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Clustering-Based Display Calibration

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Abstract:

This publication describes techniques for clustering-based display calibration. In aspects, a calibration manager groups displays in a manufacturing line into clusters based on similarities of the displays' color and white point properties. The clusters can be any quantity of displays and include a "seed" display. The calibration manager generates a calibration profile for the seed display of each cluster. The calibration manager may use an industry standard, such as ΔE00 (Delta E 2000), to determine similarity between displays' color properties and populate the clusters. Once a cluster is populated with similar displays, the calibration manager applies the calibration profile generated for the seed display to all displays in that cluster. By so doing, the calibration manager conserves time in the manufacturing line, improves time to market, and increases supply, while maintaining calibration accuracy comparable to individual-based display calibration.

Keywords:

display, display color calibration, calibration profile, 3-dimensional lookup table (3D LUT), color space, color gamut, RGB, International Commission on Illumination (CIE), CIE XYZ, Delta E 2000, DE00, ΔE00, color difference

Background:

A display device (e.g., a smartphone, a tablet, a laptop, a computer monitor) can be used for watching or streaming videos, editing photos, playing video games, and other visual activities.

For a satisfying user experience, the display is calibrated to a standard color gamut (e.g., standard RGB (sRGB), Digital Cinema Initiatives P3 (DCI-P3), National Television System Committee 1953 (NTSC 1953)) to accurately render specific colors and meet quality requirements for the display. Display calibration can also be used to eliminate, or at least reduce, variations in color rendering across different display vendors, intrinsic variations for a batch of displays from a single vendor, or variations from different display technologies (e.g., liquid crystal display (LCD), organic light-emitting diode (OLED) display).

To calibrate a display to a specific color gamut, colorimetric values (CIE XYZ) are transformed to color signals (e.g., RGB) for the specific color gamut. This transformation can be a simple 3x3 matrix based on measured colorimetric values for white, red, green, and blue emitted by the display at peak luminance. However, this type of simple transformation (e.g., 3x3 matrix) is based on certain assumptions (e.g., additivity, linearity) and is, therefore, restricted to display technologies that meet these assumptions, such as LCDs. OLED displays, on the other hand, violate these assumptions due to non-linear channel-to-channel cross-talk that causes an output of a color channel to affect an output of another color channel.

To calibrate an OLED display, a large number (e.g., 100, 200, 350, 1,000) of colors are measured to generate a consistent (from display to display) and accurate calibration profile (e.g., a three-dimensional (3D) lookup table (LUT)). For example, a calibration profile that approximates a mapping between CIE XYZ color space values and RGB color space values can be based on measurements of NxNxN colors, where N is a positive integer (e.g., 9, 17, 25) and corresponds to values for RGB triplet input color values. That is, the calibration profile can be based on measurements of 4,913 different colors (17x17x17), each color being a unique combination of RGB color values, such as pure red (e.g., 255x0x0), pure green (e.g., 0x255x0), pure blue (e.g., 0x0x255), and pure white (e.g., 255x255x255). Unfortunately, however, for a display manufacturer to measure that many colors for every display in a manufacturing line is not practical; it can delay time to market and limit supply.

Alternatively, a smaller number (e.g., 55, 70, 80) of colors can be measured and remaining color mappings can be estimated using various interpolation techniques (e.g., linear, bilinear, cubic, bicubic). Interpolation techniques can significantly reduce calibration time in the manufacturing line. However, these same techniques can be associated with considerable error where the measured CIE XYZ color space values are not linear with respect to the RGB color space input values, such as in OLED displays.

Description:

Unlike conventional techniques described above, which can delay time to market, limit supply, or introduce error in interpolated color values, this publication describes techniques for clustering-based display calibration. In aspects, a display module includes at least a display panel and memory, and is herein referred to as a "display." A display manufacturer may group displays in a manufacturing line into clusters based on similarities of the displays' color properties and white points. The displays can be any one of a variety of displays, including light-emitting diode (LED) displays, organic light-emitting diode (OLED) displays, in-plane switching (IPS) displays, liquid crystal displays (LCDs), and so forth. The clusters can be any quantity (e.g., five, seven, 10, 15, 50) of displays and include a "seed" display. A calibration profile, such as a three-dimensional (3D) lookup table (LUT) that maps CIE XYZ color space values to RGB color space values, may be generated for the seed display based on a large number (e.g., 100, 200) of color measurements. A mapping for colors that are not measured may be interpolated from the measured colors using, for example, linear interpolation. An additional display can be added to a cluster based on a similarity to the seed display, such as how similarly the additional display and the seed display emit white, red, green, and blue colors at full luminance. The similarity between displays may be based on a measurement, such as the industry standard ΔE00 (Delta E 2000) measurement that quantifies how similar the three primaries (red, green, and blue) and white point of two colors are. Once the cluster is populated with displays having similar primaries and white points, the calibration profile generated for the seed display can be applied to all displays in that cluster, thus reducing error in interpolated color values.

