Color Reproduction Characteristics of Liquid Crystal Display Panels and New Compensation Methods for Them

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Abstract

The color reproduction characteristics of LCD (liquid crystal display) panels are different from those of CRT (cathode ray tube) displays. This paper describes how the authors measured and analyzed such characteristics of LCD panels to develop new methods for compensating the bluish cast found on conventional LCDs. The first one is a hardware-based technique that employs a LUT (look-up table) and the second a software-based color management technique utilizing ICC profiles compensating the bluish cast. The authors achieved faithful color reproduction for standard sRGB with both methods.

Introduction

Many aspects are examined in evaluating the image display characteristics of a liquid crystal display (LCD) panel, including brightness, viewing angle, contrast, color reproduction, and gamma characteristics. Subjective evaluations of the color reproductions of LCD panels reveal they have superior rendition of the blue color system, and are highly rated for their ability to display the blue of the sky, as memory colors readily recalled by human beings. Nevertheless, an LCD's color reproduction differs from sRGB color space[1)], the standard color space used on the Internet, and thus the color reproductions of LCD panels must be made to coincide with the standard sRGB color reproductions. For example, in selling over the Internet (e-commerce), color matching is important for fashion accessories, home furnishings, and the like. Thus, it is desirable that LCD panels not only provide pleasing color reproduction, but that they have the capability to faithfully reproduce standard sRGB color.

We developed two methods to compensate for the unique color reproduction characteristics of LCD panels to achieve standard color reproduction:

1) Compensate by interposing a hardware look-up table (LUT) between the input image signal and the display panel, and

2) Compensate using software-based ICC profiles.

The color reproduction characteristics of LCDs and compensation methods for them are described below.

1. Color reproduction characteristics of color LCD panels

It is not surprising that LCD panels have unique color reproduction characteristics which differ from those of CRT (cathode ray tube) displays, because of the difference in the principles used to display color[2)]. **Fig. 1** shows an x-y chromaticity diagram resulting from measuring the color reproduction characteristics of a typical transmissive TFT color LCD (Sharp LL-T1510A). The color reproduction characteristics were measured by generating a color patch on the display and using a luminance colorimeter (Topcon BM-5A) to measure from the front of the LCD screen. Measurement methods conform to the IEC61966-4 standard[3]. **Fig. 1** shows the color gamuts after varying the input digital levels. We can conclude the following characteristics of the LCD panel from examining the color reproduction characteristics:

1) As the input levels become smaller, the color gamut shrinks and shifts toward the blue region of the chromaticity diagram.
2) The smaller the input levels, the higher the correlated color temperatures for achromatic colors (neutral gray).
3) Light is transmitted even when the input level is set to zero.

These characteristics can be considered to originate in the characteristics of the liquid crystal material and in the optical characteristics of the polarizer, an optical element placed in front of the LCD panel structure. In the case of black in which the digital value of input is zero (0,0,0), the polarizers are in a "crossed Nicols" state. Even in this state there is color leakage with a bluish cast. Even though the screen is black, it will still have chromaticity points on the chromaticity diagram. And when the LCD color gamut is compared to the sRGB standard, it tends to be somewhat narrow.

Fig. 2 shows the changes in correlated color temperatures on the chromaticity diagram resulting from varying the achromatic input level, equivalent to enlarging the gray locus of **Fig. 1**. The square marks represent a series of color temperature measurements taken at input levels from 0 to 255 at the points 0, 16, ..., 240, 255. When the input is white (255,255,255), the correlated color temperature is 6729 K, but for gray (128,128,128), the temperature is 9784 K, and for black (0,0,0), 29023 K, and thus the correlated color temperature increases as the digital input level decreases. In other words, as the input level decreases, achromatic color is rendered with a shift toward the blue.

