

ISSUES IN APPLIED VISION

# Information DISPLAY

**SID**

SOCIETY FOR INFORMATION DISPLAY

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

January/February 2017

Vol. 33, No. 1

## Building Better 3D Displays

**HOW HEAD-TRACKING  
SYSTEMS WORK**

**SIMPLIFYING STEREOSCOPIC  
DISPLAYS**

**QUANTIFYING COATING  
PERFORMANCE AND  
APPEARANCE**

**INTERVIEW WITH LEIA'S  
CEO AND FOUNDER**

**WILEY**





## Ensure Perfect Display Quality with Automated Visual Inspection

Leading display makers rely on Automated Visual Inspection from Radiant Vision Systems to measure **uniformity, chromaticity, mura** and other **defects**. Radiant combines CCD-based Imaging Colorimeters, sophisticated software and unmatched technical support to ensure quality, reduce costs, and deliver a customer experience that is nothing less than **Radiant**.



*A Konica Minolta Company*

**ON THE COVER:** It is an exciting time to be involved in the design, construction, and evaluation of visual displays. Recent developments in 3D imaging have presented great challenges but also breathtaking opportunities that will greatly enhance the viewer experience.



Cover Design: Jodi Buckley

3D smartphone illustration courtesy of LEIA, Inc.

## In the Next Issue of Information Display

### Display Week 2017 Preview and Materials

- 2017 SID Honors & Awards
- DW Symposium Preview
- Progress in TADF Emitters
- High-Mobility TFTs for Flexible Electronics
- Top 10 Display Discoveries at GES

INFORMATION DISPLAY (ISSN 0362-0972) is published 6 times a year for the Society for Information Display by Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; William Klein, President and CEO. EDITORIAL AND BUSINESS OFFICES: Jay Morreale, Editor-in-Chief, Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; telephone 212/460-9700. Send manuscripts to the attention of the Editor, *ID*. SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008; telephone 408/879-3901, fax -3833. SUBSCRIPTIONS: *Information Display* is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues \$100.00). Subscriptions to others: U.S. & Canada: \$75.00 one year, \$7.50 single copy; elsewhere: \$100.00 one year, \$7.50 single copy. PRINTED by Wiley & Sons. PERMISSIONS: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limits of the U.S. copyright law for private use of patrons, providing a fee of \$2.00 per article is paid to the Copyright Clearance Center, 21 Congress Street, Salem, MA 01970 (reference serial code 0362-0972/17/\$1.00 + \$.00). Instructors are permitted to photocopy isolated articles for noncommercial classroom use without fee. This permission does not apply to any special reports or lists published in this magazine. For other copying, reprint or republication permission, write to Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008. Copyright © 2017 Society for Information Display. All rights reserved.

## contents

### 2 Editorial: Vision for a New Year

■ By Stephen P. Atwood

### 3 Industry News: Samsung Buys Harman International

■ By Jenny Donelan

### 4 Guest Editorial: Display Imagery vs. Real Imagery

■ By Martin S. Banks

### 6 Frontline Technology: Head-Mounted-Display Tracking for Augmented and Virtual Reality

Head tracking is a key technical component for AR and VR applications that use head-mounted displays. Many different head-tracking systems are currently in use, but one called “inside-out” tracking seems to have the edge for consumer displays.

■ By Michael J. Gourlay and Robert T. Held

### 12 Frontline Technology: Visible Artifacts and Limitations in Stereoscopic 3D Displays

Stereoscopic 3D (S3D) displays send slightly different images to both eyes and thereby create an additional sense of depth compared to conventional non-stereoscopic displays. Nearly all direct-view S3D displays accomplish this by using either temporal interlacing, which alternates the images of the two eyes in time, or spatial interlacing, which alternates the images on a row-by-row (or column-by-column) basis. The two methods each have limitations, but it is possible to design S3D displays that minimize these.

■ By Paul V. Johnson, Joohwan Kim, and Martin S. Banks

### 18 Frontline Technology: Accurate Image-Based Estimates of Focus Error in the Human Eye and in a Smartphone Camera

Estimation of focus error is a key consideration in the design of any advanced image-capture system. Today's contrast-based auto-focus algorithms in digital cameras perform more slowly and less accurately than the human eye. New methods for estimating focus error can close the gap. By making use of optical imperfections, like chromatic aberration, these new methods could significantly improve the performance of digital auto-focusing techniques.

■ By Johannes Burge

### 24 Market Insights: ID Interviews David Fattal, Founder and CEO of LEIA, Inc.

David Fattal was the principal investigator of the LEIA project at HP Labs, from where he led a spin-off in late 2013 to co-found LEIA, Inc.

■ By Jenny Donelan

### 26 Frontline Technology: Quantifying Display Coating Appearance

Modern displays often utilize anti-reflection coatings to enhance contrast and improve readability. However, display manufacturers have unique requirements for coatings not found in other industries. New metrology instrumentation has been designed to obtain the necessary measurements for display makers and to work with the thin glass substrates increasingly employed in display fabrication.

■ By Trevor Vogt

### 32 SID News: SID Revises Governance Structure

### 36 Corporate Members and Index to Advertisers

For Industry News, New Products, Current and Forthcoming Articles,  
see [www.informationdisplay.org](http://www.informationdisplay.org)



## Vision for a New Year

by Stephen P. Atwood

Happy New Year and welcome to 2017. By the time you read this, many of us will be back from Seattle, where we assembled the technical program for this year's Display Week Symposium to be held in Los Angeles, May 21–26. I strongly suggest marking your calendar now and making your reservations soon. This year is sure to be another

“don't-miss” event with many new developments to see and hear. Thus far, the paper submission count is over 600, with a very high number focused on Virtual Reality (VR), Augmented Reality (AR), and holography/3D displays of various forms. When we started covering this topic a few years ago in *ID*, I said that the innovations would start coming fast once certain foundational technology problems were overcome. That prediction is looking like a safer bet every season. Of course, tomorrow is not going to bring the holodeck or the real-time light-field projection TV to your living room, but I think we are on the verge of seeing credible commercial endeavors. These include head-worn AR/VR technology and possibly a new concept that Intel terms “Merged Reality” (MR).

The definition of success might be fluid, with leading-edge applications such as gaming, social media, and entertainment novelties driving initial demand. Surely, some hardware providers will be overly eager to push new things to market to satisfy investors. But, unlike stereoscopic TV, I do not think this is going to flash and fade. I think the potential to create or enhance so many applications, along with solving current limitations in our existing user-interface world, will combine with the rapidly growing pool of hardware and software components to produce an unstoppable wave.

An example of this is on our cover, which shows a typical user trying to find their way in downtown Manhattan – an experience I believe most of us can relate to. Traditional navigation tools are good today, showing 2D maps and usually providing decent turn-by-turn directions. However, it is easy to see how a true 3D rendering of the entire area, with building sizes shown to actual scale, would dramatically enhance the value and accessibility of the application. We present this example thanks to the generosity of our friends at LEIA, Inc., a technology spinoff from HP Labs. The display shown is one of their technology illustrations which we were inspired to use based on our interview with LEIA Founder and CEO David Fattal, which appears in this issue. I think it is fair to predict that consumers would line up in large numbers to buy a smartphone with this feature in its display. We could debate whether the most useful application would be 3D navigation or something else, but I am confident this display capability, especially if combined with some type of 3D gesture sensing, would be a major value to consumers.

Our issue theme this month is Applied Vision, and in that context we bring to you three features developed by our Guest Editor Martin (Marty) Banks, professor of optometry, vision science, psychology, and neuroscience at UC Berkeley. In his Guest Editorial titled “Display Imagery vs. Real Imagery,” Martin talks about a “Turing Test” for 3D displays in which a user would be challenged to decide if they were viewing a real scene or one created by a display. It is tempting to dismiss the likelihood of us ever being fooled in such a way, but for the sake of argument I choose to believe that this is indeed a possibility.

(continued on page 34)

## Information DISPLAY

**Executive Editor:** Stephen P. Atwood  
617/306-9729, [satwood@azonix.com](mailto:satwood@azonix.com)

**Editor-in-Chief:** Jay Morreale  
212/460-9700, [jmorreale@pcm411.com](mailto:jmorreale@pcm411.com)

**Managing Editor:** Jenny Donelan  
603/924-9628, [jdonelan@pcm411.com](mailto:jdonelan@pcm411.com)

**Global Advertising Director:**  
Stephen Jezzard, [sjezzard@wiley.com](mailto:sjezzard@wiley.com)

**Senior Account Manager**

**Print & E Advertising:**

Roland Espinosa  
201-748-6819, [respinosa@wiley.com](mailto:respinosa@wiley.com)

### Editorial Advisory Board

Stephen P. Atwood, Chair  
*Azonix Corp., U.S.A.*

Helge Seetzen  
*TandemLaunch Technologies, Westmont, Quebec, Canada*

Allan Kmetz  
*Consultant, U.S.A.*

Larry Weber  
*Consultant, U.S.A.*

### Guest Editors

#### Applied Vision

*Martin Banks, University of California at Berkeley*

#### Automotive Displays

*Karlheinz Blankenbach, Pforzheim University*

#### Digital Signage

*Gary Feather, NanoLumens*

#### Materials

*Ion Bita, Apple*

#### Wearables/Flexible

*Ruqing (Ray) Ma, Universal Display Corp.*

#### Light-Field and Holographic Systems

*Nikhil Balram, Google*

### Contributing Editors

Alfred Poor, *Consultant*

Steve Sechrist, *Consultant*

Paul Semenza, *Consultant*

Jason Heikenfeld, *University of Cincinnati*

Raymond M. Soncira, *DisplayMate Technologies*

The opinions expressed in editorials, columns, and feature articles do not necessarily reflect the opinions of the Executive Editor or Publisher of *Information Display Magazine*, nor do they necessarily reflect the position of the Society for Information Display.



## Samsung Buys Harman International

Late last year, Samsung Electronics and Harman International Industries announced that Samsung would acquire Harman International, a company specializing in audio and “infotainment” solutions, for approximately \$8 billion.

In a press release, Samsung stated that the transaction was designed to make it a significant presence in the market for connected technologies, and particularly in automotive electronics, which Samsung refers to as a “strategic priority.”<sup>1</sup> More than 30 million vehicles are currently equipped with Harman’s connected car and audio systems.

According to a recent article in *Forbes*, although Harman is most commonly associated with premium audio equipment, roughly 65% of the firm’s \$7 billion in revenues (for the 12 months ending September 2016) actually came from supplying components and developing software for auto manufacturers, including navigation systems, infotainment, telematics, and driver-assistance technologies.<sup>2</sup>

*Forbes* also suggested that this is a move to diversify Samsung’s portfolio beyond smartphones in the wake of last year’s Galaxy Note 7 discontinuation. In any event, Samsung’s significant investment demonstrates a strong commitment to the connected and automotive markets in the short- and long-term future. As outlined in an investors’ presentation, the companies’ complementary technologies open up possibilities for shared applications among mobile devices, cars, public venues, smart homes, and more.

<sup>1</sup><https://news.samsung.com/global/samsung-electronics-to-acquire-harman-accelerating-growth-in-automotive-and-connected-technologies>

<sup>2</sup><http://www.forbes.com/sites/greatspeculations/2016/11/16/why-samsung-is-buying-harman/#2ab36c9323b3>

## Osram Intros World’s First Broadband Infrared LED

Osram Opto Semiconductors is utilizing converter technology for infrared emitters to produce an LED that emits broadband infrared

light in a wavelength range from 650 to 1,050 nm. The main target application for the technology at this time is near-infrared spectroscopy for measuring fat, protein, water, or sugar content in food, in a format that can be used at the consumer level.

Infrared spectroscopy detects the characteristic absorption behavior of certain molecular compounds. If a defined spectrum is directed at a sample, it is possible to determine the presence and quantity of certain ingredients

(continued on page 35)

## Connecting the Quantum Dots

Quantum dots, a “hot” display technology for a couple of years now, is showing some movement in terms of major players. Below are some brief announcements. It may be too early to say whether the changes represent maturity, consolidation, or both. We’ll report in more detail in the next issue.

### Nanoco Acquires Quantum-Dot Patents from Kodak

Nanoco Group plc, a developer and manufacturer of cadmium-free quantum dots and other nanomaterials, recently announced the acquisition of a group of patents from the Eastman Kodak Company in connection with the use of quantum dots in electroluminescent displays.

According to Nanoco, this patent acquisition reinforces its intellectual property position in quantum-dot electroluminescent displays (QLEDs), a technology with which the company hopes to replace the current materials in organic light-emitting diode (OLED) displays.

Michael Edelman, Nanoco’s Chief Executive Officer, said: “This patent purchase from Kodak broadens our intellectual-property estate and commercial position in future display technologies. The vast majority of current displays are based on LCD technology, and we expect LCDs to dominate display sales in the near and medium term. In the longer term, QLED displays could challenge current OLED displays and we aim to have a strong competitive position in this space in preparation for any market change. Our current focus remains driving near-term revenue from the supply to the LCD industry of the company’s cadmium-free quantum dots manufactured and marketed by Nanoco and our licensees, Dow, Merck and Wah Hong.” The commercial terms of the patent acquisition are undisclosed.

### Samsung Acquires QD Vision

In late November, Samsung announced the pending acquisition of Massachusetts-based quantum-dot-developer QD Vision. Samsung did not confirm the exact value of the deal but it is estimated to be approximately \$70 million or 82.14 billion won.

According to a recent article about the acquisition in *The Korea Times*, Samsung has been the global TV market leader for 11 consecutive years and is acquiring the QD Vision technology in order to strengthen the technological edge of the quantum-dot TVs it already sells. In particular, noted *The Times*, the latest announcement is expected to heat up the already-intense rivalry between Samsung and (OLED champion) LG over the next standard for the TV industry.<sup>3</sup>

QD Vision was founded by MIT researchers in 2004 and has to date partnered with TV manufacturers including China’s TCL and Hisense and Japan’s Sony of Japan. Samsung Electronics also announced that it would be collaborating with QD Vision in such areas as heavy metal-free quantum-dot technologies.

<sup>3</sup>[https://www.koreatimes.co.kr/www/news/tech/2016/11/133\\_218800.html](https://www.koreatimes.co.kr/www/news/tech/2016/11/133_218800.html)

# guest editorial



## Display Imagery vs. Real Imagery

by Martin S. Banks

A review article on 3D displays, by Banks, Hoffman, Kim, and Wetzstein (Annual Reviews of Vision Science, 2016), asked the reader to imagine a Turing test for displays. In this test, a person would view input that comes either from a direct view of the real world or from a simulated view of that world presented on a display. Then the reader would have to decide: is it real or is it imagery from a display?

The display would pass the Turing test if the viewer could not distinguish which was which.

Today's displays would clearly fail this test because no one would be unable to distinguish real from display. Many displays would fail because of limitations in spatial and temporal resolution. Many would fail because of limitations in color and the range of displayable intensities. And many would fail because they would not create a realistic three-dimensional experience or would not stimulate oculomotor function (e.g., accommodation and eye movements) appropriately. But very significant progress has been and is being made in each of these areas.

Several disciplines are involved in the design, construction, evaluation, and use of displays including materials science, electrical engineering, computer graphics, and human-factors engineering. But an understanding of human vision is proving to be crucial to the enterprise because in the end the goal is to provide the desired perceptual experience for a human viewer. And display and computer-graphics engineers cannot know how to do this without incorporating what is known about the visual system's capacities, particularly its limitations.

There are numerous areas in which an understanding of the human visual system has aided and continues to aid the design and construction of more-effective displays, as well as the development of better algorithms in computer graphics. In this issue of *Information Display*, we sample a small subset of these areas by focusing on three specific topics in which knowledge of human vision has been intimately involved. In "Visible artifacts and limitations in stereoscopic 3D displays," Johnson, Kim, and Banks describe how previous research on temporal and spatial filtering in human vision has been used to minimize flicker, motion artifacts, and distortions of perceived depth in stereoscopic 3D displays. They show how one can best utilize a display's temporal and spatial properties to enable realistic, undistorted visual experiences. In "Head-mounted-display tracking for augmented and virtual reality," Gourlay and Held review the latest techniques for implementing head tracking in virtual- and augmented-reality displays. As the accuracy of head tracking improves in space and time, we can provide the viewer of a head-mounted display the compelling experience of a stable visual world. In "Accurate image-based estimates of focus error in the human eye and in a smartphone camera," Burge reviews research on how the human eye accommodates to focus natural images. He then shows how the knowledge gained from understanding how the eye does it has led to a more efficient algorithm for focusing a camera.

It is an exciting time to be involved in the design, construction, and evaluation of visual displays. For instance, the development of head-mounted displays for virtual and augmented reality has created great challenges, but also breathtaking opportunities. I look forward to the time when the perceptual experience that devices provide will be sufficiently realistic to give the Turing test a run for its money.

*Martin S. Banks received his B.A. degree in psychology from Occidental College in 1970, M.A. degree in experimental psychology from UC San Diego in 1973, and Ph.D. in developmental psychology from the University of Minnesota in 1976. He was an assistant and associate professor of psychology at the University of Texas at Austin from 1976 to 1985 before moving to UC Berkeley where he is now professor of optometry, vision science, psychology, and neuroscience. He can be reached at [martybanks@berkeley.edu](mailto:martybanks@berkeley.edu).*

### SID EXECUTIVE COMMITTEE

President: Y. S. Kim  
President-Elect: H. Seetzen  
Regional VP, Americas: S. Peruvemba  
Regional VP, Asia: X. Yan  
Regional VP, Europe: P. Kathirgamanathan  
Treasurer: T. Tsujimura  
Secretary: A. Bhowmik  
Past President: A. Ghosh

### DIRECTORS

Bangalore: T. Ruckmongathen  
Bay Area: J. Miller  
Beijing: Q. Yan  
Belarus: A. Smirnov  
Canada: J. Vieth  
Greater Dayton: D. G. Hopper  
Delaware Valley: J. W. Parker III  
Metropolitan Detroit: J. Kanicki  
France: F. Templier  
Hong Kong: H. S. Kwok  
India: V. N. Mohapatra  
Israel: G. Golan  
Japan: K. Kondoh  
Korea: J. Souk  
Latin America: A. Mammana  
Los Angeles: L. Tannas  
Mid-Atlantic: J. Kymissis  
Mid-Europe: H. De Smet  
New England: R. Powell  
Pacific Northwest: A. Abileah  
Russia: V. Belyaev  
Singapore: T. Wong  
Southwest: K. Sarma  
Taipei: J. Chen  
Texas: Z. Yaniv  
U.K. & Ireland: S. Day  
Ukraine: V. Sergan  
Upper Mid-West: B. Hufnagel

### COMMITTEE CHAIRS

Academic: H. J. Kim  
Archives: L. Tannas, Jr.  
Audit: S. O'Rourke / R. Powell  
Bylaws: A. Silzars  
Chapter Formation: D. McCartney  
Conventions: P. Drzaic  
Conventions Vice-Chair, BC and MC: A. Silzars  
Conventions Vice-Chair, Europe: I. Sage  
Conventions Vice-Chair, Asia: K.-W. Whang  
Definitions & Standards: T. Fiske  
Display Industry Awards: W. Chen  
Honors & Awards: S.-T. Wu  
I-Zone: L. Weber  
Investment: H. Seetzen  
Long-Range Planning: H. Seetzen  
Marketing: S. Peruvemba  
Membership: H.-S. Kwok  
Membership Vice-Chair, Social Media: H. Atkuri  
Nominating: A. Ghosh  
Publications: J. Kymissis  
Senior Member Grade: H. Seetzen  
Web Site: H. Seetzen

### CHAPTER CHAIRS

Bangalore: S. Sambadam  
Bay Area: R. Grulkhe  
Beijing: N. Xu  
Belarus: V. A. Vyssotski  
Canada: A. Kitai  
Dayton: J. Luu  
Delaware Valley: J. Blake  
Detroit: J. Byrd  
France: L. Vignau  
Hong Kong: M. Wong  
India: S. Kaura  
Israel: I. Ben David  
Japan: K. Kondo  
Korea: S. T. Shin  
Latin America: V. Mammana  
Los Angeles: L. Iboshi  
Mid-Atlantic: G. Melnik  
Mid-Europe: H. J. Lemp  
New England: J. Gandhi  
Pacific Northwest: K. Yugawa  
Russia: M. Sychov  
Singapore/Malaysia: C. C. Chao  
Southwest: M. Strnad  
Taipei: C. C. Wu  
Texas: R. Fink  
U.K. & Ireland: M. Jones  
Ukraine: V. Sorokin  
Upper Mid-West: R. D. Polak

### SOCIETY FOR INFORMATION DISPLAY

1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008  
408/879-3901 e-mail: [office@sid.org](mailto:office@sid.org)  
<http://www.sid.org>

## Water Vapor Transmission Rate Testing

Providing Unparalleled Testing of Thin Films for the Most Challenging Applications



- Detectable range down to  $10^{-8} \text{ g}/(\text{m}^2 \cdot \text{day})$
- Multidirectional Sensitivity
- Utilizes patented tritiated water tracer process
- Measures continuous real-time permeation
- Profiles permeation across full temperature range (20 - 150°C)
- Characterizes film and seal permeation



Contact us to learn more | Dr. Benjamin Russ | Ben.Russ@GA.com | +1-858-455-3902



# Display Week 2017



SID International Symposium, Seminar & Exhibition

May 21-26, 2017

Los Angeles Convention Center, Los Angeles, California, USA

Display Week 2017 offers synergies unparalleled by any other display event, with attendees and exhibitors who represent the top engineering talent from all over the world, as well as leadership from both the commercial and consumer markets. Display Week is the ideal place to conduct business, discuss systems integration, network with colleagues, and above all, learn about the latest display technologies.

