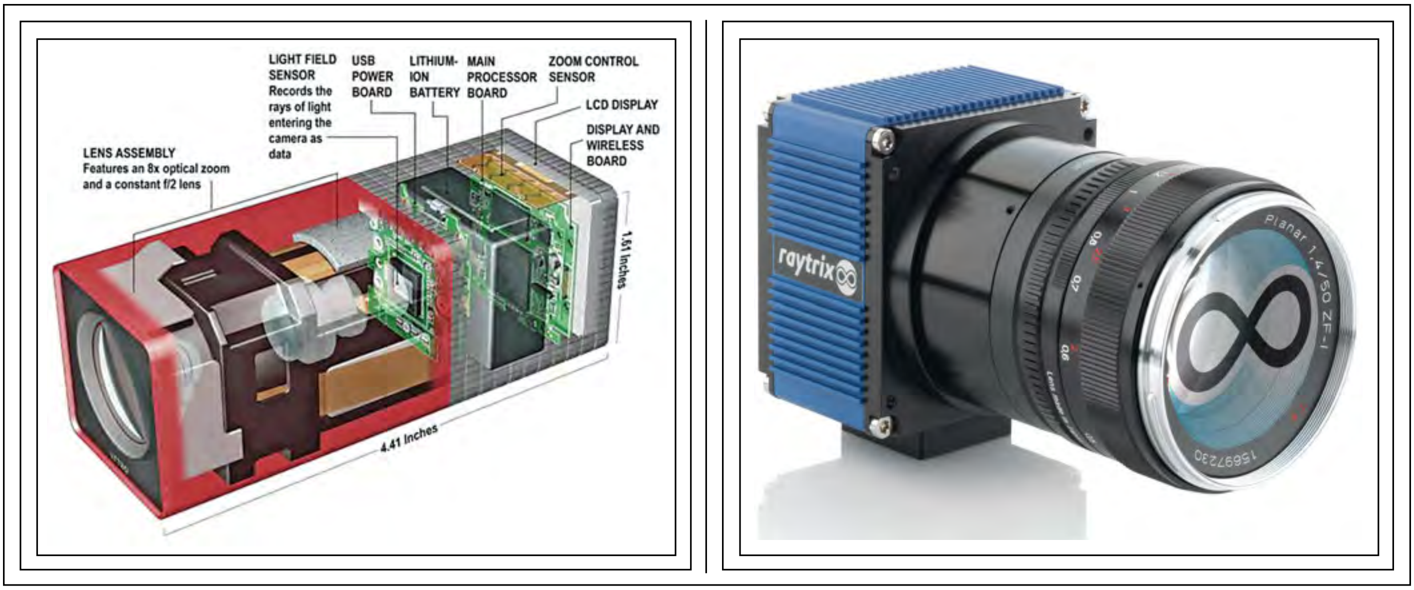

Fig. 1: Two examples of light-field cameras currently offered for sale include the Lytro camera (left) and the Raytrix R11 (right). The Lytro is intended as a consumer product. It costs $400–$500 and records static light fields. Currently, the Lytro does not have a matched light-field display but does include a built-in viewer and laptop software for selecting typical photographic parameters such as focal plane, depth of focus, and view direction for creation of conventional images after the light field has been captured. The Raytrix R11 is intended as a scientific instrument to record volumetric motion as well as static light fields and can record light-field movies. It is much more expensive, costing about $20,000. Raytrix also makes an autostereoscopic viewer for use with its cameras, as well as special-purpose analytic software for tracking movement within recorded light fields.

These are the environmental properties that guide our behavior. The last two are examples of what Gibson called affordances because they directly communicate behavioral possibilities. Such elements are, of course, the kind of visual information that displays are also intended to communicate, so it is not surprising that Gibson's work has been influential in their design.

Gibson called the informational elements of the features of the optic array "high order psychophysical variables." Examples are structures such as texture gradients in the projected view of a surface, cues to the elevation of the local horizon such as convergence points of parallel lines, and optic flow, the spatio-temporal change in the optic array due to object or viewer movement (Fig. 2). These variables may be measured as dimensionless ratios, percentages, or individualized units. They are unlike the more conventional psychophysical variables such as luminance, color, and motion, which are typically closer to the usual physical units. Optic flow, for example, can usefully be measured in terms of the viewer's personal eye height above the surface the viewer moves over; such as a measure of an optic flow rate could be eye-heights/second rather than meters/second. These features of ecological optics are not therefore themselves optical but are computationally derived from elements of the plenoptic illumination and often expressed in terms of user-specific units. These features are processed ultimately into the actors, objects, and culturally relevant elements that are the final interpretive output of our visual system.

A light-field camera and light-field display system together provide a medium for recording enough of the plenoptic illumination function so as to be able to re-project it toward viewers for them to interpret the ambient optic array as if they were present at the original scene. Consequently, the ultimate success of a light-field display system will be governed not simply by the fidelity with which the light passing into the eye represents light from a real space but also by the information that that light contains and the people and things that the light makes visible.

Some of the possible characteristics of light-field displays are absolutely remarkable. Imagine one that is hand-held, one that operates solely using ambient light and does not require power, one that not only constructs the light field for unobstructed objects but also for some that ARE obstructed – letting the viewer look around corners! Such performance may

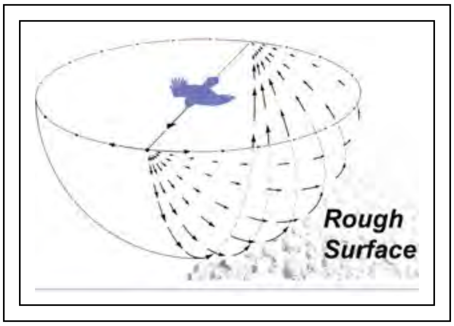

Fig. 2: This is an example of optic flow, a higher order psychophysical feature that Gibson identified as specifying a direction of movement, flight in this case, over a rigid surface (Ref. 5, redrawn after Figure 7.3, p.123). Although Gibson probably would never express it so semantically, the observer learns, or appreciates from preexisting knowledge, the connection between the parameters of the flow field and their own velocity vector.

actually currently be in the works[6,7] but nothing is exactly off the shelf and it's hard to know what the first commercial system with long-term viability will look like, how interactive it will be, if it will capture motion, or what visual resolution it will support.

Consequently, it seems to me better to consider now the list of challenges that the inventors of such displays will need to overcome in order to develop products with widespread appeal than to guess what the "killer app" will be. I will not be considering the detailed technical challenges so much as the overall performance issues. These issues are somewhat generic, but I believe they do apply to the technology; indeed, they apply to any new technology. They may be captured in a short list (Table 1).

It seems to me that the factors constraining widespread adoption of light-field systems may be broken into three categories: physical, economic, and social. Each of these has several elements that may be considered in somewhat arbitrary order.

Physical Challenges

Time counts! The benefits of amazing technology can be greatly, even completely, eclipsed if the users are forced to wait endlessly for them. At its inception, the World Wide Web was rightly lampooned as the World Wide Wait and would never have become as pervasive as it is if its original latency problems had not been solved.

Time can influence performance in many different ways. Insufficiently fast update rates can disturb image quality,[8] reading rate,[9] and subjective sense of speed.[10] Even displays accurately presenting smooth motion through high dynamic frame rates can be problematic if visual shifts of their content give rise to vection, a subjective sense of self-motion. A possibly apocryphal example of this problem is the supposed effect of the first camera pan movement on a movie audience that, reputedly unprepared for it, promptly fell over. A related more likely true example is the reported reaction to the Lumière brothers' first showing of a movie clip of a directly approaching steam locomotive. The audience, strongly affected by the sight, seems to have scattered in fear (*The New York Times*, 1948).[11]

Table 1: Would-be inventors of light-field systems face challenges in physical, ecoomic, and social terms.

Physical	Economic	Social
Time counts	Costs shock	Novelty wanes
Size matters	Costs hide	Message mediates
Resolution clarifies		Content rules
Power regulates		Story conquers
		Empowerment enables
		Art matters (too)

Size matters! Great ideas in awkward, heavy packaging do not make it. One major problem with the early tablet displays was the difficulty sharing them among a small group the way a modern tablet such as an iPad may be easily passed around like a sheet of cardboard. A reason volumetric displays, which to some extent already present light fields in that they actually create visible, dynamically deformable, physical structures (Fig. 3), have not caught on as consumer products is that they are moderately large, heavy (up to 60 pounds.) desktop products, and therefore are more transportable than really portable.

Resolution clarifies! The physical world is high-res! But the limiting factor actually is the eye rather than the world. The number of pixels needed to fill out the eye's resolution in a full 4pi steradian view is on the order of 600 Mpixels.[12] Restricting this analysis to a fixed head position but allowing normal eye movements within a field of regard cuts the number down to about 120 Mpixels, which is still large.

One of the compelling features of ordinary photographs is that they still can win in the resolution game, with chemically processed slow-speed film having ~5000 lines/in. (~20 lines/mm). Only recently are widely used electronic displays beginning to claim to approach the human-visual resolution, with Apple's so-called Retina displays. By the time light-field capture-display systems become commercially available and widely used, the purveyors of these displays will need to note that the public will likely have a well-established expectation of very high visual resolution for electronic imagery, probably exceeding that of current HDTV, thus placing a premium on anti-aliasing and other techniques to manage artifacts due to relatively lower pixel resolution.

Power regulates! One of the virtues of the Palm PDA was the relatively long run time supported by its battery technology and low power drain. I had one and loved to brag to my friends using iPhones that I could often wait days and days between charges. Power is, of course, not a major issue if you can run a system hooked up to the grid, but to the extent any part of the system is mobile, power can be critical. A system for which power is likely to be an issue is, for example, the recently announced Google head-mounted display. Its very small head-portable form factor coupled with its wireless connection, video capture capability, and more or less continuous all-day use, possibly outdoors, is likely to strain its battery power, especially if the only battery and computing system used is going to be incorporated within its spectacle-frame mount.

Economic Challenges

Costs shock! A $1500 personal display of uncertain application will not generally find an immediate mass market unless it can interact with available critical content. Totally novel and amazing display capabilities are not insensitive to price. This fact is not news. But the costs involved are not always obvious.

Costs hide! It is hard to put a cost on hassle but it can be high. Indeed, the persistent attempts to find better autostereoscopic displays attest to the high cost of conventional stereoscopic displays requiring viewing spectacles. Gestural interfaces have been touted as intuitive, powerful, and the next great thing in UI but often their cost in fatigue is not appreciated. They have only really become widely used after they were implemented on horizontal touch surfaces that could support the weight of the users' hands. In Gibson's terms, one of the affordances of the horizontal touch screen is support for the weight of a hand. This need for support is often unappreciated and; in fact, hand support is one of the virtues of the mouse and joystick. Hand gestures in the air will wear out even the dedicated gamer, as was discovered by the users of the Mattel Power Glove.[13]

Social Challenges

Perhaps the most compelling constraints on acceptance and dissemination of new technology are social. For example: Novelty wanes! In the mid 1980s, Ivan Sutherland's idea[14] for an "ultimate display" as a personal simulator, oxymoronically a.k.a. virtual reality, was reinvented at a much cheaper price point,

$100,000s per system vs. $1,000,000s for his system. One of these less expensive simulators was even adopted by Matsushita Electric Works, Ltd., as a medium for customer involvement in the design and sale of customized home kitchens. The novelty of giving anyone interested in a custom kitchen access to such an unusual system initially filled the company's show room in Tokyo and made international news. But, in time, partly because of poor dynamic performance,[13] the show room returned mainly to the use of conventional interactive computer graphics and architectural visualization.

Actually, the personal head-mounted display that Matsushita used disappeared from the show room for a variety of reasons. For one thing, there was no way to conveniently share the design view of the customized kitchen with others since the system was basically one of a kind and could not serve as a medium for communication. Message mediates! But also there was the problem of developing content for the visualization. A major effort was required to prepare the existing CAD data for visualization with the HMD. There was essentially very little pre-existing content that could be easily imported into the virtual environments that the HMD could be used to view. This situation contrasts with the rapid spread of the World Wide Web. Both the Web and virtual reality (VR) were both similarly initially impeded by poor dynamic performance, but the large amount of interesting and useful pre-existing content that existed on the Internet gave the Web a boost; users were willing to wait because there was much to wait for. Content rules!

But content in isolation has limited impact. For display content to be really useful, it needs to be woven into a story. Indeed, one way to think of the design of an interactive, symbolic information display is to imagine it as a backdrop for a story being told to a user. An air traffic display, for example, has a stage, characters, action, conflicts, rules, outcomes – all the elements of real-time drama. In fact, training in drama is not a bad background for an air-traffic controller and I know of at least one tower manager who actually has a degree in theater from Carnegie Mellon University.

Another example of the key role of content and story is the introduction of the first cell phone. Though it weighed about 2 pounds, cost on the order of $4000 (~$9000 in current dollars), and had only limited talk time, there was significant initial demand, even if the phone clearly did not have an immediate mass market. Motorola had the foresight to make sure at least some of the necessary cellular infrastructure was in place before its first public demonstration in 1973. Users could talk to each other and to others anywhere in the world who were on the phone network.[14] Story conquers!

Probably the single most important element in the widespread deployment of new information technology is the provision of a sense of personal empowerment. Part of the amazing success of the microcomputer revolution of the 1970s and early '80s was that the microcomputer enabled a single programmer, working mainly alone, to create useful software products such as word processors that previously had typically been built by a group working on a mainframe system. The word-

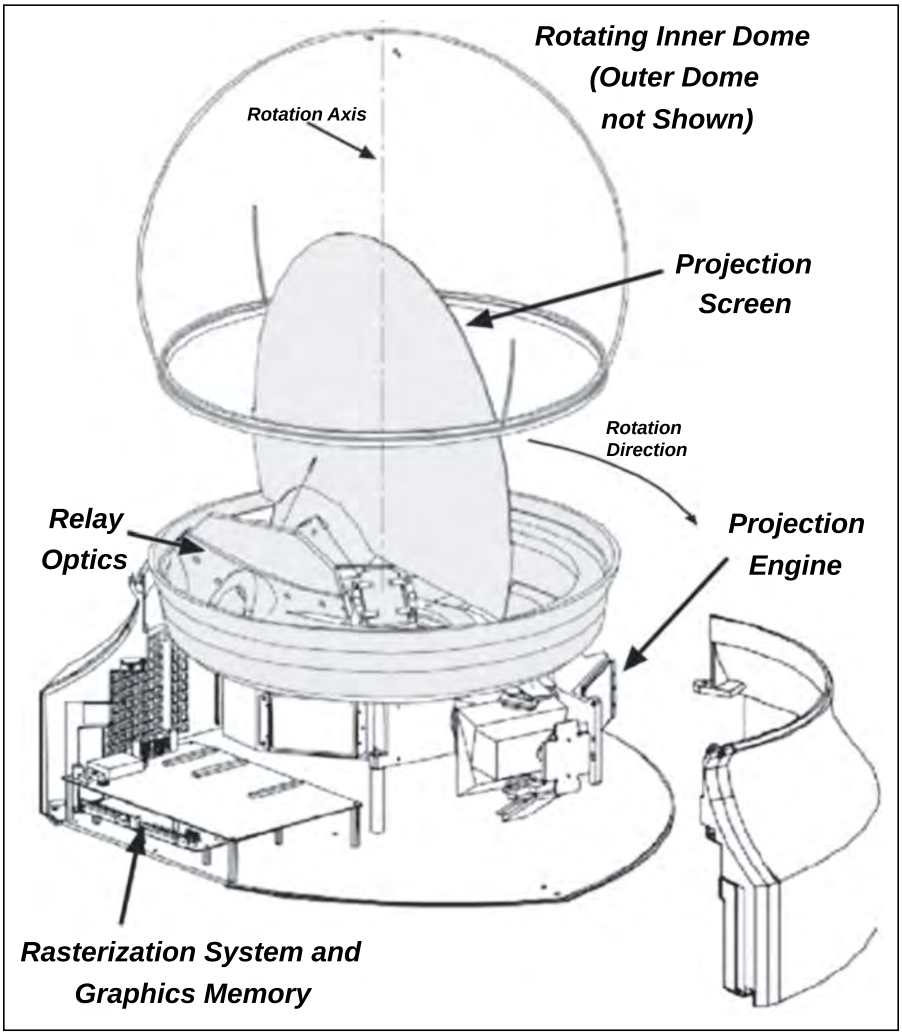

Fig. 3: *This example of an innovative contemporary, swept-screen, volumetric, multiplanar display was made by Actuality Systems. The gray central assembly along with the attached inner dome rotates at high speed while beams of light are scanned by deflecting mirrors over the surface of a 10-in. spinning disk.[17] Precise timing, placement, and coloring of the scanning light dot allow this system to produce a computer-graphics-generated, true-three-dimensional, full-parallax, colored image that can be used for information display. (For more on this display, and Actuality Systems, see "The Actuality Story" in the May/June 2010 issue of* Information Display.)

processing software in turn empowered writers with many functions previously the province of publishers. Thus, those with sufficient training and intellectual ability really could use the microcomputers as personal intelligence amplifiers in a symbiotic way as conjectured by Licklider.[15] This kind of personal empowerment has now become even more varied and widespread with the availability of powerful search and communication applications like those in Google and Twitter. Empowerment enables!

So we have now the challenge to the purveyors of light-field display systems: Can enough quickly processed, high-resolution, naturalistically colored light fields be captured for the display of storied content to provide useful visual information to personally empower the display's users?

There does seem already to be acknowledgement of some of the components of this question. The developers of the Lytro camera are tacitly acknowledging the preceding need for content by working first on the capture system, deferring the display for later. But additionally they would be wise to find ways to import existing three-dimensional data into light-field display formats so as to be able to benefit from all the existing volumetric or stereoscopic imagery available on the internet and elsewhere.

But they also will need to acknowledge that in addition to the natural information in the light field, such as full-motion parallax, which supports the natural semantics of our environment, synthetic light-field displays will also need to allow the introduction of artificial semantics. These semantic elements can take the form of geometric, dynamic, or symbolic enhancements of the display. Geometry can be warped, movement can be modified, and symbols can be introduced, all in the interest of communication of specific information. Such enhancements can turn a pretty picture into a useful spatial instrument in the way cartographers do when they design a map. Geometry of the underlying spatial metric can be warped as in cartograms (Fig. 4). Control order can be reduced through systems using inverse dynamics. Symbolic elements can be resized to reflect their importance.[16] There can be truth through distortion! Consequently, the naturally enhanced realism of the coming light-field systems may be only the beginning of the design of the next "ultimate display." Art matters too!

