Improving the Gray Tracking Performance of LCD

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Abstract

LCD dominates the display market in both desktop and TV due to improved performance and reduced cost. In this paper, the two remaining LCD color issues (color crosstalk and color primary shift) are analyzed. The two issues cause a LCD to deviate from an ideal additive display and lead to a gray tracking problem. A new gray tracking algorithm was developed. The algorithm iteratively measures and corrects the white point of the display until the target chromaticity is reached. The algorithm can be implemented in the 1D gamma table and significantly improves the gray tracking performance of LCD.

1. INTRODUCTION

The LCD has improved significantly in both resolution and size so that it is display of choice for both desktop monitor and TV. With its wide use in both desktop displays and TV monitors, there is increasing need for color management of LCD[1,2]. One particular important issue with LCD is the gray tracking, which is the consistence of white point at various gray levels. Poor gray tracking causes color casting in the displayed output, which is a very distracting artifact. There are three primary causes for the inconsistency in gray tracking: (1) leakage due to limited contrast ratio, (2) color crosstalk between the sub-pixels, and (3) unstable primary. The contrast ratio problem is well recognized and has been improved significantly in recent years. In this paper, the other two issues that contribute to the gray tracking problem are analyzed and a new algorithm is proposed to improve the gray tracking performance of LCD.

2. COLOR CROSSTALK IN LCD

The use of color triads in LCD provides independent control of each color; but, sometimes, the signal of one channel can still impact the output of another channel, which we refer to as "crosstalk"[3]. The drive for larger size, higher spatial resolution, and increased aperture ratio LCD has worsened the electrical crosstalk between electrodes in the driver circuit. The electrical crosstalk can cause gray tracking problem.

To identify the crosstalk pattern, multiple configurations of pixel patterns were displayed on a LCD and captured by a CCD imaging colorimeter[4]. Figure 1 show a captured micrograph of one of the test patterns. The LCD digital counts were 128 except the three brightest patches which was 255. In some patches holes were used, in which a subpixel was turned off within the patch. In other patches, the patch was black, with only localized subpixels turned on. These patterns were used to analyze the adjacent effects for both positive and negative crosstalk. Each LCD subpixel was segmented out of the micrograph and averaged to get the XYZ values. The XYZ values were normalized to the corresponding 255 patches to get the normalized RGB value.

The patches D1 D2 and D3 were RGB subpixel alone (all the neighboring subpixels are off). The values from these patches (R_0, G_0, and B_0) established the subpixel output without crosstalk. All the other patches were different arrangement of subpixels. If there were no crosstalk, the measured luminance be the same as the value from the three patches (i.e. $R=R_0$, $G=G_0$, and $B=B_0$). Two patches of particular interest were patch B1 and D4. Both had the same input value except in patch D4, there was an off subpixel in between RG and GB. The measured brightness in D4 was the same as the patches without crosstalk, while patch B1 showed positive crosstalk in R and G, and a smaller negative crosstalk in B.

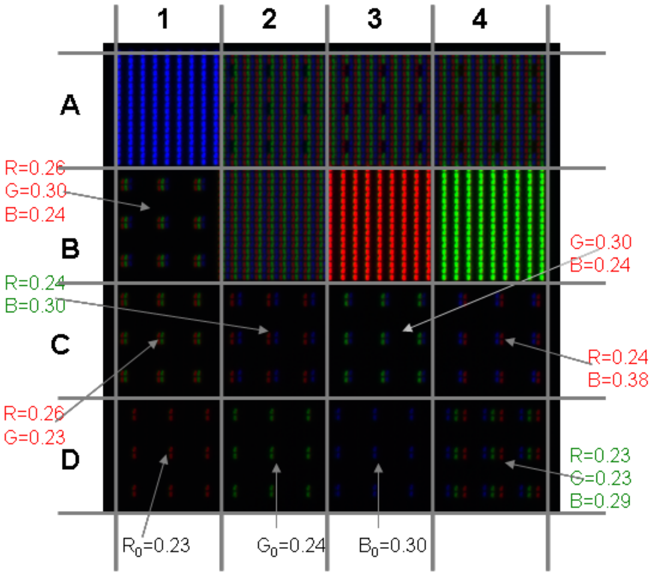

Figure 1 Microphotograph of a LCD showing the crosstalk between subpixels

Figure 2 shows the measured crosstalk between red and blue subpixels (R_{i+1} to B_i and to B_i to R_{i+1}). There is significant amount of red to blue crosstalk (right to left), but little blue to red (left to right). The subpixel crosstalk between red and green, green and blue exhibits a similar trend, but with a slight different magnitude. The experiment shows that whenever any two neighboring subpixels are "on" at the same time, there is crosstalk from one subpixel to another, but whenever there is one "off" subpixel between the two "on" subpixels, there is no crosstalk between the "on" subpixels.

