Evaluation of Image Quality on Reflective-type LCD: Calibration Based on the PCA

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Abstract

A new measurement method of EOTF (Electro Optical Transfer Function) based on the PCA (Principal Component Analysis) is proposed for colorimetry of RLCD (Reflective type Liquid Crystal Display). Spectral radiance of primary color with different reflectance displayed onto the RLCD under D65 illuminant were measured and analyzed by PCA. It is shown that the reflectance spectra of arbitrary color on the RLCD can be estimated with high accuracy by using those obtained eigen vectors. The new model named PCA model is compared to the conventional GOG (Gain Offset Gamma) model. As a result, it is shown that the PCA model is very significant to the colorimetry of both RLCD and CRT.

Introduction

In recent years, many kinds of display and printer have been developed to get color image with high quality. Therefore, it is increased to exchange and transform color picture between different devices, particularly from color image onto the CRT and LCD to printer. Therefore it has become increasingly important to do the research on the color management and it is required to develop accurate method for colorimetry of CRT and LCD. One of the most important characteristics of EOTF is a transfer function from digital data to XYZ tristimulus values and spectral radiance of display devices. GOG-model defined as Eq.1 has been widely used to colorimetry of CRT.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R(d_r)\begin{bmatrix} X_R \\ Y_R \\ Z_R \end{bmatrix} + G(d_g)\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} + B(d_b)\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} + \begin{bmatrix} X_K \\ Y_K \\ Z_K \end{bmatrix}, \tag{1}$$

where X_R, Y_R, Z_R are monitors tristimulus values of maximum red minus black level flare and X_K, Y_K, Z_K are tristimulus values of black level flare. Coefficient $R(d_r)$ is defined by using gain, offset and gamma as follow.

$$R(d_r) = (gain \times d_r + offset)^{gamma}. \tag{2}$$

This model is very effective for CRT displays, however it is not always significant for LCD since GOG-model is based on the modeling of CRT display system.

In this paper, we introduce a new EOTF model named PCA-model which can be used to CRT, LCD and R-LCD.

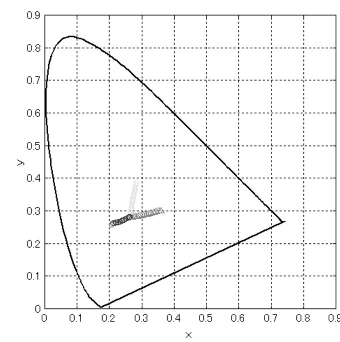

Figure 1. Chromaticity of primaries with varying digital counts

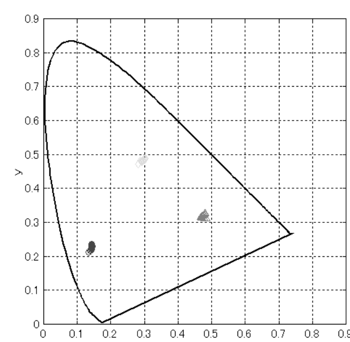

Figure 2. Chromaticity of primaries with varying digital counts subtracting black level flare.

Chromaticity Constancy of Primaries

Figure 1 shows the chromaticities of primary color (red, green and blue) of R-LCD by changing the digital count as other two primaries are kept to be zero, which were measured by spectrophotometer(Minolta CS1000). As shown in Fig.1, the chromaticities of primary color are dependent on the digital count of input. On the other hand, Fig. 2 shows the chromaticities calculated after removed the black level flare from measured values. It is clear that the chromaticies are approximately same in different input data. In this paper, we named this property as chromaticity constancy of primary color.