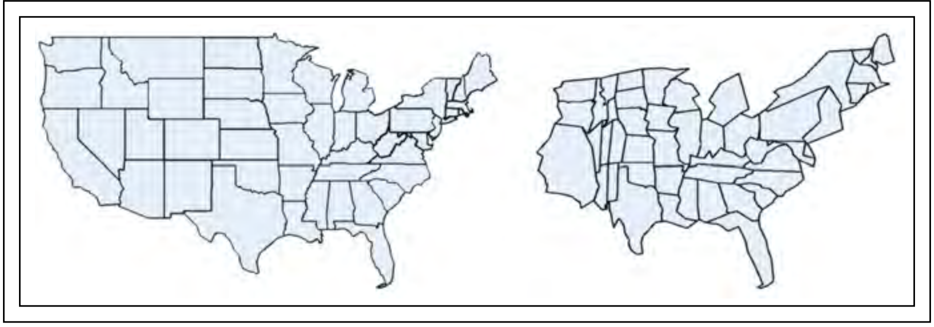

Fig. 4: Cartograms are topological transformations of ordinary cartographic space based on geographically indexed statistical data. For example, in this classic cartogram based on 1998 U.S. data discussed by Keim, North, and Panse,[18] the areas of U. S. states in a conventional map (left) can be made proportional to their populations in a cartogram (right). Their paper develops new transformation techniques that can improve preservation of some geometric properties such as adjacency and shape of the state borders while making others such as area proportional to arbitrary statistical indices.

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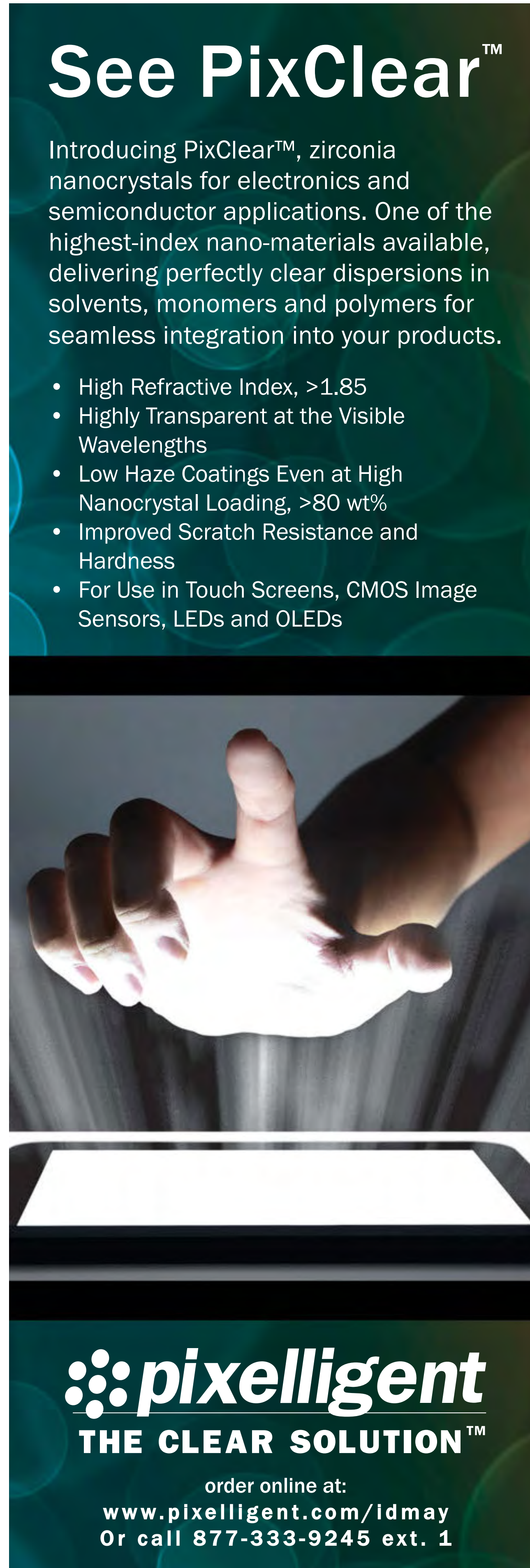

See Us at Display Week 2013, Booth #1129

Binocular Fusion Camera Enables Photography of 3-D Displays for Evaluation Purposes

The binocular fusion camera is a simple apparatus that permits a user to see what is on the screen so that the eyes can converge to create 3-D imagery. Left- and right-eye images can be overlapped to render how 3-D images will appear to both eyes, or the images can be rendered above and below each other in order to make motion artifacts visible. With this valuable tool, new insights into the visual performance of 3-D displays can be achieved.

by Edward F. Kelley and Paul A. Boynton

WHEN we look at a stereoscopic three-dimensional (3-D) display that requires glasses, but without using the glasses, the overlapping images are hard to interpret. It is sometimes helpful to put the images that can be seen by each eye into a single image representing the view of two separated eyes. Conversely, for examining motion artifacts, such as created by the motion of a small box across the screen, it is useful to separate the images of the box above and below to see how each eye image changes in time. The authors therefore created an apparatus that permits either the blending or separating of the view from each position of the eye onto a single detector or camera.[1] The apparatus has an interocular distance of 65 mm so that it can use the normal 3-D glasses that accompany many 3-D displays or it can be used with autostereoscopic displays without glasses.

A schematic of the binocular-fusion (BF) camera apparatus is shown in Fig. 1. There are two versions. When there is a single detector such as a lensless camera pixel array, photodiode, or photomultiplier tube upon which one wishes to place the left and right images together, lenses are employed at the front of the device. Irises adjustable from 1 to 12 mm in diameter are mounted in front of coated 300-mm focal-length achromatic lenses. The irises permit changing the effective resolution of the camera should it be desirable to simulate the resolution of the eye. These iris–lens combinations and elliptical mirrors (25-mm minor axis) oriented at 45° are mounted on small rails that can be rotated by manual positioners in order to simulate the

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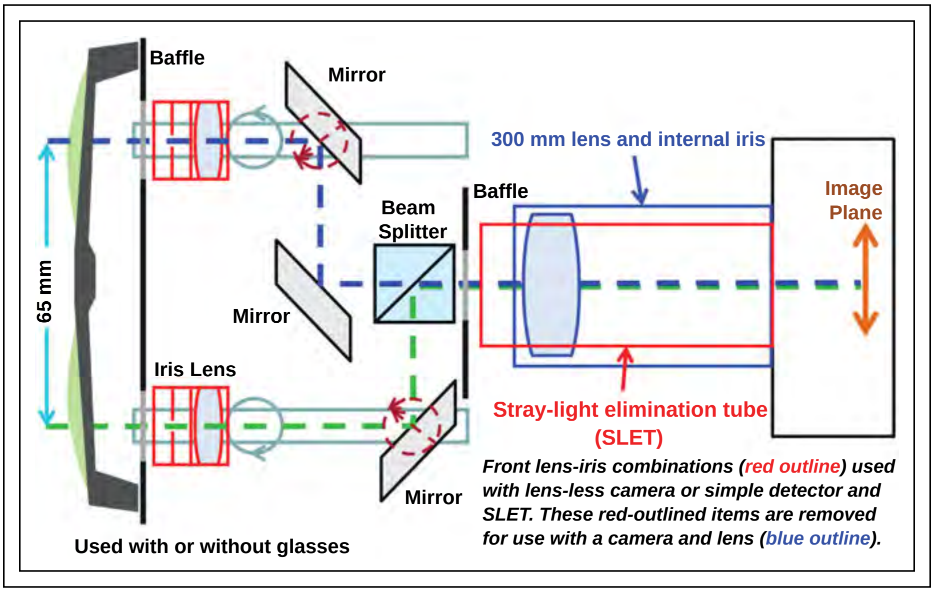

Fig. 1: A schematic layout of a binocular-fusion camera shows configurations for both a lens-less camera/detector and a camera with a lens.

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vergence of the eyes. Those mirror mounts have differential adjusters that are indispensable in providing very fine control of the position of the left and right images.

By using a second non-adjustable elliptical mirror positioned at 45° in the center, the image of the right eye is directed straight through a 25-mm non-polarizing 50:50 beam splitter into the detector or camera. The left-eye image is directed into the side of the beam splitter and reflected into the detector or camera. This arrangement is used so that the left and right image paths have the same length. A front baffle must be provided to prevent leakage of the light from the display bypassing the optics into the detector. A second baffle is placed at the output of the beam splitter to further prevent stray light and other scattering problems from the optical components (see Fig. 2).[2]

The configuration in Fig. 1 that uses a 300-mm focal-length lens on the camera instead of the front lenses and irises is probably the easiest configuration to use because both eye paths employ the same lens and iris that is on the camera. The reason for the long-focal-length lenses in either configuration is so that the pixel information can be resolved as well as being able to have the long paths through the apparatus where the observation or viewing distance is approximately 2 m.

The alignment of the BFC is the most difficult part of using the camera. By removing the camera (or front lens–iris components) and looking at a target with markings at 65 mm placed at the measurement distance, it is possible to use one's eyes to align the markings for infinity viewing. However, this is only a very coarse alignment. Putting the camera back in place and looking at a 3-D display with horizontally separated objects will require much finer adjustments. The tilt of the beam splitter can greatly affect the alignment at the magnifications sufficient to resolve individual pixels.

Application Examples

One use of the BF camera is to record how a stereoscopic image might be binocularly fused by removing the horizontal separation of the left and right images to simulate what would be seen with both eyes.

Figure 3 shows a frame from a popular computer-animated movie, the enlarged image of the right eye in the image (left to the viewer), and the BF camera image of the 3-D result.[3] The images are taken from a film-patterned-retarder (FPR) 3-D display where the odd lines are seen by the left eye and the even lines by the right eye.

For the fused image to represent what the eye sees, recall that it is necessary for the viewer to be a sufficient distance from a FPR display, usually 3.2 screen heights or farther for 20/20 vision acuity.[4] There are two ways

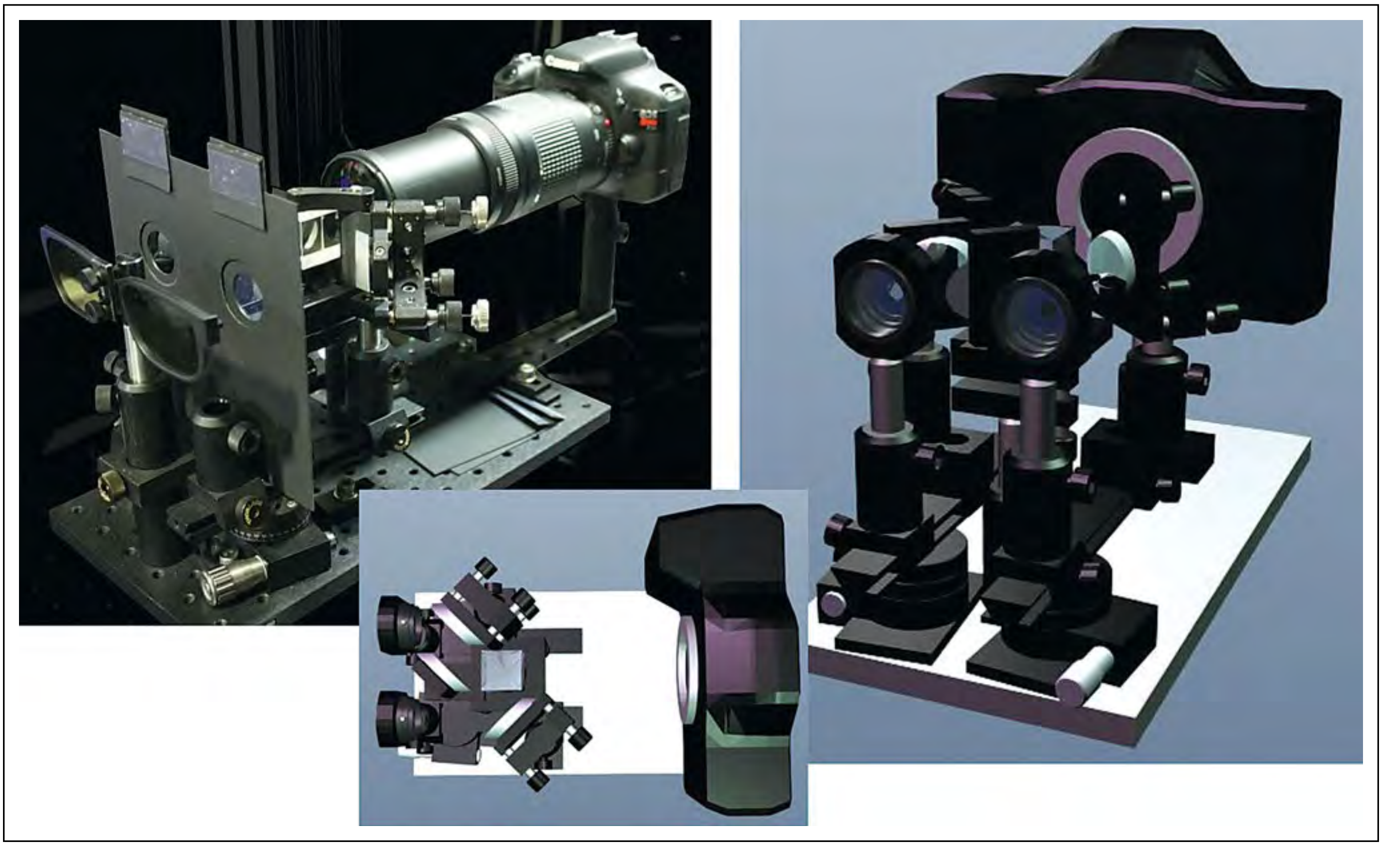

Fig. 2: The photograph of the binocular-fusion camera (top left) shows the configuration with a single lens on the camera. The graphical images above and at top right show the use of a camera body and frontal lens-iris combinations without baffles or SLET.

to align the left and right images for the FPR display: (1) vertical alignment of the pixels or (2) alignment of the contours of the edges of objects. We would suspect that the eye would align the contours and not the pixels. The bottom BF camera image in Fig. 3 has the pixels vertically aligned at the highlight. The resulting fused image shows excellent rendering of the 3-D image where each line is different and representative of 1080p vertical resolution.

Is this what the eyes see? No, the eyes see better than this. Note that in Fig. 3 some of the edges away from the highlight are ragged. This can be because those parts of the image are not in the same plane as the highlight. When the eye sees other parts of the image, it quickly fuses the two images properly, making the contours smooth. Thus the BF camera is really only good for fusing the two-eye images at a single plane of the object being studied if that object spans a range of depths in the 3-D image. Some of the ragged edges in the image in Fig. 3 also arise because of different exposures for the left and right lines owing to imperfections in the BF camera and a slight coloration difference from the beam splitter. It is very difficult to properly tilt the beam splitter to assure accurate pixel alignment across the entire image.

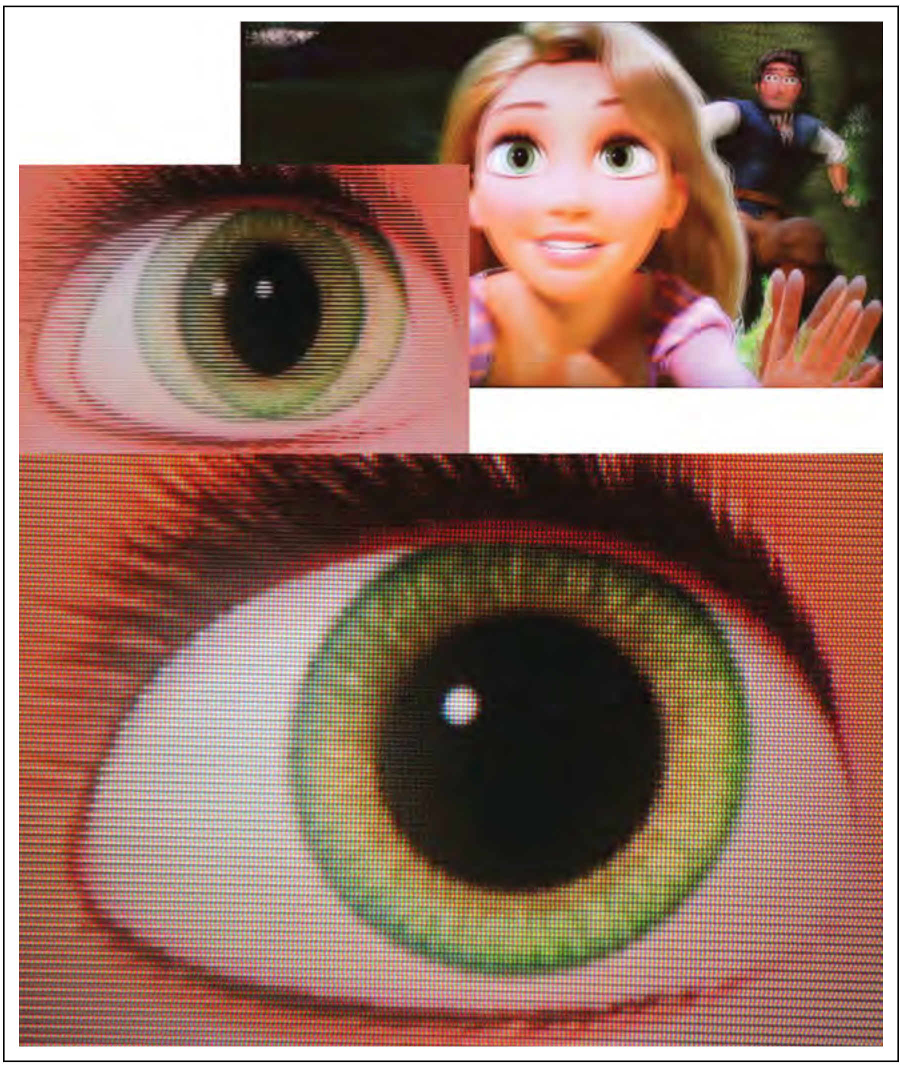

Fig. 3: This frame from the movie Tangled *shows an apparent face image in front of the screen surface on a film-patterned-retarder 3-D display. The binocular-fusion camera can attempt to align the separated left and right images of the character's eye to binocularly fuse the images together. The highlight on the cornea was used to establish the plane of alignment. Parts of the image at different depths show misalignment and ragged edges.*

The BF camera can separate the images of the left and right eyes as well as combine them. It is interesting to investigate whether the motion artifacts are different for left and right eye images on a 3-D display; for example, if a white box could be moved horizontally across a black background on the display at a specified pixel increment for each frame. Here, the authors used the side-by-side mode of the 3-D display with the motion increment of four pixels in the original moving pattern, resulting in an 8 pixel per frame movement in the side-by-side 3-D image. Using a high-speed camera and a FPR 3-D display, the horizontal motion of that small block can be recorded for both eye images at the same time. Figure 4 shows (a) the high-speed camera in use with the binocular-fusion optics, (b) the pattern on the screen with stationary small vertical lines in addition to the moving boxes, and (c) one sequence of the 10 × 50 moving white box against a black background with the right image oriented directly above the left image.