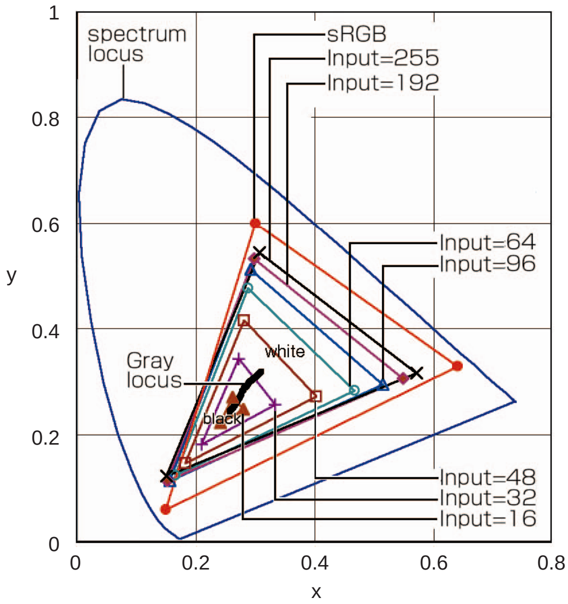

Fig. 1 Color gamuts of an LCD varying the input digital level.

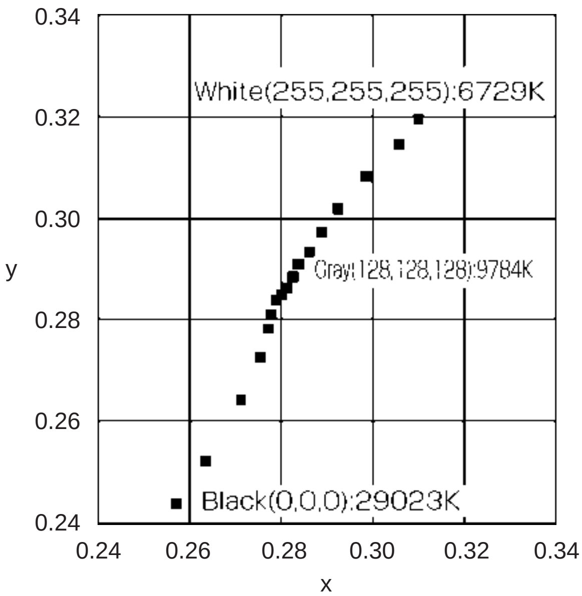

Fig. 2 Locus of gray chromaticity points on (x,y) diagrams varying the input digital level.

It should also be noted that in the color reproduction characteristics of CRT displays, no chromaticity variations in varying the input levels occur for the measurement of RGB primary colors or for white, as in LCDs.

2. Using a LUT (Look-Up Table) to reproduce standard colors[2)]

As shown in **Fig. 2**, the standard sRGB color space is premised on no input-level-dependent achromatic color variations, and thus compensation is required. LCD color reproduction is based on the principle of additive color mixture, so the addition of three primary colors (R, G, and B) equally yields an achromatic color (neutral gray). Because the intermediate-level achromatic color (gray) shifts toward the blue, the bluish cast can be toned down by reducing only the B input level among the input signals and mixing the other R and G colors. The bluish shift in achromatic color can be controlled by interposing a compensation LUT (look-up table) between the RGB input signal and the LCD panel as shown in **Fig. 3. Fig. 4** shows a LUT that compensates for the variations in color temperature shown in **Fig. 2**. In the LUT of **Fig. 4**, R (red) and G (green) are shown as a 45° straight line, representing the fact that the input and output are the same. Only the B (blue) output is attenuated by an amount corresponding to its input level. For example, for an RGB input of (128,128,128), the output is converted to (128,128,92).

The calculated results of the blue shift in achromatic color using the LUT shown in **Fig. 4** are shown in the (x,y) color graph of **Fig. 5**. With the exception of extremely low input levels, the correlated color temperature is nearly constant in the vicinity of 7300 K, indicating that the bluish cast can be compensated for.

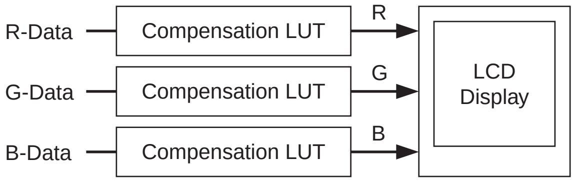

Fig. 3 Schematic diagram of compensation on display data model.

