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Fractional Pixel Method for Improved Pixel-Level Measurement and Correction (Demura) of High-Resolution Displays

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Fractional Pixel Method for Improved Pixel-Level Measurement and Correction (Demura) of High-Resolution Displays

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Abstract

As display resolution and pixel density increase, measuring the characteristics (luminance, chromaticity) of individual display pixels becomes more difficult for current imaging technology. Single-image analysis is important for optimizing efficiency for viable production processes. Imaging systems must continue to accurately measure the increasing number of pixels in a display while applying increasingly limited relative imaging resolution. This paper describes a method of display pixel registration and measurement using fractional image sensor pixels, which improves the accuracy of pixel-level luminance values obtained in single-image measurements for effective qualification and demura of emissive (OLED, mini/microLED) displays.

Introduction

Because they are individual emitters, the pixels in OLED (organic light-emitting diode), miniLED, and microLED displays can exhibit broad variability in luminance and color output from pixel to pixel. This variability manifests as non-uniformity or mura across the display, resulting in low yield of acceptable displays, rejection of expensive components, or costly rework. Automated visual inspection of displays has been proven for identification of defects like non-uniformity, with quantitative pass-fail results, fast cycle times, and reduced operational costs necessary for mass production and commercialization. For emissive displays, pixel and subpixel measurement methods have enabled the calibration of display uniformity by identifying, measuring, and correcting the luminance output of each pixel, thereby producing displays of entirely uniform appearance. This process—referred to as pixel uniformity correction, or "demura"—relies on the accuracy of pixel-level luminance measurement in order to calculate accurate correction coefficients for each pixel.

For emissive displays (i.e.,OLED, miniLED, and microLED), pixel and subpixel measurement methods have enabled the calibration of display uniformity by identifying, measuring, and correcting luminance output of each pixel, thereby producing displays of entirely uniform appearance.

Ensuring measurement accuracy for qualification and correction at the pixel level becomes more challenging as the resolution of emissive displays grows and pixels become smaller, more numerous, and closer together. The latest smartphones contain anywhere from two to over four million pixels per display (with three or four times the number of subpixels) at 400 to over 500 pixels per inch (PPI). To increase the accuracy and repeatability of measured pixel-level luminance values, image-based display measurement systems must apply several image sensor pixels across each display pixel. However, covering and isolating each display pixel using multiple image sensor pixels is challenging, especially when sensor resolution of the measurement system is limited relative to the high quantity of pixels in the display. Measuring a display using multiple images can increase the effective imaging resolution per pixel, but single-image measurement is important for correcting a display at low takt times, supporting efficient high-volume production processes and commercialization of new display types.

Single-image measurement is important for correcting displays at production takt times. Imaging systems must continue to provide accurate pixel-level measurement values for the increasing number of pixels in a display while applying increasingly limited relative imaging resolution.

Pixel-level measurement relies first on pixel registration, a method of dynamically locating and setting a region of interest (ROI) around each pixel in the measurement image. This technique was originally patented by US7907154B2[1] for the purposes of measuring individual LED pixels in large-format outdoor screens,where measurements are performed over long periods of time and multi-image measurement of a single display is common. In these applications, ROI are set as a uniform grid aligned to the image sensor array. This is adequate for multi-image measurement, which increases sensor resolution per display pixel. However, smaller displays (i.e., smartphones, watches, or microdisplays) require single-image measurement to ensure production speeds, which reduces sensor resolution per display pixel. In these cases, it is unlikely that the center of a display pixel will be aligned with the center of a sensor pixel, increasing moiré effects at each display pixel and reducing the ability of the ROI to precisely cover and isolate each display pixel.

