WHITE PAPER

How to Use Imaging Colorimeters to Correct OLED, MicroLED, and Other Emissive Displays for Improved Production Efficiency and Yields

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VISION SYSTEMS

A Konica Minolta Company

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Introduction

Emissive OLED, microLED (µLED), and miniLED are emerging as the next wave of technology in the display market. This is exciting because these displays promise improved display performance and visual appearance with greater efficiency than other display technologies, thanks to their individually emitting pixel elements. Both OLEDs and microLEDs have superior contrast ratios and sharper images with deeper blacks and more vibrant colors than traditional LCDs. These emissive displays require no backlight, resulting in thinner, lighter-weight displays that use less electricity. OLEDs also bring a dramatic boost in responsiveness, about 1,000 times faster than existing technologies, virtually eliminating blur on fast-moving and 3D video. MicroLEDs match OLED technology for response time and view-angle performance, but exceed OLED in brightness and ruggedness, with even lower power consumption.

Both OLEDs and microLEDs have superior contrast ratios and sharper images with deeper blacks and more vibrant colors than LCDs. They require no backlight, resulting in a thinner, lighter-weight display that uses less electricity.

Figure 1 *- The 219-inch microLED display "The Wall" by Samsung. (Source: Samsung)*[1]

As manufacturers work to launch commercially viable emissive display products, high costs due to material prices and manufacturing yield issues have hindered widespread technology adoption—most dramatically in large-format implementations, as they drive up end-customer prices. The smartphone market has been the most successful segment for OLED technology to date and will likely be the catalyst that drives long-term adoption of OLEDs and microLEDs for other applications. Display Supply Chain Consultants (DSCC) cites smartphones as the dominant OLED market, accounting for around 91% of units per year with revenue share around 79% by 2022.[2] Yole Développement (Yole) projects a similar trend for microLEDs, with a longer ramp up period, and a market reaching up to 330 million units by 2025.[3] With this type of growth in demand, improvements in manufacturing efficiency are needed.

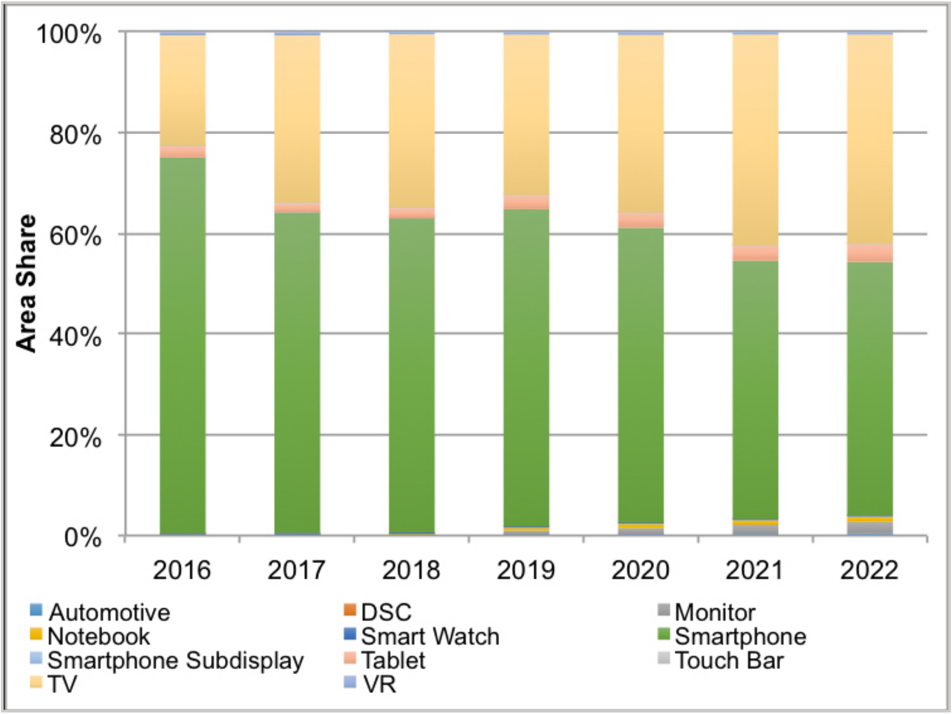

Figure 2 *- The smartphone market leads the way for OLED adoption. [Source: DSCC's Quarterly OLED Shipment and Fab Utilization Report]*[2]