Get started building a better future for your company now!

[www.displayweek.org](http://www.displayweek.org)

# Head-Mounted-Display Tracking for Augmented and Virtual Reality

*Head tracking is a key technical component for AR and VR applications that use head-mounted displays. Many different head-tracking systems are currently in use, but one called “inside-out” tracking seems to have the edge for consumer displays.*

by Michael J. Gourlay and Robert T. Held

IN 2016, several head-mounted displays (HMDs) reached the consumer marketplace, providing users with the ability to augment the real world with digital content and immerse themselves in virtual worlds. A key technical component for this is “head tracking.” Tracking estimates the pose (orientation and sometimes position) of the HMD relative to where it has been in the past. Having that pose permits synchronization of a virtual camera with real-world head motion, which in turn allows virtual models (holograms) to appear as though they are locked to the world. This article provides a brief overview of how most tracking systems work, with a focus on technologies in use in contemporary HMDs.

## Tracking Overview

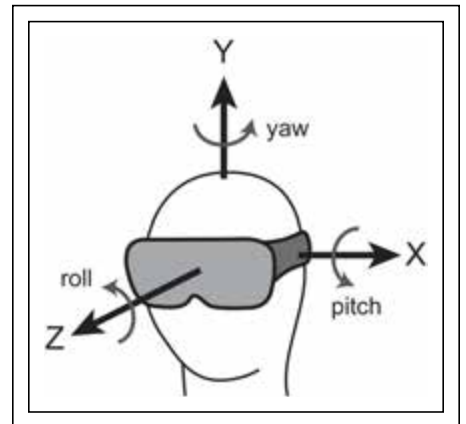
Head position can be represented by the position along three head-centered axes (X, Y, and Z in Fig. 1) and by orientation relative to those axes. Tracking can be accomplished with a variety of sensors, including inertial

and visual. (Others are possible, such as GPS and magnetic, but they will not be discussed here.) Some trackers provide only orientation, which entails three degrees of freedom (DoF). They are called 3 DoF trackers. Other trackers also provide position, so they are called 6 DoF trackers.

Inertial tracking is fast, cheap, and robust, but typically suffices only for 3 DoF tracking because the inertial tracking of position requires integration of noisy acceleration measurements over time, which leads to a gradual accumulation of error. Visual tracking is comparatively slow and expensive but can be extremely accurate with essentially no drift. Combining these two techniques into visual-inertial tracking through “sensor fusion” yields the best of both worlds – low latency, high accuracy, and no drift – and enables high-quality augmented-reality (AR) and virtual-reality (VR) experiences.

## How 6-DoF Tracking Works: Inertial and Visual Tracking

Inertial tracking involves integrating measurements from components of an inertial measurement unit (IMU), which typically contains an accelerometer (that measures linear acceleration), a gyroscope (that measures angular velocity), and sometimes a magnetometer (that measures the local magnetic field). Integrating those values can be conceptually straightforward; the mathematics would be



**Fig. 1:** The momentary position of the head is described by three position numbers: X corresponds to left-right position, Y corresponds to up-down, and Z corresponds to forward-backward (where the origin of the X-Y-Z coordinate system is the center of the head). Positional changes are described by changes in those three numbers. The momentary orientation of the head is described by rotations about the X, Y, and Z axes (where zero is normally referenced to earth-centered coordinates). Pitch corresponds to rotations about the X axis (head rotating up or down); yaw corresponds to rotations about the Y axis (rotating left or right); and roll corresponds to rotation about the Z axis (tilting the head to the side).

**Michael J. Gourlay** is a Principal Development Lead at the Environment Understanding group in Analog, the division of Microsoft that makes HoloLens, Hello, and Windows Holographic. He can be reached at [mija@mijagourlay.com](mailto:mija@mijagourlay.com). **Robert T. Held** is a Senior Software Engineer in the HoloLens Experience Team at Microsoft. He can be reached at [robert.held@gmail.com](mailto:robert.held@gmail.com).



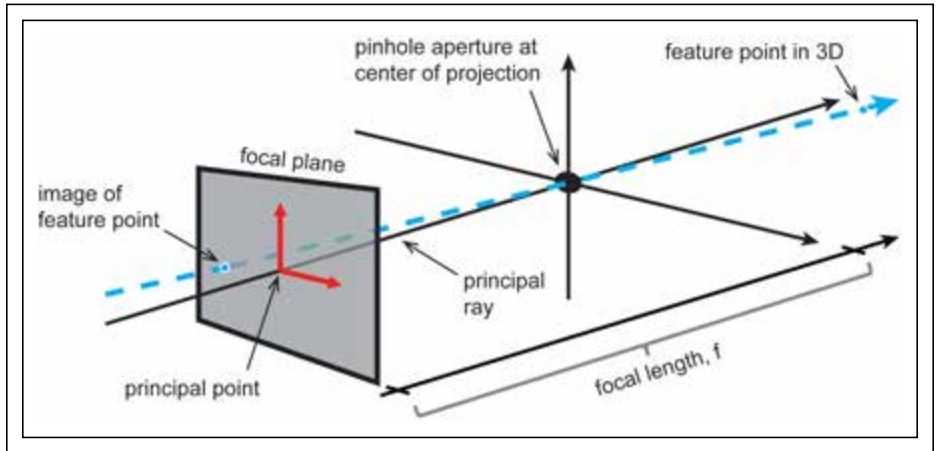
familiar to a person who took physics, calculus, and linear-algebra classes. Integration can be used to obtain a linear velocity from linear acceleration and a position from the velocity. Likewise, orientation can be obtained from the angular velocity. Furthermore, the constant and uniform acceleration due to gravity can be used to obtain orientation in two dimensions (elevation, which is similar to pitch except it's fixed to the earth coordinate frame, and tilt, which is roll relative to gravity) and the magnetic-field-reading relative orientation in the azimuthal direction (yaw relative to an initial direction).

In practice, inertial tracking also must handle noise, bias, and other sources of errors in IMUs and combine inertial tracking estimates with estimates obtained through visual tracking. Otherwise, the pose obtained from inertial tracking tends to drift away from the correct value (especially when using small inexpensive IMUs as used in consumer devices).

### Inside-Out Tracking: Sparse Feature Tracking and Mapping

There are two major types of visual tracking: inside-out and outside-in. There are many variations within the two types. This section describes one variation of inside-out tracking and one of outside-in tracking. We also describe “lighthouse tracking,” which is similar to inside-out tracking but with some key distinctions.

Inside-out vision-based tracking is also called “ego-motion tracking,” which means that the object being tracked is the camera itself, *i.e.*, not what the camera is looking at. The distinction is somewhat artificial because if the camera were stationary and the world were moving, the results would be visually identical. This point reflects a key aspect of visual tracking: To estimate the pose of the camera, the algorithm also needs a geometric model of the environment captured by the camera. The motion of the camera can be tracked relative to the environment, so either entity could move and have its motion tracked. If the geometry of the environment is not already known (and in most consumer situations it is not), the algorithm must simultaneously model the environment and track the camera pose. Hence, this type of algorithm is called “simultaneous localization and mapping” (SLAM) or “tracking and mapping.”<sup>a</sup> The model of the environment



**Fig. 2:** This diagram shows the projection of a 3D point onto the image plane of a pinhole camera.

could be sparse, dense, or somewhere in between the two. A sparse model consists of a collection of feature points (such as corners), whereas a dense model consists of dense regions of either scene geometry or images. We will focus on sparse models.

Visual tracking requires accurate knowledge of the locations of feature points in the environment relative to the camera. Mathematically, an ideal camera can be modeled as a pinhole through which light rays pass. Such a camera maps light reflected off points in 3D space onto a 2D plane (Fig. 2). Such a camera can be described by the position of the pinhole and the position and orientation of the plane onto which light is projected.

Real cameras have lenses that distort the directions in which rays pass through the aperture. With calibration, those distortions can be measured. That distortion can be modeled with a function and then one can “undistort” rays, after which a real camera can be effectively treated as a pinhole camera.

### Stereo Triangulation

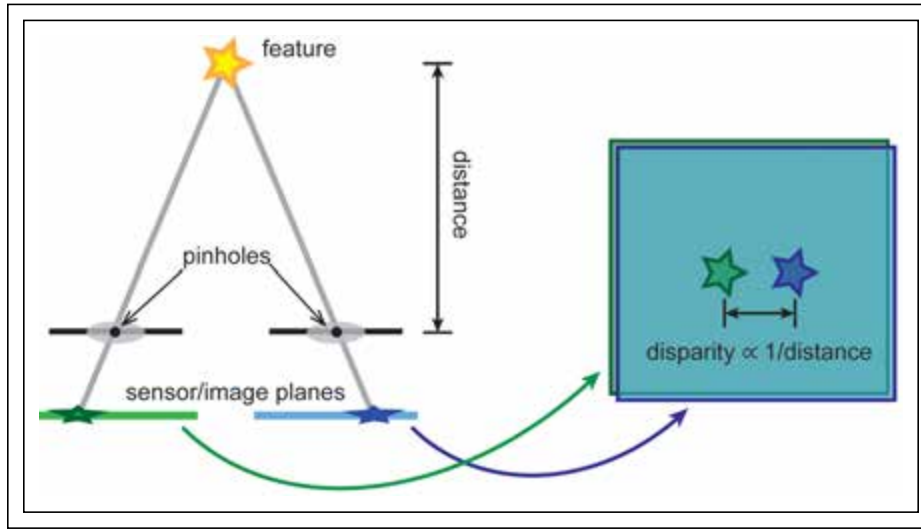
Visual trackers can use either one camera or a “rig” of cameras rigidly mounted together, some of which might have overlapping fields of view. In practice, these options are imple-

mented in a variety of ways. For example, a “stereo rig” has two cameras with overlapping fields of view. Such a rig can be used to determine the distances of image features relative to the cameras (Fig. 3). In contrast, visual tracking with a single camera means that distances can never be determined in world units; all distances would be relative to other distances within the images; *i.e.*, the scale is ambiguous. A tracker for which the distance of features to the camera rig is known, for example, through stereo triangulation and how that triangulation works will be described. It suffices for the following description to know that image features have a position in three-dimensional space relative to the camera, and those 3D positions can be known, from a single stereo image, with some uncertainty.

To use a stereo rig to determine the 3D positions of features within a scene, the relative position and orientation of the camera pair need to be known. This can be done by taking a photograph of a calibration target, such as a checkerboard, that has known structure with sufficient complexity (*e.g.*, has enough identifiable features, like corners on the checkerboard), and then solving a system of linear equations for the positions and orientations of the two cameras and the marker-board plane. Assuming the rig is rigid, this calibration can then be used to infer the 3D structure of any scene it captures.

Triangulation involves finding pairs of corresponding feature points in the images of the two cameras and measuring their disparity

<sup>a</sup>Technically, a visual tracker could estimate relative motion without retaining a map; tracking could always be relative to a previous frame. Such tracking is called “visual odometry” and has practical applications, but that concept will not be described further.



**Fig. 3:** Stereo triangulation uses knowledge of the relative positions and orientations of two cameras to convert a real-world feature's disparate projections into a distance measurement.

across the two images. In general, the differences in the positions of images from one object (*i.e.*, the disparity) occur along a line: an epipolar line. When the cameras are parallel and horizontally displaced from one another, epipolar lines are just horizontal lines in the camera's sensors. Thus, the search for pairs of corresponding feature points and the measurement of disparity is simpler. Even a single set of 3D features from a single stereo image pair suffices for tracking.

### Tracking with a Known Map

If the 3D structure of the environment is known, the algorithm for tracking against the known map works like this:

- Start with a hypothesis for camera pose.
- Numerically project 3D points from the environment's map into the current camera.
- Find correspondences between image features and projected 3D points.
- Compute the distance (in image space) between corresponding image features and projected 3D points.
- Minimize error with respect to pose.

Note that this tracking algorithm does not need (or even use) stereo overlap or depth information from tracking images. Tracking can be "monocular" even if the rig is stereo.

**Step 1: Start with a hypothesis for camera pose.** The "hypothesis" for the camera pose could be as simple as using the previous

camera pose. (The initial pose is arbitrary.) The hypothesis can be made more sophisticated by assuming the camera will continue on its current trajectory; *i.e.*, assume the camera moves according to a motion model (*e.g.*, constant acceleration) and then predict where it is currently.

**Step 2: Numerically project 3D points from the environment's map into the current camera.** Mathematically, a camera is just a function that maps 3D points to a 2D plane; *i.e.*, "projection." The inputs to that function include the 3D position and orientation (a.k.a. pose) of the camera relative to the 3D positions of all the points in the map. So, Step 2 entails applying that function to the 3D points in the map to synthesize a virtual image.

**Step 3: Find correspondences between image features and projected 3D points.**

Now there are two images: The real image captured by the camera and the virtual image. The virtual camera is meant to have the same properties (*e.g.*, pose, focal length, aspect ratio, and field of view) as the real camera. So features in the virtual image are meant to match features in the real image. Each feature point in the real image should have a corresponding point in the virtual image. Step 3 entails associating each of these pairs of points, a process called "data association."

There are many ways to accomplish this step. Among the simplest is to assume that, for any point in the real image, the corresponding point is the one nearest to it in the virtual

image. Instead, each feature can also be described in the real image with some function (like a hash), and then one can apply the same function to the virtual image and form correspondences according to this feature description. Each data-association method has benefits and drawbacks, but ultimately the outcome of Step 3 is some collection of corresponding pairs of feature points, one from the real image and one from the virtual image.

**Step 4: Compute the distance (in image space) between corresponding image features and projected 3D points.** Given each pair of features from Step 3, compute the distance between those features. The units could be in pixels or in the angle subtended by that distance. This error is "reprojection error."<sup>b</sup>

**Step 5: Minimize error with respect to pose.** As shown in Fig. 4, the idea is to wiggle the virtual camera, trying various perturbations in position and orientation, and repeat steps 1–4 until the pose that results in the smallest reprojection error possible is determined. In principle, this could be done by brute force: try every possible position and orientation. But this takes too long to compute because pose exists in a six-dimensional space. So, in practice, a numerical model of how the error varies with each component of the pose (three translations and three rotations) can be formulated, then the reprojection error can be minimized by using some numerical optimization algorithm, such as least-squares or one of its variants such as gradient descent, Gauss-Newton, or Levenberg-Marquardt.

Multiple sources of pose estimates can be combined, such as from inertial and visual trackers, for example, by using a Kalman filter. This yields the benefits – and reduces the drawbacks – of the various sources. They can be combined into a weighted running average where the weight is inversely proportional to the uncertainty of each measurement source.

### Hiding Latency

The naïve way to render a virtual scene given a real camera pose would be to render the virtual scene using a virtual camera whose

<sup>b</sup>There are multiple subtle variations possible for precisely how to compute this, and among them only one is properly called "reprojection error," but the details are beyond the scope of this article.



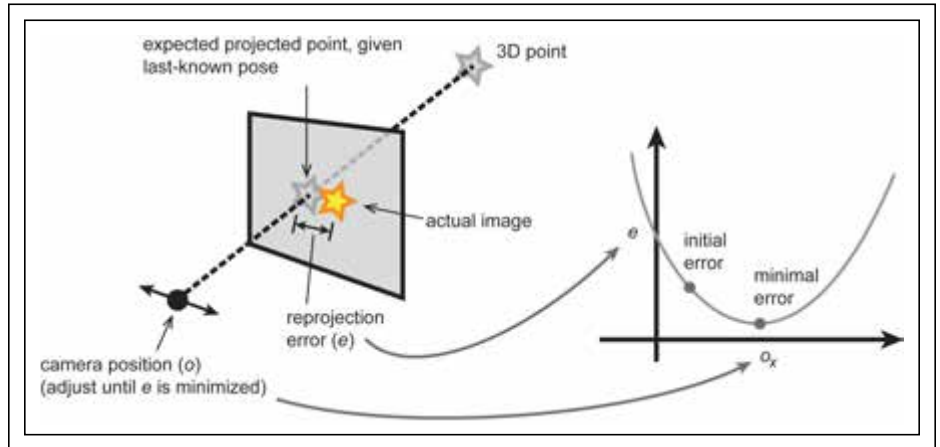
pose matched the latest estimate of the real camera pose. But rendering takes time, and by the time the rendered scene goes through the display pipeline and hits the user's eyes, the pose used to render the scene is out of date. Fortunately, there is more than just the latest pose; there is also a pose history, inertial measurements, and a dynamical model (e.g., rigid body motion) to help estimate where the camera is headed. Thus, where the camera will be by the time light from the display hits the user's eyes can be predicted. In that sense, the perceived latency can be by construction zero, as long as you know the timings involved (and they often can be measured).

But the prediction is only as good as the latest measurements, so any deviation from the motion model leads to misprediction. Users will perceive this error as jitter. But it is possible to mitigate jitter. Rendering the scene takes several milliseconds. During that time, the IMU generates many more samples, permitting a refinement of the camera-pose estimate. Because the scene has already been rendered that information might seem useless. But after, the scene (including color and depth) is rendered to a back-buffer, it is possible to transform that buffer to make it conform to the latest view. For example, if that scene is treated as though it is a picture projected onto a sphere centered on the user, then that sphere can be rotated according to how the camera pose rotated. Rotation accounts for a major portion of the motion perceived, so this solution goes a long way toward hiding the residual latency.

### Lighthouse Tracking

Lighthouse tracking refers to the tracking technology developed by Valve as part of the SteamVR platform. Lighthouse tracking is a form of inside-out tracking because it uses sensors on the HMD (or any other tracked device) to determine its orientation and position. However, the system also requires the use of base stations (the "lighthouses") that emit infrared (IR) light so it cannot work in any environment without prior setup.

Lighthouse tracking requires each tracked object to be covered with multiple IR sensors. Valve has developed software to optimize the number and placement of these sensors to ensure that the object can be robustly tracked in any orientation relative to the base stations. As discussed below, the spatial relationship



**Fig. 4:** New camera positions and orientations can be determined by minimizing the expected and actual projected position of a real-world 3D point.

between these sensors must be known by the tracking system in order to recover the object's position and orientation.

Prior to operation, two IR-emitting base stations are fixed in locations that allow them to sweep the entire tracking volume with IR light. During operation, each base station repeatedly emits an IR flash, followed by a horizontal sweep of IR light, followed by another flash, and then a vertical sweep of IR light. The flashes occur at 60 Hz, and each one serves as a synchronization pulse. On the HMD, a timer is started as soon as each pulse is detected. Next, the times at which the ensuing IR sweep hits each sensor are recorded. The rotation and position of the HMD is computed by combining the known relative placement of the sensors, the angular speed of the IR sweeps, and the detection times of the vertical- and horizontal-sweep pulses. These positional data are fused with a high-speed IMU to produce 6-DoF poses at a rate of 1000 Hz.

### Outside-In Tracking

One can also track a camera using outside-in schemes. The principles are similar to those in inside-out tracking but reversed. As mentioned above, visual tracking really only tracks the motion of the camera relative to the scene. If the cameras are stationary and the "scene" is the HMD, the same algorithms (or at least algorithms with the same underlying principles) yield a pose trajectory, which indicates how the "scene" (the HMD in this case) has moved.

Outside-in tracking has the benefit that the feature points being tracked are manufactured into the HMD, usually in the form of light emitters, so they are guaranteed to be illuminated regardless of the ambient scene, and their structure is known in advance. This setup drastically simplifies the situation, making such trackers much easier to implement.

The main drawback of outside-in trackers is that the tracking cameras and the HMD are separate devices, so the "playspace" – the region where the HMD can be tracked – is limited by the range of the fixed tracking cameras. Inside-out trackers have no such limitation because the tracking cameras travel with the device. Inside-out trackers do not require setting up external tracking cameras and permit the HMD to travel any distance.

For both inside-out and outside-in tracking, the IMU is attached to the HMD; that aspect of tracking works the same.

### Inside-Out Tracking Has the Edge

Visual-inertial tracking facilitates world-locked digital content such as images and sound. Vision-based tracking includes inside-out and outside-in implementations. Both entail tracking visual targets; the difference is whether the targets are in the environment or on the HMD. Outside-in requires setting up equipment within the environment but can be simpler to implement to achieve a given accuracy target. Inside-out can track natural features and is better suited to mobile experiences, but requires more sophisticated algorithms and expensive computation.

Both technologies can be found in current consumer products, but the trend seems to be toward inside-out tracking due to the simplified user experience and mobility.

### Further Reading

Kalman, "A new approach to linear filtering and prediction problems," *Transactions of the ASME – Journal of Basic Engineering* **82**, series D, 35–45 (1960).

Horn, "Closed-form solution of absolute orientation using unit quaternions," *J. Opt. Soc. Am. A*, **4**, No. 4 (April, 1986).

