Masking Model for Accurate Colorimetric Characterization of LCD

Nobuhiko Tamura, Norimichi Tsumura, and Yoichi Miyake
Department of Information and Image Sciences, Chiba University
Chiba, Japan

Abstract

Color management system (CMS) using ICC profile or sRGB space is becoming popular since the number of color devices are increasing. In such CMS, accurate colorimetric characterization of display device has a critical role for achieving device independent color reproduction. In case of CRT, colorimetric characterization based on GOG model is accurate enough for this purpose. However, there is no effective counterpart in Liquid Crystal Displays (LCD) since the characterization of LCD has many difficulties such as channel interaction, non-constancy of channel chromaticity. In this paper, a new method of display characterization is proposed which is applicable to the assessment of color reproduction of LCD. The proposed method characterizes electro-optical transfer function considering both channel interaction and non-constancy of channel chromaticity. In the experiment, comparisons with five conventional characterization methods proved that the proposed method is very significant to the colorimetry of LCD.

Introduction

Flat-panel monitors become increasingly popular with its less power consumption and versatility with respect to placement. Therefore, it is important to establish an accurate CMS in LCDs. In CMS, one of the most important characteristics of the color reproduction is relationship between digital input values and XYZ tristimulus values of display. If the relationships are known, we can handle the color on LCD based on device-independent XYZ tristimulus values. GOG model[1] is well-known characterization model for CRT display. GOG model can predict XYZ value of arbitrary digital input with high accuracy. However, characterization of LCD is rather difficult compared to CRT display with the presence of channel interaction and non-constancy of channel chromaticity. Many researches have been done for characterizing colorimetry of display devices. S-Curve model[2] was proposed for LCD colorimetry which characterizes electro-optical transfer function using S-shaped curve. Polynomial model, Matrix model[3] and LUT method is not based on an internal structure of display devices. Therefore, the usage for these models is not limited for LCDs. We will review these models in the next section. Accuracy of these conventional models are not enough for characterization of LCD for the difficulties such as channel interaction and non-constancy of chromaticity.

The proposed calibration model named Masking model can be classified as the model which doesn't consider the internal structures of display. Relationship between digital input and luminance of each channel were approximated using spline interpolation. Masking model also considers two major problems in characterizing LCD colorimetry; non-constancy of channel chromaticity and channel interaction. In Masking model, primary color vector is calculated using principal component analysis (PCA) to minimize the error caused by variation in channel chromaticity. In addition to the measurement of RGB primary colors, CMYGr (Cyan, Magenta, Yellow, Gray) secondary and thirdly colors were measured to approximate the color variation caused by channel interaction. Masking model provides these two improvements to reduce the error caused by deviation from linearity while keeping measurement times comparable to the conventional models. In other words, the proposed Masking model is the most suitable for the system which contains weak non-linearity. Comparison with conventional characterization methods using three LCDs proved that the proposed method is more effective for colorimetric characterization of LCD than the conventional methods.

Review of Conventional Display Characterization Models

GOG model, S-curve Model and Polynomial Model

GOG model, Polynomial model, S-curve model have same structure defined in Eq.(1).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{R,\max} & X_{G,\max} & X_{B,\max} \\ Y_{R,\max} & Y_{G,\max} & Y_{B,\max} \\ Z_{R,\max} & Z_{G,\max} & Z_{B,\max} \end{bmatrix} \begin{bmatrix} R(d_R) \\ G(d_G) \\ B(d_B) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \quad (1)$$

where X_0, Y_0, Z_0 are XYZ of ambient flare and $X_{i,\max}$, $Y_{i,\max}$, $Z_{i,\max}$ (i=R,G,B) are maximum XYZ of each channel after black correction. $R(d_R)$ for each model was defined as follows.