A new pixel registration and measurement method uses fractional image sensor pixels to improve pixel-level measurement accuracy for today's high-resolution displays. This method sets a display pixel ROI based on a floating-point limit (rather than centering the ROI on the image sensor pixel). Then, the method isolates the fractional sensor pixel area contained within the ROI to calculate a measurement, thereby improving the precision of measured luminance values over traditional (whole pixel) methods for display qualification and demura. The benefit of a fractional pixel method is accurate display pixel or subpixel measurement using reduced imaging resolution, enabling optimization of the measurement system for testing speed and cost effectiveness.

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Fractional Pixel Method

Because several image sensor pixels per display pixel are needed for accurate pixel-level luminance measurement, the center of each display pixel in an image will not necessarily align with the center of a single image sensor pixel (see Figures 1 and 2, where the center of the display pixel is actually the intersection of four image sensor pixels). ROI centered on an image sensor pixel can exclude significant areas of the display pixel (see Figure 1, left), especially when fewer image sensor pixels are applied.

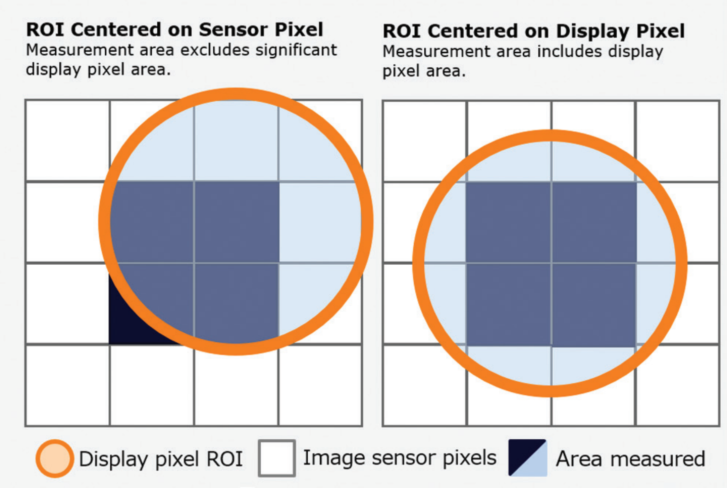

Figure 1 *- Illustration of the effect of centering a display pixel ROI on a single image sensor pixel (left) where significant area of the display pixel may be excluded from measurement, versus weighting luminance values of fractional pixels to determine the true center of the display pixel for alignment of the ROI (right).*

In contrast to traditional whole pixel methods, a fractional approach determines an ROI that better approximates the limits of a display pixel by weighting the average luminance values across image sensor pixels to determine a center of gravity for each display pixel (as shown in Figure 1, right). In other words, a floating-point representation (i.e., fraction) of a number of sensor pixels is used. This ROI can be very precisely defined. Accordingly, a fractional pixel method can provide more accurate registration of even closely spaced pixels and subpixels than whole pixel methods using a single-image measurement, where imaging system resolution is limited.

To determine the centroid location of a display pixel ROI, the fractional pixel method uses initial input for a single display pixel location to scan the display and set preliminary ROI for all display pixels based on pixel pitch of the device. These ROI are refined using the fractional pixel approach to calculate the center of gravity of each display pixel weighted to the highest average luminance across image sensor pixels. The ROI is then set as a bounded area around the display pixel center and determinations are made as to whether the image sensor pixels fall within, partially within, or outside the ROI. The fractional luminance values in each of the image sensor pixels within the ROI are summed to determine an overall value of the ROI (e.g., the luminance per display pixel). See Figure 2.

