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Color and Luminance Management for High-Resolution Liquid-Crystal Displays

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Abstract

A new method of color management is described which takes advantage of the high pixel density achievable with TFTLCDs. In this method, a calibration 10-bit look-up-table can be loaded into the monitor and implemented as a 2x2 spatial dither block to provide a 10-bit color palette for 8-bit color drive. Other sub-pixel dithering techniques are also described for monochrome and color high-resolution TFTLCDs. These techniques can create a very large palette, and combined with a 10-bit digital data source to achieve precise luminance and color calibration.

1. Introduction

Over the past several years, the viewing-angle characteristics of TFTLCDs have improved greatly. For the best liquid crystal modes, the just-noticeable-differences in color over a large viewing cone are roughly the same as the lowest differences which occur in the process of image capture, rendering, and print. At the same time, the pixel density which can be achieved in TFTLCDs has increased to beyond 200 pixels per inch. With digital data input, TFTLCDs can be constructed with programmable front-end circuitry for digital signal processing. Among other functions, this circuitry can implement a lookup table function to modify the input data to refine the palette of available colors. All of these features have been combined to render calibrated color and luminance with high precision.

With 24-bit color, a display can render more than 16 million colors. It has been estimated that humans cannot distinguish more than a few million colors, yet very small differences in luminance and hue are easily discerned. For best results, it is necessary to carefully choose the rendered colors from a large palette of possible colors. For many applications, it is necessary to adjust and calibrate the display characteristics. For example, it may be necessary to change the monitor white point, or adjust the luminance gamma characteristics (tone reproduction curve). To provide accurate 8-bit levels of each primary color requires that they be chosen from a large palette of primary colors, such as 10-bit or larger. Although TFTLCD column drivers are limited to 8-bits, and are likely to remain so for some time, dithering methods can be used to extend the effective bit-depth. Temporal dither has been commonly used to increase bit depth to 8-bits in notebook displays, utilizing 6-bit drivers. The complex nature of temporal liquid crystal response and circuity interaction limits the utility of temporal dither for accurate modulation. However, as the display

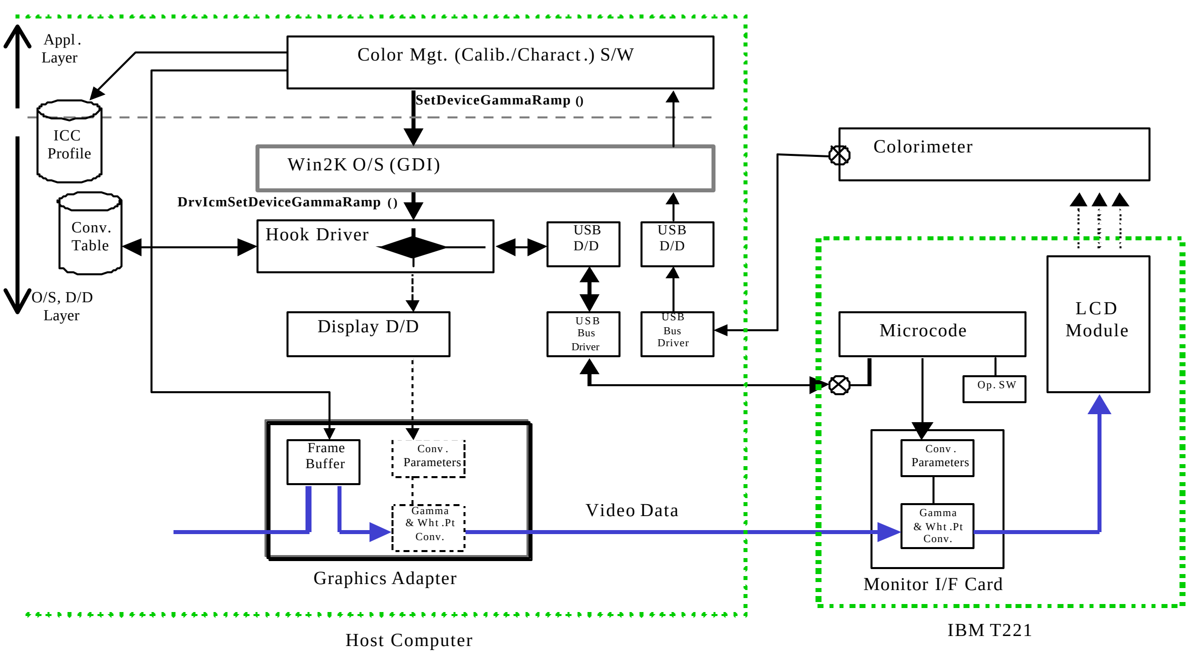

Figure 1. Block diagram of color management function utilizing monitor color LUT.

