Proposal for Color Management of LCD

Yasuhiro Yoshida and Yoichi Yamamoto
IC Development Group, SHARP Corp.
Tenri-City, Japan
e-mail: yasuhiro.yoshida@sharp.co.jp

Abstract

A color profile that is suitable for the color management of LCDs is proposed. The color coordinates of primary colors and reference white of the LCDs has been reported to displace depending on its code value. These problems relate to essential characteristics of the LCDs that can only realize a limited range of contrast. Since the conventional ICC profile cannot describe effects due to the limited range of contrast, it has been unable to provide effective color management for the LCDs. In order to realize the color management that can satisfy the actual LCD performance, we propose following two points: (1) The tri-stimulus value $(X_OY_OZ_O)$ obtained through the measurement of leakage light due to the limited contrast ratio of the LCD shall be added to conventional display device profile. (2) For the color management system, $(X_OY_OZ_O)$ shall be subtracted in advance from the tri-stimulus value $(X_TY_TZ_T)$ of the target color, and then result of the subtraction should be sent to the display. Experimental results showed that the use of the profile and CMS proposed in this paper enabled the color reproduction error to be low. The effect in improving the color management under an ambient light condition is also demonstrated.

Introduction

For the purpose of implementing the color management of CRTs, various reports have been offering studies from many aspects including the examination of basic technologies,[1] performance assessment,[2] and modeling.[3] The results of such studies are generally and widely utilized today as the color management specifications stipulated by the ICC (International Color Consortium).[4]

The color management specifications, which employ the ICC profile, models color compensation in two stages as described in **Figure 1**. The procedure is that, first, it compensates for the deviation of the color coordinates for primary colors and reference white of the display from the standard by using linear matrix computing, and second, it compensates for the γ-characteristic of the display. This model functions successfully when a well-aligned and high quality display is used in a dark room.

On the other hand, with regard to the present circumstances for LCDs, the study results of the CRT case are employed as they are, and no systematic studies have been made on color management focusing on LCDs, except for some reports regarding contrast[5] or luminance.[6]

Against this background, we studied the ICC profile for color management while focusing on LCDs. Furthermore, we studied the color management of LCDs which were placed in an ambient light environment, in addition to a dark room.

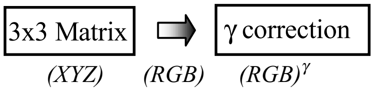

Figure 1. Signal processing at the conventional color management system

Reconsideration of Display Characteristics Form the View Point of ICC Assumption

Since the real display device is not a perfect entity, the ICC model may provide the following problems:

(1) Displacement of the color coordinates of the primary color and reference white of the display that is depending on the CV (code value) :

It has been reported that LCDs typically exhibit this phenomenon.[7] If the color coordinates for primary colors and reference white vary depending on the CV, color conversion using a simple 3 × 3 matrix becomes difficult to achieve.

(2) Variation in γ depending on average CV of a picture: Popular CRTs typically have this phenomenon. If γ varies depending on average CV of a picture, it is clear that the color compensation can hardly be achieved by using the existing ICC profile which is based on the assumption that the γ value should be in constant. In general, this phenomenon does not occur with LCDs. **Figure 2** shows an example.[8]

Characteristics of Components of the LCD

With LCDs, the variance in the color coordinates of primary colors and reference white in accordance with the CV principally depends on the fact that the maximum contrast ratio of LCDs is no more than approximately 300 to 1. This is attributed to the fact that all polarizer or the LC panes do not have ideal characteristics. The cut-off characteristics of the polarizer against the crossed nicol light slightly vary in terms of the wavelength. In addition, the transmission factor of the LC panel and the rotation characteristics of the light axis also have variable wavelength characteristics to some extent, and furthermore, such transmission factors and wavelength characteristics vary depending on the voltage applied. Due to the factors stated above, the contrast ratio is subjected to certain restrictions. In addition, the contrast ratio varies by the respective wavelengths, or by the respective channels of R,G and B. Generally, the contrast ratio of the B channel is low, and the channel provides a large amount of leakage light.

