Effective Channel-Independent Inverse Characterization Method for Display Device

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Abstract

This paper proposes a channel-independent inverse characterization process based on the GOG model for a display device. The CIEXYZ values for each of RGB channel can estimated from nine channel-independent interpolation TRCs (Tone Response Curves), and the result of this characterization method is better than that from conventional three channel-independent interpolation TRCs. However inverse characterization is impossible when using nine channel-independent interpolation TRCs, as the CIEXYZ values that correspond to each RGB values are inseparable directly. Accordingly, inverse characterization is usually implemented using the 3D-LUT (Look-Up Table) method. Yet, although the result of a 3D-LUT is accurate, creating the LUT requires a lot of memory space and considerable amount of measurements.

Therefore, an accurate inverse characterization method is proposed based on the simple modeling of channel-dependent values and nine channel inverse processes based on the GOG model. CIEXYZ values are computed for three normalized luminance values using an inverse matrix. The channel-dependent values are subtracted from the normalized luminance values that are generated by an overlapped spectral distribution of the primary digital values based on modeling the channel-dependent values. Each of the three normalized luminance values is modified into the corresponding nine channel TRCs using a gamma correction of each channel and modifying the tone response curve. The digital values are estimated by the nine channel-independent interpolation TRCs based on an inverse GOG model using the parameters of forward characterization, considering weighting factors. Three digital values are determined for each RGB channel based on the maximum CIEXYZ values for each red, green, and blue channel. As such, the proposed method reduces the time complexity and number of measurements required for accuracy.

1. Introduction

Various display devices have already been developed in relation to display device technology. Yet, when the same input signals are sent to such display devices, each device reproduces different colors. Thus, color fidelity has become a key issue for the color management of display devices, which includes characterization, gamut mapping, and white color balancing, etc..

Therefore, this paper discusses characterization and inverse characterization, which establish the relationship between the signals sent to a device and the produced colors using the following parameters: the white and black points, chromaticity, luminance at maximum output, and gamma of each color channel.

Generally, display device characterization consists of two parts, where the first step involves a nonlinear transformation relating normalized DAC values to the TRCs of display devices, and the second step is a linear transformation, where the normalized luminance values are transformed to the CIEXYZ values. The GOG model is a common method that uses three channel-independent TRCs. Plus, the colorimetric characterization should be limited only by measurements and display variances, or within perceptibility tolerances.[1-2]

According to a recent study, CIEXYZ values can be obtained for each RGB channel by interpolating the tri-stimulus values measured for the corresponding primary RGB values, plus the channel-independence assumption can be used to predict the CIE tri-stimulus values for any arbitrary combination of RGB values.[2] The model has nine channel-independent interpolation TRCs using three CIEXYZ values, which correspond to the values for each of the three RGB channels. As a result, the characterization result is accurate.

For practical use with a display, color calibration requires the inverse characterization of the device, which provides the RGB values corresponding to the desired tri-stimulus values. Generally, the inverse characterization process is a reverse of the forward characterization, for example, the inverse TRCs of the GOG model. Yet, the inverse characterization is limited, as the reverse of mathematical formulations is impossible.[2]

For example, inverse channel-independent characterization is impossible in the case of nine channel-independent characterization TRCs, as the CIEXYZ values corresponding to each RGB values are inseparable.

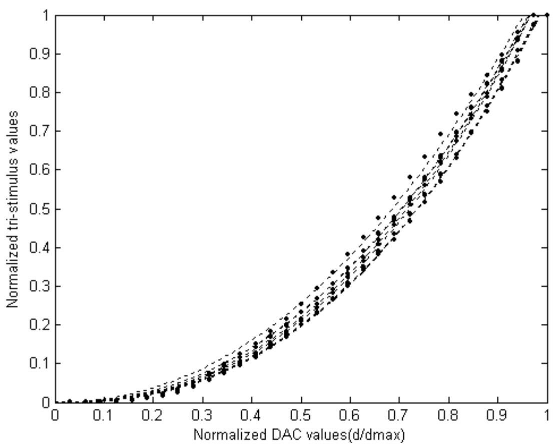

Figure 1. Channel-independent characterization for LCD monitor (SAMSUNG SyncMaster Magic CX171T).