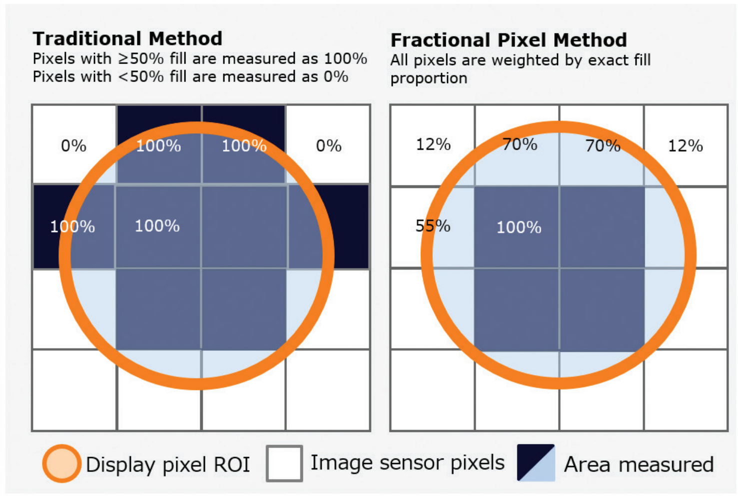

Figure 2 *- Illustration of a traditional whole pixel measurement method versus the fractional pixel method. In the traditional method (left), display pixels are measured using 100% of the data from sensor pixels whose area is more than 50% inside the ROI, and 0% of the data from sensor pixels whose area is less than 50% inside the ROI. Using the fractional pixel method (right), display pixels are measured using a percentage of data based on the percentage of sensor pixel area inside the ROI.*

To ensure measurement accuracy, ROI must be precisely centered to each display pixel, and image sensor pixels located partially within the display pixel ROI must be weighted to ensure nearby pixel values are not factored into the measurement of the target pixel.

For pixel-level luminance measurement, the fractional pixel method has a significant impact on measurement accuracy when applied to high-resolution, pixel-dense displays. As display resolution increases and single-image measurement resolution is limited, a measurement image may contain image sensor pixels that fall partially inside or outside of a single display pixel ROI, increasing the likelihood of measurement error depending on whether luminance values are factored in or out of the overall measurement of a target pixel. Furthermore, a single image sensor pixel that falls partially inside an ROI may capture values for both the target display pixel as well as a neighboring pixel. It is very important, therefore, that ROI be precisely centered to each display pixel, and image sensor pixels located partially within the display pixel ROI are weighted to ensure nearby pixel values are not factored into the measurement of the target pixel.

Figures 3 and 4 depict the fractional pixel measurement method, as described in US Patent 10971044.[2]

US Patent 10971044 describes methods and systems for measuring electronic visual displays using fractional pixels, and includes registration and measurement capabilities for subpixels with non-circular shapes.

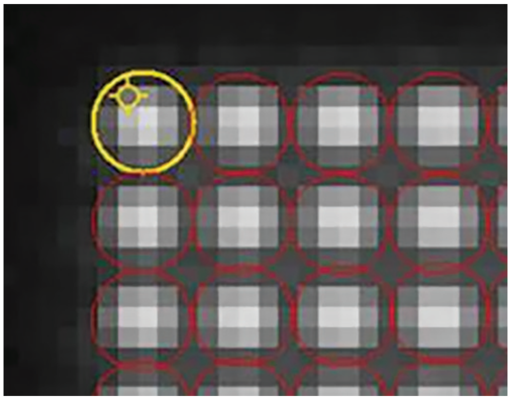

Figure 3 *- A portion of a display measurement image with ROI whose center is aligned to the display pixel center.*