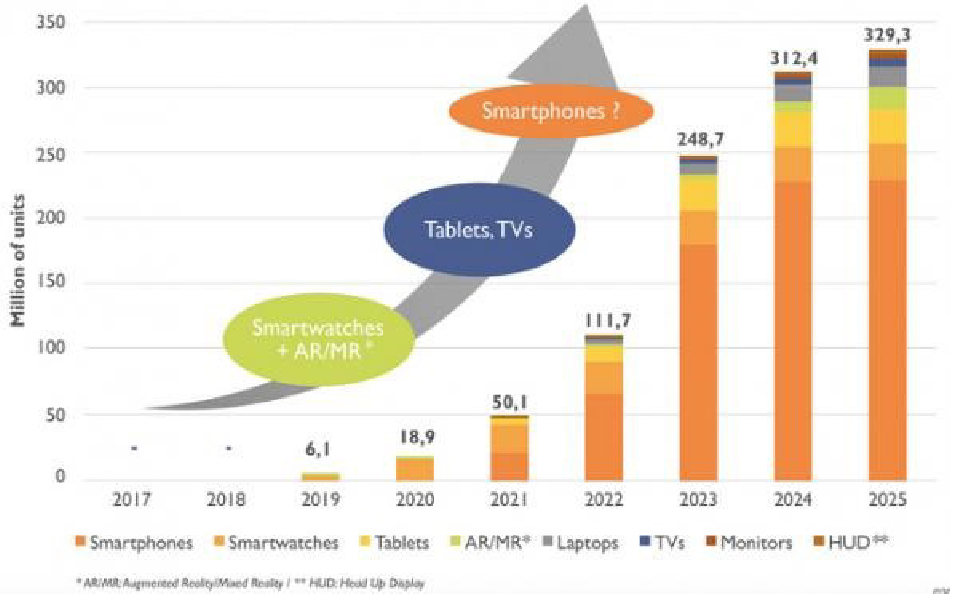

Figure 3 *- Smartphones are similarly forecast to drive the microLED market. [Source: Yole's MicroLED Displays report]*[3]

For both OLED and microLED, low production yields due to manufacturing complexity and—once manufactured—visual quality issues impact the timing of viable market entry and drive up retail prices for finished display panels.

Although the near-term market size is small, analysts at DSCC predict that large-format OLED TVs will take second seat to smartphones, rising to 42% market share by 2022, overtaking LCDs by as soon as 2021.[2] A limited sample of large-format microLED displays have been showcased by manufacturers like Samsung (The Wall) and Sony (Crystal-LED), whereas small-format displays continue to be more viable for mass production. For both OLED and microLED, low production yields due to manufacturing complexity and—once manufactured—visual quality issues impact the timing of viable market entry and drive up retail prices for finished display panels. Current commercially available, large-format OLED TVs are priced into the thousands of dollars (USD), while microLED screens remain cost prohibitive to most consumers, making lower-cost, high-definition LCD and LED options more appealing to the budgets of price-minded buyers. The price point for volume market adoption of new emissive display types and replacement of current technologies must be significantly lower, demanding greater efficiency and control in manufacture.

Display Manufacturing Challenges

OLED and microLED technologies add several unique challenges to the manufacturing process, regardless of the size of display.

Large-format OLED screen manufacturing has been somewhat costly to date due to inefficiency of deposition methods for adding organic molecules to their substrate (with the exception of new inkjet printing methods), which has limited the application of OLED technology primarily to smaller screen sizes like smartphones. Likewise, producing an entire television screen out of microLED chips has so far proven to be challenging. MicroLEDs require new assembly technologies, die structure, and manufacturing infrastructure. For commercialization, fabricators must find methods that yield high quality with microscopic accuracy while also achieving mass-production speeds. As a point of comparison, a miniLED backlight screen may be made up of thousands of individual miniLED units; a microLED screen is composed of millions of tiny LEDs.

To fabricate a microLED display, each individual microLED must be transferred to a backplane that holds the array of units in place. The transfer equipment used to place microLED units is required to have a high degree of precision, with placement accurate to within ±1.5 μm. Existing pick & place LED assembly equipment can only achieve ±34 μm accuracy (multi-chip per transfer). Flip chip bonders typically feature accuracy of ±1.5 μm—but only for a single unit at a time. Both of these traditional LED transfer methods are not accurate enough for mass production of microLEDs.