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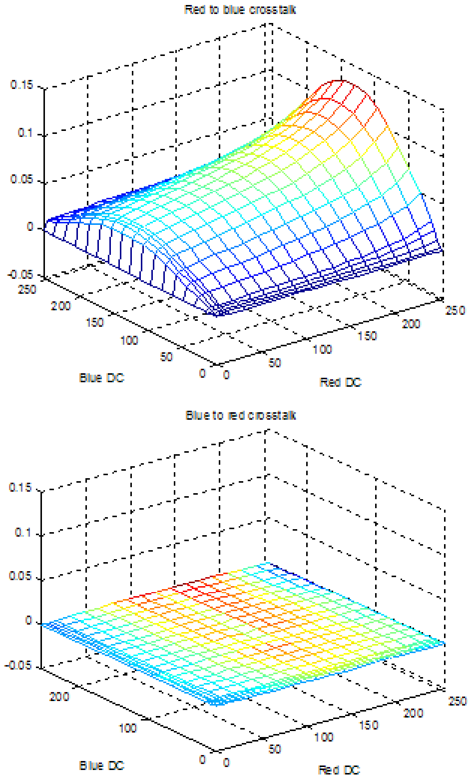

Figure 2 Measured crosstalk between red and blue (top: red to blue, and bottom: blue to red)

3. PRIMARY SHIFT IN LCD

The primary shift is mainly due to the wavelength dependency of LCD transmittance at different driving values [5,6]. Figure 3 shows measured chromaticity of the white point and the three primaries at various gray levels. The chromaticity value x increases with the driving value for the green primary, which causes the white point (the black *) in the figure to also change.

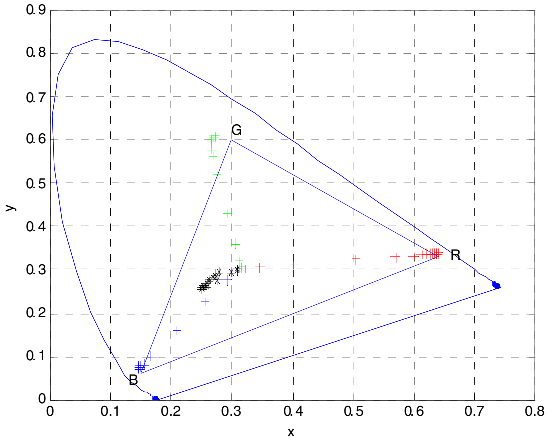

Figure 3 Chromaticity of RGB primaries as a function of gray level

4. LCD COLOR MIXING MODEL AND GRAY TRACKING

The LCD color output is often modeled as additive color mixing where the primary colors (R, G, and B) are measured at its maximum. Two matrices are derived from the measured data: one converts normalized RGB to XYZ, and the other matrix converts from XYZ to RGB. The X, Y, and Z are the CIE tri-stimulus values.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

and

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2}$$

The white point is defined to be the color coordinates of maximum RGB input and it is often specified in CIE chromaticity: x and y. The white point can be changed by adjusting the relative strength of the RGB channels. According to Equation 2, equal RGB input will produce a gray output with the same chromaticity as the white, thus the neutral color is consistent throughout all the gray levels. But with consideration to color crosstalk, primary shift, and leakage, Equation 1 becomes:

$$\begin{aligned} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = & \begin{bmatrix} X_r(R) & X_g(G) & X_b(B) \\ Y_r(R) & Y_g(G) & Y_g(B) \\ Z_r(R) & Z_g(G) & Z_g(B) \end{bmatrix} \\ & \begin{bmatrix} 1 & C_{gr}(G,R) & C_{br}(B,R) \\ C_{rg}(R,G) & 1 & C_{bg}(B,G) \\ C_{rb}(R,B) & C_{gb}(G,B) & 1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} X_{leak} \\ Y_{leak} \\ Z_{leak} \end{bmatrix} \end{aligned} \tag{3}$$

where C is the crosstalk coefficient and its subscripts r g and b denote the color channels, and the first subscript denote the source color and the second subscript denote color that get the crosstalk. For example, C_{rg} is the crosstalk coefficient from red to green. The X_{leak}, Y_{leak}, and Z_{leak} are the leakage values when the LCD is set to black. Due to the nonlinear characteristics of crosstalk and primary shift, both the RGB to XYZ matrix and the crosstalk matrix are a function of R, G, and B. Although the ideal display has no gray tracking problem, an actual LCD can exhibit gray tracking problem due to color crosstalk, primary shift, and leakage. Figure 4 shows the chromaticity of a display as a function gray level. The color temperature changes from 10,000K at a gray level of 255, to 23000K at 50, and back to 6700K at 0. Clearly, a gray tracking algorithm is needed to improve the consistence of the white point.