Almost one display frame is shown in (c) where the interval between images is 4 msec, making 16-msec total duration; the original high-speed sequence is captured at 1000 camera frames per second. (To see all the processes going on, such as a rolling backlight, the authors generally use from 10,000 to 15,000 frames per second.) The resulting image sequence can be analyzed according to standard methods to determine moving-edge blur profiles.[5]

Uses of the BFC

What the binocular-fusion camera provides is a means to document what is on the display surface of a 3-D display whenever the overlapping left and right images are difficult to interpret with normal 2-D photography. If the left and right images of any object are in the plane of the screen, then we can use normal 2-D photography to capture what is on the screen because both left and right images are aligned when the object is in the plane of the screen. However, when any object is *not* in the plane of the screen, then we can use the BF camera to fuse and photograph the left and right images together to simulate what the eyes will see when looking at the object

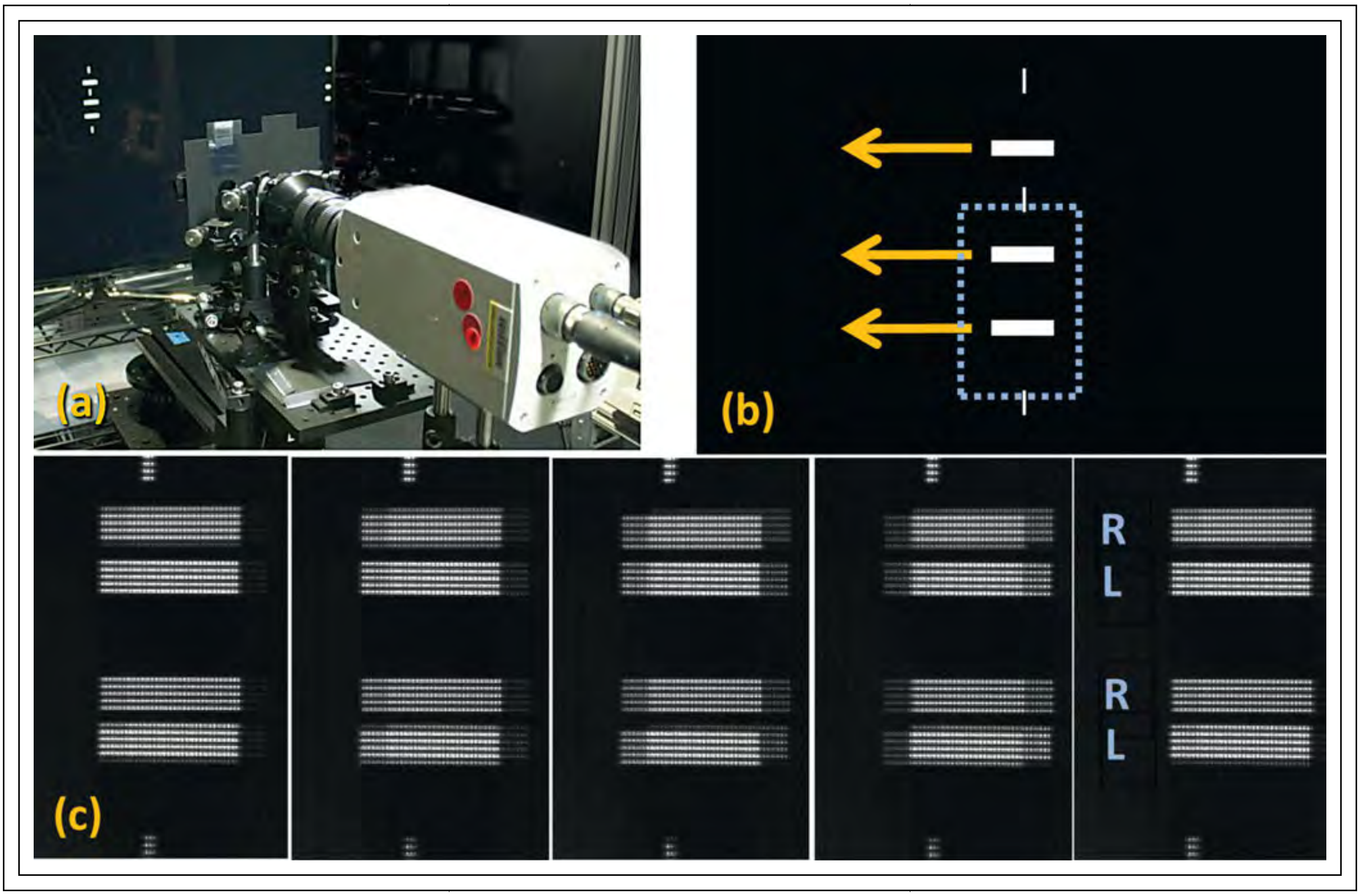

Fig. 4: In (a), the high-speed camera is shown in use with the binocular-fusion optics. In (b), the pattern on the screen with stationary small vertical lines appears in addition to the moving boxes. In (c), one sequence of the 10 x 50 moving white box against a black background is depicted with the right image oriented directly above the left image. Almost one display frame is shown in (c), where the interval between images is 4 msec, making a 16-msec total duration.

through 3-D glasses. We can also separate the left and right images to examine motion artifacts created by moving objects. In all this, the objective is to use the binocular-fusion camera to help document how a 3-D display is performing with the presentation of either static or moving 3-D images.

References and Comments

[1]E. F. Kelley and P. A. Boynton, "Binocular Fusion Camera to Render Pixel Detail in 3D Displays," *SID Symposium Digest of Technical Papers* **43**, Paper 12.5L, 145-148 (2012).

[2]Certain commercial equipment, instruments, materials, systems, and trade names are photographically identified in this paper in order to specify or identify technologies adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the systems or products identified are necessarily the best available for the purpose.

[3]*Tangled* by Walt Disney Animation Studios, distributed by Walt Disney Studios Motion Pictures, © 2010 Disney Enterprises, Inc. This is a Blu-ray® 3D movie. We use frame 15 at time 1:00:05 of scene 8 (of 13); this is where Rapunzel is saying "easy."

[4]E. F. Kelley, "Resolving Resolution," *Information Display* **27**, No. 9, 18–21 (2011).

[5]Information Display Measurements Standard, 12.3.3 Moving-Edge Blur from Digital Pursuit, of the International Committee for Display Metrology of the Society for Information Display, Ver. 1.03 (June 2012). ■

How High-Frame-Rate Dual-Projector 3-D Made Its Movie Debut at the World Premiere of *The Hobbit*

Enabling the first-ever 48-frames-per-second showing of a major motion picture in 3-D required a massive effort involving projection technology, sound and screen equipment, and earthquake and wind protection.

by Terry Schmidt

WHAT was that crackling noise? Here I was, sitting in the back row of a glorious old movie theater (Fig. 1) at the November 2012 world premiere of *The Hobbit*, with Peter Jackson and James Cameron in the house, and all I could hear, and all I could think about, was the crackling sound. After a month on-site in Wellington, New Zealand, and after years of R&D to bring high-frame-rate (HFR) cinema to major motion pictures, was the big debut for this technology going to be undone by some mysterious audio problem? Then it struck me. The red carpet stretched more than half a kilometer and took more than 2 hours to traverse. The movie-goers were likely hungry. Everyone had found a goody bag on their seat that included a crackly little bag of potato chips – which they were now digging into. It was the potato-chip bags – not an audio malfunction – making the racket!

My heart rate went back to normal, and I started to enjoy the first-ever true movie-going experience of 3-D HFR cinema. It had been an intriguing technical journey to that moment, which was arguably the night when digital cinema and movie-going entered a new age.

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World-First Pressures

As Chief Scientist for Christie Digital Systems, I led a team in Wellington in November 2012 that installed three Christie CP2230 projectors with integrated media blocks into the circa 1924 Embassy Theatre for what was to be the

Fig. 1: *The historic Embassy Theatre in Wellington, New Zealand, was the site of the world premiere of* The Hobbit: An Unexpected Journey, *and also of the first-ever showing of a major motion picture shot in 48-fps 3-D.*

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world premiere of *The Hobbit*: *An Unexpected Journey*, director Peter Jackson's much anticipated prequel to the Lord of the Rings movie trilogy.

It was the first mainstream, mega-budget movie to be shot, edited, and shown at 48 frames per second (FPS) cinema, and in 3-D. The collective eyes of movie-lovers and the motion-picture technical community were squarely fixed on Wellington and this event. The pressure was high for Christie, which was providing the projectors and systems, to deliver a flawless premiere.

The physical properties of the venue, timing, and pure pressure made for some long days and late nights, but in the end, movie executives and film fans started to understand why leading directors like Jackson and *Avatar*'s James Cameron are such avid proponents of HFR cinema. Much was learned from that premiere about this evolving medium, and the technical challenges and possibilities it introduces.

Planning the Parts

Each of the celebrated *Lord of the Rings* movies has had its world premiere at the Embassy in downtown Wellington, the city closest to Jackson's New Zealand home, as well as to visual effects house Weta Studios and the Park Road Post Production facilities. The vintage movie house was originally designed for live stage productions and has since then been strengthened to withstand earthquakes. For the *Hobbit* premiere, this grand old theater was to seat 758 VIPs in its ornate auditorium.

To provide a truly rich HFR 3-D and sound experience for the premiere, two synchronized Christie CP2230 projectors were to display 48 frames per second, showing 3-D images at the extraordinary brightness level of 11 ft-L, up from the conventional 4.5-ft-L target of standard digital-cinema screens (Fig. 2).

The projectors were fitted with passive RealD XLDP boxes to drive high-efficiency 3-D. Two synchronizing Christie Integrated Media Blocks (IMBs) were installed into the projectors, to project onto a state-of-the-art, high-uniformity, silver screen from RealD. To complete this ultimate movie-going experience, the Dolby company was asked to fit a 35-channel version of its Dolby Atmos digital surround audio system into the ceiling and walls of the movie house.

In all, three projectors were planned into the design to ensure continuity and redundancy, even in the face of an unlikely failure. The two main units would use a specially mastered version of *The Hobbit* that factored in the exceptionally high brightness levels, while a third backup projector was schemed in to run a standard sequential flashing 3-D configuration, with a standard master timed for 4.5 ft-L brightness. The dual synchronized projectors each output a separate continuous image, one for each eye, presenting the viewer with the ultimate realism in 3-D.

Fig. 2: *An adjustable stacking frame is used to accurately align two 3-D Christie projectors for a higher brightness showing of* The Hobbit *at the Embassy Theater in Wellington, New Zealand.*

None of this was in place when the Nov. 28 premiere date was set. The planning started weeks ahead and far away from New Zealand. I arrived 3 1/2 weeks early to supervise the project and work with our technical partners.

The Embassy Gets Fitted

Our very modern equipment and mounting frames — first assembled and staged in Christie's engineering and manufacturing headquarters in Kitchener, Ontario, Canada, and then shipped "down under"— had to somehow fit into a very old building. This proved a challenge: the only way the projectors were getting into the Embassy Theatre booth was through the roof.

We hired a street-level crane (Fig. 3) to lift all of our equipment to the roof. Thankfully, we had sunshine on crane day and were able to unpack outdoors. Some very strong, very eager locals manhandled three projectors, one pedestal, one unassembled stacking frame, and all the accessories through two small doorways and a narrow passageway. With the equipment inside, we had a first good look at the technical challenges in front of us.

Fig. 3: *Wellington city council blocked off traffic while a huge crane hoisted three projectors, mounting frames, and pedestals to the roof for unpacking and hand delivery into the projection booth.*

The deep cinema stage had been refitted with the 60-ft. 3-D silver screen, with its silver particles that reflected with circular polarization preserved vs. flat white diffusers that scrambled the polarization. There was no screen structure other than a peripheral frame tilted back at a 10° angle to aim directly at the projection booth. This new RealD screen called "Precision White" had a half-angle of 40° and a gain of 1.5 vs. a standard gain of 2.4. This meant the usual hot spot was not evident, and the high-brightness 3-D was more uniform than usual.

The projection booth needed major upgrades. We required a new, very tall projection port glass for our dual-stack system. Since Wellington is in an active earthquake zone – rated at 1000 per year – there are very strict construction laws in place, in this case dictating the need for a new 12-in. U-channel steel beam to be bolted through the wall over a window. This was brought on by having to

Digital Cinema and 3-D's Symbiotic New Relationship

Digital cinema and 3-D are now in a kind of marriage relationship, with digital's electronic speeds enabling 3-D that was otherwise cumbersome and expensive using film. In turn, 3-D has hastened the wide adoption of digital cinema in the past few years, accelerating what had been a somewhat stalled adoption rate.

High-speed DLP imagers from Texas Instruments enable 3-D as a valuable tool in a cinematographer's storytelling arsenal. Together, they form a practical means to add realism, and a new dimension to movie presentations to large group audiences.

3-D digital cinema, more properly called video stereography, uses what is called Z-Screen liquid-crystal technology, which allows two completely separate eye images to be sequentially displayed efficiently from a single projector. Inexpensive left- and right-hand circularly polarized filters are typically used in disposable, recyclable glasses to separate left and right images. When used with new polarization-preserving high-tech silver screens, less than 100:1 crosstalk is possible, reducing so-called bleed-through ghosting from one eye to the other.

Although there are several eye-separation techniques used in digital cinemas worldwide today, I like the efficiency of those from RealD. Its RealD XL box cleverly recovers the normally "lost polarization" into a second image, which is recombined with the original at the screen. When this box is slid on its rails in front of the projection lens, one of the planet's largest wire-grid polarizers splits the light path into two polarized channels.

The box's two liquid-crystal dual pi-cell structures, the Z-screens, switch the polarization at 144 Hz (or 192 Hz for HFR) rate between left and right eyes. This provides amazingly clear and bright full-color 3-D realism.

The original, and still most accurate, way to reproduce a stereo image and see 3-D in a cinema is with two projectors (Fig. 4). One is dedicated continuously to the left eye and one is dedicated continuously to the right eye. In amusement parks, where there are 3-D rides and special theaters, this is still done with film loops in two projectors. Using two DLP Cinema projectors and synchronizing the content doubles the effective brightness and can prevent any flashing artifacts for people who cannot tolerate a 50% black flash period in each eye, even at high frame rates.

It turns out that the alignment of two projectors for 3-D presentations does not need to be nearly as accurate as for 2-D presentations; when only one image is in each eye, our eyes and brain align them automatically with low fatigue.

However, for 2-D movies without glasses to separate the images, alignment must be virtually perfect all over the screen. This alignment is easy to do in a vertical stacking frame once the concept of projected image keystone and lens offset is understood. Keystone distortion results when the aim of the projector is off perpendicular to the screen. There is almost always some keystone due to the steep down angle in modern stadium seating theatres.

In dual-projector systems, this keystone must be matched in both vertical and horizontal directions by observing each image carefully, using a red test pattern designed for the purpose from one projector and a green one from the other. By starting with the projectors as parallel to each other as possible, lens offset is used to align the images in the center, and lens zoom is used to make the images the same size. Using the adjustable feet of the projectors, leveling and aim are adjusted until the images overlay each other as closely as possible. The confusing factor seems to be that the adjustment needed to align the center crosshairs of both images can be done by both by aim and lens offset. The breakthrough concept is to learn that adjusting the aim of the projector increases or decreases keystone, but the adjustment of lens offset does not.

– *T.S.*

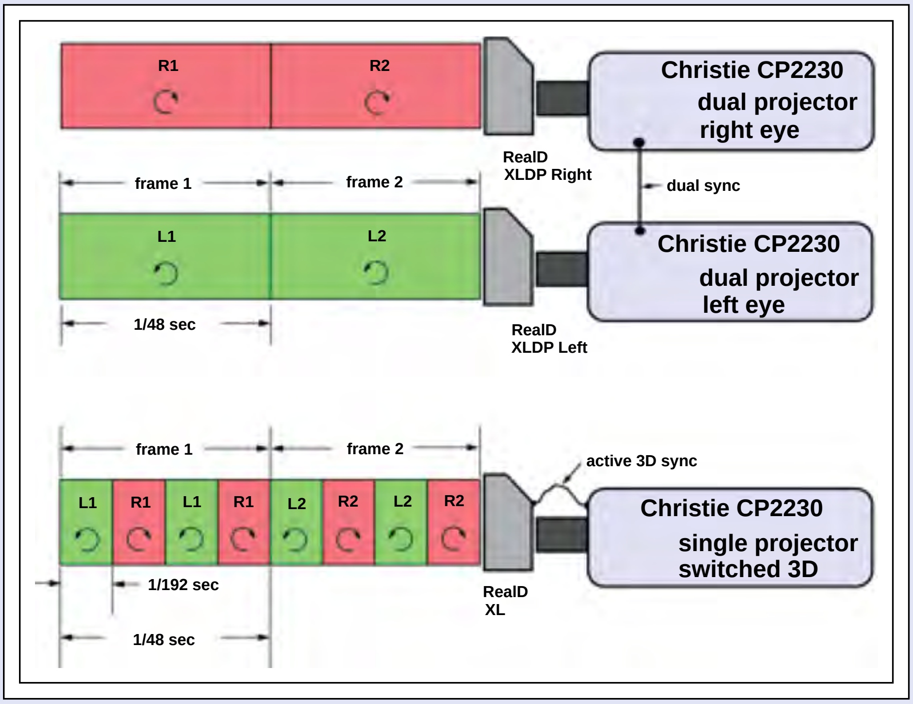

***Fig. 4:** Dual-projector 3-D shows continuous images to each eye, replicating the "real world" more closely than so-called "double flash" techniques used for HFR 3-D single-projector presentations.*

cut a larger port opening for the dual projectors in a solid concrete wall, a process that removed some internal steel reinforcement.

The sheet of noise-reducing port glass arrived broken in half. With no time to get a replacement, we were forced to make do. Fortunately, the crack was almost horizontal and centered, so by using the adjustable extrusions of the stacking frame, we were able to adjust the two beams from the top RealD XL system to clear over the crack, and the lower projector to clear under. It worked!