pixel density increases, spatial dither can be utilized, with little or no visual artifacts. Sub-pixel spatial dither is currently being employed to achieve accurate luminance with high-resolution monochrome medical displays.

2. Color Management Utility / Monitor LUT

Conventional color management approaches for displays involve a calibration device and software application, which generate a color profile. The color profile retains the calibration data which is used to load gamma ramp values to the graphics card lookup table (LUT), also known as the palette DAC. The gamma ramp LUT consists of 256 entries of 16-bit values. For analog drive, this 16-bit LUT is utilized for increasing the color palette, wherein the 8-bit/color digital input data is converted into analog output. For digital drive, the 8-bit input color digital data is converted into 8-bit digital output. Depending upon the color conversion requirements, the converted digital output levels can have large quanitization error, i.e. repeated output levels.

The IBM T221 3840x2400, 9.2 Mpixel display has a pixel density of 204 ppi, and can be driven with one to four DVI digital inputs. The T221 has programmable electronics which contain a frame buffer memory and can perform digital signal processing on the input data. Via USB, a 10-bit LUT can be stored in the monitor, as shown in Figure 1. In this way, the calibration data can be stored in the monitor, as opposed to the graphics card or in the registry. This LUT is used to perform a 2x2 spatial dither which allows a 10-bit extension of the inherent 8-bit levels for each color. Thus, the 256 luminance levels for each primary color are selected from a field of 1024 available luminance levels.

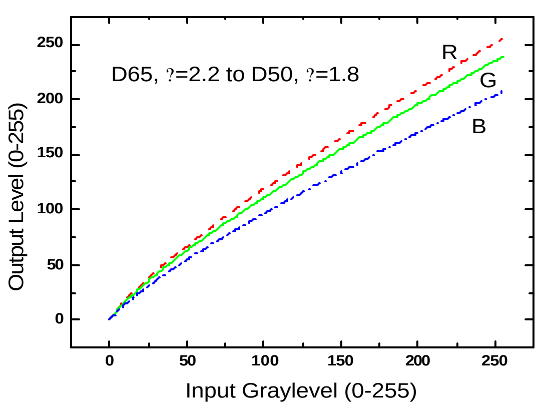

Figure 2. Table for changing D65 whitepoint and 2.2 gamma to D50 and 1.8 using 8-bit to 8-bit conversion.

The effects of the 2x2 spatial dither at 204 ppi are minimal, because the human contrast sensitivity function drops sharply in the range 30 to 60 cycles/degree [1]. Furthermore, the contrast sensitivity function for both chromatic differences [2] at red and blue wavelengths [1] falls off at much lower spatial frequencies than for luminance differences. The combination of high pixel density and dither applied to the two least significant bits minimizes any visual artifacts. However, the 2x2 spatial dither clearly has an effect on the local area average luminance.

A color management utility program has been created which manages the flow of calibration data into various LUTs. One mode directs system gamma ramp calls solely to and from a LUT in the monitor. Another mode directs system gamma ramp calls solely to the graphics card. A third mode blocks both the graphics card and monitor LUTs from changes. This color management utility works in conjunction with other commercially available calibration software and colorimeter hardware.

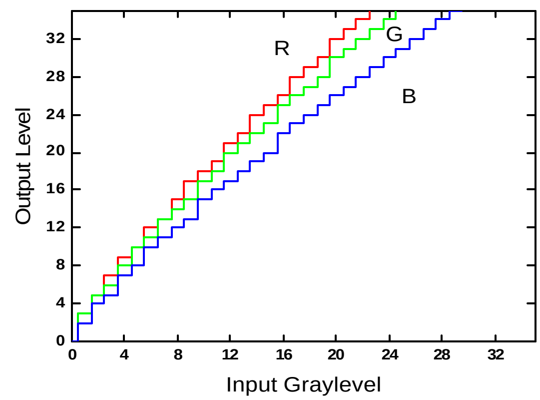

Figure 3. Quanitization errors introduced at low end.