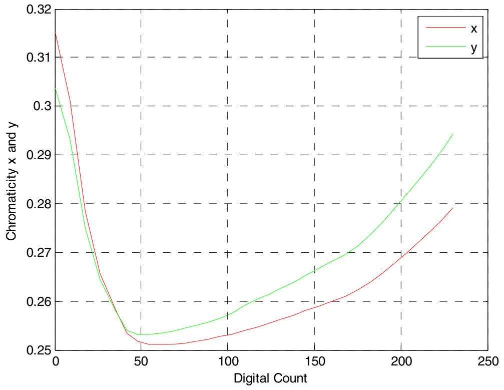

Figure 4 Chromaticity of a display for gray input without gray compensation

The white point of display can be derived from Equation 3 for any gray level, and the desired white point can be achieved by adjusting the RGB driving values for that gray level based on the same equation. But characterizing the parameters for Equation 3 can be very time consuming, thus a new gray tracking algorithm is developed to reduce the color shift for neutral input color. The algorithm uses an iterative approach that involves measuring the display, calculating the chromaticity error, and deriving the correction values in LCD driving. The process is repeated until the desired white point is achieved. Since it is too time consuming to correct every gray level; a few control points in the gray range are selected. For each control point,

1. Set r=g=b=control point to gray level g_i, where g_i is the gray level of the i_{th} control point.
2. Display the color patch
3. Measured the color : X, Y, Z, x, and y
4. If $|Y-Y_0| > Y_{tol}$ or $|x-x_0| > x_{tol}$ or $|y-y_0| > y_{tol}$ do the follow steps:
    a) Calculate the desired color in XYZ, where Y_w is the white point, and ϒ is the desired gamma value

    $$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \left(\frac{g_i}{255}\right)^{\gamma} Y_w \begin{bmatrix} x_0 / y_0 \\ 1 \\ (1-x_0-x_0) / y_0 \end{bmatrix} \quad (4)$$

    b) Calculate differences in XYZ

    $$\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \quad (5)$$

    c) Approximated differences in normalized RGB

    $$\begin{bmatrix} \Delta R \\ \Delta G \\ \Delta B \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \quad (6)$$

    d) Calculate the new LCD driving digital counts

    $$\begin{bmatrix} r' \\ g' \\ b' \end{bmatrix} = \begin{bmatrix} r \\ g \\ b \end{bmatrix} - \frac{255^{\gamma}}{\gamma} \begin{bmatrix} \Delta R / r^{\gamma-1} \\ \Delta G / g^{\gamma-1} \\ \Delta B / b^{\gamma-1} \end{bmatrix} \quad (7)$$

5. Repeat step 2-4
6. done

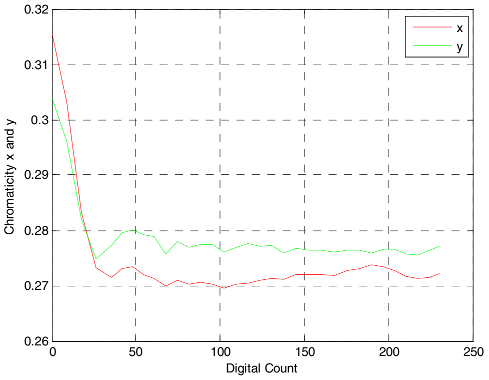

Figure 5 Chromaticity as a function of gray level before and after gray compensation algorithm

Once the correction was done for all the control points, a linear interpolation is used to construct the three 1-D lookup table. Figure 5 shows the chromaticity as a function of gray level after the gray tracking algorithm with the target chromaticity of x: 0.272 and y: 0.277 (12,000K). The color shift is clearly reduced from gray levels of 24 to 255. The color shift in the dark portion of the tone scale was not corrected to preserve the contrast ratio of the display.

5. Summary

Both color crosstalk and color primary shift causes a LCD to deviate from an ideal additive display. One particular problem is the gray tracking problem where the white point color varies for a gray input at different gray levels. A new gray tracking algorithm is developed. The algorithm uses an iterative method that measures the display and applies a correction until the target chromaticity is achieved. The algorithm is tested on many LCD and shows very good convergence. The correction is implemented in the display gamma table without adding extra hardware.

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Author Biography

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