GOG model :

$$R(d_R) = \begin{cases} \{k_{g,R} d_R + k_{o,R}\}^{\gamma_R} & , \{k_{g,R} d_R + k_{o,R}\} \geq 0 \\ 0, & \{k_{g,R} d_R + k_{o,R}\} < 0 \end{cases} \quad (2)$$

Polynomial model:

$$R(d_R) = a_R d_R^2 + b_R d_R + c_R \quad (3)$$

S – curve model:

$$R(d_R) = A_{RR} f(d_R) + A_{RG} f'(d_G) + A_{RB} f'(d_B) \quad (4)$$

$$\text{where } f(d_R) = \frac{d_R^{\alpha}}{d_R^{\beta} + C}, \quad f'\text{: derivative of } f$$

where all variables except d_R, d_G, d_B are constant which is calculated to minimize the error between training XYZ and predicted XYZ. $G(d_G)$, $B(d_B)$ are similarly defined. GOG model characterizes each transfer step from digital input to XYZ of CRT through video card, gun, and phosphor gamma. Prediction of XYZ using GOG model is accurate enough for CRT. However it is not always effective when GOG model is applied to LCD for structural difference between CRT and LCD. S-Curve model has the same structure as the GOG model but differs in non-liner relationship between digital input and luminance of each channel.

S-curve model characterizes the relationship using S-shaped function which is defined in Eq.(4) instead of gamma-shaped function used in GOG model. S-curve model further considers non-chromaticity constancy of LCD. However, S-curve model is not always effective for LCD, since some manufacturers transform the S-curve characteristic into the gamma characteristic on IC. Therefore S-curve model is not always effective for LCD. GOG model, S-curve model and Polynomial model always have the prediction error due to the channel interaction since Eq.(1) assumes the channel additivity.

LUT Method

Characterization using LUT method requires considerable amount of measurement. The difficulty with LUT method is not only the time, but the size of data to describe the characteristics of the display. For instance, including LUT in ICC profile would increase the overhead.

Unless the system far deviates from linearity such as additivity and non-consistency of chromaticity, LUT method would be of little worth.

Matrix Model

Matrix model is defined as Eq.(5). Firstly, non-liner relationship between digital input d_R and luminance R was calculated using measured data. Secondary, matrix A was calculated to minimize the error using 32 neutral colors (see Ref. 3). Matrix model can handle the channel interaction by including cross terms RG, GB, BR, RGB as regression variables. However, Matrix model is not suitable for practical use since inverse transformation which converts XYZ to corresponding digital input is very difficult to define.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A[1 \quad R \quad G \quad B \quad RG \quad GB \quad BR \quad RGB]^T \quad (5)$$

Masking Model

Channel Interaction

Figure 1 shows two electro-optical transfer functions of LCD (SHARP LL-T180) for R channel where the digital input of G, B channels are kept 0 and 255 respectively. Note that Fig.1 shows the luminance of R channel, not the total luminance of display. The presence of channel interaction can be seen in Fig. 1. Although it is known that channel interaction is caused by interconnection of electrode, formulation of this characteristic of interaction is rather difficult since the effect of interconnection largely depends on the internal structure of driving circuit. In the Masking model, we directly measure the secondary and thirdly color to approximate the channel interaction. Then, XYZ of arbitrary digital input is calculated using RGBCMYGr characteristics. The concept of Masking model is similar to that of UCR (under color removal) in printing technology. The same amount of each RGB digital count are replaced by gray which digital count is equal to the smallest digital counts in RGB (see figure 2). Similarly, remaining digital counts are replaced by red and yellow as shown in Fig. 2.