We also had to upgrade the heat-extraction system, the existing system having been calculated by city engineers to be inadequate to handle the new Christie outputs. We mounted three huge, low-noise heat extractors on the ceiling and used two louvered window boxes that exhausted to the roof area through the booth outside wall. This was by design, to prevent back drafts from the notoriously high winds of Wellington. The third-party Network Attached Storage (NAS) system − between unplanned sleep modes and rebuild processes and passwords – took some finagling, but we tamed it in time for the premiere.

Team Effort

The HFR speeds necessitated the installation of integrated media blocks (IMBs) into the card cage of each projector. This allowed data to be connected to the highly parallel internal backplane of the projector. Each IMB was connected to its respective NAS device via a CAT6 Ethernet cable, where the content was stored in a Raid 5 configuration of four 1-terabyte drives. A small coax cable connected the two projectors to each other, so specialized dual-projector software could keep the left- and right-eye images in perfect synchronization.

All-electronic systems possible were also connected to battery backed-up UPS power supplies, in case of a short power outage that would require a long microprocessor re-boot delay. This included all three projector signal electronics, and three of the six redundant NAS power supplies, as well as the Dolby Atmos processor. In this way, a small power hiccup would require only a fast lamp re-strike in order for the show to carry on. Ultimately, this hard work led to a very successful first showing of the film, and this powerful new cinema technology. At this point, I offer a closer look at the progress of HFR.

HFR's Big Moment

The worldwide conversion of film cinemas to digital has seen many bumps along the road. Initially, hardened film buffs missed the shaky and grainy film look they grew up with, and purists nostalgically yearned for the simplicity of output from the old mechanical film projectors.

With the advances in DLP Cinema, speeds fast enough to support 3-D with a single projector became possible. The frame rate, however, remained at 24 frames per second (fps) to match the look and feel of film. Even home TV exceeded film with its 30 fps, and with the popularity of HD digital TV, most home theaters have now reached 60 frames progressive for HDTV broadcasts.

Despite all these advances, digital cinema frame rates seemed stuck at 24 fps. All that started to change 2 years ago, when Jackson, Cameron, and other influential directors started exploring what a faster frame rate would do for cinematic storytelling.

Cameron showed a specially shot series of higher-frame-rate 3-D test clips at Cinemacon 2011 in Las Vegas. These consisted of medieval feast and fighting sequences shot at 24, 48, and 60 fps for the cinema industry's technical community at the Colosseum at Caesar's Palace. The demo was supported by four projectors set up for fast-switching audience evaluation among the three frame rates. This content demonstrated that high panning speeds and fast-action sequences could benefit in clarity at the higher frame rates of 48 or 60 fps versus the standard film rate of 24 fps.

The demonstration was a huge success, as everyone could see that 48 fps delivered significant improvements. Jerky motion artifacts disappeared and action scenes flowed smoothly. There was a discernible further improvement in going to 60 fps, but the difference from 48 fps was relatively small.

A year later, again at Cinemacon, Jackson showed an unfinished 10-minute excerpt from *The Hobbit* at 48 fps using Christie projectors. The excerpt drew a lot of controversy from film-buff bloggers who objected to the hyper-realism and missed the soft, classic "film look." Many thought it looked more like actors on a stage because the 3-D effect and increased motion accuracy and increased clarity paralleled real life. This is called the 'presidium effect' – presidium being the name for a stage surround.

Some extreme comments likened it to a TV soap-opera look, which "cheapened" the medium. Jackson counter-argued that the short, unfinished clip did not allow enough time to draw viewers into the story to then forget about the projection medium and enjoy the realism of the movie. It did not dissuade him from finishing and releasing the film in HFR.

The experience in some ways mirrored the transition from standard-TV to HDTV resolution. As with HDTV, the acceptance of the strong advantages of HFR's realism, and increased detail in both fast motion and scenery, will take some time, but is predicted by many to be inevitable. Cameron has promised both of the *Avatar* sequels to be in HFR, although at the time of writing he has not declared whether it will be 48 or 60 fps.

Having seen the final product, I am happy to report *The Hobbit: An Unexpected Journey* has met mostly with encouraging acceptance in its newly introduced HFR format in almost 900 screens worldwide, as well as standard 24-fps 3-D showings. Early reports of nausea from too much HFR realism in the action scenes were replaced with reports of breath-taking scenery and very realistic close-ups that perfectly conveyed the story and characters. According to many, HFR cinema is here to stay. ■

PQM: A Quantitative Tool for Evaluating Decisions in Display Design

Display manufacturers must continually make decisions about device performance with regard to such characteristics as resolution, luminance, and color. 3M has developed a new tool that enables product developers to forecast how these design factors affect users' perceptions of quality.

by Jennifer F. Schumacher, John Van Derlofske, Brian Stankiewicz, Dave Lamb, and Art Lathrop

DISPLAY DEVELOPERS now have extraordinary opportunities for advancing performance. They can create displays that approach the limits of human perception (in resolution) and produce more than enough luminance in most cases. Displays can also offer a much larger color gamut – a performance characteristic that has lagged behind gains in resolution and luminance – thanks to new display architectures and technologies such as quantum dots and organic light-emitting diodes (OLEDs).

However, even though manufacturers have the technical capability to do so, most do not produce displays that provide the highest levels of resolution, luminance, and color gamut. (Similarly, automakers do not give every vehicle top-of-the-line horsepower and interior styling.) Instead, they might decide to moderate performance characteristics to meet consumers' cost constraints. They recognize the consumers' and regulators' concerns about energy consumption. And they take advantage of consumers' color and resolution expectations, which do not require a perfectly faithful representation of reality.

The impact of some of these tradeoffs can be calculated with relative ease. For example, if a product developer were considering a reduction in backlight performance resulting in reduced display luminance, the impact on display performance in exchange for cost savings could be measured using readily available tools. Potential improvements in energy consumption would also be easy to quantify.

Measuring the impact of display characteristics on consumers' perceptions of quality is more difficult. It is harder still to gauge the change in consumers' attitudes if a reduction in one performance attribute – luminance, for example – is accompanied by an improvement in another, such as color or resolution.

Large-scale consumer surveys could, in theory, provide the detailed information about consumer preferences that developers would like to have when considering tradeoffs; however, such research is expensive. Furthermore, research on consumer preferences is often useful for only short periods; key performance characteristics improve rapidly and consumer expectations change with them. (What was a desirable resolution in 2007 was subpar in 2010.) Not surprisingly, few large-scale studies of consumer preferences have been undertaken.

As an alternative, some researchers have pursued computational models of consumer preferences, such as P. G. J. Barten's Square Root Integral (SQRI) metric. First published in 1987, the SQRI calculates expected viewer preferences for size, resolution, and luminance.[1] SQRI's value is limited, however, in that it does not consider color gamut and contrast.

Recently, the authors and other researchers at 3M developed the Perceptual Quality Metric (PQM), a new computational model based in part on the SQRI. The goal of this metric is to predict the subjective quality of a display, not the fidelity of the images rendered on it. PQM calculates expected viewer perceptions of quality based on viewing distance, display size, resolution, luminance, and color gamut. By using this tool, product developers can now quantify the perceptual quality improvements in products based on changes in display specifications. These assessments can then be used to guide the inevitable tradeoffs that are made in display design or, more intriguingly, drive toward a display that achieves levels of perceived quality hereto unforeseen.

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Metric Development

To develop the new metric, 3M conducted a series of experiments to determine subjects' preferences for images displayed with varying luminance and color gamut characteristics.

In the first experiment, 14 adult subjects (equally divided by gender) were shown a set of 10 images over multiple trials. The images were randomly generated shapes (triangles, squares, and circles) of various sizes and random colors (Fig. 1). The random shapes and colors were used as a context-independent condition where humans would have no expectations of color ("memory colors").

In a second experiment, 24 adult subjects (equally divided by gender) viewed one image randomly selected from a set of five photographs (Fig. 2). (Based on the first set of studies and the added complexity of and number of real images, additional subjects were warranted for statistical reliability.)

Each subject viewed the same photo multiple times, with variances in color gamut and luminance. The photographs were used as a context-dependent condition to simulate display usage where objects such as the sky have an expected color; photos included multi-color and single-color (red, green, and blue) objects.

Each of the 15 stimuli was processed to simulate every possible combination of four gamut sizes and three luminance levels, for a total of 12 simulations for each photo and image.

In both experiments, subjects were seated 36 in. from two high-performance monitors, arranged side-by-side. For each stimulus, two variations (with different luminance and color) were presented simultaneously on the two monitors (one image per monitor) for 2 sec, after which white noise appeared until a preference was recorded. Every possible pairing was presented, including comparisons with identical characteristics. Additionally, to ensure that one monitor was not preferred over the other, each pairing was repeated with the images on the opposite monitor. Therefore, a total of 156 trials were given to each subject.

The data were used to obtain several computational models incorporating luminance and color-gamut area. A validation experiment was then conducted using 36 subjects (22 male). Subjects ranged in age categories from 20 to 60. Five color-gamut areas and four luminance levels were varied (creating 20 conditions) and subjects rated these display simulations for each of three images. The equation with the highest correlation to the validation data was selected as the final PQM.

Results: Multiple Routes

Initial results suggest that PQM is an accurate tool for forecasting how changes in color gamut, luminance, and resolution will affect viewers' perceptions of quality, as measured by Just Noticeable Differences (JNDs). (One JND represents a difference between compared devices that is noticeable but does not have a large impact on preference; three JNDs represent a significant impact and 10 are substantial.) The validation experiment showed a correlation of 0.97 between predicted quality values and actual values

The implications of this tool are significant. By graphing luminance and color gamut, for example, developers can readily predict the relative impact of performance improvements or reductions (Fig. 3) without investments in large and expensive studies of consumer preferences.

The graph shown in Fig. 3 reveals that improvements in luminance and color are both nonlinear, starting with sharp increases that gradually become less steep. Gains in luminance affect perceptions of quality, even as the display approaches 400 cd/m^2, but between 200 and 300 cd/m^2 , the return on

Fig. 1: Random shapes and colors were used to provide context-independent imagery for which viewers would have no preconceptions about what color the images should be.

Fig. 2: Photographs were used as a context-dependent condition to simulate display use where subjects have an expected color.

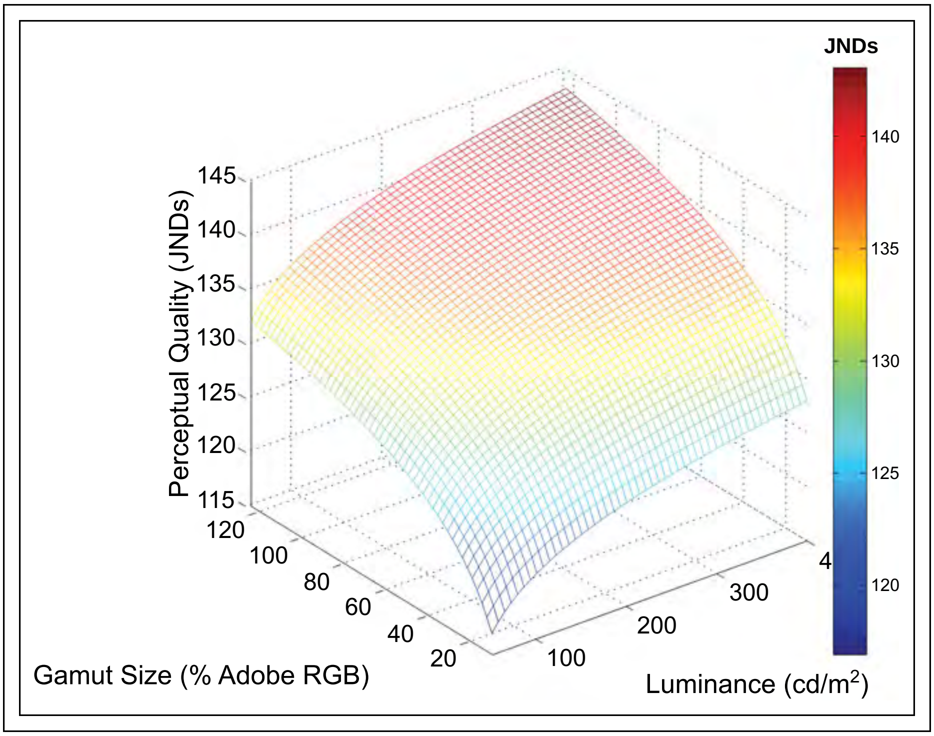

Fig. 3: The interaction of luminance and gamut area affects perceptual quality. A larger perceptual-quality value indicates higher preference. The display modeled is a 46-in. LCD TV with 1080p resolution and a viewing distance of 1.5x the display diagonal (69 in). With increases in color gamut or luminance, improvement in perceived quality is non-linear.

improvement begins to diminish substantially. Improvements in color gamut, however, result in continuous strong improvements in perceptual quality, up to 120% of the Adobe RGB standard.

It should be noted that this assessment addresses the effect of brightness on perceived quality under conventional indoor lighting (in this case, 310 lux of overhead illumination). The results would obviously be affected by less favorable lighting conditions, such as a phone being used outdoors or a television being viewed in a bright room.

In general, PQM suggests that the highest luminance and a low color gamut will generate an acceptable quality value, but superior quality values are not achievable without a higher color gamut. Color saturation can be used to maintain high values if the developer opts to lower another performance characteristic. For example, if a developer sought to improve a display's energy efficiency by lowering luminance, the display's quality value could be maintained (or even increased) by expanding the color gamut. As shown in Fig. 3, by increasing color gamut, excellent quality values can be achieved even at mid-range (250–300 cd/m^2) luminance levels.

Figure 4 demonstrates the interaction between gamut size and luminance for a 46-in. LCD TV with 1080*p* resolution at the recommended viewing distance of 1.5 times the display diagonal (69 in.). Note that the same JND score can be achieved with higher color/lower luminance or lower color/higher luminance. As luminance drops from 350 to 280 cd/m^2, perceived visual quality can be maintained by increasing the color gamut size from approximately 50% to 60%.

Figure 5 illustrates how these tradeoffs could apply in actual devices with consider-

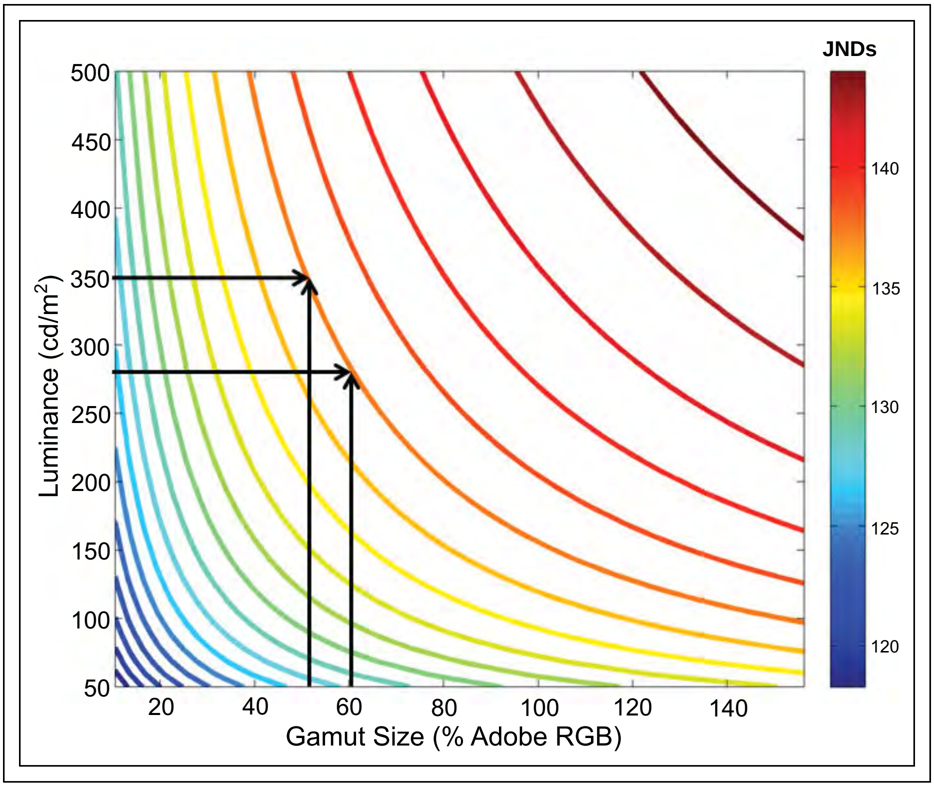

Fig. 4: Isoquality curves for display quality show the interaction between gamut size and luminance. The display modeled is a 46-in. LCD TV with 1080p resolution and a viewing distance of 1.5x the display diagonal (69 in.). The same JND score can be achieved with higher color/lower luminance or lower color/higher luminance.

Fig. 5: As this comparison of devices demonstrates, similar perceptual quality values can be attained via different display specifications.

Device Generation	Model	Display Diagonal	Resolution	Luminance [cd/m²]	% Adobe RGB	PQM Value (JNDs)
Gen 1	Model A	3.5″	960x640	541	53.13	131
	Model B	4.0″	800x480	365	109.38	129
	Model C	3.7″	854x640	449	69.79	131
Gen 2	Model D	4.0″	1136x640	556	72.92	134
	Model E	4.8″	1280x720	283	111.46	134

able variations in performance attributes. In this example, five models are analyzed using PQM: the first three models represent first-generation devices, while the others represent second-generation models with better resolu-

PQM in Action: Is 4K Resolution Worth the Cost?

The value of PQM is not just in assessing tradeoffs (*i.e.*, the impact of improving one performance characteristic while constraining another). It can also reveal when an improvement will produce little or no change in the consumer's perception of quality – when the benefit is "maxed out."

The latest models of ultra-high-resolution LCD televisions – so-called 4K sets – provide a good case in point. Objectively, the displays are a significant improvement; current HD sets with 1080*p* have one-quarter the resolution of the 4K sets. However, some reviewers have questioned whether that much higher resolution would translate to a meaningful increase in consumers' perception of quality.[2,3]

Based on PQM, the short answer is yes, especially among the largest displays, but the effect diminishes quickly after 4K (making 8K resolution a less attractive improvement). At a viewing distance of 9 ft., PQM analysis predicts that on any display of 32 in. or more, the improvement from 720*p* to 1080*p* results in a meaningful improvement in perceived quality (Fig. 6). On 42-in. and larger displays, the improvement from 1080*p* to 4K resolution creates a meaningful difference in perceived quality; the difference is dramatic for sets that are 55 in. and larger.