Model Formulation

In general, EOTF is formulated as

$$\mathbf{I} = \mathbf{I}(d_r, d_g, d_b)\,, \tag{3}$$

where d_r,d_g,d_b are input digital counts (0~255) for red, green, blue channel and **I** shows a vector which element has spectral radiance of certain wavelength. We analyzed the EOTF of R-LCD, T-LCD and CRT based on the two assumptions. First assumption is that the signal of each primary color is independently determined from other primaries. This assumption is shown mathematically as

$$\frac{\partial^2 \mathbf{I}}{\partial d_r \partial d_g} = 0, \quad \frac{\partial^2 \mathbf{I}}{\partial d_g \partial d_b} = 0, \quad \frac{\partial^2 \mathbf{I}}{\partial d_b \partial d_r} = 0\,, \tag{4}$$

Eq.3 can be rewritten using Eq.4 as follows

$$\mathbf{I} = \mathbf{I}_R(d_r) + \mathbf{I}_g(d_g) + \mathbf{I}_b(d_b)\,, \tag{5}$$

where $\mathbf{I}_R$, $\mathbf{I}_G$, $\mathbf{I}_B$ are arbitrary functions of d_r, d_g, d_b respectively. Equations 4 and 5 mean the additivity of each channel in the primary color of display. Secondary, we can assume that the chromaticity constancy of primaries as described in a previous section. Using Eq.3, black level flare $\mathbf{I}_0$ is obtained as follows.

$$\mathbf{I}_0 = \mathbf{I}_R(0) + \mathbf{I}_g(0) + \mathbf{I}_b(0)\,. \tag{6}$$

Using Eqs.5 and 6, the spectral radiance minus black level flare is calculated as

$$\begin{aligned}\mathbf{I} - \mathbf{I}_0 &= \{\mathbf{I}_R(d_r) - \mathbf{I}_R(0)\} + \{\mathbf{I}_g(d_g) - \mathbf{I}_g(0)\} \\ &\quad + \{\mathbf{I}_b(d_b) - \mathbf{I}_b(0)\}.\end{aligned} \tag{7}$$

$\mathbf{I}$-$\mathbf{I}_0$ is proportional to some constant vector from the assumption of chromaticity constancy, which can be formulated as follows,

$$\begin{aligned}&\mathbf{I}(d_r, 0, 0) - \mathbf{I}_0 \\ &\quad = \{\mathbf{I}_R(d_r) - \mathbf{I}_R(0)\} = C_r(d_r)\mathbf{R}_{pri}.\end{aligned} \tag{8}$$

where C_r is coefficient of a scalar function with digital count d_r. Eqs.9 and 10 for green and blue channels yield identical results.

$$\begin{aligned}&\mathbf{I}(0, d_g, 0) - \mathbf{I}_0 \\ &\quad = \{\mathbf{I}_G(d_g) - \mathbf{I}_G(0)\} = C_g(d_g)\mathbf{G}_{pri}.\end{aligned} \tag{9}$$

$$\begin{aligned}&\mathbf{I}(0, 0, d_b) - \mathbf{I}_0 \\ &\quad = \{\mathbf{I}_B(d_b) - \mathbf{I}_B(0)\} = C_b(d_b)\mathbf{B}_{pri}.\end{aligned} \tag{10}$$

From Eq.7 to Eq.10, **I** can be represented as linear combination of four vectors;

$$\mathbf{I} = C_r(d_r)\mathbf{R}_{pri} + C_g(d_g)\mathbf{G}_{pri} + C_b(d_b)\mathbf{B}_{pri} + \mathbf{I}_\mathbf{0}\,. \tag{11}$$

It is noted that Eq. 11 is derived on the basis of two assumptions, namely chromaticity constancy of primary color and independency of each channel. Equation. 11 shows that spectral radiance can be calculated by three basis vectors $\mathbf{R}_{pri}$, $\mathbf{G}_{pri}$, $\mathbf{B}_{pri}$ and offset vector $\mathbf{I}_0$.

