Understanding Imaging System Specifications for Pixel-Level Measurement of Displays

Comparing Measurement Performance of Current CCD and CMOS Sensors
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Introduction

Imaging systems are highly efficient visual inspection solutions for display measurement and qualification. Images enable contextual analysis of a display to identify defects by comparing visual deviations in luminance, color, and other characteristics across the full display area. The process of converting light to digital input to create an image, however, is not precisely one-to-one—inconsistencies in electronic signals occur as values of light are translated into electronic data. Imaging sensor types (CCD and CMOS) accomplish this conversion process in different ways, each with distinct benefits and limitations. Depending on the imaging system’s sensor (among other system specifications), inevitable inconsistencies that result during the process of converting light data into an image may be more or less apparent—hindering or improving imaging system performance. Understanding the effect of imaging system specifications and sensor properties is critical for choosing a system that optimizes the accuracy and repeatability of measurement data. This becomes even more important when evaluating the extremely limited data-sampling area of a single display pixel—a significant quality indicator for today’s high-resolution, emissive displays.

Figure 1 - Measurement images of an emissive OLED display taken by a high-resolution imaging photometer. The luminance level of each display pixel is measured to evaluate discrepancies in uniformity from pixel to pixel. Data can be used to adjust pixel output of non-uniform displays (left) to correct display uniformity at the pixel level (right). (Luminance values are shown in false-color scale to illustrate variations in brightness.)
Display Trend: More Pixels
At the Society for Information Display (SID) 2017 Display Week, the call from keynote speaker Clay Bavor (VP, Virtual and Augmented Reality at Google) was simple: "We need more pixels. Way, way more pixels." Display innovation is a continued pursuit of higher resolution and increased pixel density in displays that are viewed ever closer to the eye. To produce lifelike visuals with greater contrast and color depth, improve sharpness of visual elements, and eliminate screen-door effects in immersive virtual-reality environments (among other objectives) requires increasing the number of pixels in a given display area, and improving the pixel fill factor. As a virtual medium for conveying reality, a display must blend the virtual experience seamlessly with reality— everything that is visible in a display should be presented with equivalent (or improved) detail. This precision ensures displays have value as a tool for visualization.

In smart devices and wearables, displays have become smaller in an effort to improve mobility and integration flexibility. Viewed at limited distances, these small-format displays must pack more pixels into limited spaces to achieve the seamless visual qualities consumers desire— meaning, not only do displays contain “way, way more pixels,” but pixels are becoming much, much smaller.

Figure 3 - Increasing the number of display pixels per area requires that pixels become smaller. This illustration shows the impact on pixel size as display resolution increases within a 2.54-centimeter (approximately 1-inch) square area.

The Importance of Pixel-Level Measurement
The performance of a display’s pixels dictates the visual quality of a display. Manufacturers may analyze displays for several pixel-related defects to ensure quality. At the very basic level of pixel measurement, imaging systems identify dead or stuck-on pixels. This defect can be easily spotted by measuring pixel-level luminance values across display test images. With the market trending toward emissive displays based on LED, OLED, and microLED technology, more complex measurement criteria have emerged for detecting pixel and subpixel non-uniformity. Because light is emitted by each pixel in these emissive displays, with no broad-scale uniformity provided by a backlight, the luminance per pixel can vary greatly, especially across different brightness levels (or “bright states”) of the display.
Beyond testing each individual pixel, display measurement may need to be performed at the subpixel level of the display. Output luminance of each subpixel (typically producing red, green, and blue) determines the overall color of each display pixel. Equally mixing RGB subpixel values produces a pixel that is white in color. However, if subpixels exhibit variations in red, green, and blue values, as subpixel sets are illuminated, color mixing will yield a wide variety of white values. This inconsistency can create noticeable areas of non-uniformity (also called mura) as viewed by a consumer.