At shorter distances (at the recommended viewing distance of 1.5 times the screen's diagonal), the improvement from 1080*p* to 4K also creates a strong increase in perceived quality (Fig. 7). At either range (9 ft. or 1.5 times the diagonal), there is a measureable but considerably less powerful increase in perceived quality when the resolution improves from 4K to 8K.

Obviously, the introduction of displays with ultra-high resolution raises issues about content and infrastructure (specifically, the bandwidth necessary to allow video streaming). PQM does not address these important considerations. That said, product developers might find some value in the metric's analysis, which concludes that ultra-high resolution does appear to improve consumers' perceptions of quality, up to about 4K, especially on larger (42-in. and above) displays.

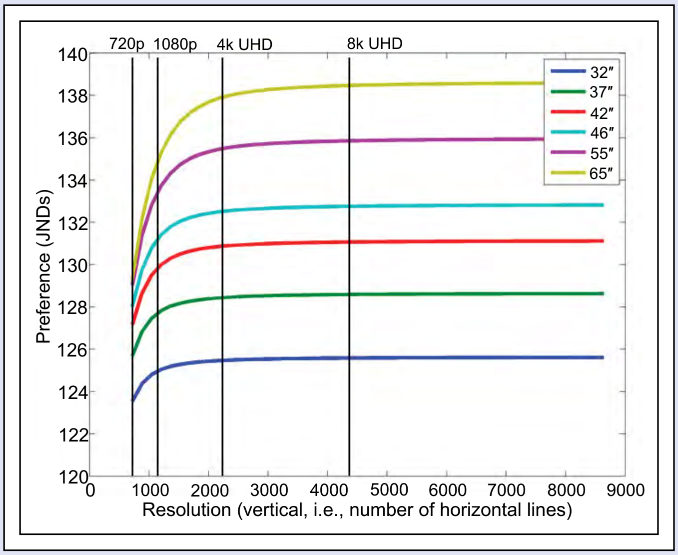

Fig. 6: At 300 cd/m² and a viewing distance of 9 ft., calculated improvement from 1080p to 4K creates a strong increase in perceptual quality of larger TVs. Improving resolution from 4K to 8K creates a measureable but much less powerful increase in perceptual quality.

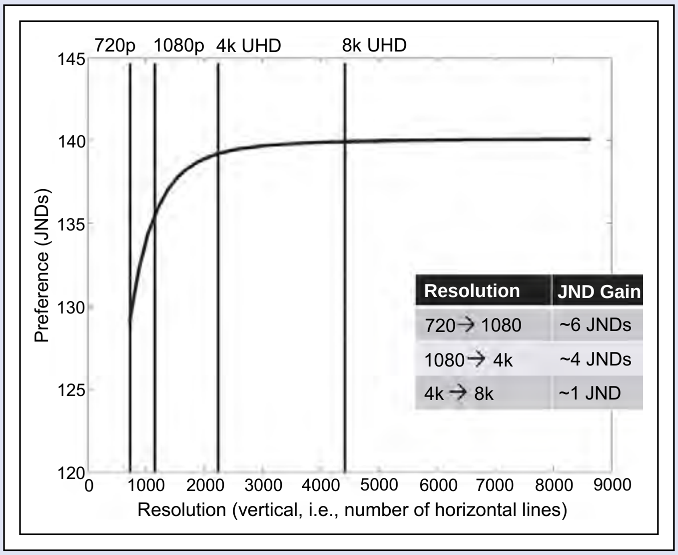

Fig. 7: At the recommended viewing distance (1.5 times the display's diagonal), the improvement from 1080p to 4K creates a strong increase in perceived quality. There is a measureable but considerably less powerful increase in perceived quality when the resolution improves from 4K to 8K.

tion. Models within each generation have significant differences in luminance and color gamut, but they achieve similar PQM values. The second-generation devices are particularly instructive. Here, the “D” and “E” devices attain the same PQM value with significantly different luminance and color gamut specifications.

PQM can also reveal when additional improvements in a performance attribute will produce little or no change in consumer perceptions of quality, when the attribute has been “maxed out.” For example, PQM analysis indicates that significant gains in the perception of quality can be achieved by upgrading resolution from 1080*p* to 4K. This was especially true when the display size increased and the viewing distance was held constant. The predicted benefit from upgrading to 8K was negligible, however, even for the 65-in. display. See, “PQM in Action: Is 4K Resolution Worth the Cost?”

Impact on Color Management and Content

PQM does not necessarily encourage the use of larger color gamuts. However, it does demonstrate that – if resolution and luminance are held constant – larger color gamuts will improve the perceived quality of the majority of consumer displays. It also suggests that higher gamuts can compensate for decreases in other performance attributes (such as luminance and resolution).

The authors believe that this demonstration of the power of color, combined with new enabling technologies (such as quantum dots), will lead to more displays that have the ability to express a larger color gamut.

This, in turn, will have repercussions for the display industry; two consequences seem obvious. First, a renewed emphasis on color management is likely. For years, many operating systems and programs have had insufficient or poorly implemented color management. Instead of interpreting the display’s color capabilities, these systems and programs have simply assumed that the display is capable of expressing colors that correspond to the sRGB gamut. Often, this generates images with undersaturated or skewed colors – a problem in any case but especially on retail websites where the images do not match the actual products. The weakness of this approach is exaggerated with high-gamut displays or with gamuts that are not approximately the same shape as sRGB. As higher gamut displays become increasingly common due to the continued growth of OLED and the emergence of quantum-dot-enabled LCDs, well-executed color management at the systems level becomes that much more critical.

Second, a heightened color gamut could influence content. Once content providers have the ability to use expansive color, they will be inclined to use it. Intuitively, one recognizes that heightened color is preferable

Supplementing PQM

PQM demonstrates how product developers can manage perceptions of quality as they alter performance characteristics. Final decisions on how those performance characteristics should be configured will usually be determined by the cost or technical capabilities of the manufacturer. And in some instances, the application – how and where the display will be used – can provide additional information that can supplement the PQM analysis and guide the configuration of luminance, color, size, and resolution.

This is particularly the case when the display is presented in a retail or other environment where viewer attention is crucial. Here, initial research shows, a display with a wider color gamut will receive more attention than a lower color gamut display.

In a pilot study conducted by 3M, five subjects were shown nine colored images. Each image was manipulated to produce four different color gamuts: standard RGB (sRGB), saturated green, saturated red, and saturated red and green. The four color gamuts for each image were displayed simultaneously for 1–3 sec to avoid scanning heuristics; placements were also varied to eliminate location artifacts.

Subjects’ eye movements were tracked and the time of fixation on each image was aggregated. During the 3-sec trial, as shown in Fig. 8, subjects fixated on the saturated green and saturated red and green images longer than the sRGB images. (Results of the one-second presentation showed a similar pattern in mean fixation duration.)

Given the sample size, it is difficult to draw detailed conclusions on the interaction between specific images and color gamuts. Also, the device used in this pilot study had a red primary that was only slightly more saturated than the sRGB standard, which likely had a negative impact on the “Saturated Red” test case.

Despite these limitations, the study has implications for product developers. It suggests, for example, that the perception of quality should not be the sole consideration when designing a display for use in digital signage. A display with a high color gamut will attract more attention (as reflected in longer fixation times) than a display with a lower color gamut. Likewise, the relationship between attention and color saturation should be considered by content developers as they choose the icons and images used in retail displays.

The authors are currently considering additional research, using a larger sample and more capable devices, which will be able to draw more detailed conclusions on the relationship between fixation time and color gamut.

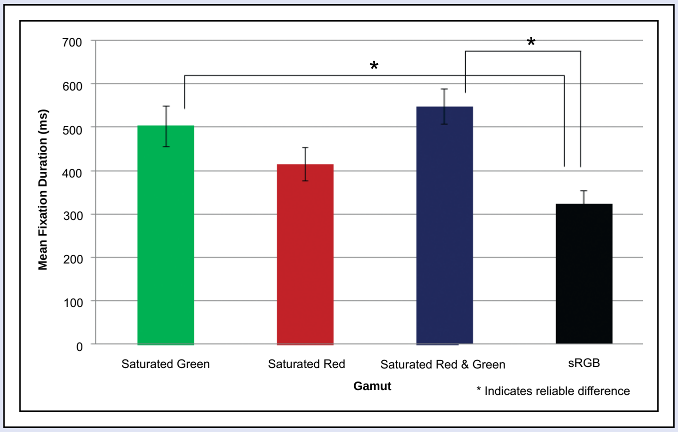

Fig. 8: *During a 3-sec trial, subjects fixated on the saturated green and saturated red and green images longer than the sRGB images.*

to a lower gamut. Initial research confirms this. A pilot eye-tracking research project by 3M suggests that content with a higher color gamut receives more attention (as measured by aggregated fixation or dwell time) than content with a lower color gamut. (See "Supplementing PQM.") This wider color gamut content could then make narrow gamut displays look even worse because the color encoding of the images is less saturated. For example, DCI-P3 content will not look as good on a 45% NTSC notebook as sRGB if color management is ignored.

This is not to say that content providers will feel compelled to use a wide color gamut – or color at all – in every circumstance. (Any art director who does not appreciate the power of black and white imagery should be compelled to study Walker Evans and re-watch *Casablanca*.) But once the tool of a higher color gamut is available, it will be used.

Additional impacts should become obvious as the model is refined and extended. Over the coming year, for example, the authors plan to expand the model by adding a measure of contrast. Further improvements could include accounting for the impact of changing specific gamut primaries as opposed to overall gamut size and a validation of the model for outdoor use and for video and animation. As of this writing, 3M is evaluating how to make PQM available to its partners and customers, as well as to the broader display industry.

References

[1]P. G. J. Barten, "The SQRI method: A new method for the evaluation of visible resolution on a display." *Proc. SID* **28**, 253–262 (1987).

[2]"The truth is, as nice as these TVs are, you probably will not see much difference. A 60-in. 4K will not look dramatically better than the 1080*p* TV you have in your home right now unless you shove your nose up against the screen. The average person's eyes cannot see the difference when sitting 10 ft. away from a 60-in. TV." http://www.wired.com/gadgetlab/2013/01/the-4k-push-ces-2013/

[3]See, also, "Why Ultra HD 4K TVs are still stupid," http://reviews.cnet.com/8301-33199_7-57566079-221/why-ultra-hd-4k-tvs-are-still-stupid/ ■

Shipments of AMOLED TV Panels Will Be Limited for the Next Few Years

Compared to LCDs, AMOLED TV panels will represent a small part of the total panel market in the years ahead, even as AMOLED TV panel production increases.

by Vinita Jakhanwal

ACTIVE-MATRIX organic light-emitting-diode (AMOLED) televisions have been appearing at consumer-electronics shows and are just entering the marketplace, but shipments of AMOLED TV panels will remain limited during the next few years, according to the Emerging Display Service at information and analytics provider IHS. AMOLED TV panel shipments are expected to climb to 1.7 million units in 2015, up from just 1600 units in 2013, as shown in Fig. 1.

While the jump in shipments appears phenomenally large, the total number of AMOLED panels by 2015 remains negligible compared to the vast number of liquid-crystal display (LCD) panels being shipped. As a result, AMOLED TV panel production, even as it increases, will make up a mere fraction of the total LCD panel market – expected to reach 266.3 million units in 2015 – in the years ahead.

The viewing public caught an eyeful of AMOLED TVs when they were featured prominently at the Consumer Electronics Shows in Las Vegas the last 2 years, with prototype models exhibited by leading manufacturers such as Samsung, LG, Panasonic, and Sony generating major excitement. As its name implies, AMOLEDs use organic materials that play a significant role when transforming electrical energy into light energy. AMOLEDs do not need additional backlighting, leading to displays with high contrast ratios, fast response times, thinner profiles, and the potential for better power efficiencies.

Korean manufacturers LG Display and Samsung Display are spearheading investments in research and development as well as manufacturing capacity to take AMOLED TVs from early technology demonstrations to market reality. However, limited availability – as well as the high retail pricing – of AMOLED TVs will likely restrict their shipments during the next few years. This article looks at how the different AMOLED panel makers – Samsung Display and LG Display, as well as Sony, Panasonic, and some other newer players – have approached the market and what their plans for the future may be (Fig. 2).

Vinita Jakhanwal is Director of Mobile & Emerging Displays and Technology for IHS. For media inquiries on this article, please contact Jonathan Cassell, Senior Manager, editorial, at jonathan.cassell@ihs.com. For non-media inquiries, please contact analyst.inquiry@isuppli.com. Learn more about this topic with the IHS iSuppli Display Materials & Systems service. For more information, please visit http://goo.gl/72n4S.

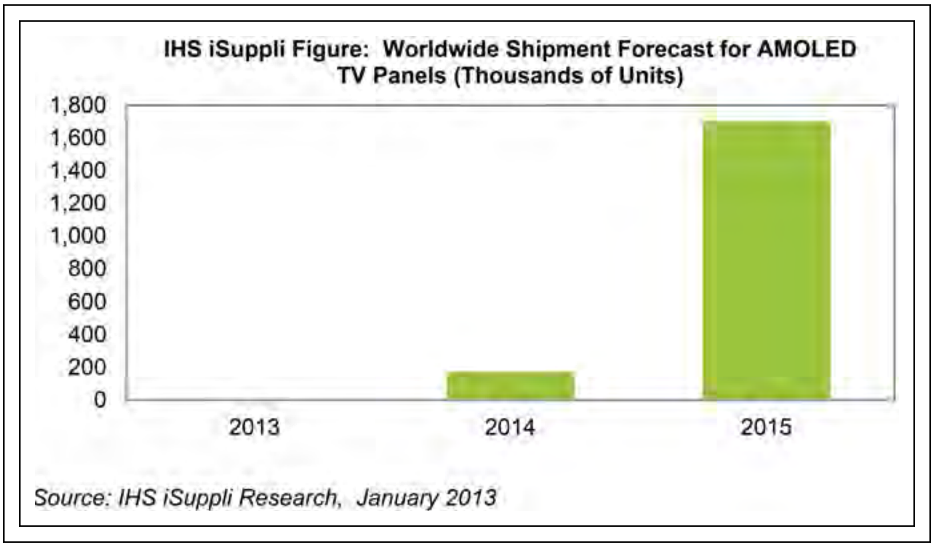

***Fig. 1:** AMOLED TV panel production will increase at an impressive rate between 2013 and 2015. Source: IHS.*

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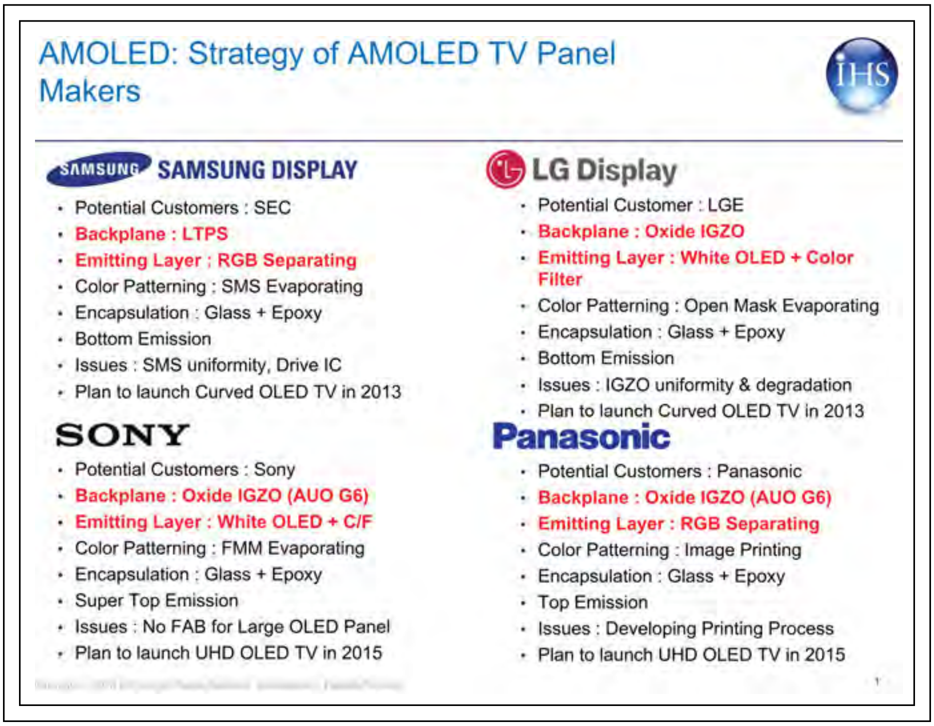

Fig. 2: AMOLED TV panel marketing strategies of the major manufacturers are compared above. (SEC = Samsung Electronics and LGE = LG Electronics.)

Samsung Display

AMOLED displays entered the commercial marketplace on a significant scale in 2007, when Samsung began mass-producing panels for smartphones and media players. Since then, Samsung Display has led the industry in capital investments and technology developments, with much-needed support coming from the Samsung Electronics handset design and development team.

In Q2 2011, Samsung started production of mobile handset displays at the AMOLED industry's first Gen 5.5 fab. The subsequent output helped the overall AMOLED market to reach the shipment volumes needed to support the large numbers required for the growing phone market. The increased panel shipments, the larger panel sizes (for smartphones), and technological advances such as on-cell touch that helped raise unit prices per panel, all contributed to more than doubling the total market value of AMOLED. At the end of 2012, AMOLED panels accounted for around 10% of the smartphone display market. With success in the smartphone market and associated achievements in improving yields and manufacturing costs, Samsung started focusing its efforts toward creating AMOLED panels in sizes suitable for TVs.

To create its AMOLED TV prototypes, Samsung used low-temperature polysilicon (LTPS) TFT backplanes, RGB OLEDs, and the evaporation method, similar to what the company had successfully been using in its smartphone displays. TV sets made with LTPS TFT backplanes and RGB OLED evaporation technology exhibit improved OLED performance, achieving much wider color gamuts and extremely high contrast ratios, it is generally agreed. But with low yields and high costs, Samsung may find it difficult to launch AMOLED TVs on a large scale in 2013 using these technologies. Samsung recently announced that it may be considering a white OLED with color-filter approach as well to help commercialize AMOLED TVs faster. For more about OLED TV manufacturing techniques, see the article "RGB Color Patterning for AMOLED TVs" in the March/April issue of *Information Display*.)

In terms of manufacturing preparation, Samsung's Gen 8.5 plan for TV mass production calls for two 8.5G lines to be set up in the second and third quarters of 2013, to be used for R&D purposes until the end of the year. The equipment will then be put into use for mass production in 2014, when Samsung begins making TV panels in earnest. Each equipment line will be capable of producing approximately 9000 panels per month.