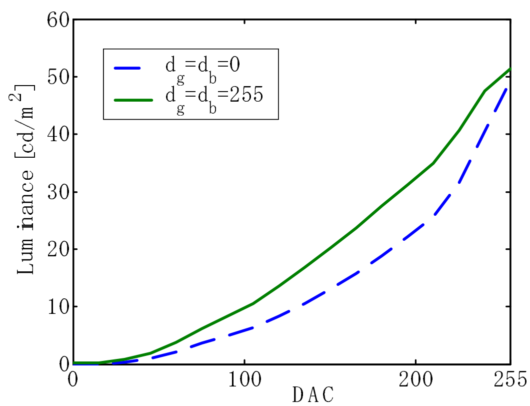


Figure 1. Difference of Electro-Optical Transfer Function caused by channel interaction

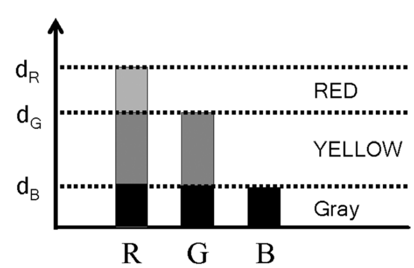


Figure 2. Masking in the proposed model

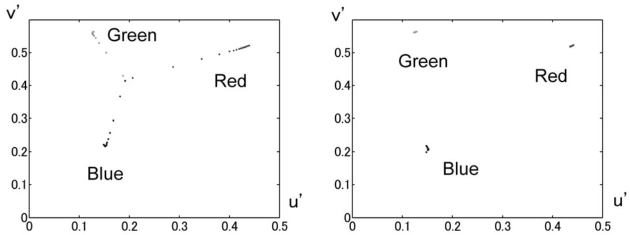


Figure 3. Color tracking before (left) and after (right) black correction

Let $\mathbf{I}(d_R, d_G, d_B)$ be XYZ value of display in vector form which is corresponding to digital input (d_R,d_G,d_B). We also define yellow of digital input d_Y as $\mathbf{I}(d_Y, d_Y, 0)$ or $\mathbf{I}_Y(d_Y)$ in this paper. Using these notation, XYZ of arbitrary digital count (d_R,d_G,d_B) is approximated as follows.

$$\hat{\mathbf{I}}(d_R, d_G, d_B) = \hat{\mathbf{I}}_K(d_B) + \{\hat{\mathbf{I}}_Y(d_G) - \hat{\mathbf{I}}_Y(d_B)\} + \{\hat{\mathbf{I}}_R(d_R) - \hat{\mathbf{I}}_R(d_G)\}, \quad \text{if } d_B < d_G < d_R, \tag{6}$$

where $\hat{\mathbf{I}}_i(d_i)$ (i=RGBCMYGr) denotes the approximation of $\mathbf{I}_i(d_i)$, which is explained in the next section. Equation 6 is more accurate approximation compared to the conventional model that use only $\hat{\mathbf{I}}_R(d_R), \hat{\mathbf{I}}_G(d_G), \hat{\mathbf{I}}_B(d_B)$ since channel interaction is considered by introducing $\hat{\mathbf{I}}_K(d_K), \hat{\mathbf{I}}_Y(d_Y)$.

Non-Constancy of Channel Chromaticity

Figure 3 shows chromaticity of each primary color where digital input is varied from 0 to 255 with interval of 15. From Fig. 3, channel chromaticity is nearly constant after subtraction of black (black correction). In Masking model, XYZ of single channel (RGBCMYGr) is calculated as follows.

$$\hat{\mathbf{I}}_i(d_i) = C_i(d_i) \begin{bmatrix} X_{i,PCA} \\ Y_{i,PCA} \\ Z_{i,PCA} \end{bmatrix} + \mathbf{I}(0,0,0) \quad (i = RGBCMYGr) \tag{7}$$

In order to reduce the error caused by slight deviation of channel chromaticity, we applied the principal component analysis to the measured XYZ value of each channel. $X_{i,PCA}$, $Y_{i,PCA}$, $Z_{i,PCA}$ in Eq. (7) denote the first principal component of the measured data and normalized to be unit length. $C_i(d_i)$ for the measured digital count d_i can be calculated as,

$$C_i(d_i) = \{\mathbf{I}_i(d_i) - \mathbf{I}(0,0,0)\}^T \begin{bmatrix} X_{i,PCA} \\ Y_{i,PCA} \\ Z_{i,PCA} \end{bmatrix} \tag{8}$$

C_i for arbitrary digital input can be calculated by interpolating measured C_i using spline interpolation. In order to exclude device dependent assumption, no specific function was assumed in this model.