Measurement Objectives
To effectively test the visual quality of today’s increasingly high-resolution, pixel-dense displays, measurement systems need to achieve accurate pixel- and subpixel-level measurement that improves performance at each light-emitting element. Two-dimensional photometric measurement systems (imaging photometers or colorimeters) are particularly efficient for measuring display defects. Leveraging high-resolution image sensors, these systems can be used to evaluate displays at the pixel and subpixel level and calculate discrepancies in luminance between each element. In emissive displays like LED, OLED, and microLED, the photometric imaging process allows manufacturers to calculate corrections for each pixel to achieve overall display uniformity.
As pixels become smaller and more densely populated across a display, the challenges of evaluating display quality compound. Adequate display qualification requires that measurement systems capture enough visible detail of each pixel to discern their individual characteristics and photometric values, and offer consistent measurement data from pixel to pixel. This requires high imaging resolution (that is, the resolution of the imaging system's sensor) to achieve more measurement pixels per display pixel. It also means reducing the unwanted image noise captured in each measurement pixel to ensure the repeatability of evaluation at this scale.

Figure 6 - **High imaging-system resolution ensures that each display pixel is sufficiently isolated for measurement.** This measurement image shows an imaging resolution of 10x10 sensor pixels to capture a single display pixel.

Figure 7 - **High imaging system signal-to-noise ratio (SNR) ensures that measurement accuracy is repeatable across display pixels.**

**Imaging System Specifications**

Imaging systems are ideal for measuring displays because—like the human eye—imagers capture all visible detail at once to enable contextual analysis across the entire spatial area of the display. Imagers characterize display characteristics like mura (or dark or light masses in the display), non-uniformity across the display, and other visual characteristics like brightness, color, and contrast.
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Figure 8 - A photometric imaging system captures the entire display area in a single two-dimensional image for analysis (actual measurement images shown in “false color” to represent luminance values).

When a digital camera captures an image, photons of light are mapped to the pixels on the camera’s sensor. The more pixels a sensor has (the higher its resolution), the more photons can be mapped to specific spatial positions, and the more detail can be seen in the captured image. Through the process of converting light to image data, an inevitable amount of electron “noise” is also captured in each pixel on the camera’s sensor. This noise can reduce the accuracy of the details in the captured image.

Figure 9 - An illustration of imaging sensor pixels, where each sensor pixel captures photons from a specific spatial position on the light-emitting display.

Imaging performance can have a fundamental impact on the ability of the imaging system to collect and interpret photometric data from a display with precision and consistency. The imaging system selected for display measurement should provide the optimal specifications for the measurement need. With pixel density of displays increasing, a display test system requires increasingly accurate imaging system performance, which is primarily driven by optical quality, sensor resolution, and electron noise to ensure the ability of a system to distinguish accurate light values at the pixel and subpixel level.
Figure 10 - A display captured with a low-resolution imaging system. The measurement image (left) captures each display pixel across 3x3 sensor pixels. The pixel luminance is shown in the cross-section (right), where contrast between pixels is very low, with potential cross-talk of measurement data from one display pixel to the next.

Figure 11 - A display captured with a high-resolution imaging system. The measurement image (left) captures each display pixel across 6x6 sensor pixels. The pixel luminance is shown in the cross-section (right), where contrast between pixels is much higher, reducing cross-talk of measurement data between pixels.

Resolution

Resolution of an imaging system is key to acquiring detail in display measurement. Without sufficient sensor resolution, it becomes very difficult to isolate small points of interest, such as display pixels and subpixels, to obtain discrete measurement data for each light-emitting element in the display.

The data in Figure 10 shows an image-based measurement of pixels on a smartphone display. This imaging system has acquired each display pixel across 3x3 sensor pixels. The amount of detail visible for each display pixel is very poor in the measurement image to the left. The cross-section to the right shows the imaging data with percentage of maximum luminance across the display area (in millimeters). Between each pixel, the contrast is very low, indicating a lack of precision in defining each pixel by its illuminated area (increased cross-talk with neighboring pixels). Due to limited resolution,
the imaging system is not able to acquire sufficient detail to determine the true contrast between light and dark areas of the display (the areas between each pixel). In much noisier images, the luminance value for each display pixel would be even less accurate.