Nonetheless, the forward characterization method had nine independent interpolation TRCs. Usually, arbitrary CIEXYZ values only have a normalized luminance value using an inverse matrix. As such, inverse characterization generally uses a 3D-LUT for accuracy, however, creating a LUT requires a lot of memory space and large number of measurements.

Accordingly, this paper presents a channel-independent inverse characterization method that involves the modeling of channel-dependent values, which are generated through the overlapped spectral distribution of the primary digital values, as a simple second order polynomial and a reverse process based on nine parameters of the nine independent interpolation TRCs using a modification of normalized luminance values. Experiment results confirm that the proposed nine channel-independent inverse TRCs method is better than any other existing methods.

2. Characterization of Display Device

Although the color characteristics of an LCD display device usually differ from those of a CRT display, the color characteristics of some LCD monitors have recently been fitted with the color characteristics of a CRT display. Thus, our study conducted a nine channel-independent characterization process based on the GOG model for an LCD monitor, and, in case of three channel TRCs, when the TRCs for digital values were modeled in luminance Y channels, the TRCs of X and Z channels were different from TRCs of luminance Y channels. Figure 1 show the nine channel TRCs of CIEXYZ values for each of the RGB channels. Thus, nine channel-independent interpolation TRCs consider the difference between the channel TRCs. Plus, before the characterization process, the estimated black-level emission was subtracted for characterization accuracy.[3,4]

$$
\begin{aligned}
R_i &= \{k_{g,ri}[d_r/(2^N-1)]+k_{o,ri}\}^{\gamma_{ri}} \\
&\qquad \text{if} \quad \{k_{g,ri}[d_r/(2^N-1)]+k_{o,ri}\} \geq 0 \\
&= 0 \qquad \text{if} \quad \{k_{g,ri}[d_r/(2^N-1)]+k_{o,ri}\} \leq 0
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
G_i &= \{k_{g,gi}[d_g/(2^N-1)]+k_{o,gi}\}^{\gamma_{gi}} \\
&\qquad \text{if} \quad \{k_{g,gi}[d_g/(2^N-1)]+k_{o,gi}\} \geq 0 \\
&= 0 \qquad \text{if} \quad \{k_{g,gi}[d_g/(2^N-1)]+k_{o,gi}\} \leq 0
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
B_i &= \{k_{g,bi}[d_b/(2^N-1)]+k_{o,bi}\}^{\gamma_{bi}} \\
&\qquad \text{if} \quad \{k_{g,bi}[d_b/(2^N-1)]+k_{o,bi}\} \geq 0 \\
&= 0 \qquad \text{if} \quad \{k_{g,bi}[d_b/(2^N-1)]+k_{o,bi}\} \leq 0
\end{aligned} \tag{3}
$$

where d_i are the digital input values, and N is the number of bit, 2^N -1 becomes the maximum digital input value. R_i, G_i, and B_i are normalized i (i = X, Y, and Z) values from 0 to 1 for the red, green, and blue channel, respectively. To estimate the optimal parameters, $k_{g,ci}$, $k_{o,ci}$, and $_{cici}$ (c = r, g, and b and i = X, Y, and Z), 32 patches are created with equally-spaced digital values, then the XYZ values for each patch are measured for each channel. After modeling the TRCs, the normalized XYZ values which correspond to an arbitrary digital input values for each channel are estimated using equations 1, 2, and 3. Finally, the estimated R_i, G_i, and B_i values are used to estimate the CIEXYZ values as follows;[3]

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = diag\left(\begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{bmatrix} R_X & R_Y & R_Z \\ G_X & G_Y & G_Z \\ B_X & B_Y & B_Z \end{bmatrix} \right) \tag{4}
$$

where the $X_{c,\max}$, $Y_{c,\max}$, and $Z_{c,\max}$ (c = r, g, and b) values are the maximum CIEXYZ values for each red, green, and blue channel. Table 1 shows the results of characterization. The result of channel-independent characterization is better than any other methods. Yet, it is impossible to apply inverse characterization using nine channel-independent interpolation TRCs, as the CIEXYZ values that corresponded to each of the normalized luminance values, are inseparable, as shown in figure 2. The same luminance values are never send to three TRCs, because the nine channel TRCs are different from each other. wi (i = $1,2,3,\ldots,9$) is weighting factor in figure 2. Accordingly, inverse characterization is usually implemented using the 3D-LUT method. Although the result of a 3D-LUT is accurate, the LUT requires a lot of memory space and considerable amount of measurements.[2,5]

Table 1. Characterization Result for LCD Monitor.