Inverse Transform of Masking Model

In many practical cases, conversions from XYZ to corresponding digital inputs are of great importance. From Eqs. (6), (7), transformation from digital inputs to XYZ can be written as follows.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \{C_i(d_i) - C_i(d_j)\}\mathbf{P}_i + \{C_j(d_j) - C_j(d_{Gr})\}\mathbf{P}_j + C_{Gr}(d_K)\mathbf{P}_{Gr} + \mathbf{I}(0,0,0), \tag{9}$$

where i(i=R, G, B) and j(j=C,M,Y) are indices of primary color and secondary color respectively. **P** represents vector [X_{PCA},Y_{PCA},Z_{PCA}] in Eq. (7). The C_i, C_j, C_{Gr} can be obtained using the inverse matrix as follows.

$$\begin{bmatrix} C_i(d_i) - C_i(d_j) \\ C_j(d_j) - C_j(d_{Gr}) \\ C_{Gr}(d_{Gr}) \end{bmatrix} = \begin{bmatrix} \mathbf{P}_i & \mathbf{P}_j & \mathbf{P}_{Gr} \end{bmatrix}^{-1} \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \mathbf{I}(0,0,0) \right) \tag{10}$$

From Eq.(10), we can calculate the digital input of gray d_{Gr} using C_{Gr} defined in Eq. (8) using spline interpolation. Similarly, d_i and d_j can be calculated using d_K and C_i, C_j. There are 6 possibility of (i,j); (R,M), (R,Y), (G,Y), (G,C), (B,C), (B,M). We select the combinations which satisfy following conditions.

$$\begin{cases} d_K \le d_j \le d_i \\ 0 \le d_K, d_j, d_i \le 255 \end{cases} \tag{11}$$

Comparison of Model Performances

Performance of Masking model was tested and compared with the conventional characterization methods; GOG model, S-curve model, LUT, Polynomial model and Matrix model. Although GOG model is originally designed for characterization of CRT, comparison with Masking model was made since it is also used for LCD in some papers (such as Ref. 4).

Condition of Measurement

Table 1 lists the display used in this experiment. Generated colors were displayed on full screen. Spectral radiance was measured in two degree field of central area using spectroradiometer (MINOLTA CS1000). All display was warmed up for 4 hours. All measurements were performed in a dark room.

Channel Interaction

Table 2 shows characteristics of channel interaction for the measured LCDs. Sum of R, G, B does not equals to Gray of the same digital input.

Table 1. Lists of Measured Display

Model	Type	Resolution
SHARP LL-T180A	18.1" TFT LCD Monitor	1280x1024
iiyama AS4635U	18.1" a-Si TFT LCD Monitor	1280x1024
Sony PCG-C1MR/BP	8.9" Ultra-Wide TFT LCD (Laptop)	1280x600

Table 2. Result of Channel Interaction Test

	I(140,140,140) XYZ	$\mathbf{I}_R(140)+\mathbf{I}_G(140)+\mathbf{I}_B(140)-2\,\mathbf{I}_0$ XYZ	Error $\Delta X\Delta Y\Delta Z$
SHARP	32.3,33.0,35.1	22.1,22.5,24.2	10.2,10.5,10.9
iiyama	30.1,31.9,23.1	29.6,31.4,22.6	0.5,0.5,0.5
VAIO	46.7,46.4,66.9	52.3,52.1,74.2	-5.6,-5.7,-7.3

Measurement of Training Data

For Matrix model, measured color contains equally spaced 32 steps from 8 to 255 per channel, and 32 neutral color (see Ref. 3). We used the same digital inputs as defined in Ref. 3.