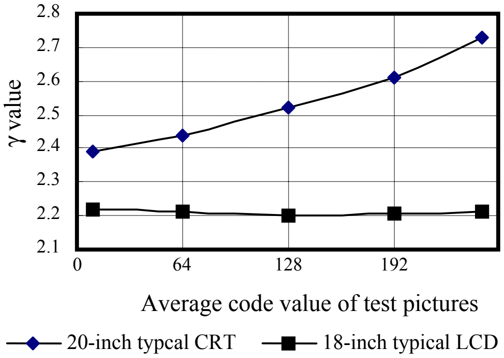

Figure 2. Changes in γ value corresponding to average code value of test pictures.

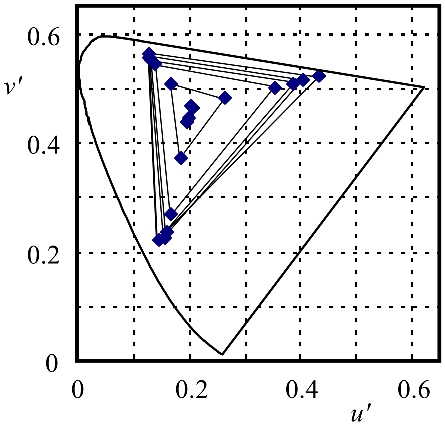

Figure 3. Measured chromaticity coordinates of primary colors and reference white under dark room. From outside to inside, triangles represents color coordinates of primary color correspond to code value of 255, 128, 96, 64, and 32, respectively. Plots at center of the triangle are locus of the reference white.

Displacement of Color Coordinates of Primary Color

Figure 3 shows a measurement example in a dark room.

The contrast ratio of 300:1 is equivalent to the fact that the leakage light with the intensity of 1/300 of the maximum transmittance is continuously superimposed on the displayed color. Accordingly, when the primary color CV is reduced, the intensity of leakage light reaches a level that cannot be disregarded relative to that of the primary color. Furthermore, the sum of the leakage light and the light from all primary colors is observed on the color coordinates of each primary color. Since general display devices have γ>1, such status may occur even under a comparatively medium CV.

Figure 4 shows the simulation results on the change in size of triangle of the primary colors inherent to LCDs which have contrast ratios of 300:1 and 3000:1. The measured results from an LCD with 250:1 contrast is also shown. From the figure, it can be recognized that, due to the leakage light, the color reproduction range deforms depending on the CV. The physical displacement of the color coordinates of primary colors based on the retardation of liquid crystal can be disregarded (I.e. the variable wavelength characteristics mentioned earlier in this section).

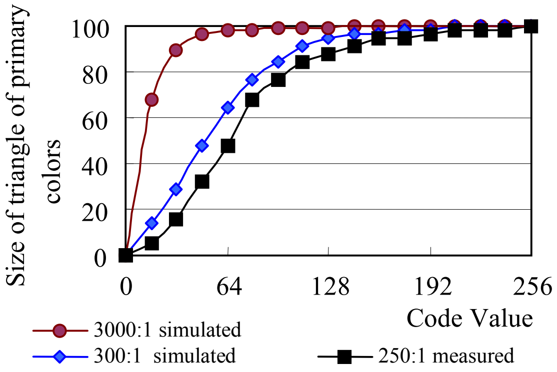

Figure 4. Changes in size of triangle of primary colors at u' – v' color space correspond to code value.

Displacement of Reference White

Since the contrast ratio differs between RGB channels, the color coordinates of reference white will vary subtly depending on the CV : *R = G = B = 0/255 - 255/255*. At a lower CV, the reference white may frequently displace toward Blue particularly due to the leakage light in the B channel.

Figure 3 also shows an example of the color coordinates for reference white measured in a dark room. From the figure, it can be recognized that, at a lower CV, the color coordinates for reference white displace toward Blue.

Summary of Problems

The fact that the color coordinates for primary colors and reference white of LCDs displace depending on the CV relates to the essential problem inherent in current LCD devices: they can only realize a limited range of contrast. More specifically, the problem lies in the effect of leakage light which is attributed to the marginal characteristics of LCD components. Since leakage lights are not dependent on CV, they constantly present a certain amount of light. Accordingly, when the intensity of primary colors reduces as CV reduces, the leakage light will not be able to be disregarded, the color coordinates for primary colors will be displaced, and the color coordinates for reference white will also be displaced, depending on the CV, toward the color coordinates of the leakage light.