Hartley and Zisserman, *Multiple View Geometry in Computer Vision* (Cambridge University Press, 2004).

Boyd and Vandenberghe, *Convex Optimization* (Cambridge University Press, 2004).

Klein and Murray, "Parallel Tracking and Mapping for Small AR Workspaces," ISMAR 2007.

Szeliski, *Computer Vision: Algorithms and Applications* (Springer, 2011).

Valve, "SteamVR Tracking" (2011), <https://partner.steamgames.com/vrtracking/> ■



## JOIN SID

We invite you to join SID to participate in shaping the future development of:

- Display technologies and display-related products
- Materials and components for displays and display applications
- Manufacturing processes and equipment
- New markets and applications

In every specialty you will find SID members as leading contributors to their profession.

<http://www.sid.org/Membership.aspx>



# Information DISPLAY



Information Display welcomes contributions that contain unique technical, manufacturing, or market research content that will interest and/or assist our readers – individuals involved in the business or research of displays.

Please contact Jenny Donelan, Managing Editor, at [jdonelan@pcm411.com](mailto:jdonelan@pcm411.com) with questions or proposals.

Turn to page 31 for a list of 2017 editorial themes, with approximate dates for submitting article proposals.



## For the latest information on Display Week 2017:

[www.displayweek.org](http://www.displayweek.org)



***Your company and Information Display magazine***

**See how  
powerful  
the right  
partnership  
can be.**

**Information  
DISPLAY**

**SID**  
SOCIETY FOR INFORMATION DISPLAY

**WILEY**

Contact: Roland Espinosa: [respinosa@wiley.com](mailto:respinosa@wiley.com) • 201-748-6819



# Display Week 2017



**SID International Symposium, Seminar & Exhibition**

**May 21–26, 2017**

**Los Angeles Convention Center, Los Angeles, California, USA**

Display Week 2017 offers synergies unparalleled by any other display event, with attendees and exhibitors who represent the top engineering talent from all over the world, as well as leadership from both the commercial and consumer markets. Display Week is the ideal place to conduct business, discuss systems integration, network with colleagues, and above all, learn about the latest display technologies.

**Get started building a better future for your company now!**

**[www.displayweek.org](http://www.displayweek.org)**

# Visible Artifacts and Limitations in Stereoscopic 3D Displays

*Stereoscopic 3D (S3D) displays send slightly different images to our two eyes and thereby create an additional sense of depth compared to conventional non-stereoscopic displays. Nearly all direct-view S3D displays accomplish this by using either temporal interlacing, which alternates the images of the two eyes in time, or spatial interlacing, which alternates the images on a row-by-row (or column-by-column) basis. The two methods each have limitations, but it is possible to design S3D displays that minimize these.*

by Paul V. Johnson, Joohwan Kim, and Martin S. Banks

THE binocular disparity between what the left and right eyes see in an everyday environment is a strong cue to depth. Stereoscopic 3D (S3D) displays recreate this by sending slightly different images to each eye. This creates an enhanced sensation of depth compared to conventional non-stereoscopic displays. Nearly all current S3D displays use one of two methods to present different images to each eye: temporal interlacing or spatial interlacing.

The two methods each have a unique set of artifacts or limitations, such as flicker, motion artifacts, depth distortion, and reduced spatial resolution. But with an understanding of how the visual system processes information in space and time, we can design S3D displays that minimize objectionable artifacts and constraints. In this article, we review the

perceptual problems that occur with different methods of stereoscopic presentation and describe alternative display methods that minimize some of the artifacts by taking advantage of known properties of the visual system.

Temporal interlacing delivers the left- and right-eye views alternately over time by using active glasses that transmit and block images to the eyes in synchrony with the display or by using passive glasses and alternating polarization from the display. In temporal interlacing, only one eye receives light at any given time, but it receives all the pixels. This method is schematized on the left side of Fig. 1.

Spatial interlacing alternates left- and right-eye views on a row-by-row (or column-by-column) basis, simultaneously delivering half the pixels to one eye and the other half to the other eye. This is typically done using a film-patterned retarder on the display that polarizes the emitted light in opposite directions row by row (or column by column). The viewer wears passive eyewear that transmits alternate rows (or columns) to both eyes. With spatial interlacing, each eye receives images at any given moment, but each receives only half the pixels. This protocol is schematized on the right side of Fig. 1.

Each method is prone to visible artifacts due to the way the display is sampled in space and time. Temporal interlacing is prone to temporal artifacts, while spatial interlacing is prone to spatial artifacts.

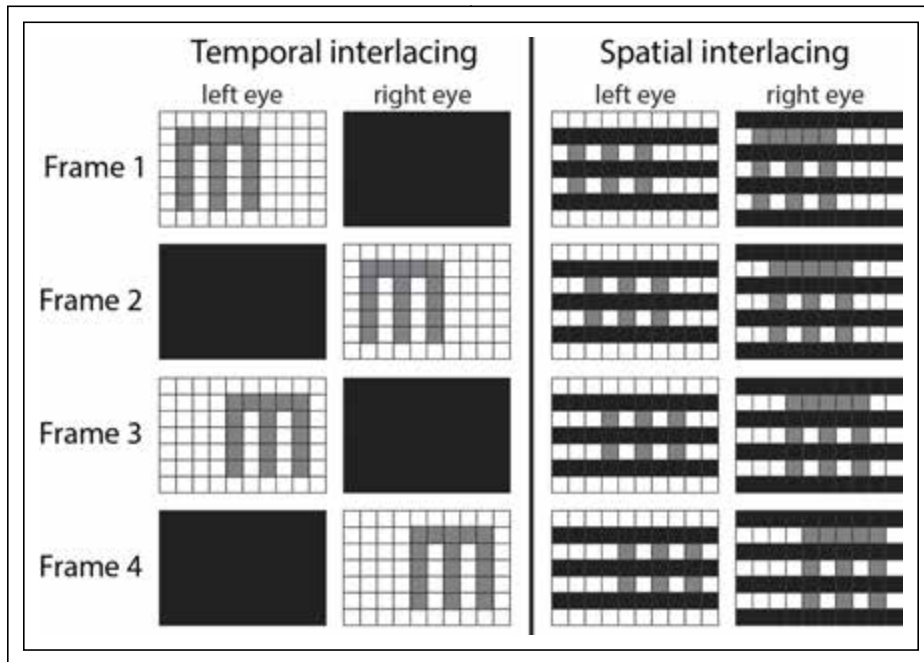
A significant problem with spatial interlacing is lower effective spatial resolution because each eye receives only a half-resolution image at any given time. Some researchers and manufacturers have claimed that the visual system can fuse the two half-resolution images to create a full-resolution image in the visual brain.<sup>8,14</sup> But an understanding of how binocular fusion occurs in the human visual system casts doubt on this claim. A fundamental principle in binocular fusion is that image features with dissimilar properties will not be matched in both eyes. Consequently, illuminated pixel rows (or columns) in one eye will almost always be matched with illuminated rows in the other eye and, likewise, non-illuminated rows will be matched in both eyes.<sup>12</sup> Because of this, the claim that full-resolution images can be created from two half-resolution images in a spatial-interlacing display is very questionable.

Kim and Banks<sup>10</sup> measured effective spatial resolution in spatial- and temporal-interlacing displays. In a series of psychophysical experi-

---

*Paul V. Johnson* is a display engineer at Apple. He can be reached at [pjohn98@gmail.com](mailto:pjohn98@gmail.com). *Joohwan Kim* is a research scientist with Nvidia. He can be reached at [skim@nvidia.com](mailto:skim@nvidia.com). *Martin S. Banks* is a professor of optometry, vision science, psychology, and neuroscience at UC Berkeley. He can be reached at [martybanks@berkeley.edu](mailto:martybanks@berkeley.edu).





**Fig. 1:** Temporal interlacing is shown at left and spatial interlacing at right. To illustrate these two protocols, we show the images seen by the left and right eyes with time proceeding from top to bottom. The grid pattern represents individual pixels. The stimulus being displayed is the letter “E” with a height of 5 pixels.

ments they found that resolution was indeed lower with spatial interlacing, but the resolution loss depended on viewing distance. At short distances, resolution was significantly lower with spatial interlacing than with temporal. At such distances, resolution is display limited, that is, resolution is determined primarily by the density of pixels. Said another way, the pixel rows can be seen at short distance, so fusion occurs with bright rows being matched to bright rows and dark rows to dark rows, thereby creating a fused but half-resolution image. The recommended viewing distances for HDTV and UHDTV fall into this regime.<sup>4,5</sup> Kim and Banks found that resolution was equivalent for the two types of interlacing at long viewing distances because, at those distances, resolution is eye limited, that is, resolution is determined primarily by the acuity of the viewer’s eye.

Temporal interlacing is prone to temporal artifacts such as flicker and unsmooth motion appearance.<sup>3,7</sup> These artifacts can be best understood by an analysis in the spatio-temporal frequency domain using the concept of the window of visibility.<sup>15,16</sup> The window represents the range of spatial and temporal

frequencies that are visible to a typical viewer. It is depicted by the red diamonds in Fig. 2.

Consider a thin object moving in the world at constant speed. Its spatio-temporal amplitude spectrum (in the Fourier domain) is a diagonal line in plots like that in Fig. 2. When the same object is presented on a digital display, its amplitude spectrum is given by the convolution of the smoothly moving object with the spatio-temporal point-spread function of the display. This creates replicates (or aliases) in the spectrum, which are the diagonals in the figure that do not run through the origin. When the replicates are low in spatio-temporal frequency they fall within the window of visibility and therefore become visible. In this case, the viewer perceives the displayed and real objects as different: the displayed object has visible artifacts such as flicker, judder, and pixelization. Sampling in temporal and spatial interlacing differs, so the spatio-temporal frequencies of the replicates in the two methods differ as well.<sup>1,6</sup>

Temporal interlacing creates replicates primarily in temporal frequency, while spatial interlacing creates them primarily in spatial frequency. For this reason, temporal inter-

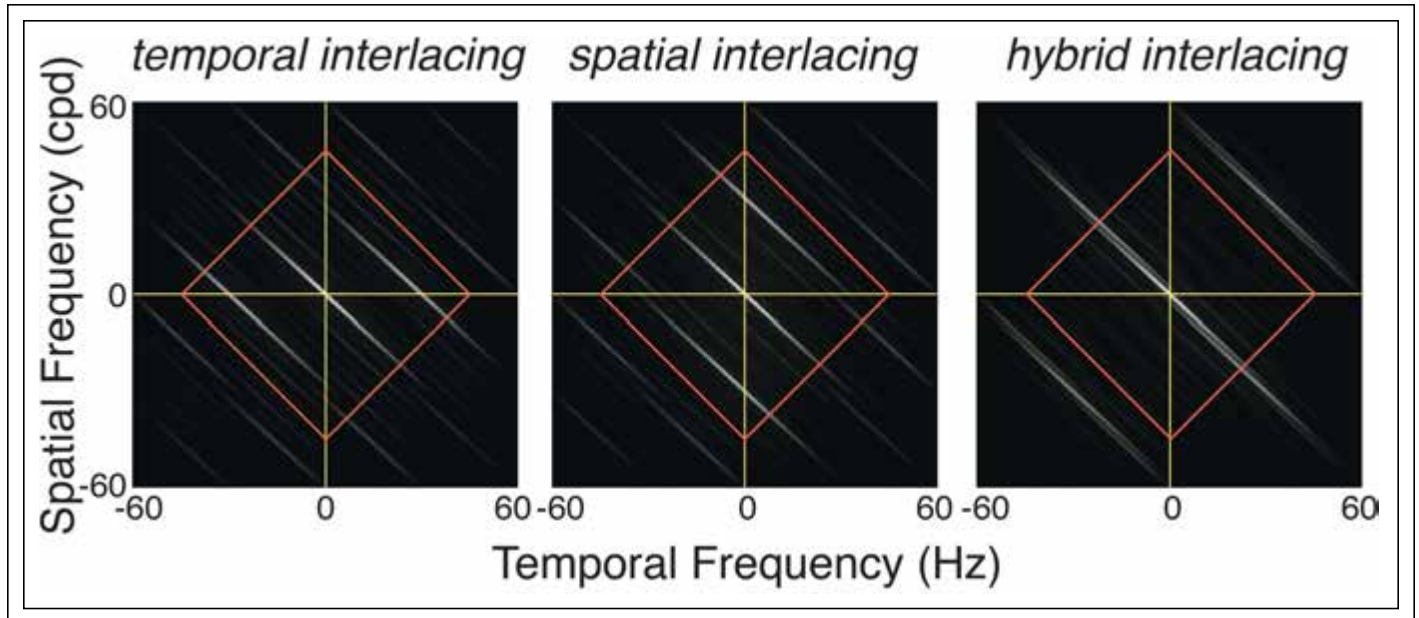
lacing is prone to artifacts in time such as flicker and judder and spatial interlacing to artifacts in space such as spatial aliasing and pixelization.<sup>3,6,10</sup>

Hoffman *et al.*<sup>3</sup> and Johnson *et al.*<sup>7</sup> carried out a series of psychophysical experiments to quantify the determinants of the temporal artifacts associated with temporal interlacing. The artifacts include judder (jerky or unsmooth motion appearance), motion blur (apparent smearing in the direction of stimulus motion), and banding (appearance of multiple edges in the direction of stimulus motion).

The researchers observed that the primary determinants of motion artifacts are capture rate (the number of unique images presented per unit time) and the speed of a moving object: artifacts become more visible with decreasing capture rate and increasing speed.<sup>3,7</sup> Motion artifacts occurred at higher capture rates and lower stimulus speeds with temporal interlacing than with spatial interlacing because the former requires two sub-frames to present the two images while the latter requires only one. These results were well predicted by the spatiotemporal frequencies created by the two stereoscopic protocols and the degree to which those frequencies fall within the window of visibility.

Another type of artifact occurs with temporal and spatial interlacing: distortions of perceived depth. In temporal interlacing, an object moving horizontally across the screen can appear displaced in depth because of an ambiguity in how the visual system matches left- and right-eye images. With this type of interlacing, the two eyes do not receive images at the same time. Thus, a given frame presented to the left eye could in principle be matched with a preceding or succeeding frame in the right eye.<sup>3,13</sup> This is illustrated in Fig. 3.

Depending on how the temporal interlacing is done, one of those matches yields the correct disparity while the other match yields an incorrect disparity. The visual system has no way of knowing which value is correct and which is incorrect, so it averages the two estimates, causing perceived depth to be displaced by an amount that depends on object speed and frame rate. The direction of the depth distortion (object seen as too far or too near) depends on whether the object is moving leftward or rightward. Experimental measurements of perceived depth confirm the predictions of the model depicted in Fig. 3.<sup>3,7</sup>



**Fig. 2:** Shown is the amplitude spectra for temporal- and spatial-interlaced displays. A diagonal line through the center of each plot (from upper left to lower right, not shown in the figure) would be the spectrum for a continuously moving stimulus in the real world. The white diagonal through the center of each plot represents the amplitude spectrum of a stimulus moving at constant speed but presented on a typical display. The other diagonal lines are replicates (aliases) caused by the discrete sampling of the display. The red diamonds represent the window of visibility: spatio-temporal frequencies within the diamond will be visible while frequencies outside the window will not. Temporal and spatial interlacing have different replicate patterns. The differences mean that the two methods produce different visible artifacts. Hybrid interlacing pushes the replicates to higher spatio-temporal frequencies that are less visible to human viewers, and this makes the artifacts less objectionable.

One can eliminate this artifact by capturing the image data in stereo cameras in alternating fashion rather than simultaneously.<sup>3</sup>

Distortions of perceived depth also occur in spatial interlacing. This form of depth distortion is caused by the way the visual system fuses images from both eyes to form a binocular percept. When the pixels are large enough to be resolved (which occurs at short viewing distance), alternating bright and dark pixel rows (or columns) are visible to each eye. The visual system nearly always fuses features with similar luminances (*i.e.*, bright with bright and dark with dark).

To make these matches in a row-by-row temporal-interlacing display, the viewer makes a small vertical vergence eye movement (one eye moves slightly upward while the other moves slightly downward) in order to align bright rows and dark rows in both eyes.<sup>2,10</sup> This vertical vergence eye movement causes a change in the horizontal disparity at the retina and therefore a change in perceived depth. The amount of induced horizontal disparity depends on the feature's orientation:

there is no induced disparity for vertical features and successively greater disparity for features that are closer to horizontal. This effect is seen, for example, when viewing an X on the screen. One limb of the X is perceived as closer than it should be and the other limb is seen as farther than intended.<sup>2</sup>

### Alternative Methods

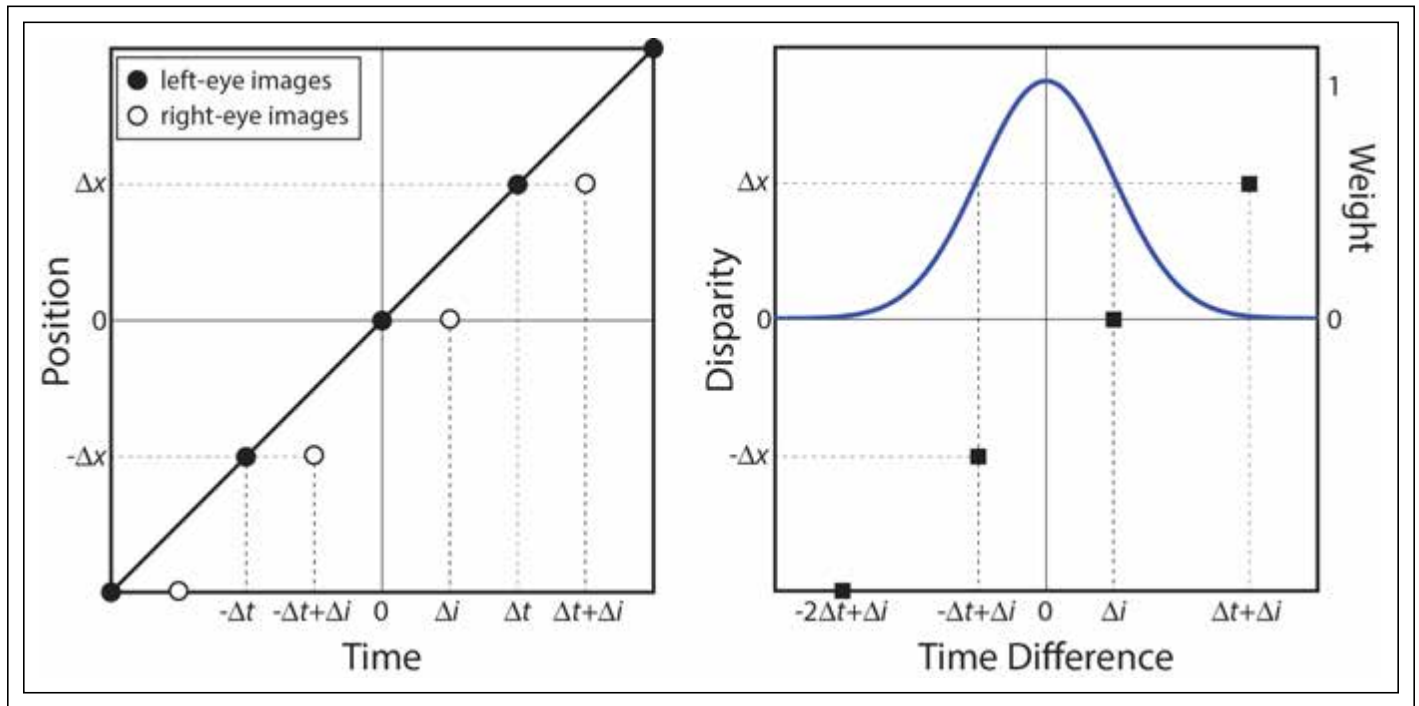
Consideration of the properties of the human visual system has led to two alternative methods for presenting stereoscopic imagery that minimize, and sometimes eliminate, the visible artifacts that plague conventional temporal and spatial interlacing. As we said earlier, temporal interlacing is prone to temporal artifacts such as judder and depth distortion with moving objects, while spatial interlacing is prone to spatial artifacts such as reduced spatial resolution.

Johnson *et al.*<sup>6</sup> proposed a hybrid spatio-temporal-interlacing protocol that is designed to minimize the temporal artifacts associated with temporal interlacing while minimizing the spatial artifacts associated with spatial

interlacing. It accomplishes this by sampling differently in space-time in order to move aliases to spatio-temporal frequencies to which the human visual system is insensitive<sup>9</sup> (right panel of Fig. 2).

In the hybrid protocol, which is schematized on the left side of Fig. 4, the left- and right-eye views are interlaced spatially, but the rows presented to each eye alternate frame by frame. Johnson and colleagues<sup>6</sup> showed that the hybrid protocol retained the benefits of temporal and spatial interlacing while eliminating the shortcomings. Unlike temporal interlacing, it produced no depth distortion with moving objects and had minimal motion artifacts. At the same time, it yielded better spatial resolution than spatial-interlacing displays. The left panel of Fig. 5 shows results from a psychophysical experiment that confirms that depth distortions that occur with temporal interlacing (blue symbols) are eliminated with hybrid interlacing (green).