A higher-resolution imaging system can acquire more precise pixel detail, which increases repeatability of data even amid image noise. In Figure 11 (previous page), the same smartphone pixels from Figure 10 are analyzed using a system that achieves 6x6 sensor pixels per a single display pixel. Compared to the left image in Figure 10, there is much more visible detail in the left measurement image of Figure 11. Additionally, in the cross-section in Figure 11, there is much higher contrast between pixels, limiting cross-talk and significantly improving the accuracy of luminance values for each display pixel.

**Signal-to-Noise Ratio**

**Signal** is the amount of accurately interpreted light input, and the **noise** is the inevitable, undesired electron activity. Signal-to-noise ratio, or SNR, provides a data point for imaging system performance comparison. Higher SNR improves imaging system repeatability (the system’s ability to acquire consistently accurate data) from measurement to measurement and from pixel to pixel in a display. Lower SNR can lead to data inconsistency as instances of noise are interpreted as meaningful variations in the measurement, rather than as random fluctuations due to electron activity.

High SNR results in an image with accurate light measurement data at more precise spatial locations on the display, which is critical when using imaging systems for pixel-level measurement and analysis. In a small measurement area, like the area of a single display pixel, there are a limited number of image sensor pixels with which to build an understanding of the display pixel’s true light values (brightness, color, etc.). If an imager’s sensor captures a high amount of noise per measurement pixel, our limited window of understanding of the display pixel can become even more inaccurate, and may result in variability of measurement data from pixel to pixel (that is, low repeatability).

**The Rule of Six Sigma in Imaging SNR**

An imaging system with high repeatability must have a low failure rate when it comes to distinguishing meaningful signal from unwanted noise. As a general rule of thumb, imaging systems should apply principles of six-sigma (6σ) to set a tolerance for SNR performance. To repeatably detect defects and limit false positives, the defect contrast achieved for each pixel in a display should be six standard deviations (6σ) beyond the sensor’s image noise level. When measuring displays containing millions of pixels, optimizing SNR to this standard tolerance can limit our measurement “failure” or inaccuracy rate per pixel. A very small defect in a display, like a pixel defect that varies in contrast only slightly from neighboring pixels, provides relatively low signal versus the background. A 6σ difference would allow the system to reliably detect this defective pixel effectively 100% of the time. As defect contrast falls below six standard deviations, the defect becomes more easily confused with the sensor’s noise, and the rate of failure increases.

**Figure 12 - Illustrations of signal-to-noise ratio (SNR), where blue is the meaningful signal and red is the undesirable noise. Improving this ratio (as in the bottom image) increases the likelihood of discerning the signal.**
Figure 13 - Data extrapolated from actual display measurement images to compare luminance deviation from background noise (SNR). Where SNR of 6\(\sigma\) is achieved (left), the signal is clearly discernable, even when sampling millions of data points. Where SNR of ~4\(\sigma\) is achieved (right), the signal may become confused with image noise due to statistical variation among millions of data points.

The Argument for Larger Pixels

Pixels on a sensor can be different sizes. A small pixel has a smaller capacity for photons (its “well capacity”), while a larger pixel has more well capacity. Because it can store more photons, a sensor with larger pixels is more sensitive to variations in light values and therefore provides more precise, repeatable measurement data.

As discussed above, all cameras capture images with an inherent, consistent amount of electron noise, at several electrons per sensor pixel. Larger sensor pixels that capture more photons increase the ratio of true input (photons that create the image), to false input (electron noise).

Once saturated (when a sensor pixel’s well capacity is reached), a larger sensor pixel will provide a larger ratio of good signal compared to unwanted electron noise. The illustration in Figure 14 shows the impact of a given amount of electron noise as observed in a small sensor pixel, (which captures fewer photons per noise, resulting in lower SNR), as compared with a large sensor pixel, (which captures more photons per noise, resulting in higher SNR).

Sensor Resolution vs. Sensor Size

An imager’s resolution is given by the number of pixels within the physical area of its sensor. A sensor can maintain the same physical dimensions while increasing resolution—for instance, an 8-megapixel sensor can be the same physical size as a 29-megapixel sensor. The difference is the pixel size.