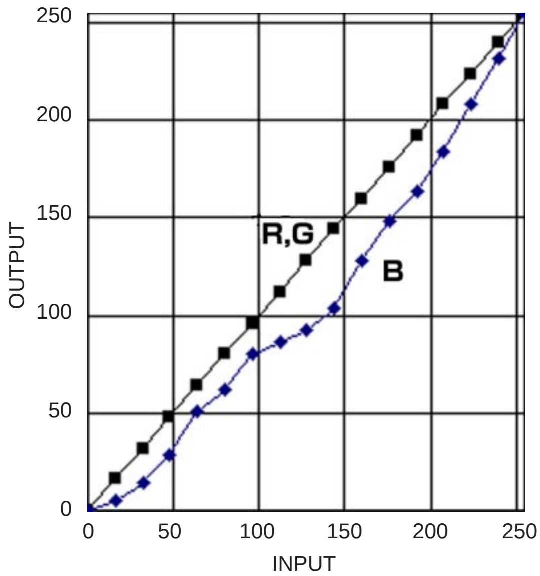

Fig. 4 Compensation LUTs for an LCD.

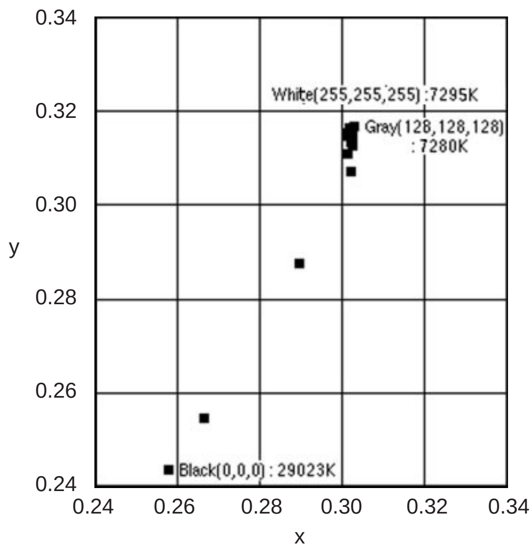

Fig. 5 Correlated color temperatures compensated by using LUTs shown in Fig. 4.

3. Using ICC profiles to reproduce standard colors[4)5)]

ICC profiles are files describing the color characteristics of color imaging devices (digital cameras, printers, monitors, scanners, etc.), and were standardized by the International Color Consortium (ICC) to reproduce the standard colors among imaging devices[6)].

Fig. 6 shows the calculation flow for standard color reproduction for monitors as stipulated by the ICC.

In the ICC model, color information is calculated on a device-independent color space. The PCS (Profile Connection Space) shown in **Fig. 6** is a device-independent color space using an XYZ color space. For the case of monitors, the input RGB image signals are presumed to be standardized sRGB colors, and are converted using the LUT (gamma value of 2.2), and further converted to an XYZ space from the RGB space using a 3x3 matrix calculated based on sRGB chromaticity points. The image data in this PCS is converted back to RGB space from XYZ space using a 3x3 inverse matrix and output as RGB signals using the inverse LUT determined from the gamma characteristics of the LCD panel.

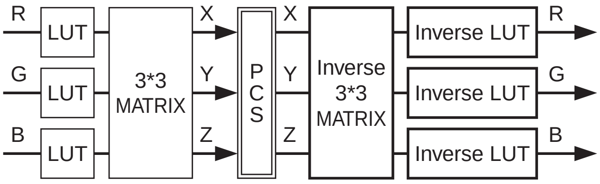

Fig. 6 ICC's calculation flow for monitors.

These calculations can be performed in software using readily available color management software (for example, ICM 2.0 under the Windows 98 OS, or ColorSync on the Macintosh).

3.1 ICC profiles to compensate for the bluish cast of LCD panels

With the exception of header data, ICC profiles for LCDs comprise the data from RGB primary color chromaticity points used to calculate the inverse matrix in the calculation flow, white chromaticity points, and the inverse LUT shown in **Fig. 6**. Here, the input to the inverse LUT is mapped onto the vertical axis, and the output onto the horizontal axis. Applying the compensation LUT shown in **Fig. 4** to compensate for the blue-shift characteristics yields the graph of the inverse LUT of **Fig. 7**. The inverse LUT is not a representation of the LCD's gamma characteristics itself. But applying the inverse LUT of **Fig. 7** to the RGB signals causes the output to take on the 2.2 gamma correction of the sRGB color standard.