It is necessary to measure and quantify every pixel and subpixel element of an emissive display to identify defects and ensure uniformity, to produce the level of quality that consumers expect at these displays' higher price points.

There are also visual quality and performance issues. Inspecting OLED and microLED displays is in many ways more challenging than inspecting LCDs. Traditional LCD displays using LED backlights produce only a mostly uniform luminance (brightness) and color output across the display screen. With emissive display types, however, every individual emitter in the display can be subject to a high a degree of variability. For instance—although microLEDs are LEDs—traditional binning processes are virtually impossible for microLEDs, which can be as small as 1/100th the size of a conventional LED. Without these controls in place, ensuring brightness and color uniformity in microLEDs can be extremely challenging. It is necessary to be able to measure and quantify every pixel and subpixel element of an emissive display to identify defects and ensure uniformity, to produce the level of quality that consumers expect at these displays' higher price points.

Visual Quality Issues

Line Mura

In the OLED manufacturing process, material is deposited on a substrate to form the individual subpixels, while extremely tiny microLEDs are transferred to backplanes with the goal of achieving extreme precision. If this process is not completely uniform, implications emerge in terms of visual quality. One such issue is line mura, which appears as well-defined horizontal and/or vertical orientation in the display.

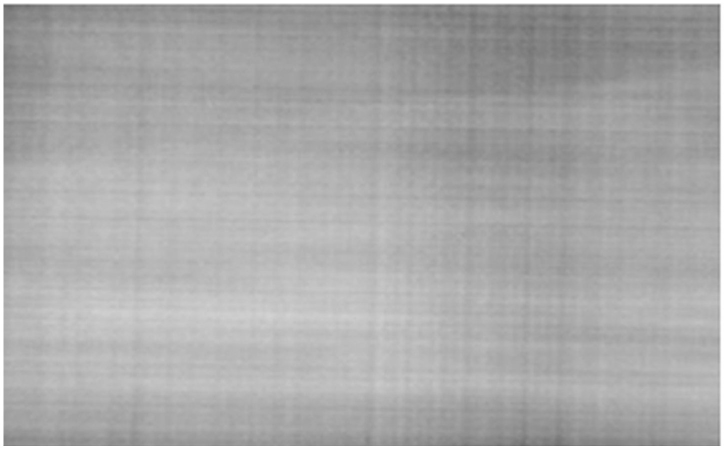

Figure 4 *- Image of an OLED display with uncorrected line mura.*

Extreme precision is needed to deposit the individual emissive elements of a display onto a substrate or backplane to form the subpixel elements. If this process is not completely uniform, the end result may be line mura, which appears as well-defined horizontal and/or vertical orientation in the display.

Subpixel Luminance Performance

Emissive display pixels are composed of red, green, and blue subpixels. When current is applied, each subpixel lights up individually, and the output of each subpixel is also individually controlled. The brightness and color of each pixel in the display is determined by combining the subpixel outputs. Due to production discrepancies in the manufacture of emissive display types, there may be variations in luminance when the same electrical signal is applied throughout the population of same-colored subpixels on the display. This results in differences in brightness from pixel to pixel of the same color. When combined, subpixels of each color—outputting light together at various brightness levels—produce display pixels that exhibit even more variability in brightness and color, and consequently the overall visual quality of the display appears poor.

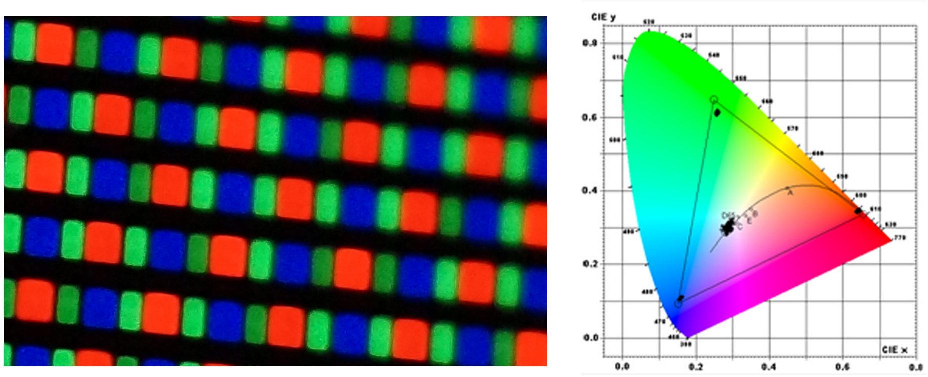

Figure 5 *- Subpixels combine to create pixels with various colors and brightness levels.*

This subpixel-level variability in OLED and other emissive displays results in different performance issues than those that occur in LCDs. In LCD panels, all pixels rely on light from the same backlight, so adjacent pixels generally have the same luminance and the brightness across the display will be fairly uniform.