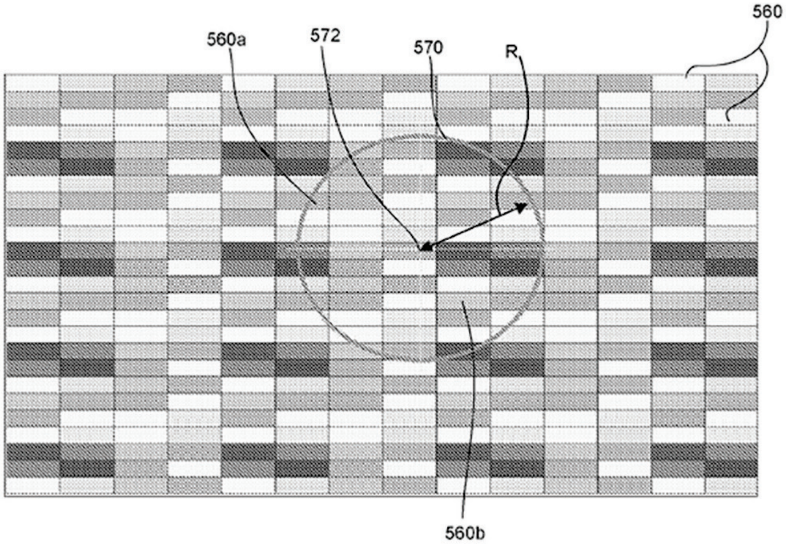

Figure 4 *- A schematic illustration of display pixels (560) and a single circular ROI (570) having a center (572) and a radius (R). Some of the sensor pixels (560b) are wholly contained within the ROI, while other sensor pixels (560a) are partially inside and partially outside the ROI.*

Evaluating Method Effectiveness

To evaluate the effectiveness of a fractional pixel measurement method, an experimental evaluation was conducted by Radiant Vision Systems using measurements of an OLED device. This evaluation compared the accuracy of pixel-level luminance measurements from whole and fractional pixel methods to a reference measurement.

To establish a reference for pixel-level luminance values, a Radiant Vision Systems ProMetric® Imaging Photometer paired with a microscope objective lens was used to capture an extremely high-resolution measurement image of an OLED display with 577 pixels per inch (subframed to an area at the center of the display, 150 H x 200 W display pixels). In the reference measurement image (Figure 5), display pixel ROI are 30 image sensor pixels in diameter (30 x 30 sensor pixels per display pixel). To simulate a typical measurement resolution, a measurement image of the same OLED display was produced by down-sampling the high-resolution reference measurement image. In this down-sampled image (Figure 6), the display pixel ROI are 3.2 image sensor pixels in diameter (3.2 x 3.2 sensor pixels per display pixel).

Luminance values were measured for each horizontal row of pixels in the reference measurement image (Figure 5), providing the true luminance values of the display pixels. Luminance values were then measured for each row of pixels in the down-sampled measurement image (Figure 6) using whole and fractional pixel methods, providing luminance values for a typical measurement scenario.

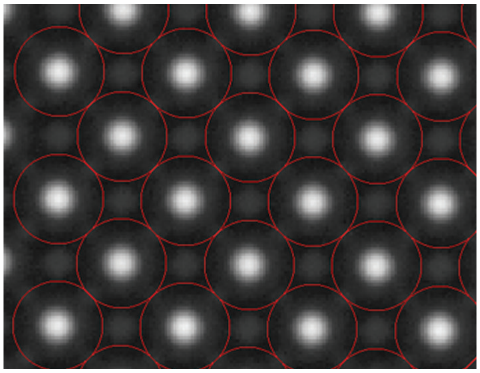

Figure 5 *- Reference measurement image of an OLED display with ROI measuring 30 x 30 image sensor pixels per display pixel.*

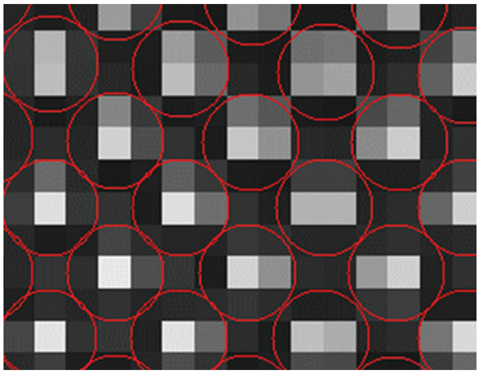

Figure 6 *- Down-sampled measurement image representing a typical measurement resolution with ROI measuring 3.2 x 3.2 image sensor pixels per display pixel.*