	Regression 3X20		GOG model		Nine channel-independent GOG model	
	ΔEavg	ΔEmax	ΔEavg	ΔEmax	ΔEavg	ΔEmax
216 patches	4.02	20.68	5.63	19.50	3.07	12.61

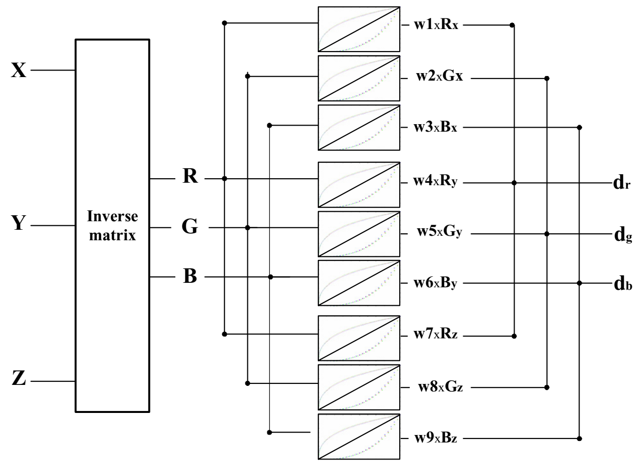

Figure 2. Nine channel-independent inverse characterization.

3. Inverse Characterization of LCD Display

A nine channel-independent inverse process was performed based on the GOG model, and figure 3 shows the structure of the channel-independent inverse characterization. First, the tri-stimulus values of black level emission are subtracted from the CIEXYZ values. CIEXYZ values are computed for all three normalized luminance values using an inverse matrix. Then, the normalized luminance values are subtracted from the channel-dependent values generated by an overlapped spectral distribution of the primary digital values based on modeling of channel-dependent values.[6-9] Each of the three normalized luminance values is modified into the corresponding nine channel TRCs using a gamma correction for each channel and modifying tone response curve. The digital values are estimated using an inverse GOG model of the nine channels with parameters from the forward characterization, considering weighting factors. The three digital values for each RGB channel are determined using the maximum CIEXYZ values for each red, green, and blue channel.

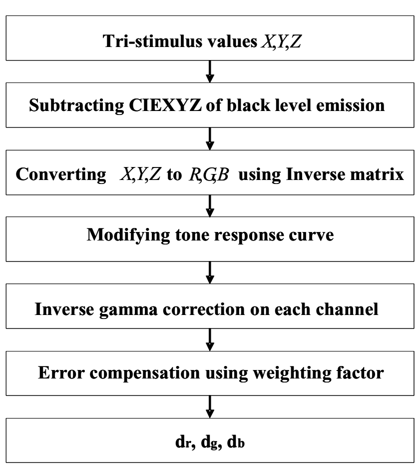

Figure 3. Flowchart for channel independent inverse characterization.

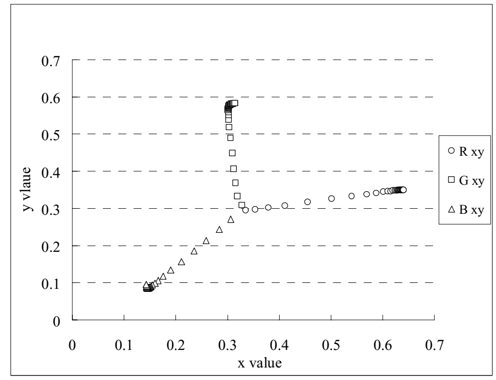

Figure 4. Chromaticity of each channel varying in digital values between 0 and 255.

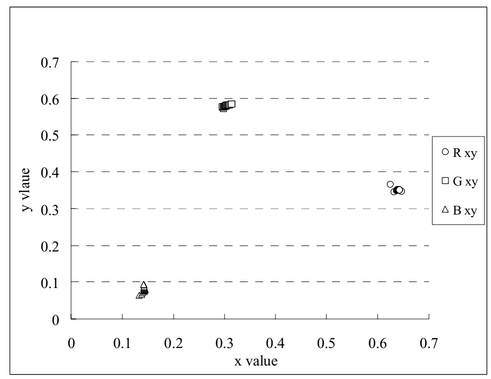

Figure 5. Chromaticity of each channel varying in digital values with subtraction of the estimated black-level emission.