LG Display

LG Display, which acquired Kodak's AMOLED patent portfolio in 2009, has also been supporting the AMOLED mobile handset market, using its Gen 4.5 fab mainly to manufacture displays for Nokia handsets. LG has been focusing on a white-OLED with color-filter TV panel process using both phosphorescent and fluorescent materials that could help ease the mass production of AMOLED TV panels as compared to the RGB approach. The process also uses oxide-TFT backplanes and an evaporation method, eliminating the need for fine-metal-mask technology in OLED production.

LG Display is currently speeding up its TV panel development and nearing completion of preparation for mass production, with partial production having begun in early 2013. The company is also focusing on making panels through a Gen 8.5 fab. LG Display recently announced a $650 million investment for a new Gen 8 line likely to start production in January 2014. Approximately 7000 panels per month are expected to be produced by LG starting in the second quarter. The company hopes to produce 75,000 AMOLED TV units annually.

Both Samsung and LG also unveiled their own curved 55-in. AMOLED TV prototypes at CES, with sets boasting a 4-m radius of curvature and full-HD resolution. The success of Samsung and LG in implementing a large-sized curved OLED was thought to be a meaningful achievement in the display industry. However, both companies still face challenges with mass production and market availability of curved OLED TVs is not a near-term possibility

Sony and Panasonic

Also showing AMOLED TVs alongside Samsung and LG this year at CES were Panasonic and Sony, which both unveiled 56-in. 4K (ultra-high definition or UHD) AMOLED TV prototypes. The sets boasted four times– hence 4K – the resolution of current 1080p televisions. For the 4K

AMOLED samples, both manufacturers used oxide-TFT backplanes, which should incur lower manufacturing costs than LTPS backplanes at some future time, when processes are perfected.

Back in 2007, Sony launched an 11-in. AMOLED TV based on RGB emitters at CES and then continued to produce this TV in small volumes for 5 years before discontinuing it by 2012 because of high manufacturing costs and low yields. To make the TV it showed at CES this year, Sony used evaporation technology to deposit organic material in its top-emitting white-OLED structure with a color filter. Sony's panel was provided by AUO of Taiwan in joint development efforts between the Japanese and Taiwanese partners. Sony's (top) emission technology optimizes the OLED structure, which helps achieve better light management, enhances color purity, and attains higher contrast at lower power-consumption levels. For its 56-in. 4K AMOLED TV at CES, Panasonic used the so-called "printing" method, a technology designed to make OLED production adaptable for a wider range of display sizes. (The details of Panasonic's "printing" method remain undisclosed at the moment.) At CES, AUO also introduced its own 32-in. AMOLED TV using an oxide-TFT backplane with a white-OLED structure.

Using different technological approaches, Sony and Panasonic were both able to make UHD 56-in. displays that reached 79 pixels per inch (ppi) –twice the density of the 55-in. FHD displays used in the OLED TVs from LG and Samsung. The latters' TVs are closer to mass production, however. LG and Samsung had positioned themselves to release large-sized AMOLED TVs at an earlier date than Sony or Panasonic. In Japan, Panasonic and Sony have started joint work to study how to make large-sized AMOLED panels on a commercial basis by using Panasonic's Himeji fab, but it is not certain if investing capital is being considered for a production line. Sony is currently producing 17- and 25-in. AMOLED monitor panels for the broadcasting industry.

Other Market Players

While the South Koreans appear to have a head start in AMOLED panel production, panel makers in China, Taiwan, and Japan are also hoping to enter the market. In China, backed by government support, most Chinese panel makers are looking at starting their own AMOLED business. Nonetheless, given the twin challenges of high costs and low yields associated with commercializing backplane and deposition processes, large-scale AMOLED production from China is unlikely anytime soon. Many Chinese panel makers – including CSOT from Shenzhen, Visionox from Kunshan, Tianma from Shanghai, BOE in Herfei, and CCO from Chengdu – all have announced investments and plans for AMOLED production, but none has materialized with immediate production.

For their part, panel makers from Taiwan are trying to achieve commercial success with as little investment as possible, as financially they cannot afford on their own to bring in new production equipment for AMOLED, LTPS, and oxide TFTs. AUO, which has facilities in Singapore and Linkou that are focused on producing small- and medium-sized AMOLED panels, failed to keep up with its plan to produce 4.3-in. AMOLED panels in the second quarter of 2012 – and then rescheduled production for the first half of this year. AUO's Lungtan facility will likely be used for producing AMOLED TV panels, however, with technological support from Sony in developing oxide-TFT backplanes to produce 32-in. OLED TVs beginning the second half of this year.

Yield Improvement and Cost Reduction Remain Barriers

While OLED TV makers all hope to become the acknowledged leaders in their space, more improvements in technology, materials, and manufacturing appear to be needed in order to bring large numbers of AMOLED TVs to the market. And, in addition to technical and large-volume manufacturing challenges, OLED TVs also face an uphill task of competing on prices with lower-priced, low-power, higher-resolution 4K LCDs and even FHD LCD TVs. By the time AMOLED TV production achieves efficiencies in large-scale production, LCD TVs will have had an opportunity to become even more competitive in price and performance. Despite the appearance of many promising AMOLED TV prototypes at CES, the number of challenges that still need to be addressed mean that most consumers are likely to wait a few more years before they buy their AMOLED TVs. ■


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Products on Display at Display Week 2013

Some of the products on display at North America's largest electronic-display exhibition are previewed.

by The Editorial Staff

THE SID 2013 International Symposium, Seminar, and Exhibition (Display Week 2013) will be held at the Vancouver Convention Centre in Vancouver, Canada, the week of May 19. For 3 days, May 21–23, leading manufacturers will present the latest displays, display components, and display systems. To present a preview of the show, we invited the exhibitors to highlight their offerings. The following is based on their responses.

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Rancho Cucamonga, CA (909) 980-1310
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Intelligent Displays

AMP Display will feature a DWIN Intelligent display that allows for interface design with minimal programming and increases time-to-market speeds through the following advantages:

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- Extreme response speed of refresh time to meet users' real-time requirements.
- DGUS can achieve RTC display capabilities: up/down and zoom-in/out of curve as well as icon/images recycles automatic play with no involvement of MCU code.
- Users can choose to modify the display format during the operation process.

CIMA NANOTECH

St. Paul, MN 651/646-6266
www.cimananotech.com
Booth 1131

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Cima NanoTech's SANTE™ FS200 Series Touch Films enable faster-response lower-cost large-format multi-touch displays. SANTE™ Technology is a proprietary silver nanoparticle coating that self-aligns into a transparent ultra-conductive network. SANTE™ FS200 Touch Films provide outstanding electrical conductivity with surface resistance of less than 25 Ω/sq. and excellent light transmission of up to 88%. With the lower resistance and higher current-carrying capacity of the SANTE™ Network, the overall cost of the touch module is reduced through cost savings on IC chips, materials and processing.

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DELO INDUSTRIAL ADHESIVES

Sudbury, MA (978) 254-5275
www.DELO.us
Booth 539

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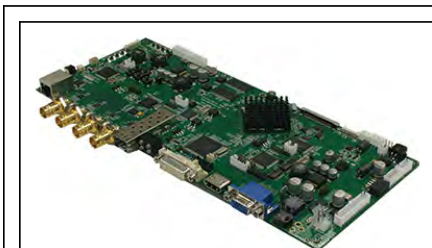
adhesion and durability with high transparency. They enable a fast and flexible bonding of touch panels or cover glasses directly onto LCDs. Thanks to their dual-curing capability they do not only cure by exposure to UV or visible light. In shadow areas, *e.g.,* under black masks, they reliably cure by means of a second curing mechanism through a reaction with moisture in the air. DELO's optically clear adhesives drastically reduce internal reflections and improve the shock and vibration performance. Furthermore, fogging, condensation, or other contaminations are avoided.

DIGITAL VIEW

Morgan Hill, CA (408) 782-7773
www.digitalview.com
Booth 732

LCD Controller

Digital View will introduce the SVX-1920-SDI LCD controller at Display Week 2013. This single-board high-integration platform provides a range of industry-standard interfaces, including VGA, DVI, and HDMI. It also supports dual-channel 3G HD-SDI and includes a built-in SFP optical interface. The SVX-1920-SDI incorporates advanced features that come standard on Digital View controllers, while including comprehensive control via the RS232 interface and an update network interface that supports 100-MB rates. The SVX-1920-SDI is ready to address applications for broadcast, post-production, security, and other segments requiring multi-interface support.



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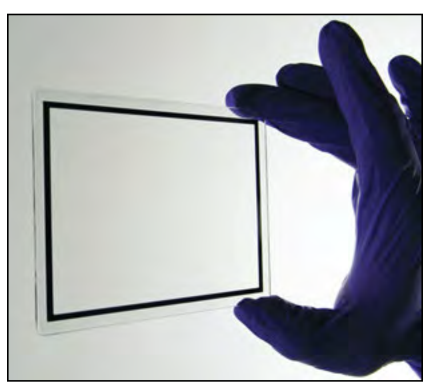
Booth 939

Dielectrically Enhanced ITO Coatings

Utilizing the latest in thin-film vacuum-deposition technology, Dontech's CAR-Series™ and VC1-IM-Series™ index-matched ITO coatings on glass filters provide exceptional optical and electrically conductive properties. Dontech's precision glass optical filters are utilized in demanding military, medical, industrial, and avionics applications. For high-end display programs, CAR-Series™ are index-matched to air and VC1-IM-Series™ are index-matched to lamination to optimize display contrast (*e.g.*, sunlight readability) while providing EMI/RFI shielding and/or transparent heating. These filters can be fabricated from a variety of glass substrates, such as chemically strengthened (soda lime, Corning® Gorilla®, Asahi Dragontrail™), borosilicate, fused silica, and optical glasses (*e.g.*, Schott nBk-7). Options include low photopic reflections and tight-tolerance resistances. Standard AR coating reflections are as low as 0.1%, the CAR-Series are at 0.4%, and the VC1-IM Series ITO resistances range from less than 1 to 300 Ω/sq.



ELECTRONIC ASSEMBLY

Gilching, Germany +49-8105-77-80-90
www.lcd-module.de
Booth 1211

Evaluation Kit for Intelligent Displays

With its rich feature set, the EA eDIPTFT57-A intelligent display from Electronic Assembly is the ideal choice for implementation of interactive control in mechanical engineering and industrial electronics applications. The high-contrast color screen, which measures 5.7 in. on the diagonal, has LED background illumination and a resolution of 640 × 480 pixels. Its most important feature, however, is the built-in intelligence which greatly facilitates integration of the display modules into the application. The Evaluation Kit, which is tailored specifically to this display, makes development work even easier. Electronic Assembly supplies the kit to speed up the commissioning process and facilitate familiarization with the world of intelligent displays. It includes everything needed to get started including an evaluation/programmer board, EA eDIPTFT57-ATP color display, USB cable, touch panel, plug-top power supply (with international adapters), and a mini-DVD containing software, documentation and sample macros.

ELLSWORTH ADHESIVES

Germantown, WI 1-800-888-0698
www.ellsworth.com
Booth 541

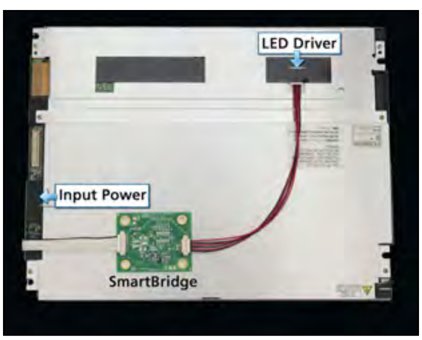
Adhesives

Ellsworth adhesives provide low-pressure molding contract manufacturing services, combining the superior performance of Henkel Macromelt thermoplastic encapsulants with the versatility of a Mold-Man™ 8000 low-pressure injection molding system from Cavist Manufacturing. Electronic overmolding is a unique process which helps to dramatically reduce costs, provide a simple one-step molding alternative, and deliver measurable improvements in manufacturing efficiency. It is ideal for low-to-high volume production quantities. This system controls volume and pressure independent of each other providing the flexibility to over-mold complex circuit boards and connectors.

ENDICOTT RESEARCH GROUP (ERG)
Endicott, NY 607/754-9187
www.ergpower.com
Booth 508

CCFL to LED Driver Connectivity

ERG's Smart Bridge modules enable quick, easy integration of a replacement OEM LED display into an existing CCFL design with one simple swap. Remove the inverter, plug in the footprint-compatible Smart Bridge module, and connect the input cable from the existing power supply or controller to the Smart Bridge. The Smart Bridge module converts the Power · Ground · Enable · Control signals and mates directly to the LCD via a small harness, powering the new backlight driver correctly. This avoids the time-consuming and expensive alternative of system re-design. Available in 5-, 12-, and 24-V modules.



EPOXY TECHNOLOGY
Billerica, MA (978) 667-3805
www.epotek.com
Booth 1035

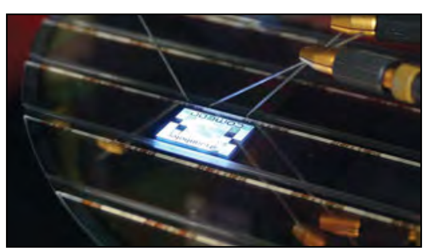
UV Curiable Adhesives

Epoxy Technology (EPO-TEK®), a leading manufacturer of specialty adhesives offers unique UV curable adhesives for display applications, especially EPO-TEK OG116-31. This thixotropic product is designed for perimeter and plug seals of LCDs and is compatible with several liquid crystals. EPO-TEK OG116-31 is a robust material with low WVTR, able to be thermally post-cured for enhanced properties. Epoxy Technology provides a comprehensive line of specialty adhesives for display applications including OLED, ITO to PCB, gasket seal of LCD glass to glass, glob top, die attach of LCD to PCB, and laminating optical glass plates.

FRAUNHOFER COMEDD
Dresden, Germany +49-3-51-88-23-0
www.comedd.fraunhofer.de
Booth 1209

Color-Filter-Less Full-Color OLED Microdisplays

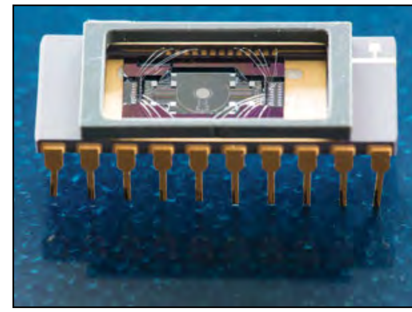
Fraunhofer COMEDD and VON ARDENNE will present color-filter-less full-color OLED microdisplay technology will introduce this technology at Display Week 2013 for the first time.



FRAUNHOFER IPMS
Dresden, Germany +49-3-51-88-23-238
www.ipms.fraunhofer.de
Booth 1209

Laser Scanning Projectors

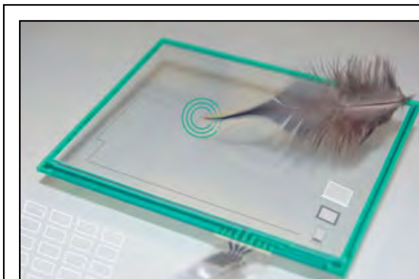
Fraunhofer IPMS will be demonstrating laser scanning projectors based on its own silicon micro scanning mirrors. Both resonant mirrors that perform a continuous sinusoidal movement around one or two axes and quasi-static scanners that move linearly in one axis or steer light at a certain direction are available. All MEMS devices are fabricated in medium quantities at Fraunhofer IPMS' own 1500-m^2 silicon clean room. In addition, FPIMS is offering complete system designs for laser projection systems, including laser integration, optics design, driving electronics, and software. The demonstrator that will be shown at Display Week 2013 features the full range of development capabilities.



FUJITSU COMPONENTS AMERICA, INC.
Sunnyvale, CA (408) 745-4900
www.usfujitsu.com/components
Booth 928

4-Wire Resistive Touch Panels

Fujitsu Components America is highlighting its new high-clarity Feather Touch 4-wire resistive touch panels. Due to advances in Fujitsu's materials and process engineering, these panels allow sharper images when used with high-resolution LCDs. Sizes include 3.5 in. up to 17 in. in 4 × 3 aspect ratio, with wide formats (16 × 9) also available. Feather Touch Panels have a proprietary top film that responds to 0.02–0.3N input force to enable pinch, expand, rotate, and flick/swipe gesturing with multiple input options, including finger, passive stylus, glove, *etc.* Specifications include 82–90% transparency and a –5 to 60°C operating temperature with 1 million finger input operations (minimum) guaranteed performance.



FUTABA CORPORATION OF AMERICA

Plymouth, MI (734) 459-1177
www.futaba.com
Booth 545

OLED Displays

Futaba Corporation of America will feature 3.5-in. OLED high-resolution (228 × 168 dots) monochrome (white) displays with an active area of 70.7 × 52.1 mm, pixel pitch of 0.31 × 0.31mm, luminance of 300 cd/m^2 , 16 gray scales, and parallel Interface parallel.

GOOCH AND HOUSEGO

Orlando, FL (407) 422-3171 x206
www.goochandhousego.com
Booth 940

Customizable Display Measurement System

With the OL 770-ADMS, fast, precise and customizable display measurements are easy and at your fingertips! This modular, motion-controlled platform is suitable for a variety of automated measurement applications, including display testing. The system features our OL 770 High-Speed Multichannel Spectroradiometer making for a complete, robust, and flexible tool. The motion system is expandable up to five axes (x, y, z, horizontal, and vertical). Powerful software allows users to create scripted automation and even the integration of other measurement tools for fully automated parameter testing.

HENKEL

Rocky Hill, CT (860) 571-5128
www.henkelna.com
Booth 431

Liquid Optically Clear Adhesives

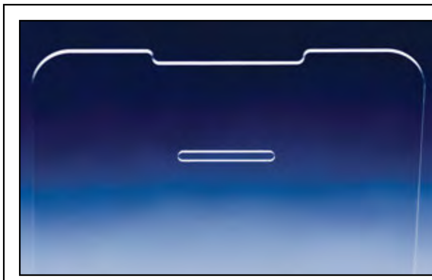
When direct bonding LCDs, liquid optically clear adhesives (LOCAs) remain uncured in shadowed areas behind ink patterns. Side, heat, and moisture curing can help, but have limitations. Henkel's groundbreaking Loctite® 3196PR LOCA cures on exposure to primer Loctite® 7389. A fast, simple, low-cost process applies the primer to shadowed areas with a felt pad. The adhesive cures rapidly when it contacts the primer – typically in 1–2 hours at room temperature. Loctite 3196PR is complementary to Loctite 3196, currently used in mass produced displays ranging from mobile phones to monitors.