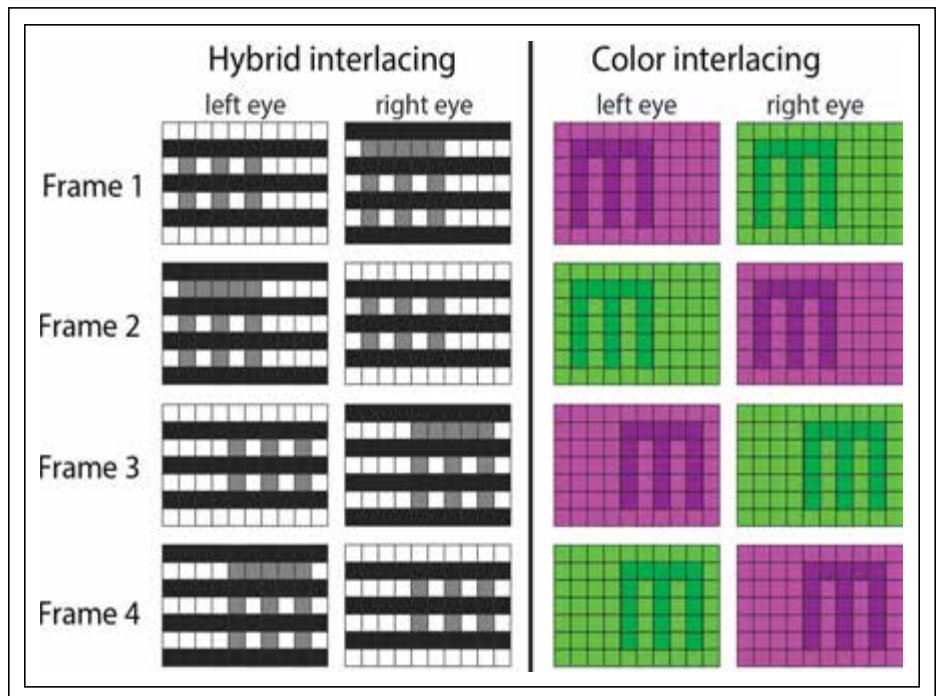
Another method, which we call color interlacing, takes advantage of another known property of the human visual system. The



**Fig. 3:** The charts illustrate disparity computation with temporal interlacing. At left appears a space-time plot of a horizontally moving stimulus on a temporally interlaced display. The stimulus has zero disparity, so it should be seen in the plane of the display screen. Each right-eye image is delayed by  $\Delta t$  relative to each left-eye image. Binocular matches could, in principle, be made between a left-eye image and the succeeding right-eye image or between the left-eye image and the preceding right-eye image. At right is a disparity estimation with weighted averaging over time. The weight given to each potential match is shown by the value on the right ordinate. In this example, the object is seen as closer to the viewer than intended.

visual system converts the signals from the three cone types [long, medium, and short wavelength (L, M, and S)] into a luminance signal ( $L + M$ ) and two color-opponent signals ( $L - M$  or red-green opponent and  $(L + M) - S$  or blue-yellow opponent). Disparity is primarily calculated from the luminance signal and not the color-opponent signals. Furthermore, flicker appearance is primarily determined by luminance variation and not color variation.

**Fig. 4:** Hybrid- and color-interlacing methods are illustrated. At left, the hybrid-interlacing protocol presents odd pixel rows to the left eye and even pixel rows to the right eye in one frame, and then even rows to the left eye and odd to the right in the next frame. At right, the color-interlacing protocol presents the green primary (G) to the left eye and the red and blue primaries (R+B) to the right eye at the same time, and then R+B to the left eye and G to the right in the next frame.





This color-interlacing method takes advantage of these properties to reduce depth distortion and flicker.<sup>11</sup> Each frame is divided into two sub-frames. In the first sub-frame, the image from the green primary is presented to the left eye while the images from the red and blue primaries (*i.e.*, magenta) are presented to the right eye. In the second sub-frame, the colors are reversed so magenta is presented to the left eye and green to the right eye. The presentation is split this way so that both eyes are being stimulated at all times, thereby keeping luminance at the eyes roughly constant over time.

Kim and colleagues<sup>11</sup> implemented this protocol and measured depth distortion and flicker. They found that both were significantly reduced with color interlacing compared to conventional temporal interlacing. The depth distortion results are shown on the right side of Fig. 5. Note that depth distortion is eliminated altogether when the displayed color is desaturated (*e.g.*, gray) and that the amount of distortion approaches that in temporal interlacing as the colors become highly saturated. Thus, color interlacing is an attractive approach for reducing artifacts due to temporal interlacing.

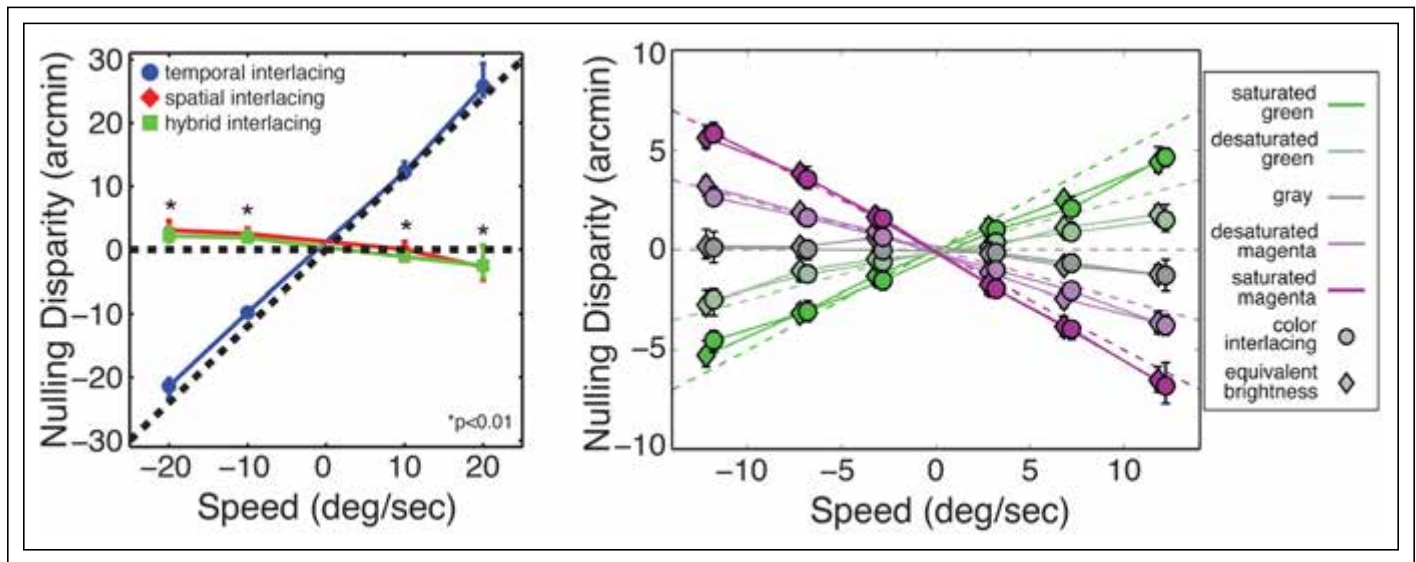
## Better Stereoscopic Displays through Understanding the Human Visual System

Single-screen stereoscopic displays create objectionable artifacts due to the manner in which different images are delivered to each eye. Whether one separates the left- and right-eye images in time or space produces different sorts of problems. We have shown, however, that knowledge of the properties of the human visual system can be considered in the design of displays that will produce less objectionable artifacts. We hope that these examples will stimulate more ideas in how to dovetail the properties of displays to the visual capabilities of the viewer.

### References

- <sup>1</sup>M. S. Banks, D. M. Hoffman, J. Kim, and G. Wetzstein, "3D Displays," *Annual Review of Vision Science* 2(1) (2016).
- <sup>2</sup>J. H. Hakala, P. Oittinen, and J. P. Häkkinen, "Depth artifacts caused by spatial interlacing in stereoscopic 3D displays," *Transactions on Applied Perception* 12(1), 3 (2015).
- <sup>3</sup>D. M. Hoffman, V. I. Karasev, and M. S. Banks, "Temporal presentation protocols in stereoscopic displays: Flicker visibility,

- perceived motion, and perceived depth," *J. Soc. Info. Display* 19(3), 271–297 (2011).
- <sup>4</sup>ITU-R Recommendation BT.2022 (2012), General viewing conditions for subjective assessment of quality of SDTV and HDTV television pictures on flat-panel displays, International Telecommunication Union, Geneva, Switzerland.
- <sup>5</sup>ITU-R Recommendation BT.709-5 (2002), Parameter values for the HDTV standards for production and international programme exchange, International Telecommunication Union, Geneva, Switzerland.
- <sup>6</sup>P. V. Johnson, J. Kim, and M. S. Banks, "Stereoscopic 3D display technique using spatiotemporal interlacing has improved spatial and temporal properties," *Optics Express* 23(7), 9252–9275 (2015a).
- <sup>7</sup>P. V. Johnson, J. Kim, D. M. Hoffman, A. D. Vargas, and M. S. Banks, "Motion artifacts on 240-Hz OLED stereoscopic 3D displays," *J. Soc. Info. Display* 22(8), 393–403 (2015b).
- <sup>8</sup>E. F. Kelley, "Resolving resolution," *Information Display* 27(9), 18–21 (2011).
- <sup>9</sup>D. H. Kelly, "Motion and Vision: II. Stabilized spatio-temporal threshold surface," *J. Opt. Soc. Am.* 69, 1340–1349 (1979).



**Fig. 5:** Two charts illustrate depth distortion in hybrid and color interlacing. At left, hybrid interlacing is compared to temporal and spatial interlacing. The ordinate is the disparity that must be added to a horizontally moving stimulus in order to eliminate depth distortion. The abscissa is the speed of the stimulus. When the added disparity is zero, no depth distortion occurred. At right, color interlacing is compared to temporal interlacing. The ordinate is again the disparity that must be added to a horizontal moving stimulus to eliminate depth distortion. The abscissa is the speed of the stimulus. Different symbols represent the results for different colors.

<sup>10</sup>J. Kim, and M. S. Banks, "Effective Spatial Resolution of Temporally and Spatially Interlaced Stereo 3D Televisions (paper 65.1)," *SID Symp. Digest Tech. Papers* **43**(1), 879–882 (2012).

<sup>11</sup>J. Kim, P. V. Johnson, and M. S. Banks, "Stereoscopic 3D display with color interlacing improves perceived depth," *Optics Express* **22**(26), 31924–31934 (2014).

<sup>12</sup>J. D. Krol and W. A. van de Grind, "Depth from dichoptic edges depends on vergence tuning," *Perception* **12**, 425–438 (1983).

<sup>13</sup>J. C. A. Read and B. G. Cumming, "The stroboscopic Pulfrich effect is not evidence for the joint encoding of motion and depth," *J. Vision* **5**, 417–434 (2005).

<sup>14</sup>R. M. Soneira, "3D TV display technology shoot out" (2011); [http://www.displaymate.com/3D\\_TV\\_ShootOut\\_1.htm](http://www.displaymate.com/3D_TV_ShootOut_1.htm)

<sup>15</sup>A. B. Watson, "High frame rates and human vision: A view through the window of visibility," *SMPTE Motion Imaging Journal* **122**, 18–32 (2013).

<sup>16</sup>A. B. Watson, A. J. Ahumada, and J. E. Farrell, "Window of visibility: A psychophysical theory of fidelity in time-sampled visual motion displays," *J. Opt. Soc. Am.* **3**(3), 300–307 (1986). ■

### Submit Your News Releases

Please send all press releases and new product announcements to:

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

**VISIT  
INFORMATION  
DISPLAY ON-LINE  
For daily display  
industry news**

**[www.informationdisplay.org](http://www.informationdisplay.org)**



## SID International Symposium, Seminar & Exhibition

**May 21–26, 2017**  
**Los Angeles Convention Center**  
**Los Angeles, California, USA**

## Rolling Out the Red Carpet



### I-Zone

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

### Individual Honors and Awards

The SID Board of Directors, based on recommendations made by the Honors & Awards Committee, grants several annual awards based upon outstanding achievements and significant contributions.

### Display Industry Awards

Each year, the SID awards Display of the Year Awards in three categories: Display of the Year, Display Application of the Year, and Display Component of the Year.

### Best-in-Show Awards

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

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

Each year a sub-committee of the Editorial Board of *JSID* selects one paper for this award which consists of a plaque and a \$1000 prize.

# Accurate Image-Based Estimates of Focus Error in the Human Eye and in a Smartphone Camera

*Estimation of focus error is a key consideration in the design of any advanced image-capture system. Today's contrast-based auto-focus algorithms in digital cameras perform more slowly and less accurately than the human eye. New methods for estimating focus error can close this gap. By making use of optical imperfections, like chromatic aberration, these new methods could significantly improve the performance of digital auto-focusing techniques.*

by Johannes Burge

THE visual systems of humans and other animals perform powerful computations that exploit information in retinal images that is useful for critical sensory-perceptual tasks. The information in retinal images is determined by the statistical structure of natural scenes, projection geometry, and the properties of the optical system and the retina itself. Task performance is determined by the quality of the information available in retinal images and by how well that information is exploited. To characterize the theoretical limits of performance in a specific natural task, all these factors must be accounted for.

Nearly all sighted mammals have lens-based imaging systems (eyes) that focus and defocus light on the retinal photoreceptors. The estimation of focus error (*i.e.*, defocus) is one particularly important natural task. Focus information is useful for a wide range

of tasks, including depth estimation, eye-growth regulation, and accommodation control.<sup>6,8,15</sup> Typical lenses focus light from only one distance at a time, but natural scenes contain objects and surfaces at many distances. Most regions in images of depth-varying scenes are therefore out-of-focus and blurry under normal observing situations. The amount of image blur caused by a given focus error depends on the lens optics and the size and shape of the lens aperture.

For tasks that depend on high-resolution images, image blur can be a significant impediment. To sharply image an out-of-focus target, the lens must be refocused so that the focus distance equals the target distance. It has been estimated that humans refocus their eyes more than 100,000 times per day.<sup>10,12</sup> Perhaps because of all this practice, human accommodation (biological autofocusing) is fast, accurate, and precise. Two- to three-hundred milliseconds after presentation of a defocused target, the human lens refocuses ballistically with (approximately) the correct magnitude in the correct direction nearly 100% of the time.<sup>7</sup>

Consumers are often frustrated by the slow speed and inaccuracy of image-based smartphone autofocus routines. Achieving the speed of human accommodation would be a great improvement. The most popular image-based autofocus routine is contrast detection. This is a “guess-and-check” procedure that employs an iterative search for maximum contrast. The procedure is non-optimal for at least two reasons: (1) Contrast-detection autofocus does not provide information about focus error sign; when simple detection algorithms start the search for best focus, the direction of the initial response (closer *vs.* farther) is random. (2) Contrast-detection autofocus does not provide estimates of focus error magnitude; in the search for best focus, the focus adjustment often crosses the point of best focus and then must turn around and come back.

Here, we describe recent advances in our ability to estimate focus error from small patches of individual images. We show that precise unbiased estimates of focus error can be obtained for both the human visual system and for a popular smartphone camera. Chromatic aberrations that are introduced by

---

*Johannes Burge is currently an Assistant Professor at the University of Pennsylvania where he is a member of the Department of Psychology and the Neuroscience and Bio-engineering Graduate Groups. He can be reached at [jburge@psych.upenn.edu](mailto:jburge@psych.upenn.edu).*



the lenses of these vision systems can be used to resolve the sign ambiguity. Thus, the approach has the potential to significantly improve image-based autofocus routines in smartphone cameras, medical devices for assistive vision, and other electronic imaging devices.

## Background

Focus-error estimation suffers from an inverse-optics problem; from image information alone, it is impossible to determine with certainty whether a given image pattern is due to focus error (blur) or some feature of the scene (*e.g.*, shadows). Focus-error estimation is also said to suffer from a sign ambiguity; under certain conditions, focus errors of the same magnitude but different signs produce identical images. These issues may make it seem that accurate focus-error estimation from individual images is impossible. However, in many vision systems, the optical properties of the lens and the sensing properties of the photosensor array, together with the statistical properties of natural images, make a solution possible. We now discuss these factors.

## Statistical Properties of Natural Images

Natural images are remarkably varied. In natural viewing conditions, the eye images a staggering variety of object colors, shapes, sizes, and textures [Fig 1(a)]. In spite of this

variation, there is one property of natural images that is relatively stable: the shape of the amplitude spectrum. Most well-focused natural-image patches have amplitude spectra with a  $1/f$  fall-off; *i.e.*, in a typical patch, there is  $10\times$  less contrast at 10 cpd (cycles per degree) and  $30\times$  less at 30 cpd than at 1 cpd. Of course, the shape of the amplitude spectrum varies somewhat with patch content, and variability increases as patch size decreases. Nevertheless, the shape of the natural amplitude spectrum is stable enough. To obtain an empirical estimate of the statistical structure of natural images, we collected a large database of well-focused images of natural scenes.<sup>2</sup>

## Optical Properties of Lenses

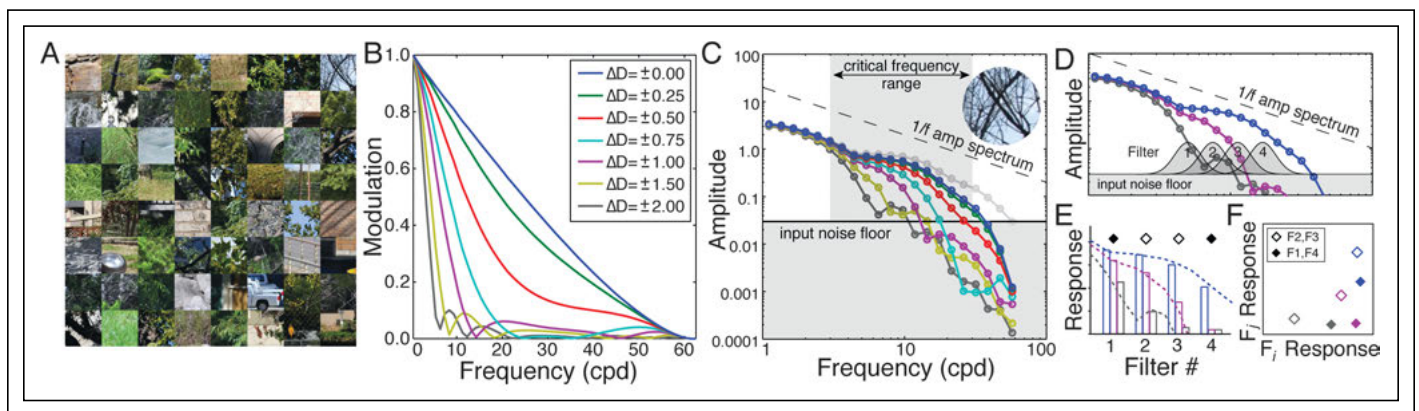
Focus-error changes the shape of the amplitude spectrum. Small focus errors attenuate the spectrum (*i.e.*, power) at high frequencies; intermediate focus errors attenuate the spectrum at intermediate frequencies, and so on [Fig. 1(b)]. These shape changes provide information about focus-error magnitude [Fig. 1(c)]. However, under certain conditions, lenses provide no information about the sign of the error (focus too close vs. too far). For example, in an ideal optical system with monochromatic light, image quality is degraded by focus error (*i.e.*, defocus) and diffraction alone. Focus errors of the same magnitude but opposite signs thus yield identical

point-spread functions (PSFs) and corresponding modulation-transfer functions [MTFs; Fig. 1(b)]. The effect of this type of focus error on the amplitude spectrum of a representative natural image patch is shown in Fig. 1(c).

In real optical systems with broadband light, image quality is degraded not just by defocus and diffraction, but also by chromatic and monochromatic aberrations other than defocus (*e.g.*, astigmatism). Although these aberrations reduce best-possible image quality, they introduce information into retinal images than can be used to precisely estimate the magnitude and sign of focus error.<sup>2,3,17</sup> Here, we focus on the usefulness of chromatic aberration in the human visual system<sup>14</sup> and smartphone cameras.