Training data for LUT were the XYZ of equally spaced 9 steps from 0 to 255. For GOG model, Polynomial model, S-curve model, measured data contains XYZ of equally spaced 5, 9, 18, 32 steps from 0 to 255 per channel. XYZ of four different steps were measured to check the dependency on the amount of training data. Parameter for each model was calculated to minimize the error between estimation and training data. Finally, the training data for the Masking model contains equally spaced 5, 9, 18, 32 steps for R, G, B, C, M, Y, Gray.

Result and Discussion

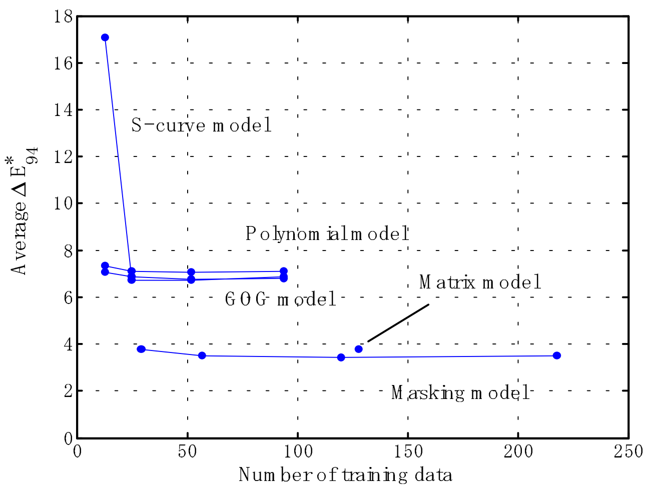
Hundred colors were randomly generated and measured as test data to evaluate the performance of each model. Difference between XYZ of measured test data and predicted XYZ was evaluated using CIELAB94 color difference. Table 3 shows the average color difference for each model. Figure 4 shows the relationship between average color difference and number of training data for each display. From Fig.4, we can see the improvements by increasing training data. GOG model is more accurate than S-curve model and Polynomial model. This is due to the correction of transfer function by manufacturers to approximate gamma curve. For S-curve model, the larger prediction error in small number of training data can be seen in the figures since S-curve model has many parameters. Prediction by Matrix model is quite accurate for all LCDs. However, it is not suitable for practical use since inverse transform of Matrix model is very difficult to define. Masking model is more accurate than almost all characterization method. However, accuracy of prediction falls for SONY PCG-C1MR/BP. This can be explained as follows. Figure 5 shows tracking of XYZ value for R channel where digital inputs of other channels are kept 0. As digital input increases, corresponding XYZ values moves along solid curve. However, characterization model which have the same structure as defined in Eq. 8, predicted XYZ value moves along the broken line which is defined by maximum XYZ value minus XYZ value of black. For example, point A on solid curve is projected to point B on broken line. This projection always reduces the luminance of predicted XYZ value since the length from the origin is shortened. On the other hand, channel interaction usually increases the luminance as shown in Fig. 1. However, channel interaction of SONY PCG-C1MR/BP decreases the luminance as shown in table.2. These two errors cancel out each other and bring unintended improvement for the test data.