Synthetic measurement images were also produced using values measured by reference, whole, and fractional pixel methods (Figures 7 through 9). In synthetic images, each image sensor pixel reports the luminance value for a single display pixel (i.e., image resolution to display resolution is one-to-one). It is visually evident from these images that luminance values measured using a whole pixel method (Figure 8) vary more severely from pixel to pixel as compared to the values measured by the reference (Figure 7) and fractional pixel method (Figure 9), which are visually very similar. Variation in the whole pixel method is due to imprecisely calculating the luminance values for each display pixel ROI across several image sensor pixels, which may include neighboring display pixel values (the pixel's measured luminance is higher than its true luminance), or excluding target display pixel values (the pixel's measured luminance is lower than its true luminance).

Traditional whole pixel measurement methods may introduce false luminance variability in measurements. This is due to imprecisely calculating the value of each display pixel ROI across several partial image sensor pixels, which may include neighboring display pixel values or excluding target display pixel values.

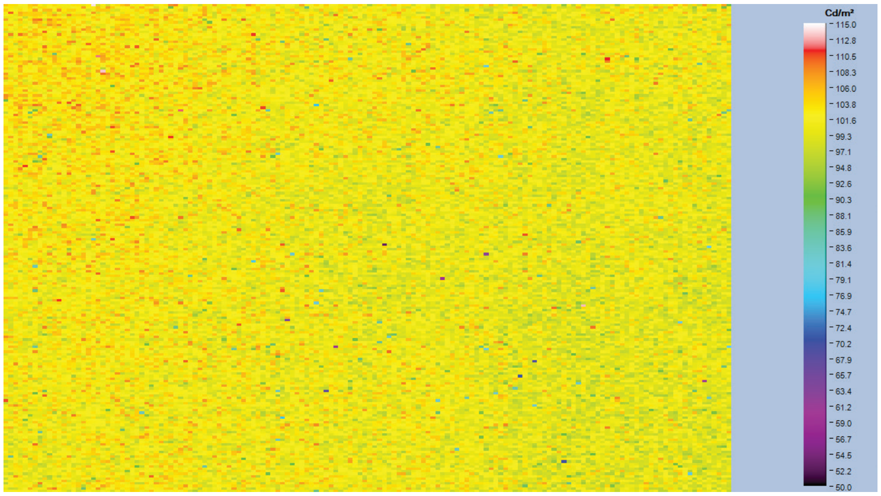

Figure 7 *- Synthetic measurement showing pixel-level luminance of the reference measurement image. Measurement image shown in "false color" scale to represent luminance values.*

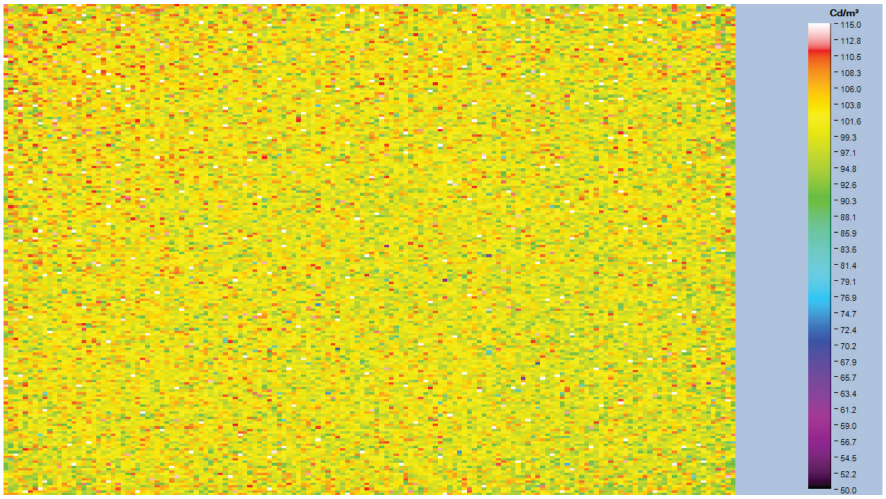

Figure 8 *- Synthetic measurement showing pixel-level luminance measured by the whole pixel method.*