Since the conventional ICC profile cannot describe such effects caused by the leakage light, it has been unable to provide effective color management for LCDs. It is assumed that this problem will be particularly significant for the lower CV grayscale range where the leakage light cannot be disregarded as compared to a screen not having this problem.

Color Management of LCDs

A method to reduce color reproduction errors caused by the replacement of the color primary by calibrating the γ table has been proposed.[7] However, it has been difficult to find substantial measures to solve this problem using the existing ICC profile. We propose color management, which can satisfy the actual LCD performance stated above.

Improvement of the Display Model

Figure 5 shows the schematic drawing where the color **[Target]** with tri-stimulus values $(X_1Y_1Z_1)$ expressed in the color coordinates of an LCD, i.e. **(RGB)**. To simplify the explanation, it is illustrated in two dimensions.

Suppose tri-stimulus value of the color **[T]** in the color coordinates of the **(RGB)** is $(R_1G_1B_1)$, $(R_1G_1B_1)$ can be obtained through the 3x3 matrix computing by using the $(X_1Y_1Z_1)$ and the description based on the conventional ICC profile. The matrix can be immediately obtained through measurement in a dark room by entering sufficiently large CVs for primary colors of the **(RGB)**. Conventionally, as described in **Figure 1**, the color displayed was achieved by applying the γ compensation to that value.

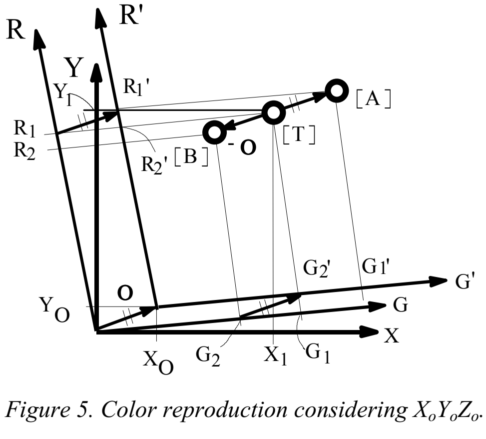

Figure 5. Color reproduction considering $X_oY_oZ_o$.

On the other hand, actual LCDs are subjected to the effects of leakage light, and they are forced to be in a situation where the black color is displaced by O (offset). Accordingly, the color coordinates of actual LCDs will be (RGB)' whose origin sits on this point. When $(R_1G_1B_1)$ is displayed on the (RGB)', the reproduced color will be the one expressed in [A]. Here, if tri-stimulus values $(X_oY_oZ_o)$ of $O << (X_1Y_1Z_1)$, then the error against the reproduced color [T] can be disregarded, but if $(X_oY_oZ_o) = (X_1Y_1Z_1)$, then the error cannot be disregarded.

The above-stated problem can be improved when **[T]** is counter-compensated in advance by –**O**. When the color thus compensated is assumed to be **[B]** as indicated in Figure 5, the tri-stimulus value $(R_2G_2B_2)$ of the color coordinates of the **(RGB)** which corresponds to the color **[B]** can easily be obtained in the same manner as stated above. When the value is displayed on the color coordinates **(RGB)'**, the tri-stimulus value $(X_OY_OZ_O)$ of **O** will be added to enable the correct display of **[T]**.

In order to realize the above, we propose the following two points:

1. The color obtained through the measurement of leakage light of LCD shall be **[O]**, and the data in regarding the tri-stimulus value $(X_OY_OZ_O)$ shall be added to the display ICC profile.
2. For the CMS (Color Management System), as described in **Figure 6**, $(X_OY_OZ_O)$ shall be subtracted in advance from the tri-stimulus value $(X_TY_TZ_T)$ of the target color **[T]**, and then $(R_2G_2B_2)$ shall be obtained so that the color can be displayed.

By executing the above, it is expected that excellent color management of LCDs can be achieved.