Determination of Basis Vectors and Coefficients

Two assumptions used in Eq.11, however, are not exactly valid for practical monitors. If the monitor does not exactly satisfy the chromaticity constancy of primaries, then equations 8, 9, 10 are no longer valid. Thus, we considered the primary color vectors $\mathbf{R}_{pri}$, $\mathbf{G}_{pri}$, $\mathbf{B}_{pri}$ to minimizes Eqs.12, 13, 14 respectively.

$$\sum_{d_r} \left\| \mathbf{I}(d_r, 0, 0) - \mathbf{I}_0 - C_r(d_r)\mathbf{R}_{pri} \right\|^2 \tag{12}$$

$$\sum_{d_g} \left\| \mathbf{I}(0, d_g, 0) - \mathbf{I}_0 - C_g(d_g)\mathbf{G}_{pri} \right\|^2 \tag{13}$$

$$\sum_{d_b} \left\| \mathbf{I}(0, 0, d_b) - \mathbf{I}_0 - C_b(d_b)\mathbf{B}_{pri} \right\|^2 \tag{14}$$

It is known that the vector $\mathbf{R}_{pri}$ which minimize Eq.12 is principal component of vectors {$\mathbf{I}(d_r, 0,0)$-$\mathbf{I}_0$}, that is;

$$\begin{aligned}\mathbf{R}_{pri} &= \textit{principal component of} \\ &\quad \{\mathbf{I}(d_r, 0, 0) - \mathbf{I}_0 \mid d_r \in D_r\}\end{aligned} \tag{15}$$

where D_r is set of digital counts of red channel for determining $\mathbf{R}_{pri}$. In Eq.15, we assume that the norm of $\mathbf{R}_{pri}$ is 1;

$$\mathbf{R}_{pri}{}^T \mathbf{R}_{pri} = 1 \tag{16}$$

Using Eqs.8 and 16, we can calculate C_r as follows,

$$\begin{aligned}\{\mathbf{I}(d_r, 0, 0) - \mathbf{I}_0\}^T \mathbf{R}_{pri} &= C_r(d_r)\mathbf{R}_{pri}{}^T \mathbf{R}_{pri} \\ &= C_r(d_r)\end{aligned} \tag{17}$$

Using samples D_r defined in Eq.15, C_r is calculated using spline interpolation. This is important property of PCA-model since functional form of coefficients is dependent on each device such as R-LCD, T-LCD, CRT.

Experiment

Equipment

In our experiment, three types of display device; CRT (Mitsubishi RDF17X), T-LCD(Sharp LL-T180) and R-LCD(sharp PC-PJ2-HR) were used to colorimetric evaluation. Spectral radiances of each display were measured using spectrophotometer Minolta CS1000 under D65 illuminant in dark room. Geometry on measuring the R-LCD is shown in Fig.3, CRT and T-LCD are shown inFig.4 respectively.

Model Implementation

Basis vectors and coefficients in Eq.11 were determined by using set of digital counts Dr, Dg, Db as follows,

$$D_k = \{0, 15, 30, 45, \cdots, 255\} \quad k = R, G, B \tag{18}$$

Monitor calibration using PCA was applied to digital counts D_{test} with black(0,0,0), white(255,255,255) and combination of three values, 44, 128, 212. Namely,

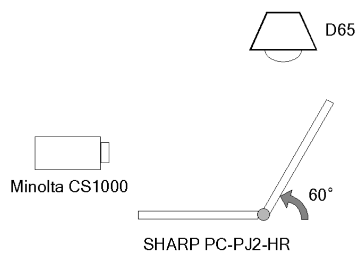

Figure 3. Geometry for measuring R-LCD

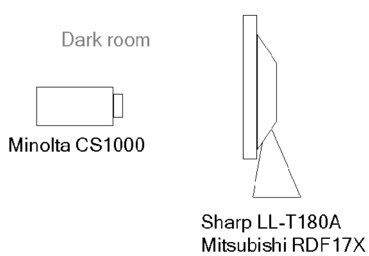

Figure 4. Geometry for measuring CRT and T-LCD

$$D_{test} = \{(0,0,0), (255,255,255), (44,44,44), \\ \ldots, (212,212,128), (212,212,212)\} \tag{19}$$

Table 1 shows the average, minimum and maximum CIE94 color difference between measured and estimated. It is clear that PCA-model is more effective than GOG-model for all three types of display. Figure 5 shows an example of spectral radiance measured and estimated by PCA-model. It is apparent that the estimated spectral radiance gives a close approximation to measured values.