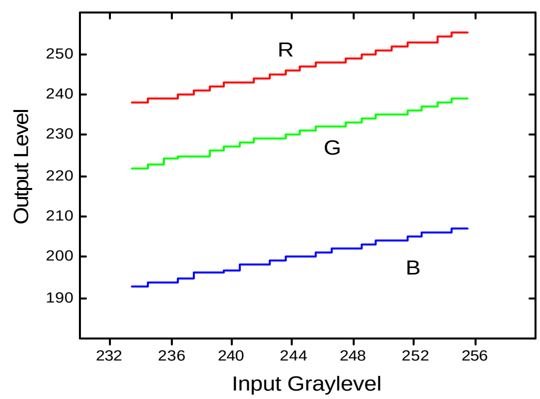

Figure 4. Degeneracy errors introduced at high end.

A common need is to shift the color temperature of the display monitor whitepoint, as shown in Figure 2. 8-bit conversion leads to quanitization errors in the output, as shown for low-end and high-end values in Figures 3 and 4. Figures 5 and 6 show plots of calculated color errors generated using 8-bit and 10-bit conversion, respectively.

3. Luminance Control for High-Resolution Monochrome TFTLCDs

For many high-resolution monochrome TFTLCDs, such as the 3 Mpixel, 123 ppi product from IDTech, the pixel array and drive architecture is basically the same as for a color panel, but the color filter layer has been removed. Each square monochrome pixel consists of three rectangular monochrome subpixels, each subpixel individually addressed, as in a standard color array. In the horizontal direction, there are 369 monochrome subpixels per inch, and there are a total of 9 million subpixels in the 3Mpixel array. The three subpixels can be utilized to provide finer control over pixel luminance. Graphics cards typically employed for medical monochrome applications provide a single luminance channel with 8-bit output, so subpixel dithering can be used to select 256 precise luminance levels from a luminance "palette" of

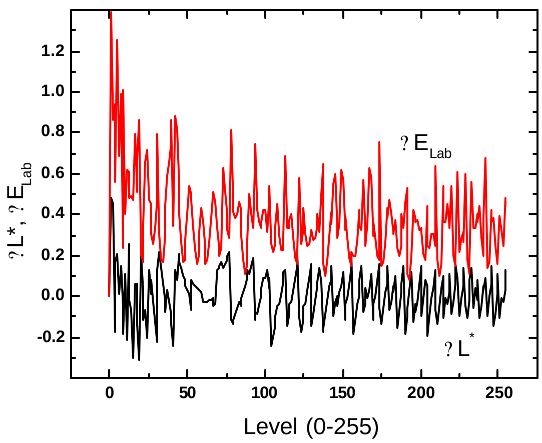

Figure 5. Calculated Lab ? E and ? L* errors for 8-bit conversion from D65, ??=2.2 to D50, ??=1.8.

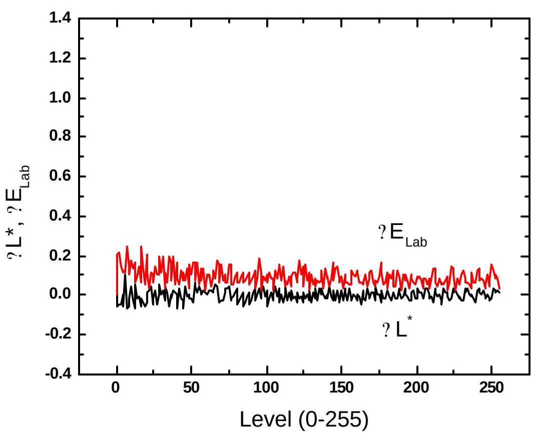

Figure 6. Calculated Lab ? E and ? L* errors for 10-bit conversion from D65, ??=2.2 to D50, ??=1.8.

766 grayshades. This approach is presently being utilized in some monochrome TFTLCD monitors [3].