To increase the number of pixels on a sensor of a given physical size, the sensor pixels must become smaller. Using smaller sensor pixels means smaller well capacity for photons in each pixel and therefore lower SNR. Although an extremely high-resolution sensor would suggest better quality images, if the pixels are reduced in size, the ratio of image noise to good signal within each pixel is increased. The result is a high-resolution
imaging system with a greater number of inconsistent pixels. The image captured by such an imaging system would be more detailed, but the details may not convey repeatable information. This can make a significant difference when measuring many very small regions of interest like pixels across a display.

The logical solution to achieving higher resolution would appear to be: simply increase the physical size of the imaging system’s sensor in order to get a greater number of larger sensor pixels.

Increasing sensor resolution while maintaining pixel size necessitates a corresponding increase in the physical size of the sensor. However, a large sensor in turn demands large camera components. This is a problem because of limitations surrounding standard hardware sizes in imaging systems. For a sensor to fit the imaging area captured by a standard 35-milimeter lens, the sensor pixel size must also be limited. Increasing the size of the pixels, without reducing the number of pixels, increases the sensor size beyond the imaging area of a standard 35-milimeter lens. This means that some of the sensor area will go unused, and—despite the sensor having more pixels—the images captured by the larger sensor will not actually be full resolution.

Customization of hardware size beyond the standard imaging components can cause issues in terms of development cost and complexity of the measurement system. The objective in optimizing imaging performance, therefore, trends toward striking the right balance of sensor properties to optimize the photo-sensing areas of the sensor within the standard size limitations of today’s imaging systems. This requires an understanding of the properties of the available sensor types, and a comparison of each sensor’s ability to maintain photosensitivity (large well capacity) with smaller pixels (high resolution).
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Figure 18 - This measurement image of OLED subpixels gives an example of a low-resolution/low-noise image (left) compared to a high-resolution/high-noise image (right). Neither is ideal for measurement—the ideal imaging system strikes a good balance.

CCD vs. CMOS Imaging
There are two primary imaging sensor types—Charge-Coupled Devices, or CCDs, and Complementary Metal-Oxide Semiconductors, or CMOS sensors.

The pixels of both CCD and CMOS sensors have photo-sensing elements. The primary difference between these sensors, however, is in the structure of each sensor pixel and the elements that accomplish the conversion of light to digital images. CCD pixels are analog and shift their charge from one pixel to the next until reaching an output amplifier at the edge of the pixel array. CMOS sensors have an amplifier in each pixel. The result is that CMOS pixels have less photo-sensing area with which to capture photons, and many photons reaching the CMOS sensor may not reach the photo-sensing area within each sensor pixel.

Figure 19 - A measurement image of OLED subpixels captured by an imaging system that provides an optimal balance of resolution and noise.

Figure 20 - An illustration comparing the size of the photo-sensing area per pixel of a CCD sensor versus a CMOS sensor.
As noted, the size of the photo-sensing area limits each pixel’s well capacity. A smaller well capacity can increase the ratio of image noise per pixel (decrease the SNR), making pixel-level defects more challenging to detect.

CCDs are designed to maximize the photo-sensing areas of each pixel, and therefore can have more pixels per sensor area while maintaining well capacity (although effective fill factor may be improved for CMOS when a microlens array is applied). This means CCDs typically have higher SNR and greater repeatability than CMOS sensors of equivalent resolution. While all sensors are good at detecting very obvious defects (like a dead pixel in a bright display), CCDs excel at detecting very low contrast defects such as non-uniform pixels, even in displays measured across bright states (dark to bright). For this reason, CCD sensors tend to be used for applications that require extremely precise, scientific imaging with excellent light sensitivity.

While CMOS sensors tend to be more susceptible to noise, there are notable benefits of CMOS technology. CMOS sensors provide faster read-out of data than CCDs. They operate with low power consumption—as much as one hundred times less power than CCDs. Since they can be fabricated on almost any standard silicon production line, CMOS sensors are also less costly to produce, which drives down the cost of CMOS-based imaging systems. While CMOS sensors have traditionally offered lower resolution and sensitivity, they are still chosen in applications where defects are more easily identified and imaging speed is prioritized for maximizing automated visual inspection application (such as high-speed machine vision applications for quality control on an active production line).