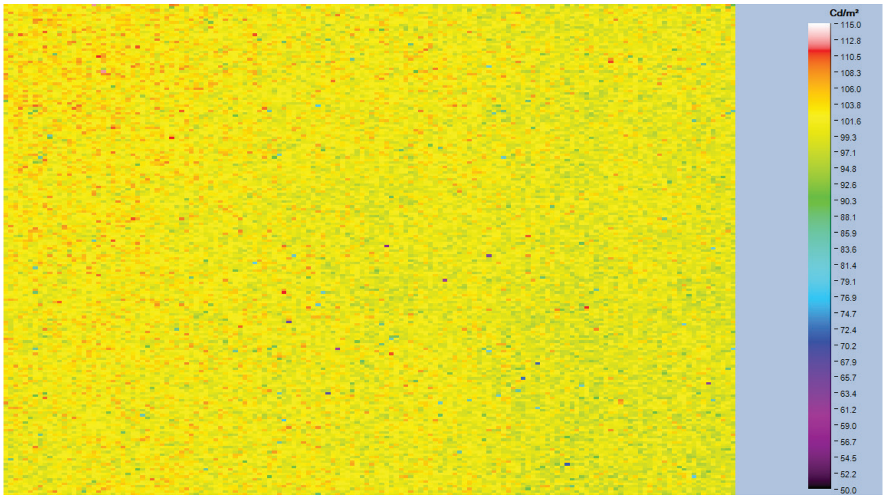

Figure 9 *- Synthetic measurement showing pixel-level luminance measured by the fractional pixel method.*

In a synthetic image, each image sensor pixel reports the luminance value for a single display pixel (i.e., image resolution to display resolution is one-to-one). These images illustrate measured luminance values from pixel to pixel in the display.

Results

Figures 10 and 11 plot the pixel-level luminance values measured for a single row of pixels using whole and fractional pixel methods, as compared to the reference (true) luminance of each pixel. In Figure 10, the fractional pixel (solid orange line) and reference (solid gray line) measurements are shown to have a close match, while whole pixel measurements (dotted blue line) exhibit a noticeable deviation from reference values. Further, Figure 11 plots the percentage error in luminance (ΔLv, %) measured for each pixel by whole and fractional methods as compared with the reference luminance values. As evidence of the accuracy of the fractional pixel measurement method, the pixel-level luminance values obtained by this method exhibit minimal deviation from the reference values, less than 2%. This indicates that a measurement system with standard resolution is able to achieve comparable pixel-level luminance accuracy to an extremely high-resolution measurement system during single-image capture when a fractional pixel method is applied. The whole pixel measurement method deviates from the reference values as much as 10%. This deviation indicates misalignment of the measurement ROI with the display pixels, and exclusion or inclusion of significant luminance data for each pixel. In cases where correction (demura) is applied, inaccurate correction factors may be calculated from this data. The application of inaccurate correction factors manifests as residual or additional mura in the "corrected" display.

In cases where correction (demura) is applied, inaccurate correction factors may be calculated from whole pixel data. The application of inaccurate correction factors manifests as residual or additional mura in the "corrected" display—negating the benefits of correction.