3.1. Estimating Black-Level Tri-stimulus Values

The black level is commonly used in computer-controlled displays to convert the light emission in an image into digital values of zero. Since the chromaticity is concentrated to a point for a linear transformation, an appropriate black-level emission measurement improves the characterization accuracy (figure 4 and figure 5). Yet many measuring instruments have a low sensitivity as regards measuring the black-level emission. As such, black-level tri-stimulus values are estimated from minimizing the objective function.[4]

$$\text{Minimize}(\sigma^2_{x,y,red} + \sigma^2_{x,y,green} + \sigma^2_{x,y,blue}) \quad (5)$$

The variance for each channel is calculated as follow.

$$\sigma^2_{x,y,l} = \frac{\sum_{i=1}^{n} (d_{i,xy,l} - \bar{d}_{xy,l})^2}{n-1} \quad (6)$$

where

$$d_{i,xy,l} = \sqrt{(x_{i,l} - \bar{x}_l)^2 + (y_{i,l} - \bar{y}_l)^2}$$

In Equation (6), d defines the chromaticity distance between the chromaticity for the ith measurement and the average chromaticity, x and y is chromaticity, n is the total number of measurements, and l is red, green, and blue channel.[4]

3.2. Inverse Matrix of Tri-stimulus Values

The inverse matrix is determined based on the forward characterization matrix and separates the channel-independent values from the channel dependent value using the primary RGB measurement data (CIEXYZ), as the spectral distribution of primary RGB overlapps a part of each primary channel.[6-7] Inverse matrix is

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{7}$$

For example, the input signal from the green channel generates not only G channel values but also small R channel and B channel values. Figure 6 shows the small channel dependent values according to each primary channel. The values should be zero if the channel-independent characterization is full for each channel.

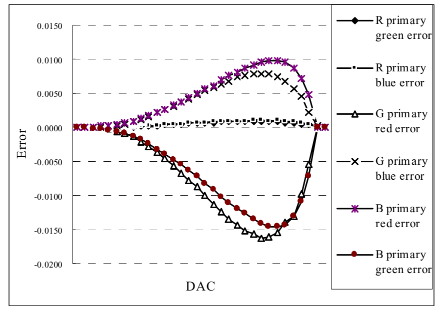

Figure 6. Channel dependent values of primary values.

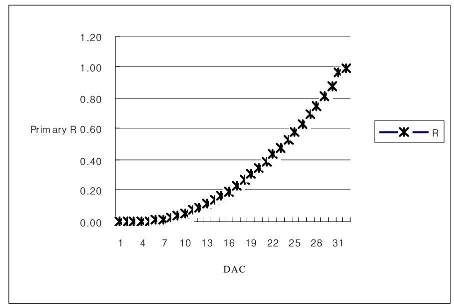

Figure 7. Estimated luminance values of primary R values.

3.3. Modeling of Channel Dependent Values

The estimated normalized display luminance levels of the arbitrary CIEXYZ values are determined through modeling channel-dependent values. For example, figure 7 shows the estimated luminance value of primary R value. The computed values generated non-zero values of G and B channel along primary R. Figure 8 shows modeled the channel-dependent values based on the estimated luminance levels of primary R.[6-9] The modeled $R_{primary}$ and non-zero values of the G and B channel using a second order polynomial are

$$\begin{aligned} R_{primary} &= \{k_{g,rp}[d_r/(2^N-1)]+k_{o,rp}\}^{\gamma_{rp}} \\ &\quad \text{if } \{k_{g,rp}[d_r/(2^N-1)]+k_{o,rp}\} \geq 0 \\ &= 0 \quad \text{if } \{k_{g,rp}[d_r/(2^N-1)]+k_{o,rp}\} \leq 0 \\ G_{R,error} &= a_{r,g}(R_{primary})^2 - a_{r,g}(R_{primary}) \\ B_{R,error} &= a_{r,b}(R_{primary})^2 - a_{r,b}(R_{primary}) \end{aligned} \tag{8}$$

where $G_{R,error}$ and $B_{R,error}$ are the channel dependent values for primary R values and a is the modeling parameter for the channel-dependent values with an optimization method. The normalized luminance values for the arbitrary CIEXYZ values denoted by

$$\begin{aligned} R &= R_{primary} - R_{G,error} - R_{B,error} \\ G &= G_{primary} - G_{R,error} - G_{B,error} \\ B &= B_{primary} - B_{G,error} - B_{R,error} \end{aligned} \tag{9}$$