Each monochrome subpixel occupies 1/3 of the total pixel area, providing 1/3 of the luminance of a full pixel. By turning on individual subpixels, the luminance can be controlled in finer steps, each 1/3 the size of the steps which could be achieved with a similar monitor containing only macro monochrome pixels. The number of selectable luminance levels is increased by a factor of three over standard methods, but these steps are not optimal, because the luminance steps are linear with level. Perceived brightness follows a logarithmic relationship to luminance, because just-noticeable-differences (JND) in brightness correspond to ~ 1% increases in the relative luminance (Weber fraction). Assuming a Weber relationship, for perceptual linearity, luminance should follow an exponential relationship with level. For standard computer monitors, the luminance follows the level raised to the power 2.2. To provide equal steps in CIE brightness, the luminance would follow the level raised to the power 3.0. For medical applications, the luminance should match the DICOM specification [4], which uses a model for brightness perception more complicated than Weber's-law.

4. Luminance Control for High-Resolution Color TFTLCDs

It is generally believed that the quality of color displays makes them unsuitable for critical monochrome applications such as medical imaging or intelligence image analysis where control of luminance is paramount. This belief is based on past experience with CRT technology. For current TFTLCD technology, the advantages of monochrome over color are primarily brightness (~3.5 times larger for monochrome for equivalent pixel structures) and contrast ratio (~600:1 for monochrome and ~400:1 for color with dual-domain IPS mode). However, the utility of color for some medical modalities and for all standard office applications provides a strong motivation to reconsider the use of specialized and expensive monochrome monitors. It is not generally recognized that high-resolution color TFTLCDs have potentially finer control of grayshade luminance than "equivalent" monochrome versions.

The luminance of red, green, and blue channels are not equal, with typical distribution of relative luminances of 23% for red, 64 % for green, and 13% for blue. For a high density pixel array, these unequal luminances can be used to achieve extremely fine control of luminance. Subpixel dithering of color pixels has been termed "bit-stealing"[5]. Several examples of bit-stealing methods are shown in Table 1. Values were chosen to closely match 1% increments in luminance. Each example shows how the intermediate subpixel levels can be chosen between pseudogray values of R=G=B=n and R=G=B=n+1. Some of the schemes involve intermediate dither of the blue or red channels as much as

R	G	B	R	G	B	R	G	B
n	n	n	n	n	n	n	n	n
n+1	n	n+1	n	n	n+1	n	n	n+1
n	n+1	n	n+1	n	n+1	n+1	n	n
n+1	n+1	n+1	n+1	n	n+2	n	n	n+2
			n	n+1	n	n+1	n	n+1
levels	bits		n	n+1	n+1	n+2	n	n
766	9.6		n+1	n+1	n+1	n+1	n	n+2
						n+2	n	n+1
			levels	bits		n	n+1	n
			1531	10.6		n+2	n	n+2
						n	n+1	n+1
						n+1	n+1	n
			levels	bits	✍	n	n+1	n+2
			3316	11.7	✍	n+1	n+1	n+1

Table 1. Examples of methods for sub-pixel dither.

2 counts higher than the starting value, introducing a noticeable color error for large, iso-luminance patches of an image. However, at a pixel density of 204 ppi, a variety of techniques can be employed to remove this potential artifact. In principle, an additional two bits of spatial dither could be added to the bit-stealing method to theoretically achieve 13.7 bits for the most extreme example shown in Table 1.

A preliminary investigation has been done regarding various implementations of the techniques described here for matching DICOM luminance specifications. JND measurement results for calibration with a standard 8-bit card are shown in Figure 7, where R=G=B. Thirty-three test measurements were done for calibration and 256 measurements were done for verification. Figure 8 shows results for the same calibration implemented in the 10-bit monitor LUT. As compared to standard 8-bit calibration, the 10-bit implementation reduced the step JND standard error by about a factor of 3. Figure 9 shows results for one commercial implementation [6] of the bit-stealing method, applied to the graphics card LUT. Both subpixel and pixel dither yielded similar results. It is likely that the dither results are masked by noise and drift in luminance measurement performed with a Si photodiode detector. Further work is needed to better quantify these results.