Color Nonuniformity

Another impact of inconsistent brightness levels at the display subpixels is reduced color accuracy and color nonuniformity across the display. To achieve accurate and uniform colors, the brightness of each individual same-colored subpixel must be tightly controlled. The reality is that even within a well-controlled manufacturing process, subpixels of emissive displays will have significant variations in brightness levels. When these variations are not compensated for, it may manifest as nonuniformity of color across the display, reducing visual quality to potentially unacceptable levels and so reducing production yields.

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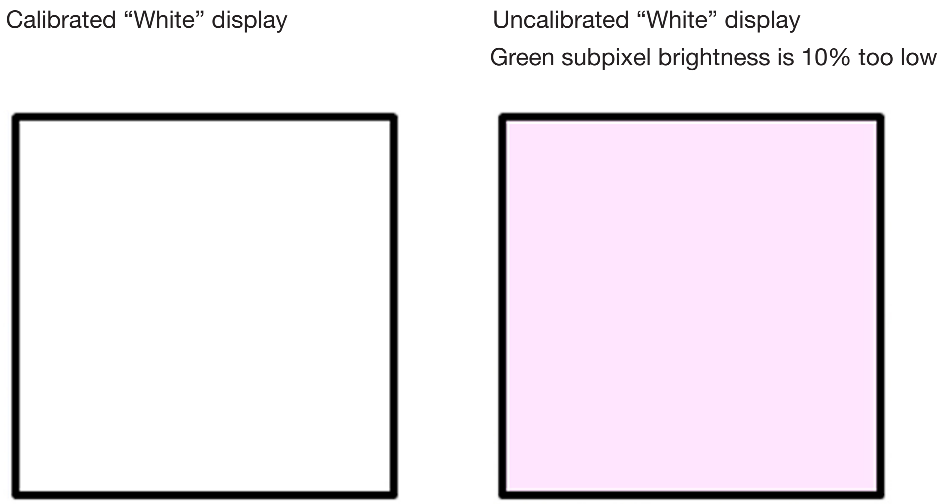

Calibrated “White” display

Uncalibrated “White” display
Green subpixel brightness is 10% too low

Figure 6 *- Incorrect brightness levels create nonuniformity in color across an emissive display. Variations in uniformity may increase as subpixels of various outputs are combined to produce a single display color, such as white.*

Imaging Colorimeter Applications for Emissive Displays

Imaging colorimetry-based display test systems have demonstrated success in improving quality and reducing production costs for traditional LCD and LED display screens. Testing applications span smartphones, tablets, laptops, TVs, and digital signage. These proven techniques can be adapted to emissive display production testing as well, enabling manufacturers to incorporate this technology into the same devices for visual quality of OLED and microLED displays, with the same positive return on investment.

The two primary components of a display test system are:

1. **Imaging Colorimeters**, which provide accurate measurement of display visual performance that matches human perception of brightness, color, and spatial (or angular) relationships. High-performance imaging colorimeters can accurately measure the luminance (brightness) of individual subpixels in an emissive display as well as overall display luminance and color uniformity.

2. **Test Execution and Analysis Software**, which is production-line software for image analysis to identify defects and quality issues, quantify their magnitude, and assess the measurements to make pass/fail determinations. This software can also include display performance correction methods that can be adapted to identify variabilities in subpixel output, calculate correction factors, and correct variations that are unique to emissive displays.

Figure 7 *- Example of an imaging colorimeter in a production display test application. (Product shown: Radiant Vision Systems ProMetric® I Imaging Colorimeter).*

Improving End-of-Line Quality to Enhance Customer Experience

In traditional manufacturing processes, display visual performance is tested by human inspectors, resulting low control of the visual quality of delivered product. With the innate variability, extremely high resolutions, and elevated quality expectations of emissive displays, ensuring visual quality is becoming an even more significant issue. Human inspectors are not able to consistently and repeatably evaluate the visual qualities of these displays to an objective and quantitative level, which is necessary to determine overall performance.