## Sensing Properties of Photosensors

For chromatic aberrations to be useful, the vision system must be able to sense them. The human visual system and most cameras have arrays of sensors that are differentially sensitive to long-, medium-, and short-wavelength light. In human vision, the sensitivities of the long- (L), medium- (M), and short- (S) wavelength cones peak at 570, 530, and 445 nm, respectively.<sup>13</sup> In the human eye, the change in chromatic defocus between the peak sensitivities of the L and S cones is approximately 1 diopter (D).<sup>1</sup> In many cameras, the sensitivity of the red, green, and blue sensors



**Fig. 1:** Signals for focus-error estimation: (a) Natural image variation is substantial. (b) Monochromatic modulation transfer function (MTF) in a diffraction limited lens for a range of focus errors (colors). The MTF is the modulus of the Fourier transform of the point-spread function (PSF). (c) The amplitude spectrum of a particular local patch ( $1^\circ$ , inset) changes shape systematically with focus error (colors matched to b). (d) Spatial-frequency filters (Gaussian bumps labeled 1–4) tiling the critical band of the spatial-frequency domain. (e) Each filter responds according to power in the spectrum in its passband. The responses provide a digital approximation to the shape of the amplitude spectrum. (f) Joint filter responses. Filter 2 and 3 responses (open symbols) to spectra with different focus errors are significantly further apart than filter 1 and 4 responses (closed symbols). Hence, filters 2 and 3 provide more useful information for classifying focus error in this patch.

peak at 590, 530, and 460 nm. In most cameras, chromatic defocus is markedly less than in the human eye. But even in high-quality achromatic prime lenses, measureable chromatic defocus occurs between the R and B sensors.<sup>3</sup>

### General Principle of Estimation

The first job of a good estimator is to determine the signal features that carry good information about the task-relevant variable. Figure 1(d) shows the amplitude spectra of four generic filters (shaded Gaussian bumps), along with spectra for three amounts of focus error. Each filter increases its response according to the local power in the amplitude spectrum (above the noise floor) at the spatial frequencies to which each filter is sensitive. This set of spatial-frequency filters [Fig. 1(d)] provides a digital approximation of amplitude spectra [Fig. 1(e)], much like a bass equalizer on a car stereo provides a digital approximation of the amplitude spectra of sound waves. Figure 1(f) plots the

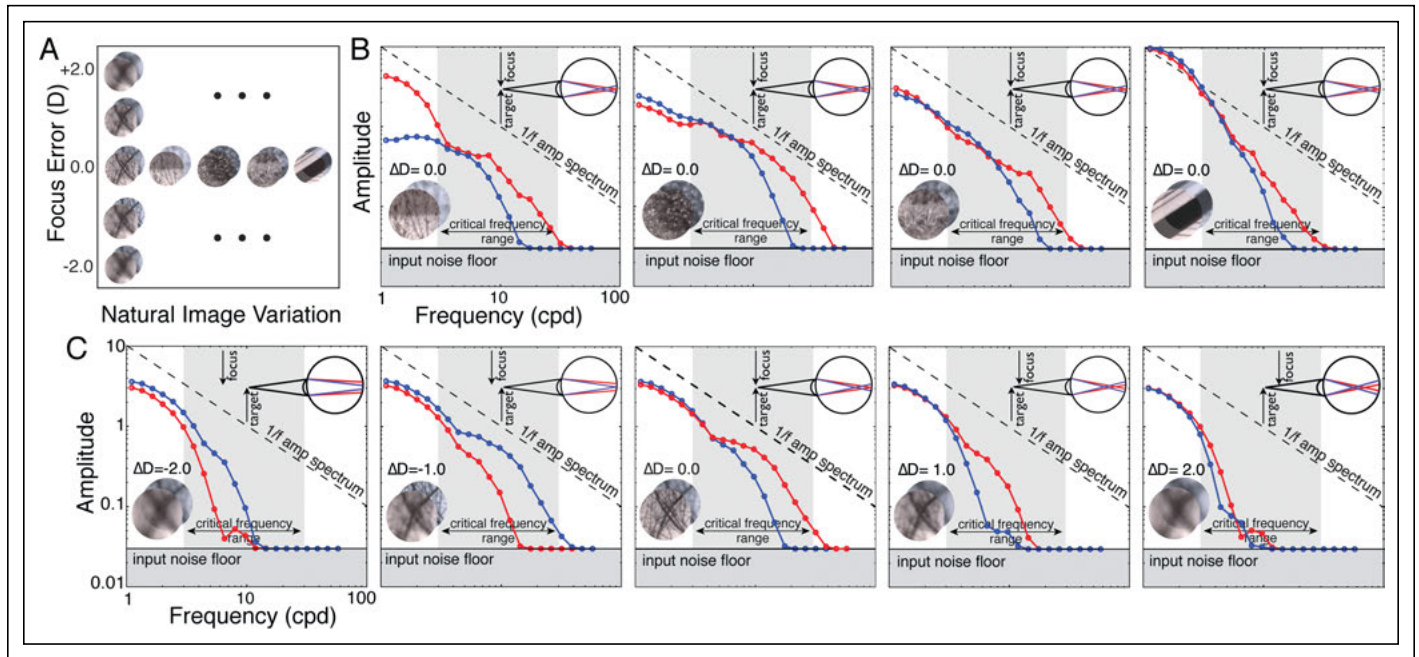
responses of the filters against each other. Filters 2 and 3 are more useful than 1 and 4 for discriminating the three focus errors in the patch.

The problem of estimating focus error in a particular image patch is trivial compared to the task of estimating focus error in a random image patch. Natural-image variation introduces task-irrelevant changes in the typical  $1/f$  shape of the amplitude spectrum that makes the problem difficult. But focus error can be estimated because it introduces shape changes that are more dramatic than those introduced by image variation. In general, if a measurable signal varies more due to the task-relevant variable than to task-irrelevant image variation, then the accurate estimation of the task-relevant variable is possible.<sup>4,5</sup> For the current task of focus error estimation in human and smartphone camera lenses, this condition holds.

Figure 2 demonstrates that this condition holds in the human visual system. Figure 2(a) shows examples from a training set; focus error

varies down the rows, image content varies across the columns [Fig. 2(a)]. Image variation introduces task-irrelevant variability in the shape of the spectrum [Fig. 2(b)], but focus error introduces much larger changes [Fig. 2(c)]. The most useful changes due to focus error occur within a critical spatial-frequency band. Natural images, because of their  $1/f$  spectra, rarely have power exceeding the noise floor at high spatial frequencies. Focus error has little effect on low spatial frequencies. Thus, intermediate spatial frequencies carry the most useful information about focus error. This is the critical frequency band.

Human chromatic aberration [Figs. 2(b) and 2(c), (insets)] causes systematic differences between the spectra in two (or more) color channels that provide useful information about the sign of focus error. For negative errors (*i.e.*, focus too far), the short-wavelength sensor image is in better focus than the long-wavelength sensor image. For positive errors (focus too close), the long-wavelength



**Fig. 2:** Impact of natural-image variability and focus error on shapes of amplitude spectra. Results shown for a lens with human chromatic aberration for the L- and S-cone images and for a 2-mm pupil. (a) Training set of natural image patches with different focus errors (8400 patches = 21 focus errors  $\times$  400 patches per error). (b) Amplitude spectra of the L-cone image (red) and S-cone image (blue) for four different well-focused image patches. (c) Amplitude spectra for the same patch with five different focus errors. The eyeball icon indicates focus error geometry: Negative and positive focus errors correspond to when the lens is focused behind and in front of the target, respectively. The shape of the amplitude spectrum varies randomly with the image patch and changes systematically with the focus error. The amplitude spectrum shape provides good information about focus-error magnitude. The L-cone or S-cone spectrum with more energy at higher frequencies provides good information about focus-error sign.

sensor image is in better focus. Chromatic aberration thus introduces a useful signal for determining the sign of a focus error.

## Results

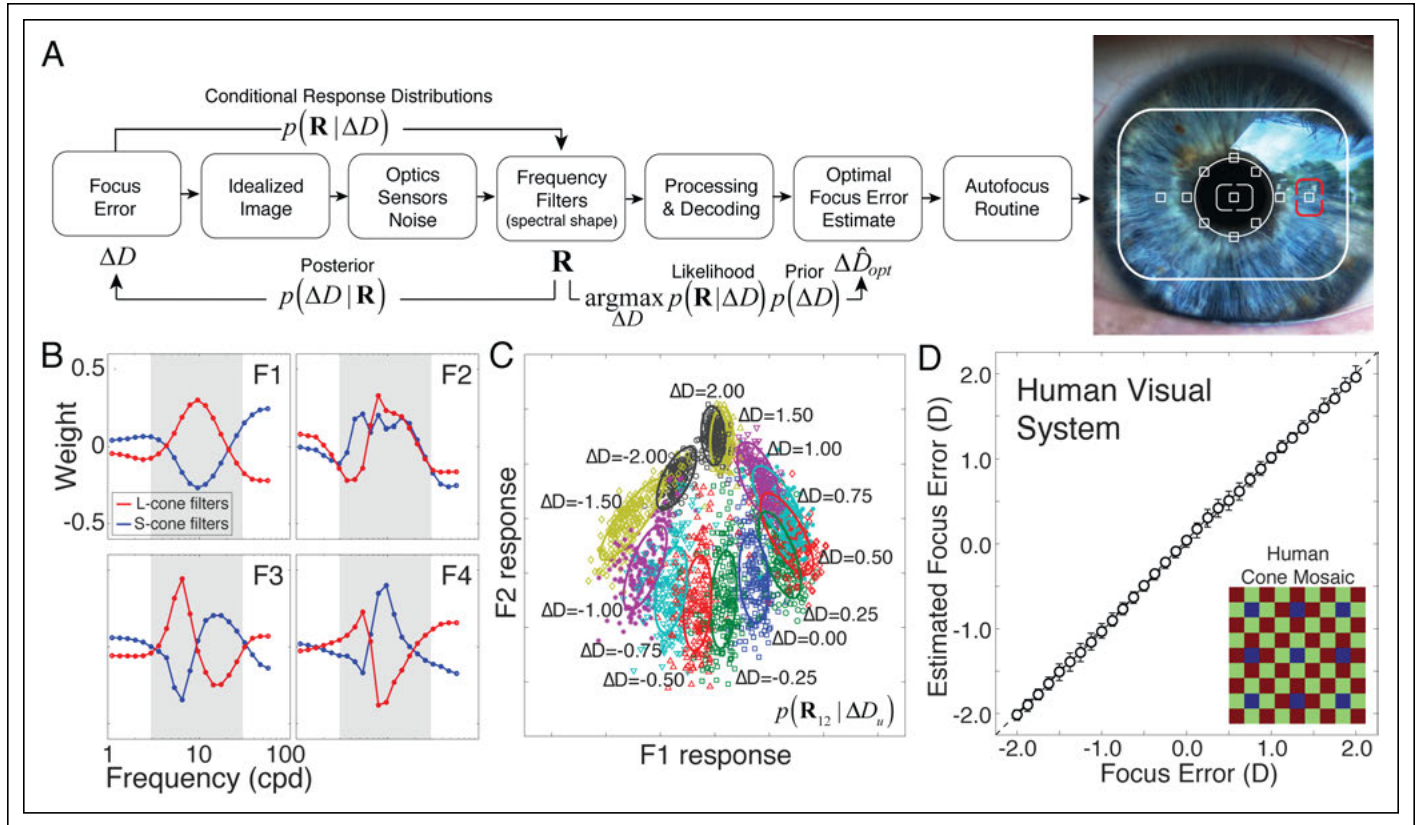
We developed an algorithm for estimating focus error based on the principles and observations described above.<sup>2</sup> We next describe its performance for the human visual system and for a popular smartphone camera: the Samsung Galaxy S4. For the human visual system, we assumed a 2-mm pupil (typical for daylight), optics with human chromatic aberration, sensors with the wavelength sensitivities of the L and S cones, and a plausible input noise level.<sup>16</sup> For the Galaxy S4, we assumed

a fixed 1.7-mm aperture and measured its optics, wavelength sensitivity, and noise in the R and B sensors.<sup>3</sup> (Two of the three available sensors are used for computational simplicity. Similar performance is obtained with all three sensors together.) Note that image blur due to focus error decreases as aperture size decreases. Vision systems with larger apertures and comparable optics will, in general, yield more accurate results than those presented here.

Next, in each vision system we found the spatial-frequency filters that are most useful for estimating focus error from  $-2.5$  to  $+2.5D$  using Accuracy Maximization Analysis, a recently developed task-specific method for dimensionality reduction. Assuming a focus

distance of 40 cm, this range of focus errors corresponds to distances of 20 cm to infinity. For the human visual system, the filters operate on the amplitude spectra of the L- and S-cone sensor images. For the Galaxy S4 smartphone, the filters operate on the amplitude spectra of the R- and B-sensor images.

The four most useful filters for estimating focus error in the human eye are shown in Fig. 3(b). These filters find the spectral features that provide the best possible information about focus error, given the variability of natural images and the effect of focus error in each color channel on the captured images' amplitude spectra. The filters concentrate in and near the frequency range known to drive



**Fig. 3:** Focus-error estimation in the human visual system. (a) Schematic of optimal focus-error estimation and how it can be used to eliminate focus error as part of an autofocus routine. The estimate of focus error can be used as input to an autofocus routine to null focus error. (b) Spatial-frequency filters that extract the most useful information for estimating focus error in the human visual system. The filters weight and sum of the amplitude spectra of captured L-cone and S-cone images. The first filter is selective for differences in the shapes of the L- and S-cone amplitude spectra and is most useful for discriminating focus-error sign. The second filter is less selective for differences between the color channels. The filters apply more weight to an intermediate frequency band because this band carries the most useful information. (c) Filters 1 and 2 responses to different retinal images (symbols) with different focus errors (colors). The conditional filter responses cluster as a function of focus error and can be approximated by a Gaussian distribution. (d) Optimal focus-error estimates across thousands of test images. Error bars represent 68% confidence intervals. Inset shows the rectangular approximation of the human-cone mosaic used to sample the images.



human accommodation.<sup>9</sup> These filters also have properties that are similar to chromatic double-opponent cells in early visual cortex,<sup>11</sup> which have primarily been studied in the context of color processing.

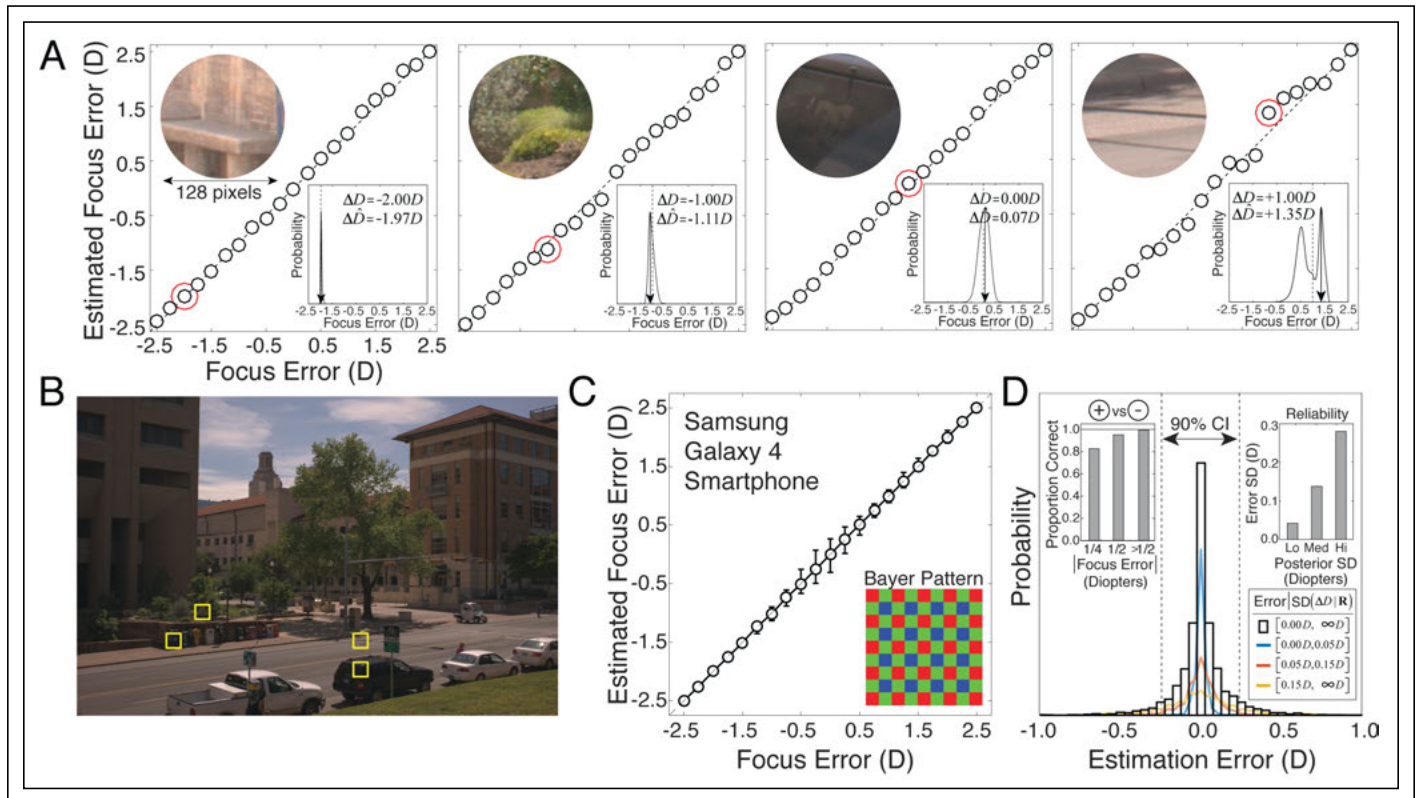
The responses of the two most useful filters to thousands of randomly sampled natural-image patches with different amounts of focus error are shown in Fig. 3(c). Each symbol represents the filter responses to a particular individual image patch. Each color represents a different focus error. The fact that the responses cluster by focus error indicates that the filters extract good information about focus error from the shape of the amplitude spectrum. Next, we characterized the

joint filter responses by fitting Gaussians  $gauss(\mathbf{R}; \mu_u, \Sigma_u) = p(\mathbf{R} | \Delta D_u)$  to each response cluster, where  $\mu_u$  and  $\Sigma_u$  are the sample means and covariance [colored ellipses, Fig. 3(b)]. Figure 3(d) shows focus-error estimation performance in the human visual system for thousands of randomly sampled image patches. In humans, high-precision ( $\pm 1/16D$ ) unbiased estimates of focus error are obtainable from small patches from the L- and S-cone sensor images of natural scenes.

The human visual system has much more chromatic aberration than the lenses in typical DSLR and smartphone cameras. How well do these same methods work in DSLRs and smartphones? We have previously examined

the performance attainable in a DSLR camera.<sup>3</sup> Here, we determine focus-error estimation performance in the Galaxy S4. We measured the R, G, and B sensor wavelength sensitivities and the optics of the Galaxy S4 over a range of 5D and then used our methods to estimate focus error.

Estimation results are shown in Fig. 4. Figure 4(a) shows focus-error estimates for each of four randomly sampled patches across the range of focus errors. In each subpanel, the inset shows the posterior probability distribution over focus error for the condition circled in red. For reference, the full-size image from which the four patches were sampled is shown in Fig. 4(b). Performance is



**Fig. 4:** Focus-error estimation with Samsung Galaxy S4 smartphone optics and sensors. (a) Focus-error estimation for four randomly sampled natural image patches (128 x 128 pixels) over  $-2.5$  to  $+2.5D$ . Insets show the particular image patch (without blur) and the posterior probability over focus error for one particular groundtruth focus error (red circle). Dashed vertical line indicates the true focus error. The variance (width) of the posterior can be used as a measure of estimate reliability. Performance is nearly identical with 64 x 64 pixel patches. (b) Original image from which the patches were sampled. (c) Average estimation performance as a function of focus error across 8400 test patches (21 focus errors x 400 patches). Error bars are 68% confidence intervals. Inset shows the sensor pattern that was used to sample the images. (d) Grand histogram of estimation errors. 90% of estimates are accurate to  $+0.25D$  (approximately the human blur detection threshold).<sup>10</sup> Colored lines show error histogram conditioned on the standard deviation of the posterior: low ( $SD = 0.00\text{--}0.05D$ ; blue), medium ( $SD = 0.05\text{--}0.15D$ ; red), high ( $SD > 0.15D$ ; orange). Upper right inset shows that the standard deviation of the estimation error increases with the standard deviation of the posterior probability distribution. Upper left inset shows the proportion of the time focus-error sign is estimated correctly as a function of the true focus error. For focus errors  $0.5D$  or larger, the sign is estimated correctly 99% of the time.

good for each patch, but it is not perfect, and some patches produce more accurate estimates than others. For example, estimates for the patch in the rightmost subpanel of Fig. 4(a) are the least accurate on average. The shadows against the street curb make the sharp patch (inset) look somewhat blurry. Some of the same features that confuse humans seem to confuse the algorithm. Also, a featureless surface carries no information about focus error, and therefore yields highly inaccurate estimates. This variability in accuracy across patches is an unavoidable aspect of estimation performance with natural stimuli.<sup>10</sup>

It would therefore be advantageous for an autofocus routine to have not just an estimate of focus error but of each estimate's reliability. The standard deviation (width) of the posterior probability distribution predicts the reliability of each patch-by-patch estimate. This signal could therefore have utility in the design of a control system for autofocusing a smartphone camera.

Estimation performance in the Samsung Galaxy S4, averaged across thousands of patches, is shown in Figs. 4(c) and 4(d). None of the test patches were in the training set, indicating that the estimation algorithm should generalize well to arbitrary images. The grand histogram of estimate errors is shown in Fig. 4(d). Errors are generally quite small. 90% of the estimates are within +0.25D of the correct value. Given the 1.7-mm aperture and 4.2-mm focal length of the Galaxy S4 ( $f$ -stop of  $f/2.4$ ), errors of  $\sim 0.25D$  will be within the depth of field. Sign estimation was also accurate.