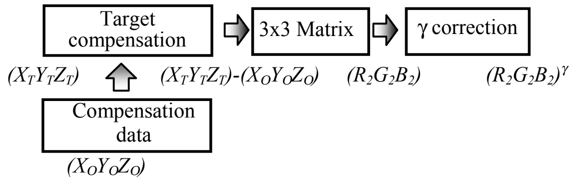

Figure 6. Signal processing at the proposed color management system.

Experimental Results

In order to evaluate the color management proposed above, we made an experiment that was comparing two groups of color patches displayed on LCD placed under dark room.

The color patches at first group were displayed on LCD through conventional ICC profile color compensation, and color patches at the second group were through experimentally developed color compensation procedure based on the profile and CMS proposed.

Since differences of both color management systems should particularly be at low L^*, color reproduction of dark colors were compared in the experiment. The color of the color patches were designed at $L^*a^*b^*$ color space. 54 colors which were combination of 0, and +/-10 for both a^* and b^*, and 2, 4, 6, 8, 10 and 20 for L^* were evaluated. Since the color reproduction range becomes narrower in the case of $L^* = 2$, a^* and b^* value was set to 0 and +/-5. We tuned both profiles to be able to display those colors as precisely as we can.

The experimental results are shown in **Figure 7**. Comparing to the conventional ICC profile compensation, the color management proposed here can provide very low reproduction error even for low intensity color to be displayed.

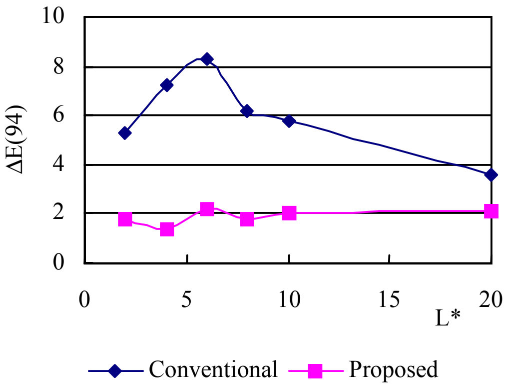

Figure 7. Comparison of color reproduction error between conventional color management results and proposed color management results.

Considerations Regarding the Color Management of an LCD Placed in an Ambient Light Condition

The color management proposed here can be applied to displays which are placed under a light-environment. This is because the surface reflection of the display does not depend on the CV, and therefore, from the viewpoint of colorimetry, it may be handled in the manner equivalent to the above-stated leakage light.

In this paper, instead of CRTs,[9] we made an experiment considering color management of an LCD that is placed in an ambient light condition. In particular, this consideration is important for the color management of a reflective-type LCD,[10] since reflective-type LCD can only be used under the ambient light condition. In this case, the reflection on an LCD surface is likely to behave in the same way as the above-stated leakage light. Accordingly, the problem here is that the displacement status itself of the color coordinates of primary colors and reference white will change in terms of light source variations

In spite of the surface reflection light will result in a reduced contrast ratio, it is reported that the contrast ratio of LCDs under an ambient light condition is superior to that of CRTs.[5] Therefore, assessments on actual LCD devices regarding how the reflection of environmental light will effect color on it, and evaluation of the operation of CMS proposed in this paper are important from practical point of view.

Surface Reflection of Display Device

When an LCD is placed in an unavoidably bright environment where ambient light is present, the light will reflect on the LCD surface, and a color will be mixed at the same time as the color displayed at the LCD.

If the tri-stimulus value of a color displayed on a LCD is $(XYZ)_{LCD}$, the following equation can be obtained:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} = \int C \begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix} d\lambda \qquad (1)$$

where $C = R + G + B + E$, and RGB and E are primary colors and the spectral distribution vector of the combined leakage of ambient reflected light, respectively, and x, y, z are the color matching functions.

Also if ***E*** has no relationship with ***RGB***, the equation (1) will be as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} = \int C_b \begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix} d\lambda + \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{E} \qquad (2)$$

where $C_b = R + G + B$.

Here, the first term on the right side member is the tri-stimulus value of the LCD obtained through the measurement in the dark room, and the second term shows the effect of the ambient light.

With LCDs, it is expected that ***E*** has no relationship with ***RGB.*** In order to verify this issue, we performed experiments by using a facility, as shown in **Figure 8**, where the reproduction of general office environments is possible.