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Automated visual inspection (AVI) (also referred to as automated optical inspection (AOI)) using imaging colorimeters has multiple benefits, elevating quality control operations to increase efficiency in manufacturing, safeguard brand perception, and ultimately enhance the user experience.

Benefits of automated display inspection using imaging colorimeters include:

- Improved consistency in display visual performance testing—from line to line, and location to location—since all systems share the same calibration and test definitions

- Quantitative assessment of defects, with precise tolerances for objectively “good” or “bad” displays (pass/fail)
- Increased testing speed, which allows more tests to be run within the same time interval, increasing throughput while ensuring a more careful assessment and a better end product
- Simultaneous assessment of contextual (full-display) quality inspection (e.g., check uniformity and color accuracy) and fine-scale quality inspection (e.g., detect pixel- and subpixel-level defects)

When applied in OLED and microLED display testing, imaging colorimeter-based AVI simplifies testing while optimizing delivered product quality and production expense.

Correcting Emissive Displays to Improve Yield

As display size scales, yields decline drastically, and the cost of each component is much higher. At a certain point it becomes viable for manufacturers to perform correction (electronic compensation, or calibration) to improve display image quality. The concept is simple: by modifying the inputs to individual subpixels of an emissive display, previously identified dim subpixels can be adjusted to a uniform brightness level resulting in improved luminance uniformity and correct color across the display.

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Display pixel uniformity correction requires, first, having in-display electronics that can control brightness of the individual subpixels and adjust this based on the calculated correction factors for each subpixel. Second, a measurement system is required to accurately quantify individual subpixel brightness and color, and compute specific correction factors for each of them. This method has been widely used for LED display screens made up of individual LEDs, and has been adapted for emissive displays like OLED and microLED using a correction technique called “demura.”

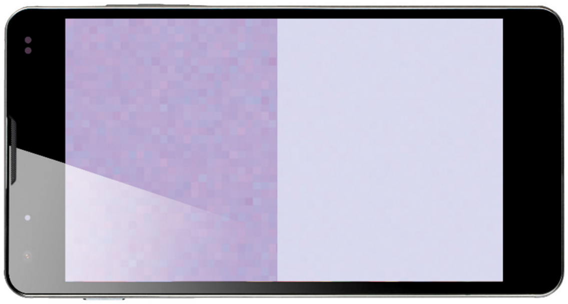


Figure 8 *- Side-by-side measurement images showing the results of a demura method applied for correction of emissive displays, captured by a Radiant Vision Systems ProMetric I Imaging Colorimeter; before demura (left) and after (right).*

The demura method employs three distinct steps:

1. **Measurement** of each subpixel in the display to calculate luminance values at each pixel location (performed on different test images to measure each series of same-colored subpixels) using a high-resolution imaging colorimeter.

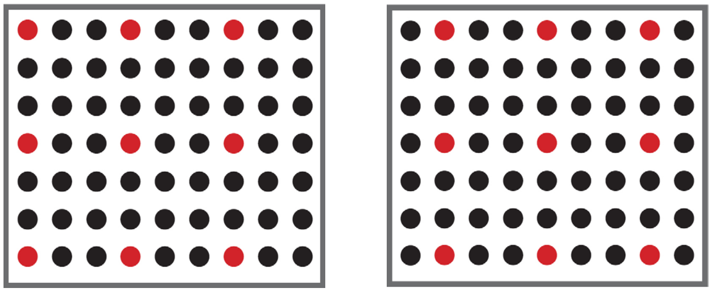
2. **Calculation of correction factors** needed to normalize luminance discrepancies between subpixels in the display using test analysis software.

3. **Application of correction factors** to the display signals using an external control IC (integrated circuit) system.

Once a display is completely assembled, test images can be displayed on-screen to target specific output color values. These images enable measurements and calibration to be computed for each of these values. For example, a “green screen” with all green subpixels turned on can be used as a sample image and the imaging colorimeter can measure and record the brightness of each individual green subpixel. This is repeated for all the primary colors and, usually, white. This data can be gathered in the course of ordinary quality testing of the emissive display.