INNOLAS SYSTEMS GmbH

Krailling, Germany +49-89-899-4828
www.innolas-systems.com
Booth 1302

Laser-Cutting Process

Chemically strengthened glass has become a must-have for advanced smart phones, tablets, and other portable electronics. It offers superior hardness and scratch resistance, but it presents challenges in production. The thicker the chemically strengthened layer, the more difficult it becomes to cut the glass with conventional methods. The InnoLas laser cutting process allows the cutting of chemically strengthened glass with a layer thickness of up to 100 µm, requiring no or little post processing. Additionally, this unique InnoLas glass cutting process allows a high-quality drilling and cutting of inner contours and features (*e.g.,* holes or slots) into chemically strengthened glass with a DOL of 40 µm and above, without chipping, micro cracks and breakouts.



INNOLUX CORPORATION

Miaoli, Taiwan +886-37-586393 #21
www.chimei-innolux.com
Booth 412

Touch-on-Display Technology

Innolux will feature its innovated Touch-on-Display (TOD™) technology that enables multitouch sensitivity all the way to the edges of the screen on different display platforms including smartphones, DSCs, AV, and tablets) at high resolution. Innolux's innovated TOD™ technology does not add to the thickness of the LCM module, does not complicate display production, provides better CG strength/protection, and does not need to be synced to the display.

INSTRUMENT SYSTEMS GmbH

Muenchen, Germany +49-89-454943-23
www.instrumentsystems.com
Booth 1120

Display Measurement System

The DMS 803 from Instrument Systems offers optimum convenience for angle-dependent analysis of electro-optical characteristics of small- to mid-sized displays. The measurement system is based on a fully motorized 6-axis goniometer for determining luminance, contrast, and color properties at different viewing angles and variable electrical driving. It is perfectly suitable for all applications in research and development, as well as quality control. The DMS 803 is ideal for determining the characteristics of displays for mobile applications (smartphone, tablet PC) with a comprehensive range of illumination devices and temperature-controlled chambers.

I-PEX

Austin, TX (512) 339-4739
www.i-pex.com
Booth 934

Single Outline Connectors

I-PEX by Dai-Ichi Seiko, Ltd., will feature the EvaFlex®5-VS for shielded FFC/FPC. High-bit-rate differential signal transmission carried by 100-Ω-differential-impedance single-sided-shielded FFC conductors have been tested at 6 GT/sec. They have an audible insertion click and tactile feedback. The contact design is unique, the W (2-point) contact and the locking features a high retention force. The PCB pad layout for the EvaFlex5-VS is same as that for the VESA® 16:9 NB panel connector Cabline®-VS. The number of positions available is 10p – 50p.

KONICA-MINOLTA SENSING AMERICAS

Ramsey, NJ (201) 818-3574
www.sensing.konicaminolta.us
Booth 1124

2D Color Analyzer

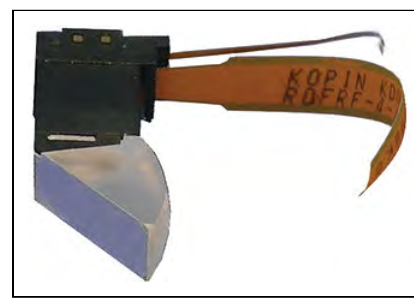
The CA-2500 2D Color Analyzer is used for high-resolution two-dimensional measurements of luminance and chromaticity in displays. It is ideal for the evaluation and inspection of a variety of display technologies such as smartphones and tablet PCs. It uses XYZ filters that closely match the CIE 1931 color-matching functions to provide luminance and chromaticity measurements that have high correlation with the spectral response of the human eye. The low-luminance measurement range has improved from 0.1 to 0.05 cd/m^2. The service-life measurement cycles have increased to approximately five times that of the CA-2000, which makes it applicable for use in production areas.

KOPIN CORP.

Westborough, MA (508) 870-5959
www.kopin.com
Booth 1307

Compact Display Module

Kopin will feature White Pearl™, a compact display module (28.7 × 12.9 × 8 mm) designed for emerging wearable computing/communications devices. Integrating a transmissive LCD (428 × 240 resolution, 0.2-in/ on the diagonal), efficient backlight, and precision optics, White Pearl provides a bright full-color image with less than 0.2% distortion in a 15° field of view with a comfortably large eye box (8 mm) and eye relief (25 mm). White Pearl and Kopin's A230 display-driver ASIC consume less than 100 mW at a display brightness of 1000 nits, sufficient for outdoor usage. A frame-buffer memory residing in the ASIC can further save system power consumption.



KYOCERA DISPLAY DIVISION

Plymouth, MI (734) 416-8500
www.kyocera-display.com
Booth 733

Industrial and Automotive TFT-LCDs

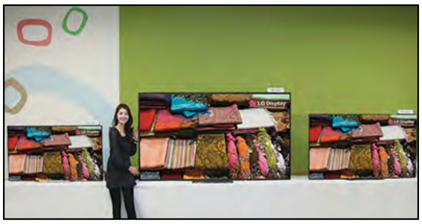
Kyocera Display Division will introduce seven new TFT-LCDs for the industrial and automotive display markets. These new products feature advanced wide-viewing technology, super high brightness, and many other exciting features. Advanced Wide-Viewing technology delivers true color (no gray inversion) from any angle and provides the best optical performance. The product is developed using high-efficiency long-lifetime LED backlighting solutions in both standard bright and high bright (1200 nit) versions. Other features include touch-screen options, built-in LED driver control, wide temperature range, *etc.*

LG DISPLAY CO., LTD.

Seoul, Korea +82-2-3777-1022
www.lgdisplay.com
Booth 1012

Full Line of Ultra-High-Definition Displays

LG Display will unveil the world's first full lineup of Ultra-High-Definition (UHD) displays in 84-, 65-, and 55-in. sizes at Display Week 2013, featuring 4× higher resolution than Full-HD displays with 8.3 million pixels and utilizing innovative IPS technology for superior picture quality at wide viewing angles which is critical for larger-sized displays. The panels also adopt LG Display's acclaimed FPR 3D technology for remarkable 3D quality with no flicker, high luminance, comfortable glasses, and minimal cross talk. As higher resolutions become mandatory for larger TVs, LG Display's UHD panels truly are setting the standard for this class of displays.



McSCIENCE, Inc.

Suwon, Korea +82-(0)-31-206-8009
www.mcscience.com
Booth 723

OLED Display Test System

McScience will exhibit its M7000 OLED Display Test System that features:

- Multichannel lifetime and IVL measurement system
- Individual temperature control
- Electrical/optical test of OLED cell/panel/module
- Optical test : luminance, chromaticity, spectrum, CCT, CRI
- Display test: Contrast ratio, gamma, uniformity, cross talk, image sticking
- Quality test : Response time, flicker, pixel quality, dark spot

MDI SCHOTT ADVANCED PROCESSING GmbH

Mainz, Germany, +49-(0)-6131-7321
www.mdischott-ap.com
Booth 1205

Ultra-Thin-Glass Laser Cutting

MDI Schott will feature laser glass-cutting machines for Gen 2 (pictured) up to Gen 5 and larger. Glass cutting solutions are available for glass thicknesses from 30 to 300 µm, featuring easy glass handling due to cutting by CO_2 lasers without microcracks. The edge strength is about 3–4 times higher than a conventional high-quality score-wheel cut! This technology enables the jump from labor samples to industrial production.

nTACT/FAS

Dallas, TX (214) 673-6423
www.ntact.com
Booth 641

Slot Die Coating Systems

The nRad line is a series of small, low priced, slot die coating systems built upon nTact's patented technology and engineered for use in R&D and pre-production environments. The nRad's simple yet flexible design provides accurate deposition of a wide range of materials for a variety of applications. The systems are compatible with inert gas gloveboxes and laboratory benchtops. The nRad is designed for processing 150 and 200-mm square substrates, with options for wafers up to 200 mm or panels up to A4 size. The new nRad2 is available for substrates up to 370 × 470 mm, as well as 300-mm wafers.

OCULAR

Dallas, TX (214) 635-1920
www.ocularcd.com
Booth 1221

Projected-Capacitive Touch Panels

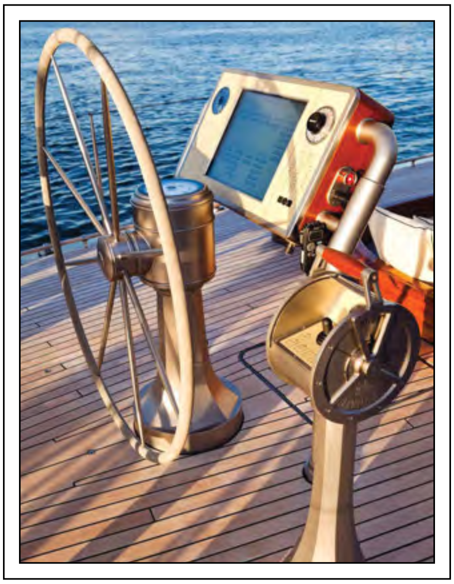
Ocular's Crystal Touch projected-capacitive touch panels are now available in custom designs that are specifically tailored for outdoor applications. The sun can cause birefringence, *i.e.*, a "rainbow effect," on a touch panel. Users wearing polarized sunglasses are impacted the most by birefringence, which significantly impacts display clarity and viewability. Ocular touch panels designed for outdoor use are constructed to eliminate birefringence without the use of special coatings, which reduce sensor durability.

OPTICAL FILTERS

Meadville, PA (814) 333-2222
www.opticalfiltersusa.com
Booth 616

Projective-Capacitive Touch-Screen Enhancements

Optical Filters has expanded its range of touch-screen enhancements to compliment the growing requirements of projective-capacitive touch-screen technology. Using class-100 clean rooms, Optical Filters offers the integration of cosmetic cover glass and plastic with the capability to add high-quality printed borders where required. Proven bonding capabilities include full optical bonding to LCDs together with both dry-film and PSA lamination. Light-control options for privacy filters and controlled viewing angles at 180° and 360° can be used on their own or combined with coatings and micro-replicated meshes for the best in emi-shielding and optical performance. For operation in extremely cold conditions, transparent heaters may be used on their own or combined with any of the technologies above for a multi-functional solution.



POLYIC GmbH & CO. KG

Bava, Germany +49-911-20249-0
www.polyic.com
Booth 1310

Transparent Conductive Films

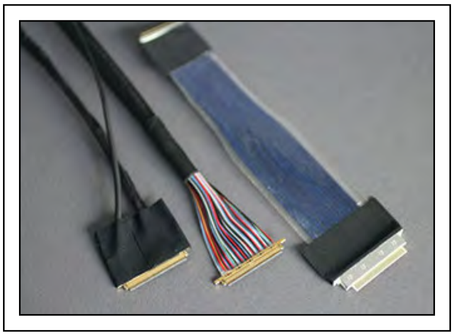
PolyTC® films are transparent conductive films for touch sensors, displays, and EMI protection and can be used for electrodes or electrical heating elements. A PolyTC® film consists of thin metal layers on a plastic film [usually polyester (PET)]. It is produced in a roll-to-roll process with a minimum structure size in the micrometer range. They are ideal in applications where high transparency and high electrical surface conductivity are needed. In many applications, PolyTC® films replace the widely used indium tin oxide (ITO). Applications of PolyTC® include touch screens, touch controls, EMI shielding, transparent heating films, and electrodes (*e.g.,* for displays or photovoltaics). Further applications includes ESD security or high-resolution flexible circuits.

QUADRANGLE PRODUCTS

Englishtown, NJ (732) 792-8035
www.quadrangleproducts.com
Booth 313

Small-Gauge Coaxial and Discrete Twisted-Pair Micro Coaxial Cables

Quadrangle Products supports Micro Coaxial Cable assemblies and interconnects for panels, motherboards, and other various components. Many of these connectors are found on LVDS devices such as LCDs (LG, Samsung, AUO, *etc.*) and embedded motherboards (most notably Intel DH61AG, DQ77KB, DN2800MT, and D2500CC). Micro-Coax-connector-based cables can be made by using both Micro Coaxial wire and Discrete Twisted-Pair construction. Quadrangle's engineers can help to guide customers through the various design and construction challenges that can be associated with micro coax cables and micro-coax-based transitions.



RADIANT ZEMAX

Redmond, WA (425) 844-5894
www.radiantzemax.com
Booth 844

Imaging Colorimeters

Radiant Zemax with feature the The ProMetric® I, next-generation imaging colorimeters optimized for automated visual inspection in high-volume manufacturing of flat-panel displays (FPDs), FPD subsystems, and illuminated keypads. The ProMetric I uses a high-resolution high-speed CCD sensor to enable more thorough and complete testing, without impacting production throughput. ProMetric I is built on a highly reliable, proven platform and incorporates features such as Ethernet and on-board calibration that is ideally suited for a manufacturing environment. ProMetric I is available in two configurations with scientific-grade thermoelectrically cooled 8- or 16-Mpixel CCD sensors.

SAN TECHNOLOGY, INC.

San Diego, CA (858) 278-7300
www.santechnology.com
Booth 220

Optical Bonding Service

Santek provides an optical bonding service with a unique material called Opt Alpha Gel, which is applied in between touch panel and LCD, or protective panel. Opt Alpha Gel improves the visibility of display by decreasing outside light reflection and LCD surface reflection. Also, a higher luminance is obtained by decreasing the reflection from the LCD. In addition, the softness of the gel improves the shock resistance and stress release of an LCD. Also, Opt Alpha Gel has flexible workability compared to that of other materials, and it's re-workable!

SARTOMER USA, LLC

Exton, PA (610) 363-4100
www.sartomer.com
Booth 1132

Curable Resins

The CN4000 series of oleophobic exterior-grade ultraviolet and electron-beam-energy curable resins provide excellent protection for polyester, polycarbonate, and acrylic films. Accelerated weathering testing proves the materials can take the abuse of a wide range of climates for top-coating highly transparent films and glass. The low refractive index provides anti-reflective properties for inter-layer coating or adhesive, reducing the loss of light transmission between layers and the top coated surfaces while maintaining excellent physical and color stability.

SEEFRONT GmbH

Hamburg, Germany +49-(0)-40-416-22-64-80
www.seefront.com
Booth 916

3D Autostereoscopic Display

SeeFront's first hardware product, its 3D autostereoscopic 23-in. display, will be launched at Display Week. SeeFront focuses on delivering the best possible 3D image quality for a single user. SeeFront's glasses-free 3D technology allows the user to move in all directions. The 23-in. display component can be integrated in customer-specific settings. With housing, it can be used as a monitor or even as an all-in-one PC. Also available with and without an integrated touch screen. The stereo camera for eye-position tracking is also integrated. It utilizes a lenticular optical filter and has an LCD panel resolution of 1920 × 1080.

SEVASA

Barcelona, Spain +34-938-280-333
www.sevasa.com
Booth 1333

Anti-Glare Glass for High-Definition Displays

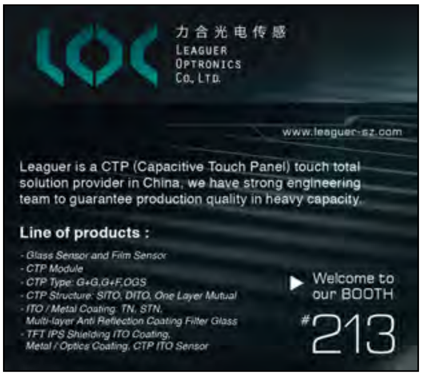
HapticGlas®, a new anti-glare glass line for HD displays launched by acid-etch specialist Sevasa, will be featured at Display Week. This non-glare micro-etched passive-haptic glass surface provides exceptional tactile feedback, reducing fingerprints and increasing scratch resistance – all at the largest-sized format [up to 225 × 321 cm (88 × 126 in.)]. HapticGlas is ideal for high-resolution applications, requiring no sparkle and low haze with no maintenance and high durability, such as multi-touch walls and tables, HD displays, digital signage, ATMs, point-of-sale, and outdoor applications. Sevasa's unique know-how comes from 30 years of specializing in acid-etching technical glass, including Environmental ISO 14001 and Quality ISO 9001 certifications.

SHENZHEN LEAGUER OPTRONICS CO.

Shenzhen, China +86-755-863-07270
www.leaguer-sz.com
Booth 213

Lamonation Process

Shenzhen Leaguer Optronics specializes in OCA and LOCA technology and performs innovative research and development that has lead to a variety of patents on glass-type or TP-on-LCM (hard to hard fit), film type (soft to hard fit), all-in-one type (explosion-proof film laminating), 3D fitting, shaped fit, *etc*. Shenzhen Leaguer Optronics has mastered the best module lamination process.

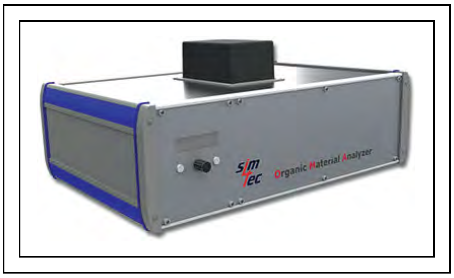


sim4tec GmbH

Dresden, Germany +49-(0)-351-4466499
www.sim4tec.com
Booth 1202

Organic Material Analyzer

sim4tec's Organic Material Analyzer (OMA) is a breakthrough in the analysis of any organic material serving the organic and printed electronics industry. The instrument measures with highest accuracy the current–voltage characteristics (I–V) of any organic material sample in a wide temperature range under vacuum conditions. The OMA calculates with superior mathematical algorithms all important electrical material parameters (*e.g.*, HOMO, LUMO, mobilities, and traps) based on the precisely measured I–V data. The tool can be used for characterization and quality control of organic materials in R&D or production environment throughout the entire organic electronics industry value chain.