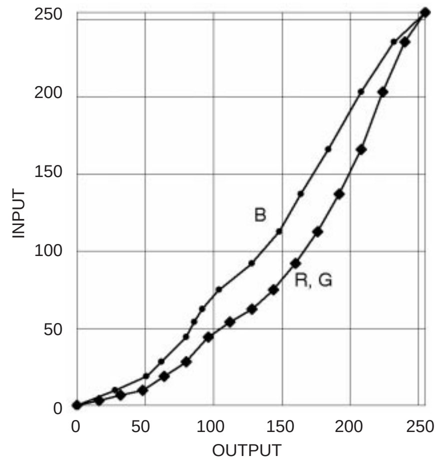

Fig. 7 Inverse LUT compensating the LCD's characteristics.

ICC profiles are specification files describing the color characteristics of an LCD panel, but this ICC profile also makes it possible to compensate for the blue shift of the LCD.

3.2 Results of compensation

Fig. 8 is a diagram using the a*b* plane in L*a*b color space to compare how well color compensation is carried out when a color-compensating ICC profile is applied to a color LCD (Sharp LL-T1510A). The black circle marks indicate chromaticity points for which an ICC profile has been applied, black triangle marks indicate points where none has been applied, and black diamond marks indicate target sRGB chromaticity

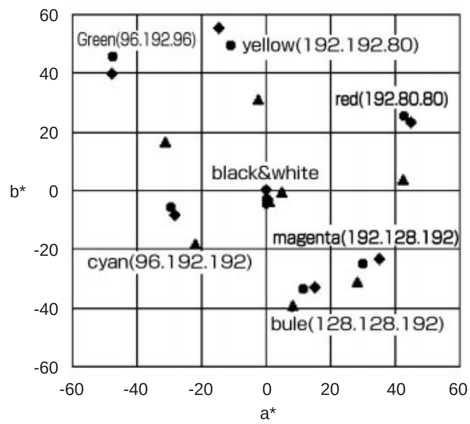

Fig. 8 Chromaticity points on a*b* diagram. ▲ : LCD display original (measured). ● : with the ICC profile (measured). ◆ : sRGB (calculated).

points. It is clear that the chromaticity based on ICC profiles approximates the target sRGB colors. It should also be noted that "Imaging" software provided under Windows 98 was used to apply the ICC profile.

Fig. 9 shows the variations resulting from different achromatic (gray) levels as a Δ E94 color difference index (based on the delta-E formula released by CIE in 1994). The vertical axis represents the Δ E94 value, and the horizontal axis represents the input level. The color difference when an ICC profile is applied (black circle marks) is reduced compared to the case when no ICC profile is applied (black triangle marks), and color reproduction more closely approximates standard colors.

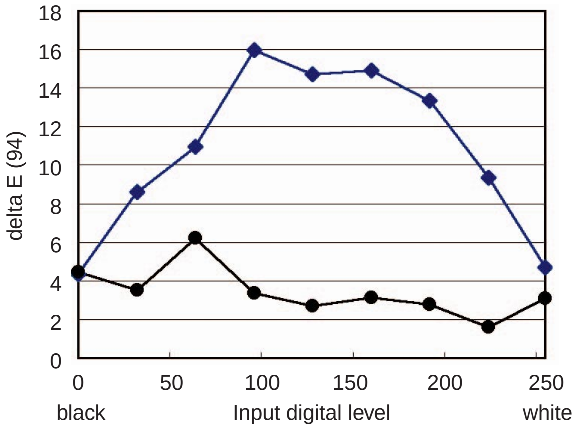

Fig. 9 Delta E (94) varying the input digital level for gray patches. References are gray for sRGB. Circle mark (●): with the ICC profile (measured). Triangle mark (▲):

Conclusions

The LUT-based color compensation described in this report can achieve faithful color reproduction for sRGB and has been applied in sRGB mode in Sharp LCD color monitors. ICC profiles that compensate for LCD color characteristics have also been applied in Sharp LCD monitors.

We can look forward to the use of color LCDs capable of reproducing standard colors in fields that require highly accurate color reproduction, such as printing, design work, and photographic rendering.

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