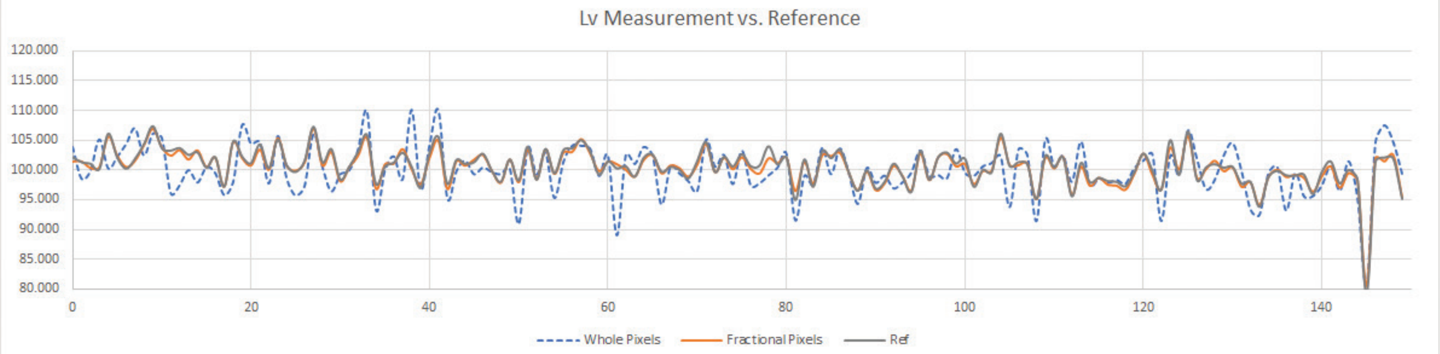

Figure 10 *- Normalized luminance (Lv) measured by whole and fractional pixel measurement methods (using down-sampled image) and reference luminance (using reference image) for the same row of pixels (row 100 of 200).*

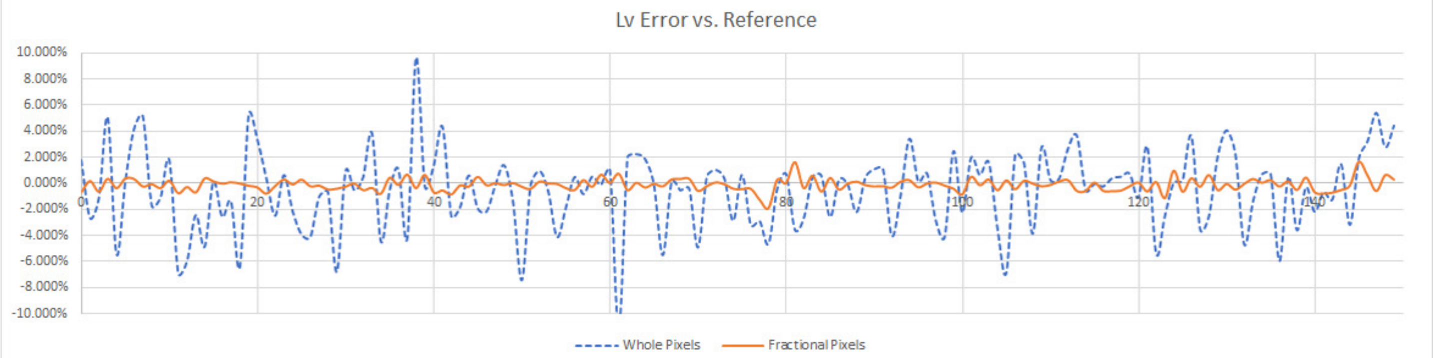

Figure 11 *- Percentage error in luminance (ΔLv, %) measured by whole and fractional pixel measurement methods (using down-sampled image) versus reference luminance (using reference image) for the same row of pixels (row 100 of 200).*

Conclusion and Impact

OLED, microLED, and other emissive displays present increasingly challenging measurement scenarios: they offer higher resolutions and pixel densities versus current image-based measurement systems, and have inherent pixel-to-pixel luminance variability, making display correction a necessary quality control measure. Developed for large displays and multi-image measurement scenarios, whole pixel methods are inadequate for measurement and correction processes applied to new display resolutions at required takt times. Whole pixel methods introduce significant error in the final measurement, which manifests as strong pixel-to-pixel variation in the final demura process and negates the benefits of correction. To the human eye, this effect can easily be perceived as poorly calibrated and non-uniform display luminance, which is often unacceptable for display manufacturers. Alternatively, a new fractional pixel method enables measurement systems with relatively low sensor-to-display resolutions to achieve measurably higher accuracy over whole pixel methods, closely matching the accuracy of high-resolution systems for single-image measurement. This ensures the effectiveness of demura correction for extremely high-quality display appearance, safeguarding manufacturing resources and streamlining production operations.