In aspects, a manufacturing line may include a computing device having at least one processor and a computer-readable medium (CRM). The CRM can include any suitable memory or storage device, such as random-access memory (RAM), dynamic RAM (DRAM), non-volatile memory (e.g., flash memory), read-only memory (ROM), a dual in-line memory module (DIMM), a solid-state drive (SSD), and so forth. The CRM stores instructions that, when executed by the processor, cause the processor to implement a calibration manager directed at clustering-based display calibration. Figure 1 illustrates a flow diagram for clustering-based display calibration.

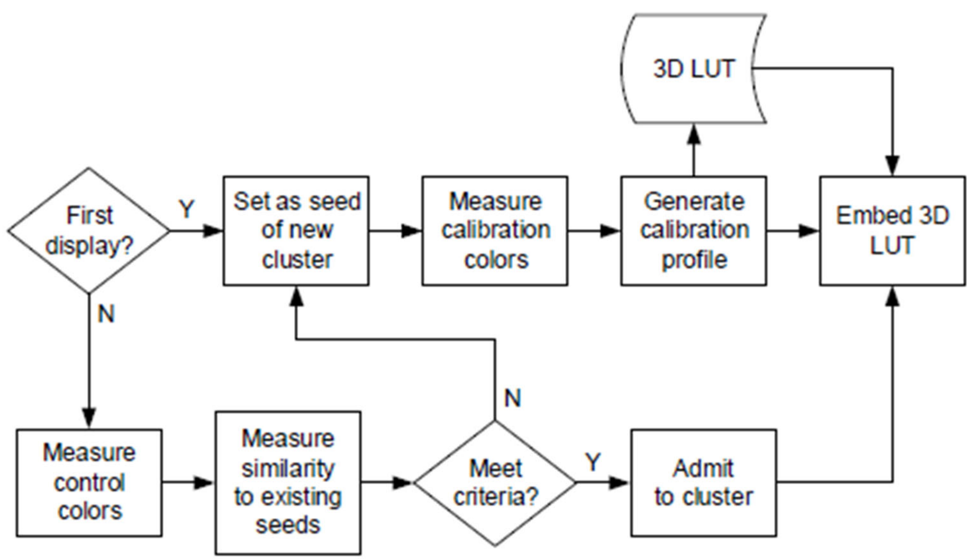

Figure 1

As illustrated in Figure 1, if a display is a first display in a manufacturing line, the calibration manager sets the display as a seed display of a first cluster. Then, the calibration manager measures a number of calibration colors on the seed display. The number of calibration colors can depend on a display technology, process capabilities of the manufacturing line, qualification criteria of a manufacturer or client, and so forth. Based on the measurements of the calibration colors, the calibration manager generates a calibration profile for the seed display. The calibration profile can be any appropriate calibration profile, such as a 3D LUT that approximates mappings between RGB color space values and CIE XYZ color space values. The 3D LUT can also store interpolated mappings for color values that are not measured. Alternatively or additionally, mappings for color values that are not measured may be interpolated in real-time, depending on capabilities of a display device having the seed display. Once the calibration manager completes generating the calibration profile, a 3D LUT in the present example, the calibration manager may embed (e.g., write to a memory) the calibration profile in the seed display or a display device thereof.

If a display is not the first display calibrated in the manufacturing line, then the calibration manager measures a number of control colors for the display. The number of control colors can be any positive integer deemed appropriate, for example, by the display manufacturer or a customer of the display manufacturer to meet certain qualification criteria. As an example, the calibration manager may measure four control colors including red, green, blue, and white at full luminance. Then, using ΔE00, the calibration manager may generate comparison results between the control colors of the display and the same colors of a calibrated seed display. For example, the calibration manager may generate comparison results between the display and, prior to embedding the calibration profile, the seed display from the previous operation. By so doing, the calibration manager determines, based on the ΔE00 comparison results meeting a threshold, how similar the display is to the calibrated seed display. If the ΔE00 comparison results meet the threshold, then the calibration manager admits the display to the cluster of the seed display. Once part of the cluster of the seed display, the calibration manager embeds the calibration profile generated for the seed display, a 3D LUT in the present example, in the test display.

However, if the ΔE00 comparison results of the display do not meet the threshold, then the calibration manager sets the display as another seed display for a second cluster. From there, the calibration manager repeats operations for measuring calibration colors, generating a calibration profile, and embedding the calibration profile in the seed display for the new cluster. The calibration manager may repeat the operations described herein for each display in the manufacturing line until a calibration profile is embedded in every display. By so doing, the calibration manager conserves time in the manufacturing line, improves time to market, increases supply, and eliminates, or at least reduces, error in interpolated color values.

References:

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