To adapt a measurement method for any arbitrary size or resolution display, a demura method may employ a measurement process that combines data from a Spaced Pixel Test Pattern analysis, a patented method that enables measurement using a single photometric or colorimetric imaging system.

Calculating luminance values of each and every subpixel in extremely pixel-dense OLED and microLED displays, however, can be challenging. For Full High Definition (FHD, 1920 x 1080 pixel) and lower-resolution displays, a single 29-megapixel imaging system offers sufficient resolution for testing. However, for higher-resolution displays (for example, Quad High Definition or QHD, 4K, and now 8K), even very high-resolution imaging systems may be unable to capture all pixels in a single image for complete analysis, especially for today’s increasingly large displays (where a larger spatial area must be measured). To overcome this challenge and adapt a measurement method for any arbitrary size or resolution display, a demura method may employ a measurement process that combines data from a Spaced Pixel Test Pattern analysis, a patented method (US Patent 9135851 by Radiant Vision Systems) that enables measurement using a single photometric or colorimetric imaging system.


Pattern 1

Pattern 2

Figure 9 *- Examples of the first two patterns used in the Spaced-Pixel Test Pattern method of pixel-level luminance measurement for extremely high-resolution displays.*

Using a Spaced Pixel Test Pattern, dot matrix patterns of pixels are illuminated at intervals and measured by the imaging system in multiple passes. Measurements are repeated for all dot-matrix patterns until each display pixel is analyzed in its illuminated state. When using an imaging system with sensor resolution higher than the display itself, each display pixel can be tested over many sensor pixels, ensuring the highest accuracy of the associated display pixel’s measured luminance value.

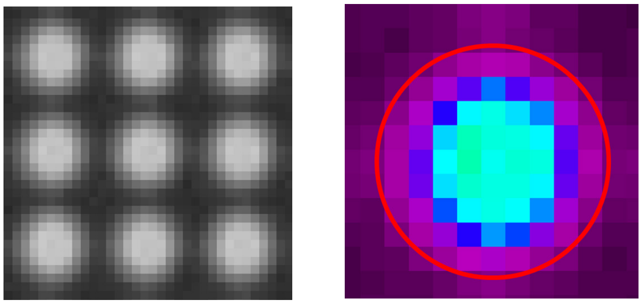


Figure 10 *- During the Space-Pixel Test Pattern method, each illuminated display pixel is automatically registered by the analysis software and defined within a region of interest (ROI). Because the imaging system resolution is much higher than the display resolution, each display pixel may be measured across an ROI captured by multiple sensor pixels, in this case about 10x10 sensor pixels to a single display pixel.*

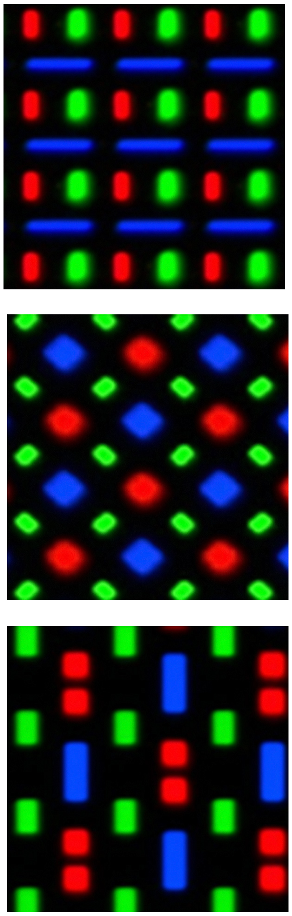


Figure 11 – *Additionally, ROI are dynamically defined regardless of OLED subpixel layout or shape, meaning any arbitrary pixel pattern can be measured to apply demura to any display design.*

Once all patterns of illuminated pixels have been analyzed, the test and analysis software of the demura solution combines all measurement images into a single “synthetic image” with the same resolution as the measured display (one sensor pixel to every display pixel). This image depicts every display pixel in rows and columns, providing accurate x,y coordinates for each pixel and their associated luminance values. This step in the demura process enables accurate detection of non-uniform pixels and their exact coordinates where correction coefficients for luminance may be applied.