**Photon Transfer Curve**

The simplest and most defining comparison of today’s CMOS- and CCD-based imaging systems is an analysis of Photon Transfer Curves, or PTC. The measurement shown in Figure 21 (next page) illustrates how the SNR of each type of imaging system changes as sensor pixels become saturated with photons (as well capacity is reached). As each sensor receives more photons in its pixels, the SNR should increase, simply because more photons are captured versus residual noise produced.

The first notable observation from the data in Figure 21 is that the saturation limit is very different for CMOS and CCD sensors. This is because of the more limited photo-sensing area per pixel in CMOS sensors. CMOS pixels are not able to store as many photons as CCD pixels because of their smaller photo-sensing areas, and therefore a CMOS pixel’s full well capacity is reached sooner. On the other hand, CCDs can store many more photons per pixel, improving SNR at full well capacity. Per the data in Figure 21, the CCD pixel can reach near-perfect SNR at complete saturation.

Another observation from the data in Figure 21 is the difference in accuracy between CMOS and CCD sensors at lower luminance levels (that is, at the low end of the X axis, where fewer photons are being received). CMOS sensors exhibit lower SNR when fewer photons are received—for instance, when the display is measured in a dark state. CCD sensors have closer to perfect SNR at these low luminance levels, meaning defects in dark displays are more easily and reliably discernable by the CCD sensor.
Figure 21 - Graphical representation of actual test data showing the single-pixel SNR of two systems with the same image size—CMOS and CCD—compared to a theoretical “perfect” system on the orange line, which has a nearly pure shot-noise limit.

**Measurement Across Luminance Levels**

Evaluating display quality normally requires display measurement at various luminance levels, or “bright states.” Individual pixels in a display can vary dramatically in their output performance across luminance levels, as they are driven by different levels of input to produce a target amount of light. Variations are especially common in emissive displays like LEDs, OLEDs, and microLEDs where each pixel is driven independently to produce its own individual luminance output.

Figure 22 - A gray-level test image displayed on a monitor is imaged by a CCD-based imaging system (left) and a CMOS-based imaging system (right) of equivalent sensor resolution. The CMOS image exhibits higher image noise at darker areas of the display.
The images in Figure 22 (previous page) show the observable difference between two CMOS and CCD sensors of equivalent resolution, which are used to image a display across different bright states. The two imaging systems capture the same display projecting a test image with a range of gray values (dark to bright). When measuring the darker gray values, the imaging systems receive fewer photons to their sensors. At the darker areas of the display, a CCD sensor exhibits less image noise than the CMOS sensor. This supports the data shown in the PTC graph in Figure 21. The CCD sensor does not need high saturation to achieve image accuracy, in part due to the large photo-sensing regions of its sensor pixels as compared to CMOS. The CCD sensor can achieve higher SNR than the CMOS sensor while still receiving fewer photons from the dark areas of the display, ensuring precision across all display bright states.

Conclusion

Currently, CCD-based imaging systems offer the most accurate measurement data for very small, low-contrast defects, such as non-uniform pixels or subpixels in a display. There are significant benefits to CMOS technology for fast, cost-effective visual inspection; however, the accuracy of current CMOS technology remains insufficient for repeatable pixel-level display measurement. As CMOS accuracy reaches CCD SNR performance levels—especially for measuring small, densely-populated points of interest like today’s increasingly small, emissive display pixels—CMOS technology could become the preferred sensor type for its benefits in speed and power consumption. For now, further development is needed before CMOS reaches CCD performance for repeatability at higher resolution.

References


Imaging systems rely on sensors to accurately interpret light as photometric data and enable evaluation of displays. This paper discusses properties of today’s high-resolution sensors used for image-based photometric display testing, and examines measurement examples to compare sensor type (CCD versus CMOS), pixel size, and signal-to-noise ratio (SNR), and the effect of these properties on the accuracy and repeatability of data for pixel-level display measurement.