The colored lines in Fig. 4(d) show error histograms conditioned on the standard deviation of the posterior probability distribution. When the posterior probability distribution has a low standard deviation [e.g., Fig 4(a), left panel] errors are very small. When the posterior probability distribution has a high standard deviation [e.g., Fig 4(a), right panel], errors tend to be larger. These results show that, in both humans and a popular smartphone camera, accurate estimates of focus error (including sign) can be obtained from small patches of individual images.

## Applications

The method described here provides highly accurate estimates of focus error, given the optics and sensors in a popular smartphone camera, and it has the potential to signifi-

cantly improve the autofocus routines in smartphone cameras and other digital-imaging devices. It has the advantages of both contrast-measurement and phase-detection autofocus techniques, without their disadvantages. Like phase detection, the method provides estimates of focus error (magnitude and sign) but unlike phase detection, it does not require specialized hardware. Like contrast measurement, the method is image based and can operate in "Live View" mode, but unlike contrast measurement, it does not require an iterative search for best focus. And because the method is image based and can be implemented exclusively in software, it has the potential to improve performance without increasing manufacturing cost.

This same method for estimating focus error may also be useful for improving certain medical technologies. A number of different assistive vision devices have hit the market in recent years. These devices act, essentially, as digital magnifying glasses. If these devices could benefit from improved autofocusing, our method could apply there as well.

## References

- <sup>1</sup>F. Autrusseau, L. Thibos, and S. K. Shevell, "Chromatic and wavefront aberrations: L-, M-, and S-cone stimulation with typical and extreme retinal image quality," *Vision Research* **51**(21–22), 2282–2294 (2011); <http://doi.org/10.1016/j.visres.2011.08.020>
- <sup>2</sup>J. Burge and W. S. Geisler, "Optimal defocus estimation in individual natural images," *Proceedings of the National Academy of Sciences of the United States of America* **108**(40), 16849–16854 (2011); <http://doi.org/10.1073/pnas.1108491108>
- <sup>3</sup>J. Burge and W. S. Geisler, "Optimal defocus estimates from individual images for autofocusing a digital camera," *Proc. IS&T/SPIE 47th Annual Meeting, Proc. SPIE* (2012); <http://doi.org/10.1117/12.912066>
- <sup>4</sup>J. Burge and W. S. Geisler, "Optimal disparity estimation in natural stereo images," *J. Vision* **14**(2) (2014); <http://doi.org/10.1167/14.2.1>
- <sup>5</sup>J. Burge and W. S. Geisler, "Optimal speed estimation in natural image movies predicts human performance," *Nature Communications* **6**, 7900 (2015); <http://doi.org/10.1038/ncomms8900>
- <sup>6</sup>R. T. Held, E. A. Cooper, J. F. O'Brien, and M. S. Banks, "Using Blur to Affect Perceived Distance and Size," *ACM Transactions on Graphics* **29**(2), 19:1–19:16 (2010); <http://doi.org/10.1145/1731047.1731057>
- <sup>7</sup>S. Kasthurirangan, A. S. Vilupuru, and A. Glasser, "Amplitude dependent accommodative dynamics in humans," *Vision Research* **43**(27), 2945–2956 (2003).
- <sup>8</sup>P. B. Kruger, P. B., Mathews, S. M. Katz, K. R. Aggarwala, and S. Nowbotsing, "Accommodation without feedback suggests directional signals specify ocular focus," *Vision Research* **37**(18), 2511–2526 (1997).
- <sup>9</sup>K. J. MacKenzie, D. M. Hoffman, and S. J. Watt, "Accommodation to multiple-focal-plane displays: Implications for improving stereoscopic displays and for accommodation control," *Journal of Vision* **10**(8), 22 (2010); <http://doi.org/10.1167/10.8.22>
- <sup>10</sup>S. Sebastian, J. Burge, and W. S. Geisler, "Defocus blur discrimination in natural images with natural optics," *Journal of Vision* **15**(5), 16 (2015); <http://doi.org/10.1167/15.5.16>
- <sup>11</sup>R. Shapley and M. J. Hawken, "Color in the cortex: single- and double-opponent cells," *Vision Research* **51**(7), 701–717 (2011); <http://doi.org/10.1016/j.visres.2011.02.012>
- <sup>12</sup>W. W. Sprague, E. A. Cooper, S. Reissier, B. Yellapragada, and M. S. Banks, "The natural statistics of blur," *Journal of Vision* **16**(10), 23 (2016); <http://doi.org/10.1167/16.10.23>
- <sup>13</sup>A. Stockman and L. T. Sharpe, "The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype," *Vision Research* **40**(13), 1711–1737 (2000).
- <sup>14</sup>L. N. Thibos, M. Ye, X. Zhang, and A. Bradley, "The chromatic eye: a new reduced-eye model of ocular chromatic aberration in humans," *Applied Optics* **31**(19), 3594–3600 (1992).
- <sup>15</sup>C. F. Wildsoet and K. L. Schmid, "Emmetropization in chicks uses optical vergence and relative distance cues to decode defocus," *Vision Research* **41**(24), 3197–3204 (2001).
- <sup>16</sup>D. R. Williams, "Visibility of interference fringes near the resolution limit," *J. Opt. Soc. Am. A* **2**(7), 1087–1093 (1985).
- <sup>17</sup>B. J. Wilson, K. E. Decker, and A. Roorda, "Monochromatic aberrations provide an odd-error cue to focus direction," *J. Opt. Soc. Am. A, Optics, Image Science, and Vision*, **19**(5), 833–839 (2002). ■

# ID Interviews David Fattal, Founder and CEO of LEIA, a Silicon Valley Startup That Is Developing an Interactive Holographic Display for Mobile Devices

*David Fattal was the principal investigator of the LEIA project at HP Labs, from where he led a spin-off in late 2013 to co-found LEIA, Inc. Fattal spent his early career in the Quantum Photonics group at HP Labs, specializing in the manipulation of light at the nanoscale. He has a Ph.D. in physics from Stanford University and a B.S. in mathematical physics from Ecole Polytechnique, France. In 2013, he was featured in the MIT Tech Review list of 35 Innovators under 35 and was also awarded the French Order of Merit for inventing the Multiview Backlight concept. He is the author of 80 granted patents.*

Conducted by Jenny Donelan

**ID:** Can you tell us a little about LEIA? How did you get started? What's the mission?

**DF:** LEIA, Inc., is a technology spinoff from HP Labs. Our research team had been working on optical interconnect for many years, an area of photonics concerned with the transmission and manipulation of information in optical-form inside computer chips. Using specially designed nano-photon structures similar to diffraction gratings, we were routinely extracting light from planar “photonics” chips into directional light beams that would be coupled to optical fibers and transported to another chip. We enjoyed great success in controlling the precise parameters of light extraction using wavefront engineering techniques.

Today, these same types of nano-structures and wavefront engineering methods are powering LEIA's core holographic-display technology. We became an independent company, based in Menlo Park, California, in early 2014. We have a clear mission to accelerate the time to market for smartphone display products. And beyond cell phones, we are also now looking at all kinds of form factors – from tablet to laptop to automotive.

Our long-term goal is to become THE interface technology to the digital world,

letting you visualize, manipulate, and touch 3D holographic content from any type of screen.

**ID:** How does LEIA's holographic technology work?

**DF:** Today, LEIA's products are based on a slight modification of an LCD. We use an off-the-shelf LCD frontplane and simply augment the backlighting unit with our nano-structures, resulting in a so-called diffractive light-field backlight (DLB). The result is a display that you can either operate in its original 2D mode – with no loss of brightness or resolution – or in a light-field “holographic” mode, where many different images can be projected into different regions of space, producing an effect of both depth and parallax for several viewers at a time.

**ID:** So what would it be like for me to use this technology?

**DF:** First and foremost, you have the option to operate the display in conventional 2D mode. In a smartphone context, this would be the normal mode of operation for the home screen, reading news and emails, or even for operation in a VR headset such as Gear VR or Google Daydream. But you would also have the option to launch a 3D app – HoloChat, for instance – where the display would transition smoothly to light-field mode and let you enjoy a conversation with a holographic image of a friend,

---

*Jenny Donelan is the Managing Editor of Information Display Magazine. She can be reached at [jdonelan@pcm411.com](mailto:jdonelan@pcm411.com).*



seen directly on the device (no headset needed). This image would provide a sense of depth, parallax, and accurate rendering of textures. Skin looks like skin (without that “plastic” effect you get with a 2D display) and metal looks truly “shiny” due to the ability to create an angle-dependent treatment of light reflections.

As long as you stay within the prescribed field of view (anywhere between 30 and 90° depending on the version), the parallax movement is coherent. If you want to see completely around objects, we use tricks to detect the relative motion of the phone to the user’s face and are able to shift the field of view dynamically to accommodate extreme points of view (our so-called dynamic-FOV feature). Last but not least, our handsets will soon be equipped with a hover touch feature that will let users manipulate holographic content above the screen using finger motion. The resulting experience is quite magical.

**ID:** It sounds like it! What are some other likely applications?

**DF:** Gaming and 3D video streaming are obvious applications for which an ecosystem is already in place, and tons of content is readily available. But this is barely scratching the surface. We are big believers in “social 3D,” a suite of apps giving you the ability to scan your friends and yourself in 3D and use these avatars in messaging, videos, chat, social networks, *etc.* (See, for example, AltspaceVR at <https://altvr.com>.) Augmented reality is another big potential application, letting you introduce 3D digital content over the real world seen through the device.

**ID:** What recent breakthroughs have made this technology commercially viable today vs. yesterday?

**DF:** There is a combination of factors. First, nano-manufacturing methods have recently achieved an unprecedented level of maturity, which allow the mass-fabrication of our backlight parts. This is how we can reliably define structures with dimensions of a few hundred nanometers at very precise locations on the surface of the backlight and in a cost-effective way. Second, mobile chipsets are now powerful enough to handle 3D rendering at sufficient speed and decent power-consumption levels. And it’s only getting better with the push for VR.



*David Fattal*

Last but not least, the 3D ecosystem has grown tremendously from that of a few years ago. Most games today are based on 3D assets rendered for a 2D screen, and they are straightforward to re-compile for a LEIA screen. Shooting real content in 3D has become routine, and content developers are now looking forward to the next multiview media platform. It could be VR or it could be us – the good news is that the data formats are almost identical.

**ID:** Do you have plans to jump-start your business?

**DF:** We announced a partnership with the technology and media group Altice back in May to bring the first holographic smartphone to the European market by the end of 2017.

**ID:** What challenges/pitfalls do you expect to encounter?

**DF:** The main challenge at this point is to get enough content ready for the launch. We are well on our way there.

**ID:** From an entrepreneurial standpoint, what does it take for someone to start a business like this?

**DF:** To tell you the truth, you need to be extremely self-confident and slightly crazy. Not many new display technologies have been successful in the marketplace in recent years. However, you don’t stumble on a major innovation like that powering LEIA very often either. When starting LEIA, we made a big bet that leaving the corporate world to build a new venture from scratch was the right thing to do. Now that the technology is commercially ready with paying customers, this seems like a no-brainer, but at the time we (and our early investors) were taking a big risk.

**ID:** What lessons have you learned so far?

**DF:** Just keep your head down and keep grinding!

Readers can see LEIA’s technology first-hand, including smartphone demos, at Display Week 2017 in Los Angeles this May. ■

“ Just keep your head down and keep grinding! ”

# Quantifying Display Coating Appearance

*Modern displays often utilize anti-reflection coatings to enhance contrast and improve readability. However, display manufacturers have unique requirements for coatings not found in other industries. New metrology instrumentation has been designed to obtain the necessary measurements for display makers and to work with the thin glass substrates increasingly employed in display fabrication.*

by Trevor Vogt

**A**NTI-REFLECTION (AR) coatings are often used on the outermost glass surface of flat-panel displays to reduce glare and increase visibility. But while AR coating technology has been utilized for decades with a variety of precision optics, including telescopes, camera lenses, microscope optics, laser components, and even eyeglasses, its use in display applications presents some challenges not encountered in those other applications. In particular, display manufacturers are often highly concerned with the apparent color and unit-to-unit consistency of the coating. Even slight variations in a thin-film coating that do not put it out of specification in terms of overall reflectance and transmittance values can change the reflected color in a way that is readily perceptible to the eye, thereby impacting perceived quality and value. These variations are common in AR coatings.

This article reviews the need for coatings and how they operate and explores the technology used for quantifying coating performance and color. Finally, we discuss the experiences of MAC Thin Films, a manufacturer of coatings for display applications, and show how this company implemented instrumentation from Gamma Scientific to successfully perform coating color measurement on a production basis.

**Trevor Vogt** is Technical Product Manager at Gamma Scientific and can be reached at [tvogt@gamma-sci.com](mailto:tvogt@gamma-sci.com), [www.gamma-sci.com](http://www.gamma-sci.com).

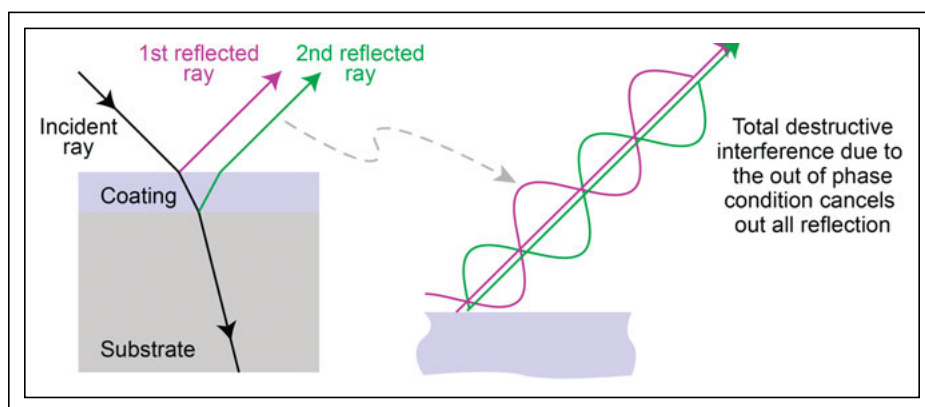
## AR Coating Basics

A glass window forms the topmost layer of most commercial display types, including LCDs and AMOLED displays and virtually all types of capacitive touch-screen displays. Glass by itself reflects about 4% of incident visible light at each interface with air (with normal,  $0^\circ$  angle of incidence). Since the glass display window is invariably bonded to another material, usually a polarizer, this 4% reflectance generally occurs only at the outermost layer of the display. However, even this relatively low reflection is still sufficient to be visually distracting and can make the display substantially harder to read in high ambient light. To compensate for this, the user will often increase display luminance, consuming

more precious battery power. The application of an AR coating to the top glass surface reduces the reflection to a much lower level and therefore improves both optical performance and battery life.

AR coatings consist of one or more thin layers of materials, typically dielectrics, which are deposited directly on to the surface of the glass. These layers modify the reflectance characteristics of the glass through the mechanism of optical interference, enabled by the wave properties of light. A simplified schematic of how this works is shown in Fig. 1.

The conditions shown in the figure for complete elimination of the reflection using a single-layer coating can only be exactly satis-



**Fig. 1:** This schematic shows a representative single-layer AR-coating operation. Illustration courtesy Gamma Scientific.

fied at one wavelength and one angle of incidence. Thus, while single-layer AR coatings are widely used, thin films for more demanding applications often comprise multiple layers of various materials and thicknesses. These more complex multilayer designs can deliver higher performance and enable operation over a wider range of wavelengths and incident angles. They also permit the use of the most practical and readily available coating materials.

### Coating Fabrication Challenges

There are a number of different technologies currently in use for producing the types of multilayer thin-film optical coatings just described. Typically, these involve converting a series of solid coating materials into vapor utilizing heating, sputtering, or some kind of chemical means. The process is performed within a vacuum chamber, and, in some cases, oxygen or other gasses are introduced to the chamber to react with the coating material and create new species. Once vaporized, the

coating material eventually recondenses on the surface of the substrate in a thin layer whose thickness is carefully controlled. The use of different coating materials in series allows for multilayer films of substantial complexity and sophistication to be created.

Of course, any real-world manufacturing process experiences variations. For coatings, these are most significantly errors in layer thickness and variations in layer refractive index from the design goal. These small variations become particularly important in coatings for consumer display applications because cosmetic coating appearance is more important in this context than for most other uses.

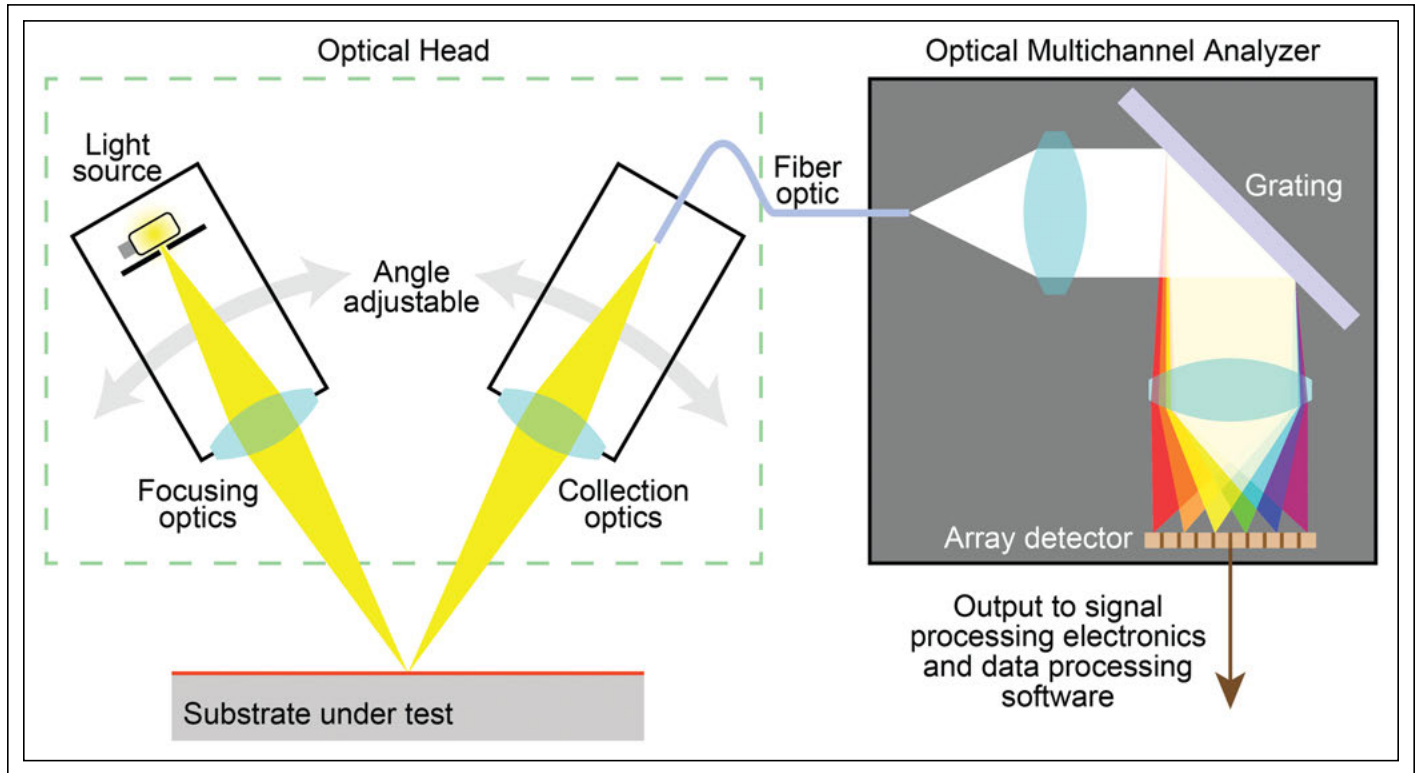
A particular problem arises because virtually all AR coatings appear to have a color cast when viewed in reflection under white-light illumination. Furthermore, this color depends very strongly on the exact thickness and refractive index of each individual coating layer. Even slight variations in these parameters, which are not large enough to keep the coating

from meeting its nominal reflectance and transmittance specifications, can significantly influence its visual appearance. Thus, it is common to see batch-to-batch variations in reflected color for a given AR coating design.

These variations in perceived coating color are particularly objectionable to display manufacturers who want a product that is visually consistent from unit to unit and that conforms to cosmetic standards congruent with brand image. For example, manufacturers want to be able to display their products side by side in retail stores without the consumer seeing obvious differences in color (whether as a result of coatings or other causes).

### Color-Measurement Basics

For the manufacturer, the first step in controlling coating color is measuring it accurately. The schematic of one type of system for quantifying surface reflectance is shown in Fig. 2. In this instrument, called a goniospectrophotometer, a light source is focused at a non-normal angle of incidence onto the surface



**Fig. 2:** The main functional optical elements of a goniospectrophotometer include (left) optics for focusing a light source onto the device under test and collecting the reflected light and (right) a dispersive element and array detector that enables the spectral content of the collected light to be analyzed. Illustration courtesy Gamma Scientific.



under test. In order to make measurements that span the entire visible spectrum, a broadband light source, such as a halogen bulb, is used.