First, the CV of an LCD whose back lighting system has been turned off was varied under the conditions of $R = G = B = 0/255 - 255/255$, and then the change in ***E*** was measured.

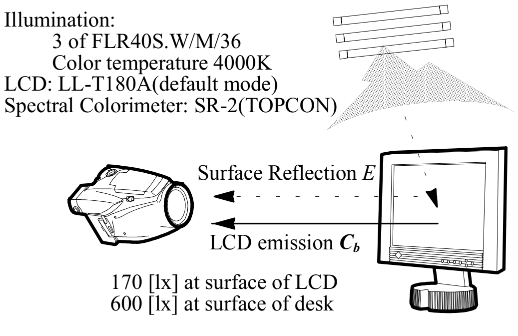

Figure 8. Experimental condition

Figure 9 shows the measurement results. It was revealed that the value of E which corresponds to a CV of $R = G = B = 0/255 - 255/255$ hardly varies when the back lighting system is turned off. From this, it was considered that equation (2) may be replaced with equation (1) as the coloring model of LCDs which are subjected to the effects of ambient light.

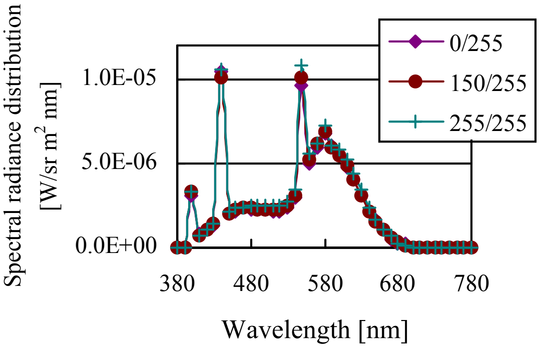

Figure 9. Measured spectral distribution of E.

Next, in order to confirm how LCDs work with back lighting system turn on, the tri-stimulus value obtained through the calculation of the right side member of equation (2) was compared with the tri-stimulus value that was directly obtained through the measurement.

While varying the CV under the conditions of $R = G = B = 0/255 - 255/255$, the spectral radiance intensity of the LCD was measured in both a dark room and an unavoidably bright environment where ambient light was present. Then, the tri-stimulus value was obtained from these data, which was then respectively applied to the left side member and the first term of the right side member of equation (2). The second term of the right side member was obtained from Figure 9.

Table 1 shows the results. As indicated at the right two columns of the table, the difference between the tri-stimulus value obtained through the calculation and that obtained through the actual measurement was approximately 5% at largest.

Judging from the above, it is concluded that LCDs affected by the ambient light can be interpreted by using the model of Equation (2) where the surface reflection components are added to the coloring that is measured in the dark room. Since these components are not dependent on the CV, it is possible to handle them equivalently with the leakage light, which may be the cause of the restricted contrast as referred to previously. This means that reduced CV could result in the displacement of the color coordinates of primary colors or reference white.

Accordingly, when the surface reflection of an LCD placed in the unavoidably bright environment is measured individually, and if such a system that handles the measurement results and the leakage light can be built, the color management of display may be possible even under such light-environment.

Table 1. Calculation results based on Equation (2)

Term		$\int C_b \, d\lambda$	E	$XYZ_{(LC}$	
		Right side (1)	Right side (2)	Left side (3)=(1)+(2)	Measured (4)
Measured condition		At Dark room BL(on)	With ambient light BL(0ff)	With ambient light BL(on)	
255/255	X	1.43e2	3.78e-1	1.43e2	1.43e2
	Y	1.43e2	3.97e-1	1.43e2	1.43e2
	Z	1.65e2	2.30e-1	1.65e2	1.65e2
0/255	X	3.67e-1	3.58e-1	7.24e-1	7.23e-1
	Y	3.60e-1	3.67e-1	7.27e-1	7.29e-1
	Z	6.70e-1	2.22e-1	8.92e-1	8.85e-1

BL: Back lighting system

Evaluation of Color Management Proposed

In order to validate the effectiveness of the proposal stated above, we made an experiment to measure color differences of displaying color patches.