Table 3. Performance Result of the Characterization Model

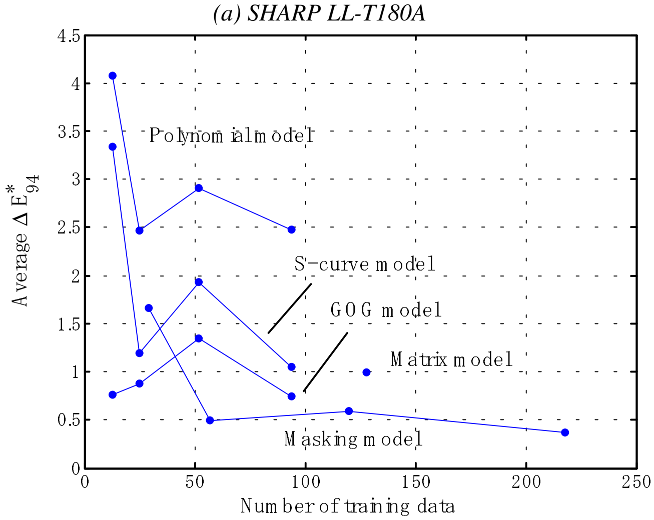
Average ΔE^*_{94}		SHARP	iiyama	SONY
Masking Model	5 step	3.77	1.66	5.79
	9 step	3.52	0.50	4.95
	18 step	3.43	0.59	4.52
	32 step	3.49	0.37	4.33
S-curve Model	5 step	17.05	3.33	10.26
	9 step	6.73	1.19	6.22
	18 step	6.70	1.93	5.35
	32 step	6.86	1.05	4.29
Polynomial Model	5 step	7.34	4.08	4.45
	9 step	7.10	2.47	4.43
	18 step	7.05	2.91	4.40
	32 step	7.10	2.48	4.38
GOG Model	5 step	7.05	0.76	4.16
	9 step	6.86	0.87	4.35
	18 step	6.76	1.35	4.11
	32 step	6.81	0.75	4.16
LUT		15.20	14.36	13.92
Matrix model		3.78	0.99	2.80

Conclusion

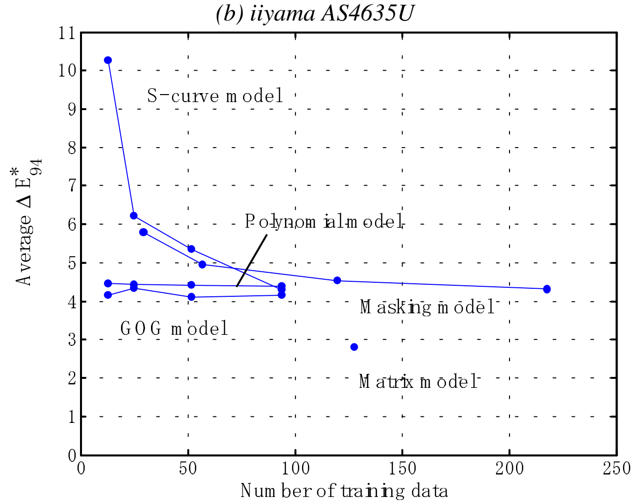
Accurate colorimetric characterization method of LCD based on Masking model is introduced. Masking model considers the channel interaction and non-constancy of primaries. Performance comparison with conventional characterization methods proved that proposed method is very significant to the colorimetry of LCD.



(a) SHARP LL-T180A



(b) iiyama AS4635U



(c)SONY PCG-C1MR/BP

Figure 4. Number of training data vs Average $\Delta E^*{}_{94}$ *(a) SHARP (b) iiyama (c) SONY*

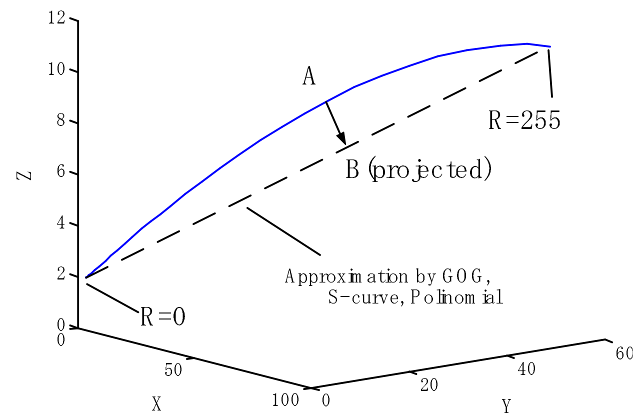


Figure 5. Tracking of XYZ in R channel (SONY PCG-C1MR/BP)

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Biography

Nobuhiko Tamura was born in Mie, Japan, on 29, November 1977. He received his B.E., M.E. degree in department of information and computer science from Chiba University in 2000, 2002 respectively. He got the first prize for his master's thesis in the department. Now, he is the doctor course student in Chiba University. He is interested in multi spectral imaging, medical imaging, and virtual reality. He is a member of Japanese Society for Medical Virtual Reality.