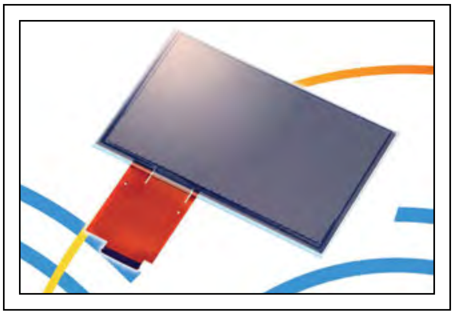


SMK ELECTRONICS CORP.
Chula Vista, CA (619) 216-6477
www.smkusa.com
Booth 1139

Projected-Capacitive Touch Panel

SMK introduces its latest projected-capacitive touch panel that meets a demand for multi-touch operations for automotive navigation systems and consoles. Its navigate multi-touch, flick, scrolling, and drag-and-drop functions operate with ease. Features include:

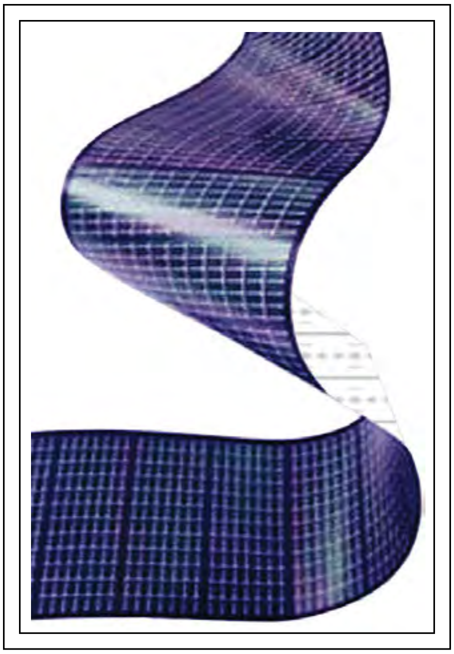
- Meets automotive high-heat operating and storage-temperature requirements
- Reflectance as low as 1.5% for improved visibility under direct sunlight
- Feather-light touch operations
- Display size of up to 10 in.
- Simultaneous input with all 10 fingers
- Operating temperature: –30 to +85°C
- Storage temperature: –40 to +95°C
- Typical transparency: 90% maximum
- Typical reflectance: 1.5% minimum
- Input force: Zero N



TFD, INC.
Anaheim, CA (714) 630-7127
www.tfdinc.com
Booth 727

Highly Transparent Conductor and Barrier Coating for Flexible Displays: OLED and OPV

TFD has developed a highly conductive film by using an engraved nanoparticle scheme with Ni:Ag:Cu materials, producing ≤ 0.5 Ω/sq. with a transmission of 92% for a range of 400–2500 nm. This economical process results in lower costs than that of traditional TCOs, *i.e.*, ITO. Offered in both glass and plastic films, *i.e.,* PET and PEN, which are coated with a superb barrier coating on both sides of the substrate and meets and exceeds less than 1×10^{-5} gm–m^2/day. This is a non-ITO coating material which is ideal for the mass production of OLED lighting and OPV large formats.



TIANMA MICROELECTRONICS
Chino, CA (909) 590-5833
www.tianma.com
Booth 206,221

TFT High-Definition Display

TIANMA will highlight one of its hottest products this year, the TL045JDXP01, a new 4.5-in. TFT-HD (720 × 1280) with an LED backlight, narrow bezel, and slim design. This is a high-quality display suitable for mobile application and similar products.

UICO
Elmhurst, IL (855) 387-2682
www.UICO.com
Booth 326

Touch Screens

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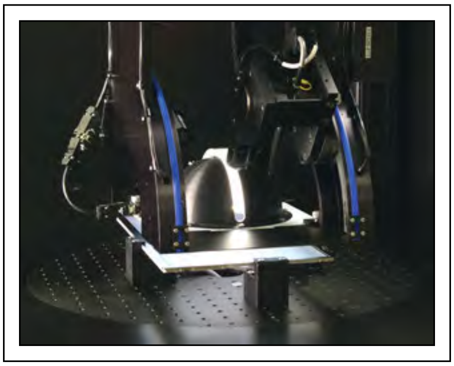


Winning *JSID* Outstanding Student Paper Describes Solution-Processed Metal Oxide on Flexible Foil

by Jan Genoe and Jenny Donelan

The current flat-panel active-matrix organic light-emitting-diode (AMOLED) display market is dominated by low-temperature polysilicon (LTPS) backplane technology on rigid glass plates. LTPS as a backplane for larger display sizes, such as TVs, has some drawbacks. The excimer laser used for LTPS does not scale to larger sizes. LTPS is fairly costly to implement and also requires relatively high processing temperatures (>300°C). These temperatures limit the integration of LTPS directly onto desirable, lighter weight substrates such as flexible foil or plastic, which degrade in high heat.

In order to create a backplane technology that could accommodate fabrication on flexible foil at a low post-annealing temperature, a multidisciplinary, cross-organizational student research team from Europe demonstrated the use of high-performance solution-based n-type metal-oxide thin-film-transistors (TFTs). These were fabricated directly on polyimide foil at a post-annealing temperature of only 250°C. This work, as detailed in the paper, "Solution-processed and low-temperature metal oxide n-channel thin-film transistors and low-voltage complementary circuitry on large-area flexible polyimide foil," appeared in the October 2012 issue of the *Journal of the SID*, earning its authors the award for the JSID Outstanding Student Paper of 2012.

The team consisted of Maarten Rockelé, Duy-Yu Pham, Jürgen Steiger, Silviu Botnaras, Dennis Weber, Jan Vanfleteren, Tom Sterken, Dieter Cuypers, Soeren Steudel, Kris Myny, Sarah Schols, Bas van der Putten, Jan Genoe, and Paul Heremans. Members hailed from institutions including the research center IMEC in Belgium, specialty chemical manufacturer Evonik DeGussa GmbH in Germany, Katholieke Universiteit Leuven and Universiteit Gent in Belgium, and the independent research entity the Holst Center in The Netherlands.

Developing and Executing the Idea

This research group had already been working for more than 10 years on the topic of thin-film electronics on foil, explains Genoe. "We first started exploring RFID tags using pentacene as an organic p-type semiconductor," he says. "In parallel, we started exploring n-type semiconductors on flexible foil, both organic and oxide n-type semiconductors. When n- and p-type semiconductors became available, it was clear that an attempt could be made to merge both in order to yield a CMOS (complementary metal-oxide semiconductor) technology with superior performance." He adds that the approach described in the paper, together with Evonik's work as part of the EU-financed R&D project ORICLA (formed to develop RFID tags based on hybrid organic-oxide complementary thin-film technology), is among several parallel tracks the team has been investigating.

The authors were also intrigued by recent research on metal-oxide semiconductors processed from solution (as opposed to methods such as vacuum sputtering). Advanced solution-processing techniques like printing promised to enable simple, inexpensive, high throughput. However, the annealing temperature required to convert soluble precursors into semiconductor oxide films was still in the 300–500°C range and hence difficult to process on foil.

The researchers succeeded in fabricating spin-coated indium-based oxide n-type TFTs at annealing temperatures as low as 250°C. These n-type TFTs were processed directly on top of polyimide foil, resulting in high-performance (saturation mobilities exceeding 2 cm^2/V-sec) and low-voltage flexible uni-polar digital circuitry. To make the flexible line-drive circuitry more robust, a hybrid complementary inorganic–organic technology was developed. The hybrid technology was further optimized and for the first time transferred to a flexible substrate, the polyimide foil.

The authors claim that both in terms of stability and speed, this hybrid complementary technology is directly applicable for complex digital circuitry, such as the line-drive circuitry of future rollable AMOLED displays, for which it can be easily embedded at the borders of the display. In this way, the conventional and rigid driving circuitry can be replaced, which should dramatically improve the flexibility of the display.

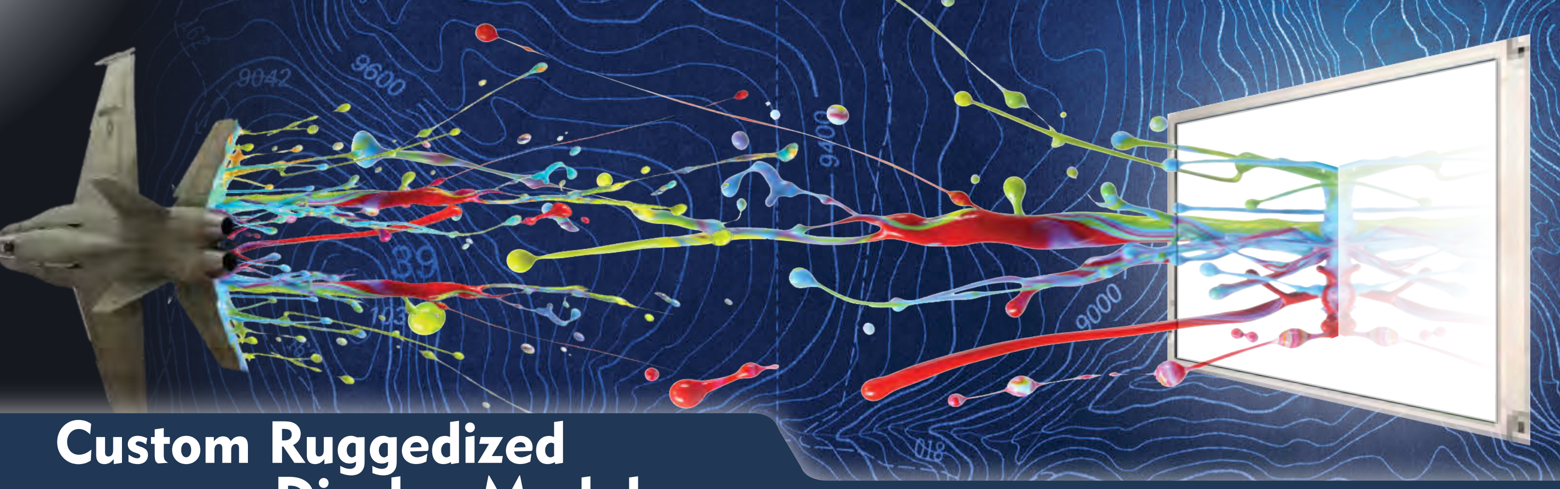
Challenges

"Lowering this annealing temperature to 250°C, while maintaining high performance and reliable transistors directly on foil, was by far the most challenging part of this work," says Genoe. "Moreover, we integrated these solution-based metal-oxide transistors together with our baseline organic transistors into a scalable hybrid complementary technology. The main challenge here was the development of an integration path where both the oxide and organic TFTs are processed next to each other and with a high density, without sacrificing the individual transistor performances."

Award-Winning Results and a Look Ahead

The paper easily itself earned the annual outstanding student paper award. "I think the committee was impressed with a high level of technical sophistication and the novelty of the approach taken by the authors. The group also provided a clear explanation of their work and provided a comprehensive set of results," says *JSID* editor John Kymissis.

"The results we obtained with the solution-based metal-oxide transistors on polyimide foil are state of the art," says Genoe¸ adding, "We are ready to make robust flexible line-drive circuitry for a future generation of flexible AMOLED displays. In the framework of the ORICLA project, we successfully realized the most complex thin-film RFID systems on foil so far. We think that thin-film electronics on foil, particularly for thin-film RFID tags, is a very exciting topic from the point of R&D as well as from the business prospect point of view." In recent years, he says, the speed of development in this particular field has lagged behind the promises of the R&D community. But now, the consistent progress the group has demonstrated in realizing complex and fast circuits on foil makes them optimistic that this technology can be pushed to commercialization. ■



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factors and imaging consultant and retired NASA scientist, envisioning "The Road Ahead to the Holodeck: Light-Field Imaging and Display." Jim is a very well-known researcher in the field of applied vision and human factors. It's an honor to publish his extremely thorough coverage of the science and future possibilities for light-field displays. As you will learn from this article, the stereoscopic displays we currently think of as "3-D" are but a crude beginning to what is really possible when we consider how human-vision works and what we can potentially render with the right imaging systems.

Next is an exciting companion article, also addressing light-field technology, from Stephen Ellis of NASA Ames Research Center with his article titled "Communication through the Light Field: an Essay." Stephen's piece introduces us to the concept of the "ambient optical array" and the information contained in light that goes way beyond the basic physical features of luminance, color, and motion. There are many fundamental challenges that developers will need to address to successfully integrate a full multi-domain light-field array display into our daily lives. Nonetheless, our ability to perceive higher-order meaning from the light field opens the door to endless possible new experiences that a light-field camera and imaging system might bring. Over the last few years, we've been building quite a library of important articles about 3-D, holography, and related topics for the next generation of immersive displays. These two are the best we've had so far and will certainly inspire some more innovative thinking.

While Larimer and Ellis are focused on the potential for creating new displays, frequent contributor and well-known optical metrology researcher Ed Kelley remains focused on how to characterize these new technologies. Addressing the challenges associated with capturing the performance of stereoscopic displays and what may follow next, Ed has developed a camera system that mimics how real people view displays and describes the methodology to capture features unique to 3-D such as crosstalk and motion blur. Ed describes this invention in his article titled "Binocular Fusion Camera Enables Photography of 3-D Displays for Evaluation Purposes." This also expands on an earlier article Ed contributed to *ID* in September of 2011 that discussed the challenges of making accurate performance measurements of stereoscopic displays compared with conventional displays. Reading both articles provides a broad understanding of the topic and this potential solution.

Our thanks also to our guest editor Nikhil Balram of Ricoh Innovations Corporation, who solicited the light-field display contributions and explains in his wonderful column some of the current limitations to adoption of stereoscopic displays and why we need the next generation of technologies like light-field and holographic displays.

I was very excited when the *Lord of the Rings* movies were released and I remember watching them in the theater and then later at home on my own large-screen panel. Both experiences were great in their own ways, but I always thought the movies would have been even more compelling if they had been shot in 3-D. Well, director Peter Jackson must have thought so too because *The Hobbit* was not only shot in native 3-D but also at 48 frames per second. How does it look? You can find out by reading Terry Schmidt's article, "How High-Frame-Rate Dual-Projector 3-D Made Its Movie Debut at the World Premiere of *The Hobbit*." As the recently retired chief scientist of Christie Digital Systems, Inc., Terry gets all the really cool assignments, and this one was quite a feat of engineering and logistics. If you do not remember his last article about setting up all the projectors for the opening ceremonies at the Beijing Olympics, you should go back and read that one also from the August 2009 issue of *Information Display*.

About 6 months ago, Jennifer Schumacher and her colleagues at 3M approached us about writing an article that would describe the results of their research into a new tool to predict the relative visual appeal of displays. Their research focused on what effect varying certain characteristics such as luminance, resolution, size, and color gamut would have on the visual appeal of displays to target audiences. They said the tool would be based on user trial data combined with a new analytical prediction engine and could become a valuable practical model for display and display product designers to work with. Well, naturally we were intrigued and after waiting anxiously to see their work titled "PQM: A Quantitative Tool for Evaluating Decisions in Display Design"; I'm pleased to say they exceeded our expectations. This is a well thought-out and promising effort that I hope they continue to expand upon.

And last, but in no way least, we also present our latest installment of Display Marketplace, brought to you this time by Vinita Jakhanwal from IHS. In Vinita's analysis of the future AMOLED market, we learn about the challenges faced by various manufacturers as they all pursue the sometimes over-hyped promise of OLED HDTV. She concludes that the landscape of different offerings, in combination with the ongoing R&D pursuits, is expansive but filled with many challenges to be met before we see AMOLED TVs come close to the volumes and price points of today's LCD TVs. Nonetheless, the technology does promise soon to exceed all our expectations and for many of you at the exhibits, you are already seeing the next generation that Vinita is writing about.

If you are reading this from here at the Vancouver Convention Centre, I, along with the rest of the *ID* staff, sincerely hope you are having a great experience. If you are not here with us but instead reading from the confines of your home or office, I hope you will check out our on-line blogs and daily news updates to at least stay in touch with those of us here at the world's center of displays (well, at least for this week). If you want to read any of the past *Information Display* articles I've mentioned, they can be found at www.informationdisplay.org. ■

guest editorial

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the writers complain that they are used to mind-blowing audio effects when they go to the theater but that the visual 3-D effects seem to be much more muted – "Why can't they blow my mind with the 3-D effects too – why are they holding back?" As experts, we know why "they are holding back" and there is no obvious solution. The key insight is that the current form of single-plane stereoscopic 3-D is just a transient and early phase of 3-D viewing.

So, in this special issue I have chosen to focus on the future instead of dwelling in the present or past. In my opinion, and that of many others, a much richer future awaits, when we can produce light-field or volumetric displays that can provide true depth, leading to rich and natural 3-D. At first glance, the technical challenges of producing full-blown volumetric displays seem to be so immense as to put them into a very distant future of interstellar travel and the kinds of "holodecks" seen on *Star Trek*. But there has been much interesting work done on compromises and subsets that could lead to a first generation of interesting and useful real 3-D displays. The work of Professor Banks and his colleagues Kurt Akeley, David Hoffman, and Gordon Love has shown that a surprisingly small number of depth planes are sufficient to produce the visual effect of continuous depth, suggesting that (depending on the application) perhaps even a display with 16 or fewer planes could suffice. The work of Dr. Schowengerdt and his colleagues has suggested that head-mounted or wearable displays could provide single-viewpoint volumetric displays that could have a number of uses.

The two 3-D articles in this special issue aim to look forward to that richer future of 3-D with a broader perspective of viewing and visual communication. The article titled "*The Road Ahead to the Holodeck: Light-Field Imaging and Display*" by Dr. James Larimer provides a good introduction to light fields in the context of human vision and imaging and display devices. It explains why light fields are the natural future of 3-D imaging and display and highlights some of the recent activities in this area. The paper titled "*Communication through the Light Field: An Essay*" by Dr. Stephen Ellis looks at the communication of information that occurs between display and human viewer. The article refers to the "ambient optic array" – the information that the human visual system detects from the light field. Dr. Ellis uses lessons from the past history of display systems to contemplate the major physical, economic, and social factors that need to be considered and addressed before the widespread adoption of light-field systems can become possible.

These two articles serve to remind us of the long and exciting path ahead for us as display researchers, engineers, marketers, and users. Indeed 3-D is dead. Long live 3-D. ■

***Dr. Nikhil Balram** is President and CEO of Ricoh Innovations Corporation. He can be reached at nbalram1@hotmail.com.*

president's corner

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within the last year, SID began partnering with international publishing company Wiley to make as many of these proceedings as possible electronically available, free of charge, to SID members. Current and past papers are now easier to find using SID's search engine or external tools such as Google Scholar. It helps that electronic documents can be machine translated, which may increase accessibility and understanding. At the same time, SID has started and is rapidly expanding its webinar series, also free to SID members, on a broad variety of topics. Of course, these webinars can be accessed from anywhere in the world. SID's webinar events are scheduled at hours that will reach the largest percentage of SID's members; however, they can also be streamed after the live event for viewing in any time zone. Naturally, SID webinars and conference recordings can always be paused or replayed as needed to increase comprehension. If only I could have hit "pause" or "replay" for everything I had to comprehend in Korean…

We look forward to seeing you in Vancouver. Welcome! 어서오십시오! ようこそ！欢迎！ ■

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