Color patches designated in the $L^*a^*b^*$ space were displayed on the LCD that was placed under the light-environment as specified in Figure 8. The color differences of the color patches between the case of the conventional ICC profile and ICM2.0 of Windows 98, and the case of a CMS and ICC profile that were newly manufactured with the configuration as described in Figure 6 were measured.

The conventional CMS was set to the absolute color reproduction, and the ICC profile that was created by using the "Display Calibrator" of Heidelberg. Furthermore, $(X_O Y_O Z_O)$ were set to (0.72, 0.73, 0.89) respectively, derived from Table 1. From the table, since the LCD can provide a maximum intensity of (143, 143, 165) for the 255/255 of CV, the contrast ratio under the setting conditions will be approximately 200. Accordingly, when the maximum intensity is taken as the reference, reproduction is possible up to approximately $L^*=4$.

For the measurement, the color patches of a total of 45 colors were used including nine test colors whose a^* and b^* value can be displayed by the combination of 0 and +/-10 for each 5-steps of $L^* = 4, 6, 8, 10$ and 12.

Figure 10 shows measured results of the ΔE(94) of color reproduction errors that were averaged across patches for each L^*. Absolute value of the color reproduction error can be reduced to approximately 1/3. Since the absolute value of the color reproduction error itself is dependent on the creation method of the ICC profile, error values should not compare directly. However, the proposed method could keep the error almost constant, while the error of the conventional technology increased as L^* is lowered.

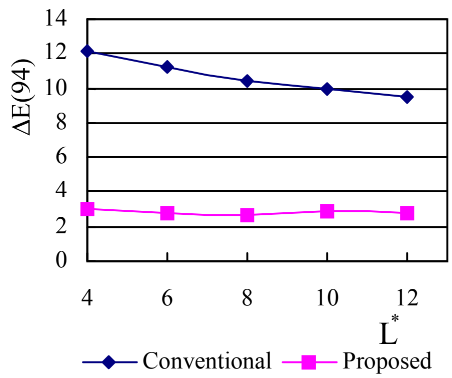

Figure 10. Measured ΔE(94)

As described above, the technology proposed in this paper could keep the color reproduction error constant even in the case where a low-key image was displayed on the LCD that was placed under the light-environment. Thus, an effective improvement in color management was acknowledged.

In addition, the values shown in Figure 10 are obtained from the definition of L*a*b* color notation which assume the human visual system has been adapted to the reference light of L* = 100. However, regarding the actual LCD display, it is quiet infrequent that a reference light of L*=100 exists within the screen of the LCD. Since it can be considered that the human visual system is adapted to an average screen display of less than L*=10011,12 it is generally expected that the improvements in lower intensity areas, for example, in the case of displaying images with almost an evenly low intensity, will be larger than the values given in the figure.

Conclusion

The ICC profile that is suitable for the color management of LCDs was proposed. Also, the color management of LCDs placed under the light-environment in addition to a dark room condition was studied.

In order to realize the color management that can satisfy the actual LCD performance, we propose the following two points:

(1) The tri-stimulus value $(X_OY_OZ_O)$ obtained through the measurement of leakage light due to the limited contrast ratio of the LCD shall be added to the ICC profile of display device.

(2) For the CMS, $(X_OY_OZ_O)$ shall be subtracted in advance from the tri-stimulus value $(X_TY_TZ_T)$ of the target color, and then result of the subtraction should be displayed

Our analysis showed that the use of the CMS proposed in this paper enabled the color reproduction error to be very low even when a low-key image is displayed on the LCD. This technique also works when the LCD is placed under the light-environment. Use of this new calibration technique, along with extra step of measuring the leakage light allows for significantly improve the color management of the LCDs.

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Biography

Mr. Yoshida is a research scientist of the IC Development Group in SHARP Corporation. He has been with SHARP since 1986 and working for over 10 years in color science. His current responsibility at SHARP is to improve the picture quality of the LCDs. Mr.Yoshida received his M.S degree in color imaging. He is a member of the IS&T, SMPTE and IEEE.

Dr. Yamamoto is a research Associate of SHARP Corporation. He main activities are in color management of the display device. Dr. Yamamoto received his Ph.D. degree in 1999 in electromagnetic field and force simulation. He is a member of the IS&T, IEEE and Imaging Society of Japan.