Collection optics are positioned exactly opposite the source angle of incidence in order to collect specularly reflected light (as opposed to scattered light). The gathered light is then focused into a fiber-optic cable. Sometimes the positions of the focusing and collection optics can be mechanically adjusted along an arc, centered on the surface under test, to enable measurements at a variety of incidence angles.

The fiber feeds into an optical multichannel analyzer (OMA). This is a type of spectrometer that uses a diffraction grating to split the broadband input light into its spectral components. This light is then focused onto the equivalent of a 1024-pixel linear-array detector so that each element of the array only collects light from a small band of wavelengths. This allows the instrument to make a rapid measurement of reflectance intensity as a function of wavelength over the entire desired spectral range all at once.

However, this spectral reflectance data does not quantify how an object appears to the human visual system (its perceived color). And even minor changes in the reflected spectrum can affect the human experience of color. Representing color in a way that corre-

lates well with human visual experience requires working in a calibrated color space, such as those defined by the International Commission on Illumination (CIE). The radiometric spectral data from the OMA is, therefore, mathematically converted into colorimetric tristimulus values which can then be mapped into any one of the numerous CIE color spaces.

### Advanced Coating Measurement Technology

Various embodiments of this type of goniospectrophotometer technology have been commercially available from a number of manufacturers for decades. This basic measurement engine design is effective and well-proven. However, all past commercial products have had some combination of practical limitations that prevented their use in high-volume industrial inspection applications such as display metrology.

One significant drawback of most commercial goniospectrophotometers is that their optics collect light from several of the many closely spaced multiple reflections that occur in a glass component, when all that is desired is the first reflection from the top surface (see Fig. 3). This is particularly problematic when measuring AR coatings on an individual glass substrate because the signal from the top

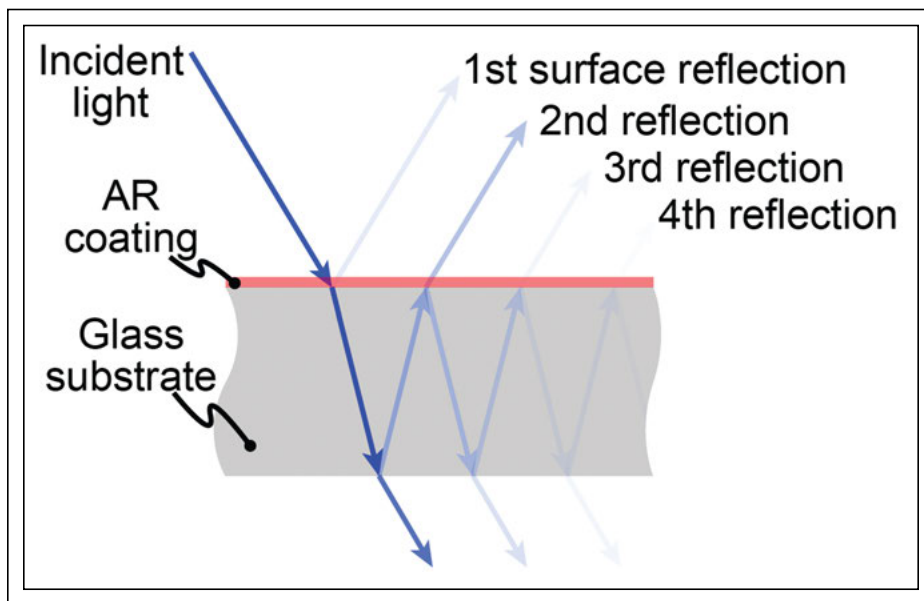
(AR coated) surface is much smaller than the unwanted returned light from the uncoated bottom surface. Note that these multiple reflections do not occur when the glass is integrated into a tablet or cell-phone display because then the bottom glass surface will be in contact with another material (usually a polarizer) having a similar index of refraction. Rather, this issue only occurs when attempting to measure the glass substrate after coating, but before it is integrated into the display assembly. This is a specific application challenge because the testing is performed by the cover-glass manufacturer, not the final display integrator. At point of test, the glass manufacturer has no access to the polarizer or the other display components that will eventually be used with it. But manufacturers still need to ensure that the glass they produce will deliver the necessary performance in the final assembly. Thus, they need to suppress the second surface reflectance (because the polarizer will eliminate it in the final display assembly) and measure just the first surface reflectance.

The reflection from the bottom surface can be reduced or eliminated by covering it with an absorptive paint or by placing that surface in contact with an index-matching fluid. However, both of these approaches introduce extra steps into the measurement process (painting, cleaning, *etc.*), often representing an unacceptable increase in production costs for high-volume fabrication.

Alternately, some instrument makers do not suppress the second surface reflection, but instead use a mathematical algorithm to subtract it from the measured data. Unfortunately, this indirect approach requires that assumptions be made about the refractive index and absorption characteristics of the glass under test, which cannot easily be verified. This method therefore substantially limits results accuracy.

A more ideal solution is to introduce some sort of spatial filtering into the collection optics. This takes advantage of the fact that, at other than normal incidence, there is a small lateral displacement between the desired top surface reflection and the other multiple reflections. Thus, the unwanted light can be physically blocked out.

This approach delivers superior accuracy, especially for AR coatings, and does not increase measurement cost or reduce measurement speed. And, importantly, this method can be successfully applied with glass



**Fig. 3:** Light striking a glass plate at an angle undergoes multiple reflections. Illustration courtesy Gamma Scientific.

substrates having thicknesses as low as 0.5 mm. This is critical because thin glass is finding increasing use in displays.

The other significant limitation of many goniospectrophotometers is that they are designed for laboratory use rather than for in-line production environments. Typically, they can only measure a small (usually 2 in. square) witness sample. Furthermore, their measurement speed (several minutes) is not always sufficient to keep pace with production processes.

Gamma Scientific has recently developed new technology to address these shortcomings simultaneously. Specifically, its goniospectrophotometers all incorporate spatial filtering to suppress second surface reflectance and deliver highly accurate measurements (Fig. 4). Spatial filtering takes advantage of the fact that, at non-normal angles of incidence, the (unwanted) second surface reflection is laterally displaced from the first surface reflection. An appropriately sized aperture, also called a spatial filter, can therefore be placed into the beam path to block the second surface reflection, preventing it from entering the OMA.

Additionally, the measurement speed has been reduced from seconds down to milliseconds through the use of use of a highly efficient optical design and the CCD-array detector in the OMA. The detector employed is of a type referred to as “back-thinned,” which offers increased sensitivity and shorter exposure times than front illuminated detectors. In a conventional front-illuminated CCD detector, the pixel drive circuitry is on the top side (where the light comes in). This circuitry reflects some of the incident light causing a reduction in signal, and hence reducing device sensitivity. A back-thinned sensor is just as the term implies – the silicon-wafer substrate of the CCD is reduced in thickness during fabrication, allowing the finished sensor to be used with light entering the back rather than the front side. Thus, the light does not have to pass through all the driver circuitry. This can improve the chance of an input photon being captured from about 60% to over 90%, thus substantially improving sensitivity. Thus, back-thinned sensors are often employed in low-light optical measurement applications.

These instruments have also been optimized to test substrates of essentially any size in line, and they can be configured with motion control and part-handling hardware to support

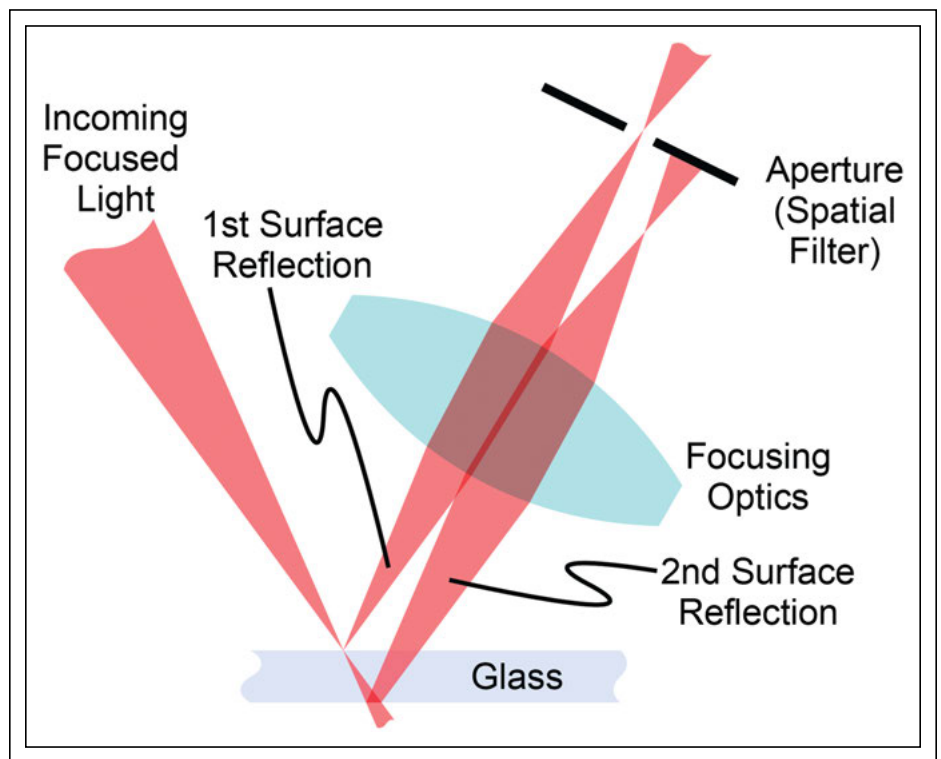
fully automated operation. This is possible because these systems are not configured like conventional spectrophotometers, which are self-contained instruments into which the operator places a small (typically 2-in. square) witness sample in order to perform testing. Instead, the Gamma Scientific system consists of a goniospectrophotometer optical measurement head (as previously described) which sits over a large testbed. This testbed can be sized to allow parts of virtually any dimensions to be placed on it, and then positioned (manually or under motorized control) for rapid measurement.

The goniospectrophotometer acquires the spectral power distribution function (*e.g.*, reflectance as a function of wavelength) of the device under test, and then inputs this raw data into the tristimulus equations. This enables the calculation of color values for any arbitrary color space under any illumination conditions (most commonly D65). In turn, this allows the visual appearance of the part, under any lighting conditions, to be determined.

Another key aspect of the system software is that it performs a non-linear regression on

the measured data. In order for this to work with an optical coating, the system is originally programmed with a model of the nominal coating design (*e.g.*, layer thickness and refractive indices) and also given information on which parameters might vary in actual production. When a part is measured, the software can then determine its likely coating parameters. Thus, if a coating is not performing to specification, the system is able to identify which coating layer(s) are in error, and the particular nature of that specific error (*e.g.*, incorrect thickness). This enables the manufacturer to rapidly identify and correct specific problems with its process without any guesswork.

The system software is originally configured by an engineer or R&D person with technical expertise who inputs all the process parameters. They can also determine how the data will be displayed to production personnel and set pass/fail criteria for virtually any measured parameter (spectral power distribution, color, various layer parameters, *etc.*). Thus, production-line personnel can be presented with anything from detailed measurement



**Fig. 4:** This simplified schematic shows the spatial-filtering technique used to effectively eliminate second-surface reflections from reflectance measurements.

results to an extremely simplified interface that simply provides pass/fail results for any criteria of interest to the manufacturer.

### Display-Glass Metrology at MAC Thin Films

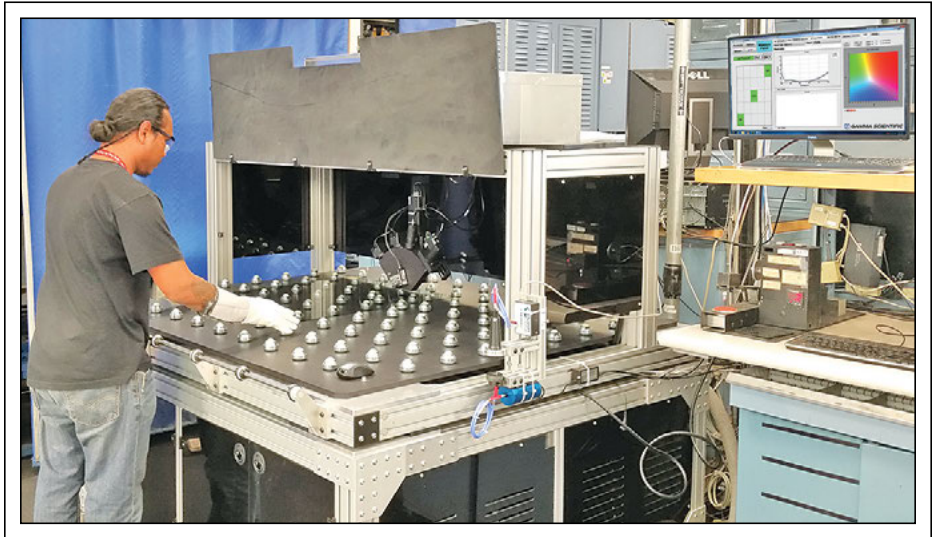
MAC Thin Films, a manufacturer of high-performance mirror and AR coatings, recently began using a Gamma Scientific goniospectrophotometer for production screening of its coatings. The rest of this article describes how this enabled a dramatic difference in process capability.

MAC Thin Films employs a continuous process for multilayer thin-film coating. Here, the glass is loaded on to a conveyor belt and then transported into a series of airlock chambers where a progressively higher vacuum is drawn. Once at the appropriate vacuum level for coating, the glass moves through a series of deposition chambers, all of which are already evacuated. In each station, a single layer of coating material can be deposited. Finally, the glass enters another series of airlock chambers where it is returned to ambient pressure. As product advances through each stage of the system, new parts are being loaded and finished parts are being unloaded.

In this type of continuous processing, it is critical to know as soon as possible when any component of the process has gone out of specification. This is because the longer the delay before a problem is identified, the greater the number of out-of-specification parts (*i.e.*, scrap) that are produced.

The AR coatings for display applications produced at MAC Thin Films are usually specified to deliver less than 1% reflectance throughout the entire visible spectrum. Over the past several years, it has also become commonplace for customers to specify the apparent color of the coating as well. However, most customers do not start with a numerical specification for this, in terms of the coating's nominal CIE color coordinates and tolerances. Rather, MAC Thin Films usually determine these parameters through an iterative process with prospective customers, in which they are shown a series of samples and then pick out the range of ones that look acceptable.

For most customers, MAC Thin Films coats  $32 \times 50$  in., or  $25 \times 32$  in., substrates. These are subsequently cut down into individual pieces that are the size of the finished display. In the case of chemically strengthened glass,



*Fig. 5: A worker places glass onto a roller bed and then positions it under the optical head in order to perform a measurement. Photo courtesy MAC Thin Films.*

the pieces are supplied already cut to final size. The thickness of the substrates ranges from 0.7 to 10 mm.

During a typical production run, one piece is taken off the line every 10 minutes for inspection using the Gamma Scientific system. The process at MAC Thin Films is highly stable, so this level of sampling has been found to be adequate. For substrates receiving the Print-Free coating, a second set of color measurements are taken after that process too.

To perform a measurement, a technician first places the part by hand on the instrument's testbed. The system's optical head automatically acquires focus with micron-level precision which is critical for proper operation of the second-surface suppression optics. To achieve this precise focus, the instrument utilizes an off-the-shelf laser-based distance sensor, which is mounted on the goniospectrophotometer optical head. The glass testbed itself is mounted on a high precision z-axis motion stage. A feedback loop is used to vertically adjust the height of the glass surface until it is at the correct distance from the optics, which have a known fixed focal distance. This eliminates any errors due to variations in glass thickness or mechanical placement on the testbed.

Once focus is acquired, which takes just a fraction of a second, a measurement is made. Typically, for a  $32 \times 50$  in. substrate, the technician samples the part at three locations

– the center and two diagonally opposite edges. Each measurement takes about 10 sec (Fig. 5).

Usually, the system is programmed to deliver a graph of reflectance as a function of wavelength and the color coordinates at each measured point. This is the data supplied to the customer. Additionally, the system software is set to display the results in a color coded, “go/no go,” map which immediately alerts the operator when a part is out of specification. Furthermore, trend charting is used to indicate how the coating process is developing over time so that nascent problems can be identified and fixed before they result in the production of scrap product. The non-linear regression capabilities of the software are particularly useful in this connection because they allow the exact nature of any problems with the coating process (such as an error in layer refractive index) to be specifically identified.

In conclusion, sophisticated thin-film coatings are now a standard part of display fabrication for many applications. This technology, together with a greater emphasis on product cosmetics, has created a need for metrology equipment that can quantify both coating performance and appearance, and which delivers the speed and ease-of-use necessary for employment in today's production environments. ■



# 2017 Editorial Calendar

Issue	Editorial Coverage	Ad Closing Date
January/February	<b>Applied Vision</b> <b>Special Features:</b> Reducing Stereoscopic Artifacts, Realizing Augmented and Virtual Reality, New Display Frontiers, Cool New Devices for a New Year <b>Markets:</b> Game developers, medical equipment manufacturers, research institutions, OEMs, software developers, wearable designers, entertainment industry research and developers	December 28
March/April	<b>Display Week Preview, Display Materials</b> <b>Special Features:</b> SID Honors and Awards, Symposium Preview, Display Week at a Glance, MicroLEDs, Progress in OLED Manufacturing, Disruptive Materials, Nine Most Important Display Trends from CES <b>Markets:</b> OEMs, deposition equipment manufacturers, entertainment industry research and developers, display and electronic industry analysts	February 27
May/June	<b>Display Week Special, Automotive Displays</b> <b>Special Features:</b> Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Head-up Designs for Vehicles, Novel Interfaces for Automobiles <b>Markets:</b> Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies <b>Bonus Distribution:</b> Display Week 2017 in Los Angeles	April 18
July/August	<b>Wearable, Flexible Technology and HDR &amp; Advanced Displays</b> <b>Special Features:</b> Flexible Technology Overview, Advanced Displays Overview, Wearables Round-up, Overcoming HDR Challenges <b>Markets:</b> Research institutions, OEMs, OLED process and materials manufacturers, entertainment industry research and development, measurement systems manufacturers	June 16
September/October	<b>Display Week Wrap-up, Digital Signage</b> <b>Special Features:</b> Display Week Technology Reviews, Best in Show and Innovation Awards, Digital Signage Trends, Ruggedization Challenges for Digital Signage <b>Markets:</b> Large-area digital signage developers; in-store electronic label manufacturers, advertising and entertainment system developers, consumer product developers, retail system developers	August 22
November/December	<b>Light-field and Holographic Systems</b> <b>Special Features:</b> Real-world light-field applications, holographic approaches, solving problems of next-generation displays <b>Markets:</b> OEMs, Consumer product developers, research institutes, auto makers, entertainment and gaming developers; measurement systems manufacturers	October 20

Contact:  
Roland Espinosa  
**INFORMATION DISPLAY MAGAZINE**  
Advertising Representative  
Phone: 201-748-6819 • Email: [respinosa@wiley.com](mailto:respinosa@wiley.com)  
View the Information Display Website: [www.informationdisplay.org](http://www.informationdisplay.org)

## SID Revises Governance Structure

*The Society for Information Display has revised its governance structure, the first such major update since the Society was founded 50-plus years ago. Among the major changes are a reduction in the size of the Board of Directors and the replacement of Chapter Directors with Regional Vice Presidents in terms of Board participation. Information Display asked SID President-Elect Helge Seetzen, one of the architects of the new structure, to describe the changes and how they will affect SID operations and members.*

by Helge Seetzen

The governance structure of the Society for Information Display has been largely unchanged for almost half a century. It is nearly as old as the Society itself, founded in 1962. That structure helped SID thrive and successfully manage its business for a very long time.

Since the 1960s, however, the world has evolved dramatically, and in order to keep pace with that evolution, SID's Executive Committee recently set about creating a modern governance structure for the Society. The goal was to retain the best elements of the existing structure while improving on it. A supporting goal was to create the least amount of disruption to members, chapters, and the organization as a whole.

The original structure, in brief, consisted of a Board of Directors (BoD) made up of five officers: the Treasurer, Secretary, President-Elect, President, and Past-President; three Regional Vice Presidents; and one elected representative from each chapter (Chapter Directors). These Chapter Directors were elected by their respective chapters to serve a 3-year period. Currently, there are 28 chapters around the world, not including student chapters. An Executive Committee (EC) made up of the officers and the regional VPs was charged with conducting the business of SID, under the direction of the Board.

Traditionally, SID business meetings have been held three times a year (in January, at Display Week in May or June, and in the fall at an international conference) with the EC meeting on the first day and the Board of Directors the day afterward. At the BoD meeting on that second day, SID business proposed by the EC was voted on, with at

least one-half of the board present constituting a quorum for conducting business.