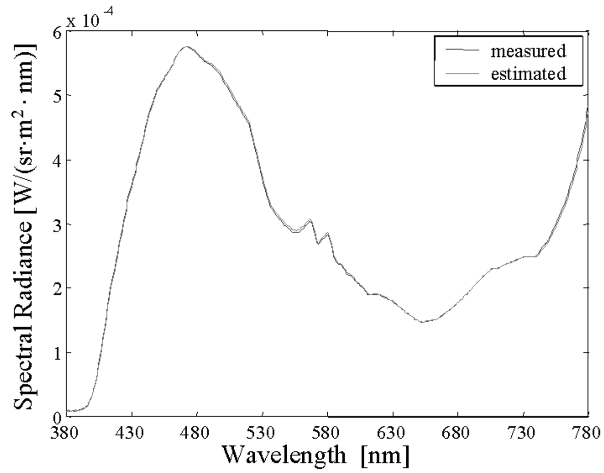

Figure 5. Estimation results using PCA-model

Table 1. CIE94 Color Difference between measured and estimated

Display	*Model*	*Average*	*Minimum*	*Maximum*
R-LCD	*PCA-model*	*0.4454*	*0.0564*	*0.9651*
	GOG-model	*0.7428*	*0.2607*	*9.9354*
T-LCD	*PCA-model*	*2.0875*	*0.0379*	*4.8231*
	GOG-model	*6.5647*	*3.1060*	*16.1739*
CRT	*PCA-model*	*0.2792*	*0.0426*	*1.0768*
	GOG-model	*0.4769*	*0.0822*	*3.3530*

Performance Comparison Between PCA-Model and GOG-Model

The experiment shows PCA-model is more accurate than conventional GOG-model. We consider that PCA used to calculate primary color vector and spline interpolation method are strong reason for accurate colorimetry. We compared four models which are GOG-model, GOG-model(1), GOG-model(2), and PCA-model. GOG-model(1) and GOG-model(2) are modified version of GOG-model. Basis vectors of GOG-model(1) are caluculated by PCA and Coefficients of GOG-model(2) are calculated using spline interpolation. For this comparison, data used in previous experiment were used. The result is shown in Table 2.

From Table 2, Spline interpolation method is very useful for improvement of the performance. On the other hand, GOG-model could not apply to gamma curve Cr(dr), Cg,(dg) Cb(db) of R-LCD used in this experiment. It is also confirmed that introduction of PCA is effective for improvement of colorimetry.

Table 2. CIE94 Color Difference for 2x2 combination of improvement factor (R-LCD)

	Average	*Maximum*	*Minimum*
GOG-model	*0.7428*	*1.1796*	*0.2607*
GOG-model(1)	*0.5811*	*1.1523*	*0.2221*
GOG-model(2)	*0.5015*	*0.8819*	*0.0736*
PCA-model	*0.4454*	*0.9651*	*0.0564*

Conclusion

PCA-model was proposed for colorimetry of CRT and LCD. PCA-model was derived from two assumptions; chromaticity constancy of primary color and independency of each channel. The experiment shows PCA-model is more accurate than conventional GOG-model. Furthermore, by including higher order principal components to PCA-model further improvement of colorimetry is possible.

Reference

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Biography

Toru Ishii was born in 1979 at Chiba, Japan. He is currently a master course student at Graduate School of Science and Technology, Chiba University. He is interested in color reproduction characteristics of display devices.