The fractional pixel method was initially incorporated into demura processes used by Radiant Vision Systems OLED display customers, who achieved significant increases in production yield, contributing to commercialization of OLED displays within the global smart device market. These improvements indicate the advantage of several measurement techniques developed by Radiant to optimize the accuracy of data measured within each pixel for displays of increasing resolutions: fractional pixel method, moiré removal using in-focus measurement and a proprietary moiré filter processes, and spaced-pixel pattern measurement method.[3]

The fractional pixel method enables measurement systems with relatively low sensor-to-display resolution to achieve measurably higher accuracy over whole pixel methods, closely matching the accuracy of high-resolution systems for single-image measurement.

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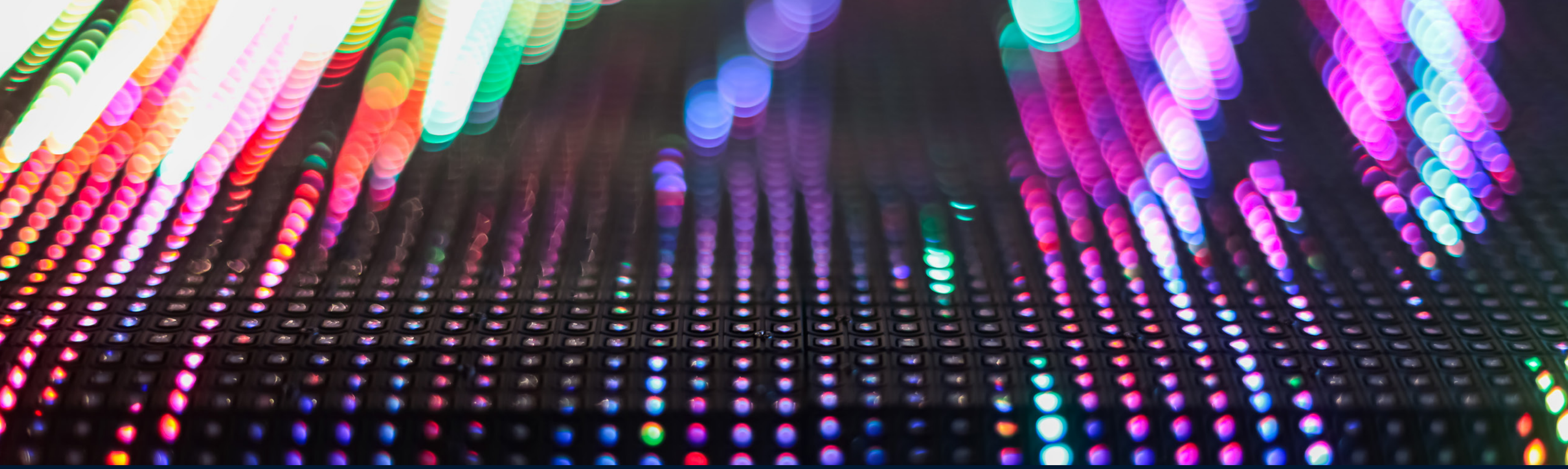

As display resolutions increase, imaging systems are challenged to continue to provide accurate pixel-level measurements while applying increasingly limited relative imaging resolution during single-image analysis (necessary for production efficiency). A fractional pixel registration and measurement method improves the accuracy of pixel-level values measured by standard-resolution systems, ensuring effective qualification and demura of high-resolution OLED, miniLED, and microLED displays.

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