Highlights of the recent changes (which went into effect starting January of 2017) and the reasons behind them are as follows:

- **Reducing the Size of the Board:** In the past, a meeting of the Board of Directors of the Society had a nominal invitation list of 36 full voting members, including Chapter Directors and assorted Committee Chairs. With such a large group, minimum attendance levels to achieve a quorum were sometimes not achieved; almost every meeting turned into an administrative struggle to secure enough proxy holders and conference-call attendees to make quorum. The new structure, with fewer mandatory attendees, should ensure that key governance can take place as needed with well-informed representatives.
- **New Board Composition:**
  - Two Tenure-Based Officers (President, Past-President)
  - Three Elected Officers (President-Elect, Treasurer, Secretary)
  - Seven Elected Regional Vice-Presidents representing the Bay Area, Pacific North West, South America, East Americas, Europe, Japan, Greater China, and the Rest of Asia

The main benefit of the new system is that the representation of the regions will greatly increase at the governance level. Previously, there were three RVPs participating in an eight-person Executive Committee. Now there are seven RVPs out of a 12-person board. So, the regions go from being "add-ons" to being the majority of the core leadership of the Society. In addition, global membership representation by Chapter Directors at the board meetings did not used to be evenly distributed – for example, there were 10 Directors for America vs. one for Japan because all of Japan is included in one SID chapter. The hope is that this change will not only provide more visibility to the various regions, but also drive regional development of SID, especially in "newer" areas such as China and India.

### Better Representation through Regional VPs

The role of the RVPs is the same as before. There will just be more of them and they will be more homogeneously distributed. Each RVP will represent between 400 and 700 members, so every member has an equal voice

(as opposed to the past system of Chapter Directors in which the director of a chapter with 10 members had the same vote as the director of a chapter with 700 members). Apart from the obvious inequality in representation, this created many problems in areas such as workload distribution, chapter funding, administrative oversight, and so forth. The new structure's proportional representation for Society members will include systems to adjust representation over time to future-proof the governance structure.

In addition, SID is planning to provide additional budget and local authority to the RVPs, which should allow them to better support the chapters in their regions. Finally, the RVPs will act as a communication interface between the Board and the chapters/members in the regions.

### Chapter Considerations

Since chapters have been a primary element of the Society since its inception, it may be helpful to take a closer look at how the governance changes will affect them. Except for the elimination of the official title of Chapter Director, nothing really changes. There are, however, two optional transitions. First, for chapters with active volunteers in the leadership team, SID recommends the introduction of a Chapter President who will perform the duties of the previous Chapter Director (with the exception of belonging to the BoD and attending its meetings). The President title is optional but may be useful in maintaining volunteer engagement and organization.

Second, SID is now offering virtual banking as an option. In the past, chapters were required to have their own financial structure – as incorporated entities – in order to receive rebates. This required financial management and reporting to HQ that could be difficult and time consuming. Moreover, setting up legal entities like this can be challenging in some regions. SID has therefore introduced a virtual banking option in which the RVP can offer to centrally administer a chapter's financials in a virtual account – assisted by HQ – from which chapter expenses can be paid. This removes the need for financial reporting while maintaining the chapter's ability to pay local expenses. Any chapter can also keep its current banking system. SID expects that virtual banking will make it easier to establish new chapters, especially in emerging regions where setting up legal entities is difficult.

Existing chapters should continue to provide member services and work with their new RVPs to see if they can encourage expansion of such services. Geographically diverse chapters could consider forming “spin-off” chapters in remote regions. For example, the Canadian chapter is largely concentrated in the Ontario area, where the bulk of the members reside, but it might be possible to create a Vancouver chapter to serve the emerging display community there (some 2000 km away from Ontario). This model has emerged organically in the US, where there are over a dozen local chapters, and the new governance model will allow the Society to do the same in other regions. The first step toward something like this will be to find local champions who can act as the leadership seed for such new chapters.

In terms of logistics, the Regional VPs will report to their chapters after each board meeting. For face-to-face interaction, SID is instituting an annual Chapter Day during Display Week that will be attended by all chapter officers and board members.

#### Timing

The election process is under way, and the new RVPs were nominated in late December and January. Voting commences February 15th and ends April 15th. The new Board will be fully in place for the May 2017 meeting at Display Week.

### Touch Taiwan 2016 Demonstrates the Strength of the Country's Display Industry

The fifth International Smart Display and Touch Panel Exhibition, Touch Taiwan 2016, held August 24–26, attracted almost 25,000 visitors from 12 different countries. The trade show, which is the world's premier touch-panel and optical-film exhibition, also featured LCD and OLED panels, flexible and wearable displays, digital signage, printed electronics, and more. Touch Taiwan is organized by the Taiwan Display Union Association in collaboration with several other display and electronics associations. The 2016 event, held at the Taipei World Trade Center's Nangang Exhibition Hall, featured 304 exhibitors from sectors including materials, components and parts, equipment and technology research, and display modules and panels.

Tsai Ing-wen, President of Taiwan (officially the Republic of China or ROC), attended the show's opening ceremony, noting that the display industry has played an important role in the country's economy and that even though faced by strong competition, Taiwan's display production output is ranked number two in the world. She said she believes Taiwan's display manufacturers are well-positioned to increase the country's industry market share.

Paul Peng, Chairman of the Taiwan Display Union Association, reiterated the importance of the display industry in the opening ceremony, noting that there are approximately 100,000 people in Taiwan employed in monitor manufacturing and relevant industries. The overall output of the panel sector in the country reaches over NT \$950 billion (US \$30.05 billion) each year, accounting for 7.4% of Taiwan's entire manufacturing output, he added. He supported Tsai Ing-wen's viewpoint by saying that Taiwan's display industry will prosper in the area of connected devices, including commercial displays, telematics, gaming, wearable, smart homes, smart medicine, and many other new applications.

Show organizers consider Touch Taiwan 2016 to be a resounding success and note that because Taiwan has successfully developed technology for flexible AMOLED displays, they expect that technology will be transferred to domestic companies and hence become a more vital part of the show in years to come.

For Touch Taiwan 2017 early bird registration, please contact TDUA Secretariat Joanna Kuan at [joanna@teeia.org.tw](mailto:joanna@teeia.org.tw) and visit <http://www.touchtaiwan.com/en/index.asp>. ■

**VISIT  
INFORMATION  
DISPLAY ON-LINE**  
**For daily display  
industry news**

**[www.informationdisplay.org](http://www.informationdisplay.org)**



## Display Week 2017

**Innovation Zone (I-Zone)**

**May 23-25, 2017**

**Sponsored by E Ink**

**T**he prototypes on display in the Innovation Zone at Display Week 2017 will be among the most exciting things you see at this year's show. These exhibits were chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. Programmable shoes, interactive holograms, the latest head-up displays, and much more will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

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

Don't miss the 2017 I-Zone, taking place on the show floor at Display Week, May 23–25.

**I-Zone 2016 Best  
Prototype Award Winner:  
*nVerpex***

**For Industry News, New Products,  
Current and Forthcoming Articles,  
see [www.informationdisplay.org](http://www.informationdisplay.org)**



continued from page 2

Consider today the computer-driven applications that might arguably pass the original Turing test. Turing proposed that a human evaluator would be unable to determine the source of natural language conversations between a human and a machine that is designed to converse like a human – *i.e.*, is it a human or machine on the other side of the conversation? Turing did not even require that the computer render actual speech, but in fact there are several examples today of computers being able to conduct natural language conversations, including those capable of producing synthetic speech with a great deal of realism and some personality.

Similarly, computers can drive cars – in many cases better than humans. In both cases, computers are designed to mimic human behavior (or improve on it) using the boundaries and conventions established by humans (like social conventions or highway rules). Essentially, you can fool a human by mimicking a human. So, with this context, we can see how fundamental it is for any true 3D display system to mimic the natural characteristics of human vision if there is a hope of achieving a Turing-like outcome. As Martin succinctly states “...an understanding of human vision is proving to be crucial to the enterprise because in the end the goal is to provide the desired perceptual experience for a human viewer.” Hence, the three outstanding articles that Martin has developed for us focus on this theme. We are very grateful for his hard work, especially through the holidays, to provide an excellent ensemble for our ID readers.

The first is a Frontline Technology article by Michael J. Gourlay and Robert T. Held, both associated with a team at Microsoft that is developing technology for HoloLens, Hello, and Windows Holographic. This article titled “Head-Mounted-Display Tracking for Augmented and Virtual Reality” provides a complete primer of the fundamental principles of head tracking as well as describing the challenges and best practices being developed today. In order for a virtual world to appear real, the technology must be able to accurately respond to an observer’s natural head and body movements exactly as they would occur in the physical world. Getting this right will be paramount to a seamless believable virtual experience. This article provides a clear understanding of the fundamentals as well as the latest thinking from people who are clearly driving this research area.

The second Frontline Technology feature, “Visible Artifacts and Limitations in Stereoscopic 3D Displays,” written by Paul V. Johnson, Joohwan Kim, and Martin S. Banks, provides the most complete treatment of this subject we have published to date and will easily be an important reference article for the future. It is especially interesting to read where the authors point out some fairly well-accepted but apparently incorrect beliefs of how observers merge the left-and right-eye images and the perceived resolution of 3D stereo images. New ideas employing hybrid spatial, temporal, and color-based interlacing are explained and explored for their advantages over current methods as well – expertly taking into account features and limitations of human vision to gain an edge over current methods.

The third Frontline Technology feature from author Johannes Burge, Assistant Professor at the University of Pennsylvania, is titled “Accurate Image-Based Estimates of Focus Error in the Human Eye and in a Smartphone Camera.” Johannes reports on some excellent work characterizing the aspects of human vision that make focusing in the physical world so intuitive and apparently instantaneous. Did you know, for example, that you probably refocus your eyes more than 100,000 times per day? When you do, I doubt you experience any noticeable searching the way the scene from a digital camera might appear during focusing. That is because the human eye has several important characteristics that help provide additional cues to aid adjustment of the lens – characteristics not currently utilized in auto-focus algorithms today. I am sure you will find this article very interesting and educational.

Earlier I mentioned our cover and the technology from LEIA, Inc., being illustrated. The company’s Founder and CEO David Fattal participated in a digital interview with Jenny Donelan for a Business of Displays feature to explain his company and technology, some creative applications, and his efforts to jumpstart the company to get its displays into the hands of customers. It’s exciting partially in part because LEIA is working with existing cell- phone and tablet LCDs with modifications to the backlight structure. Fattal refers to this capability as a “diffractive light-field backlight (DLB).” The result is a display that can be operated either in its original 2D mode or in a 3D light-field “holographic” mode,

making its implementation into existing handheld devices seem relatively easy.

Our final Frontline Technology feature for this month is still somewhat vision related. It is a story by author Trevor Vogt, Product Manager at Gamma Scientific, discussing the company’s latest advancements in “Quantifying Display Coating Appearance.” Or, more specifically, measuring the optical performance of anti-reflective (AR) and similar coatings directly from the substrate without some of the problems such as second surface reflections usually associated with this type of measurement. What I like about this article is both the innovation (and inherent simplicity) of the solution and the company’s willingness to discuss performance under real-world conditions at an actual coating manufacturer’s facility. The article includes some good background both on AR-coating technology and on the current metrology methods generally employed as well.

Turning our attention now to the good works of our Society, we offer a special addition of SID News covering the latest bylaw changes affecting the governance structure of SID. President-Elect Helge Seetzen, with some help from Jenny Donelan, outlines for us the reasons for the recent significant changes to the makeup of the SID Board of Directors and how this will help SID grow stronger in the years to come. If you were not aware of these changes, and I suspect some of you may not be, please take the time to read this news. It is a great thing that is happening and reflects the substantial vision and talents of our SID leadership team.

By now you must be thinking this is a big issue of *ID* magazine, and indeed it is. I feel like we are starting the New Year off with a strong product and we could not do that without the incredible efforts of our Guest Editors and all our volunteer authors. And so, once again I want to say thank you not only to the people who contributed to this issue but to everyone who gives us their time and effort to make *Information Display* come together each issue. To everyone I wish much good health, success, and happiness in the New Year! ■

continued from page 3

## New Products Briefly Mentioned

**APPLE** recently began shipping the latest MacBook Pro, which comes with an OLED-based touchbar on the keyboard for quick tool access.

**GOOGLE**'s Pixel and Pixel XL, the company's first forays into the smartphone business, have been getting early positive reviews for clean looks and smooth performance.

**LG ELECTRONICS** is introducing a new laser projector, the LG ProBeam, with an engine that produces a luminance of up to 2,000 lm, enabling home-cinema viewers to enjoy video content even in a bright room.

**VOLANTI DISPLAYS**, a maker of LCD-based touch-screen monitors, table displays, and video walls and other large-format displays, has announced the availability of interactive 4K collaboration touch-screen displays that use Trello collaboration software and Cnverg's whiteboard application. The displays are available in 42-, 55-, 65-, 84-, and 98-in. sizes.

from the wavelength distribution of the reflected light. This approach is used in the food industry and in agriculture, among other sectors, to measure the water, fat, carbohydrate, sugar, or protein content of foodstuffs, which is often an indication of freshness, quality, or calorie content.

The LED is based on a blue 1-mm<sup>2</sup> chip in UX:3 technology (Fig. 1). Its light is converted into infrared radiation with the aid of a phosphor converter developed specifically for this application. A residual blue component in the light helps users target the area they want to investigate.

Such compact units for spectroscopic chemical analyses have the potential to open a new range of applications in consumer electronics. One option is a compact sensor –

similar to a USB stick – that would be used with an appropriate smartphone app to measure calories, freshness, or nutritional content (Fig. 1). Experts expect that it will be possible in the near future to integrate spectrometers directly with mobile devices.

## E Ink and Japan Display Form Alliance

E Ink, the well-known innovator of electronic-ink technology, recently announced that it has agreed to enter a long-term strategic alliance with Japan Display Inc., a maker of LCD-based mobile phone and automotive displays.

By partnering with E Ink, JDI will add e-Paper technology to its existing digital

signage and mobile-phone offerings. At the same time, JDI will continue to advance the development, production, and sales of new products using LCD backplane technology, including innovative e-Paper products using JDI's proprietary LTPS and Pixel Eyes in-cell touch to enter markets such as automotive, dynamic computer keyboards, display cards, education, IOT displays, and many more. In terms of serving E Ink, JDI's LTPS technology can improve the performance of E Ink display modules. ■

## Submit Your News Releases

Please send all press releases and new product announcements to:

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

**SID**  
 SOCIETY FOR INFORMATION DISPLAY

**JOIN SID**

We invite you to join SID to participate in shaping the future development of:

- Display technologies and display-related products
- Materials and components for displays and display applications
- Manufacturing processes and equipment
- New markets and applications

In every specialty you will find SID members as leading contributors to their profession.

<http://www.sid.org/Membership.aspx>



**Fig. 1:** The SFH 4735 (left) is the first broadband infrared LED on the market. Its primary application is near-infrared spectroscopy, for example, in analyzing food (right). The chip can serve as a calorie or nutrition sensor in a smartphone, measuring the fat, protein, water, or sugar content in food. Images courtesy Osram.

## corporate members

### GOLD CORPORATE MEMBERS



### SILVER CORPORATE MEMBERS



## index to advertisers

EMD Performance Materials....C3	Radiant Vision Systems .....C2
General Atomics.....5	TFD.....C4

#### Sales Office

Steven Jeppard  
Global Advertising Director  
Wiley  
111 River Street  
Hoboken, NJ 07030  
sjeppard@wiley.com

#### Global Sales Office (Except Japan/China)

Roland Espinosa  
Sr. Account Manager  
Print & E Media Advertising  
Wiley  
111 River Street  
Hoboken, NJ 07030  
201-748-6819  
respinosa@wiley.com

#### Japan Sales Office

Kimiyoshi Ishibashi  
Associate Commercial Director – Japan  
John Wiley & Sons (Asia) Pte Ltd.  
Frontier Koishikawa Bldg., 4F  
1-28-1 Koishikawa, Bunkyo-ku  
Tokyo 112-0002, Japan  
+81-33830-1235  
kishibas@wiley.com

#### China Sales Office

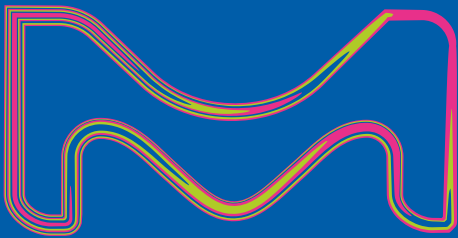
Ying Wang  
Corporate Sales Manager – China  
John Wiley & Sons (Asia) Pte Ltd.  
1402-1404 Cross Tower  
318 Fuzhou Road, Huangpu District  
Shanghai 200001, People's Republic of  
China  
+86 21 5116 3205  
ying@wiley.com

### Corporate Members

3LCD	Henkel	RealD
Abrisa Technologies	Industrial Technology	Rolic Technologies
Acer	Research Institute	Sakai Display Products
Advantech	Innolux	Sharp Corp.
Apple, Inc.	I-PEX	TDMDA
Applied Concepts, Inc.	Japan Display, Inc.	TDUA
Applied Materials, Inc.	Japan Patent Office	Teijin Dupont Films
AU Optonics Corp.	KMTC	Japan, Ltd.
CASIO	LXD Research & Display,	TFD, Inc.
CLEARink	LLC	TLC International
Coretronic	MegaChips Corp.	TOUCH TURNS
Cynora GmbH	Merck Display	TTLA
Dawar Technologies	Technologies, Ltd.	Universal Display
Dontech	Mitsu Chemicals	Corporation
E Ink Holdings	MY Polymers, Ltd.	US Micro Products
Earth LCD	NANOSYS	Vestel Electronics
Epoxy Technology	NLT Technologies	Westar Display
eMagin Corp.	Noritake Itron Corp.	Technologies, Inc.
Europtec USA, Inc.	Nvidia	YUASA SYSTEM Co.,
FocalTech Systems	Oculus	Ltd.
FUJIFILM Dimatix, Inc.	Panasonic Corp.	
Gigaphoton, Inc.	Pixel Scientific	
GIS	Precision Glass Bending	
	Corp.	



# the perfect pixel



## ADVANCED MATERIALS FOR DISPLAYS – AND BEYOND.

Our products promote an advanced visual experience, possibilities for new product design, improved process efficiency in FPD manufacturing schemes and new applications beyond displays.

**EMDgroup.com**

EMD Performance Materials is a business of  
Merck KGaA, Darmstadt, Germany



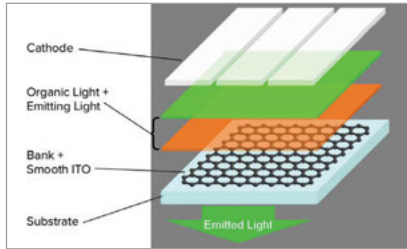
**EMD  
PERFORMANCE  
MATERIALS**

# THIN FILM DEVICES

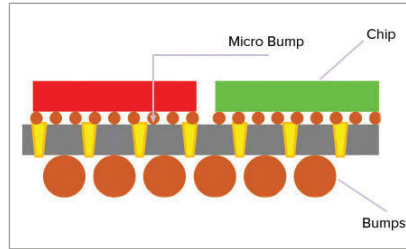
Economical and Superior Coatings and Products

Foundry Capability for MEMs, OLED, Banks, OPV, Dye Cell, Interposer, Chip on Glass & Others

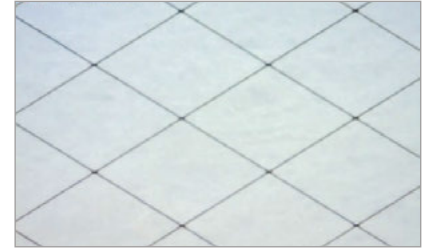
## PHOTOETCH & PATTERNING CAPABILITIES: SMALL TO LARGE SCALE



OLED + Bank

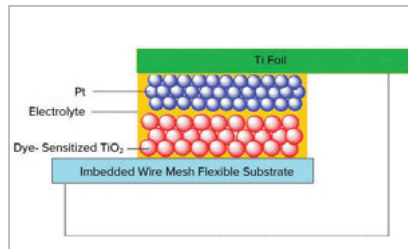


Glass Interposer

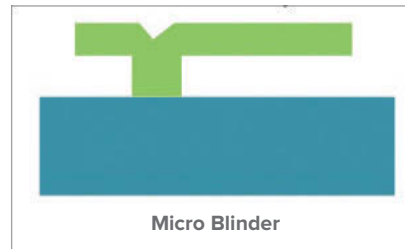


Imbedded Mesh

( $\leq 5$  OPS,  $T\% \geq 90\%$  @ 420-680nm)



Flexible Dye Cell



MEMs

## STANDARD COATING & SERVICES:

- STD TCO's ITO/IZO/AZO/FTO & WRTCO™
- BBR 200μm - 12μm Multiple Range
- IMITO™ (EMI & Heaters) Several Types
- Hot & Cold Mirrors Several Types
- Black Mask: Black Cr, Nb or Resist
- Custom P-Caps Several Types
- Color Filters (Resist Type) Several Types
- Lamination: Ruggedization, Glass to Glass, Anti-Vandal, Filters, EMI/Heater to LCD



**Thin Film Devices Incorporated**

1180 N. Tustin Avenue, Anaheim, CA 92807

Phone: 714.630.7127

Fax: 714.630.7119

Email: Sales@tfdinc.com

China Supply Chain:  
Group International  
jeanne-giil@hotmail.com

Korean Manufacturing:  
Ion-Tek  
ion-tek@hanmail.net

Taiwan Manufacturing:  
Acrosense Technologies