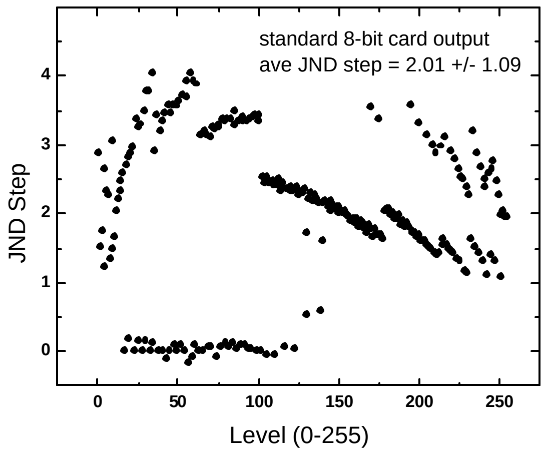

Figure 7. DICOM results for 8-bit calibration.

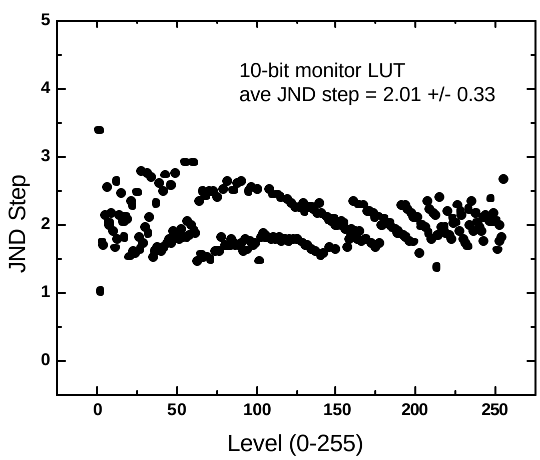

Figure 8. DICOM results for 10-bit calibration.

5. Toward True 10-bit Drive

To make optimal use of high contrast ratio and brightness of TFTLCDs, the number of distinct graylevels needs to be increased. A monochrome monitor with a contrast ratio of 600:1 can fully utilize about 640 graylevels (9.3 bits), assuming a JND Weber fraction of 1%; or about 585 levels (9.2 bits) assuming DICOM JND. With 10-bit capability, a contrast ratio in excess of 1000:1 could be fully accomodated, matching the characteristics of film, exposed, processed and viewed under the best possible conditions. Using the dithering methods described here obviates the need for 10-bit column drivers. Providing 10-bit pixel data to the panel would take full advantage of a 10-bit/color palette,

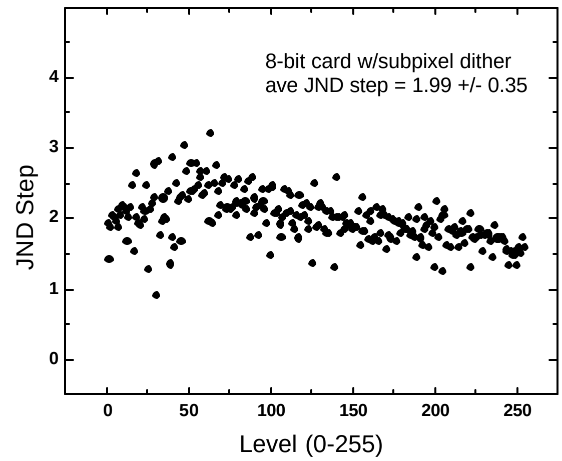

Figure 9. DICOM results with subpixel dither.

of interest for both color and monochrome applications.

Standard digital graphics cards are presently limited to 8-bit output but 10-bit output is emerging, at least for monochrome. One protocol is to place the most significant monochrome 8 bits on the green DVI channel, with the two least significant bits on the red or blue channels. Another possible protocol is to transmit standard 8-bit pixel data per clock for four clocks, followed by a fifth pixel clock, during which the two least significant bits of the previous four pixels is transmitted. This method could be applied to either monochrome or color data, but requires 20% longer time to increase the bit-depth from 8 to 10, with corresponding data refresh rate reduction. Logic design changes would be required for the monitor input signal processing unit to handle this protocol. These changes for graphics card and monitor electronics are not prohibitively expensive, and can be developed to meet the needs of applications involving critical color or luminance control. If so, then the use of high resolution color TFTLCDs for critical monochromatic imaging applications can be expected to increase, with monochrome panel use restricted only to those applications which demand the highest luminance and contrast ratio.

6. References

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