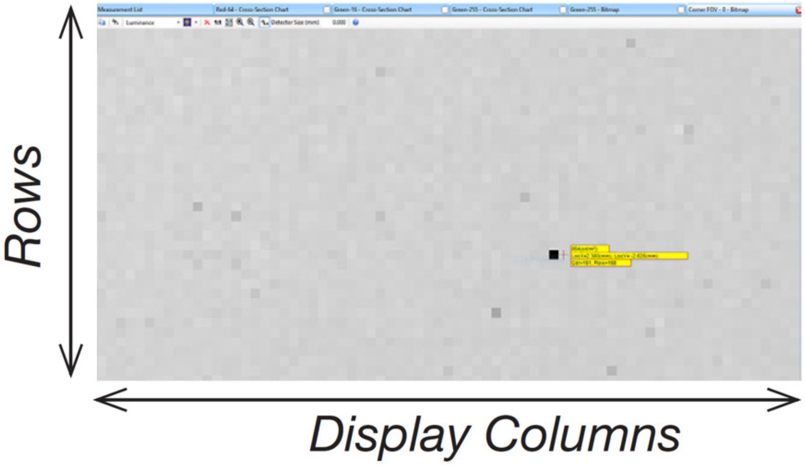


Figure 12 *- Software locates the defective pixels in the display using a synthetic image that combines the data from multiple high-resolution measurement images of the display, taken by the imaging system.*

Once luminance values at each pixel are known, correction factors can be computed and applied to the electrical input of each individual subpixel, ensuring that brightness and color will be accurate and uniform across the entire display (including at all gray levels). When this demura correction process is applied to the finished OLED or microLED display, there is a significant improvement in display visual quality. The net effect of demura is that displays that would have failed quality inspection without electronic compensation will now be able to pass, thereby reducing waste in manufacturing, improving cost efficiency, and increasing production yield.

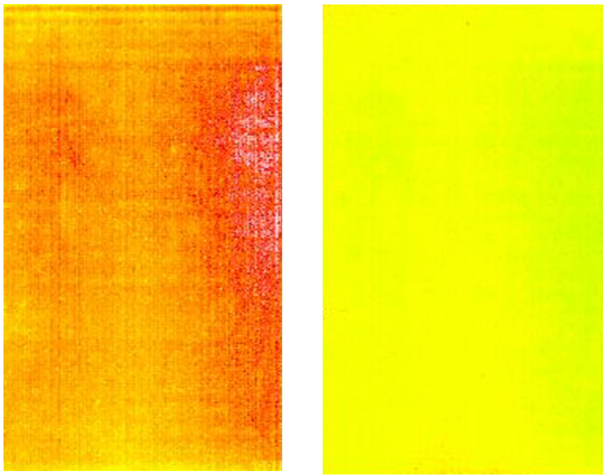


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Figure 13 *- Measurement images of a blue test screen on an OLED display, before and after demura correction (shown in a false-color scale to illustrate luminance levels).*

Radiant Vision Systems Solutions

Emissive technologies are ushering in the next generation of displays from flat-panel to curved, but technical issues related to image quality and production yields need to be resolved before display types like OLED and microLED can be considered commercially viable, especially in large formats. The issues facing manufacturers—although unique for emissive display types—are similar to technical issues that have already been solved by Radiant Vision Systems in traditional LCD production and for LED screens.

ProMetric® Imaging Colorimeters

Radiant Vision Systems ProMetric Imaging Colorimeters are highly sensitive, highly accurate, scientific-grade imaging systems calibrated to match human visual perception of spatial and angular distributions of brightness and color. Radiant Vision Systems offers more than twice as many models of imaging colorimeters as competitive solution providers in the industry—with multiple options for resolution and sensitivity. The appropriate system for specific display testing scenarios will depend on the desired measurement accuracy and resolution requirements.

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TrueTest™ Software

Accurate measurement of emissive display performance is important, but an equally-important component is the analysis of the measurement data. Radiant Vision Systems TrueTest Automated Visual Inspection (AVI) Software completes the display test solution and makes data actionable by implementing test sequences against user-defined pass/fail criteria. **TrueTest** is a software test suite and sequencer with built-in tests available for display uniformity testing, line defect detection, pixel defect detection, contrast measurement, mura analysis, and more. TrueTest allows the user to select from a test library and order tests in any sequence for rapid analysis of multiple characteristics. The user can also specify test parameters and pass/fail criteria. **TrueMURA™** is an optional license for TrueTest that adds JND ("just noticeable difference") mura and blob analysis techniques for evaluating over 15 types of mura.

TrueTest incorporates software alignment, display registration, and moiré pattern removal functions to simplify test setup. On the production line, the software runs in Operator mode where access to test parameters is locked, preventing changes. TrueTest also stores configuration information, test parameters, and pass/fail criteria for multiple models of displays; the correct data file can be applied or changed on the fly during production.

Integration and Support

Practical implementation of the Radiant Vision Systems display test solution requires both hardware and software integration on the production line. Radiant Vision Systems is experienced at working with customer-selected fixture providers, or providing full turnkey solutions that include fixtures. TrueTest Software can operate in a standalone mode, but more typically it is integrated with the Production Control System (PCS) of a manufacturer's line. This integration can provide fully-automated testing, wherein Radiant's software is triggered by the PCS, or simply provides a reporting interface for pass/fail results (and testing data). TrueTest can also be set up to work with video pattern generators and barcode readers (or the equivalent).

Radiant Vision Systems offers global support for all ProMetric and TrueTest solutions. Support includes engineering, installation, training, maintenance, and calibration services. Radiant Vision Systems support personnel are located throughout the US, China, Taiwan, Japan, Korea, Asia-Pacific, and Europe, supporting thousands of imaging colorimeters currently deployed on hundreds of production lines worldwide.

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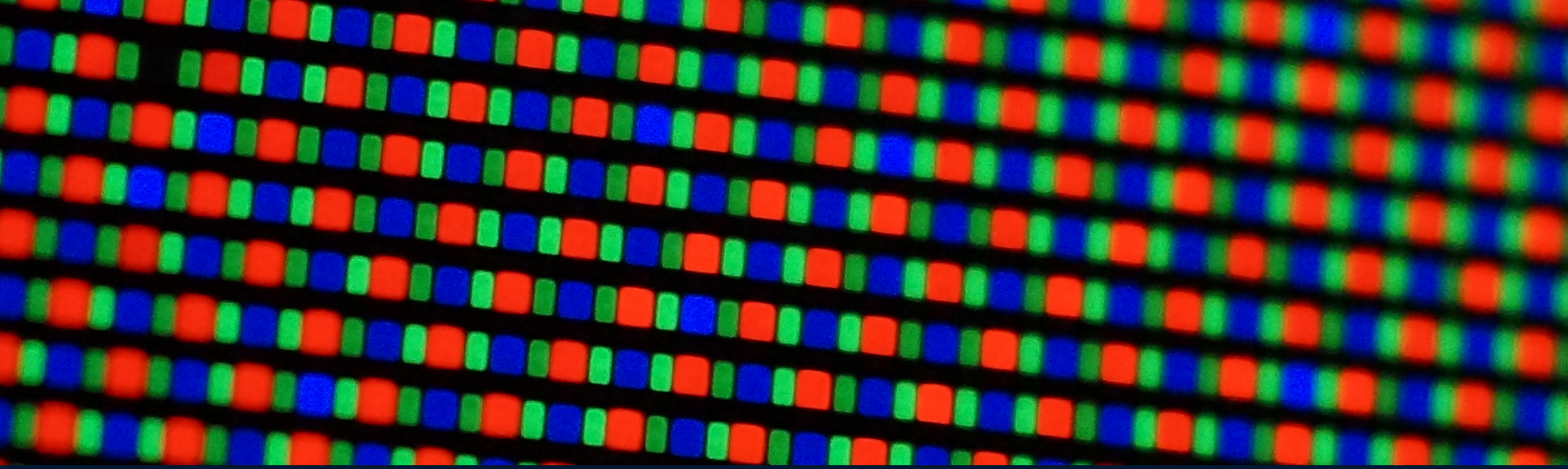

Imaging colorimetry-based display test systems have demonstrated success in improving quality and reducing production costs for LCD displays and LED display screens. Radiant Vision Systems has extended these proven techniques to production testing of other emissive displays like OLED and microLED. Contact us to learn more about “demura” display correction and how it can improve your production efficiency.

GLOBAL OFFICE LOCATIONS

Radiant maintains direct sales, engineering, and support offices and personnel throughout North America, China, and Korea. Radiant is also sold and supported in other areas of the world by our sister offices in the Konica Minolta Sensing Business.

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