3.4. Modifying Tone Response Curves

The normalized luminance values are modified to fit into the nine channel-independent inverse processes. The gamma correction and change in the TRCs parameters are carried out for linearization. Yet this process is sensitive and complex. Each of three normalized luminance values are subtracted from each of the nine channel TRCs and modified to fit into the nine channel-independent inverse processes as follow.

$$\begin{aligned} &\Delta R_i = R_{i,foward} - R, \Delta G_i = R_{i,foward} - G, \Delta B_i = B_{i,foward} - B \\ &\Delta R_i = b_{r,r}(R)^2 - b_{r,r}(R)^2 \\ &\Delta G_i = b_{r,r}(G)^2 - b_{r,r}(G)^2 \\ &\Delta B_i = b_{r,r}(B)^2 - b_{r,r}(B)^2 \end{aligned} \tag{10}$$

3.5. Inverse Tone Response Curve of Each Channel

The DAC values are determined through an inverse GOG model, which corresponds to the tone response curve of the display. The estimated normalized display luminance levels have nine parameter sets as a result of the forward characterization method.

$$\begin{aligned} d_{ri} &= [(2^n-1)/k_{g,ri}]((R+\Delta R_i)^{1/\gamma_{ri}} - k_{o,ri}) \ \text{ if } 0 \leq \text{R} \leq 1 \\ d_{gi} &= [(2^n-1)/k_{g,gi}]((G+\Delta G_i)^{1/\gamma_{gi}} - k_{o,gi}) \ \text{if } 0 \leq G \leq 1 \\ d_{bi} &= [(2^n-1)/k_{g,bi}]((B+\Delta B_i)^{1/\gamma_{bi}} - k_{o,bi}) \ \text{ if } 0 \leq \text{B} \leq 1 \end{aligned} \tag{11}$$

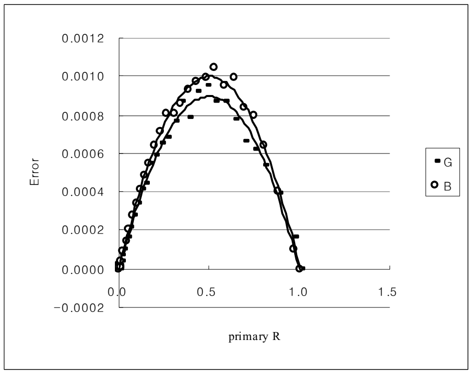

Figure 8. Modeling channel dependent values.

3.6. Determining *dr, dg, db* Values by Weighting Factor

The three digital values for the RGB channel are determined using the maximum CIEXYZ values for each red, green, and blue channel. The large magnitude of the maximum CIEXYZ value is insensitive to errors, yet the small value is sensitive. Thus, to reduce error, the estimated digital values are weighted by the maximum CIEXYZ values as follow.

$$\sum d_{ri} \times \frac{i_{r,\max}}{X_{r,\max} + Y_{r,\max} + Z_{r,\max}}$$
$$\sum d_{gi} \times \frac{i_{g,\max}}{X_{g,\max} + Y_{g,\max} + Z_{g,\max}}$$
$$\sum d_{bi} \times \frac{i_{b,\max}}{X_{b,\max} + Y_{b,\max} + Z_{b,\max}} \quad (12)$$

where d_{ci} ($c = r$, g, and b and $i = X$, Y, and Z) are estimated digital values.

4. Experiments

For the experiments, all measurements were performed on a central uniform square patch (h/5xh/5, h: the effective screen height) as the DVI input signal values in a dark room. The 32 patches were created with equally-spaced digital values. The number of the LUT patch is 6x6x6. A comparison of the inverse characterization result required the making of an 3D-LUT under Eavg 0.23. The display device is a SAMSUNG SyncMaster Magic CX171T LCD monitor and the measurement instrument is a Minolta CS-1000 spectro-radiometer. Four effective measurement data sets were created. The optimization process was carried out using *fminsearch* function of Matlab 6.5. CIELAB color space was used as the measure to compare the results. Table 2 shows the results of the inverse characterization. The average error of the channel independent inverse characterization was hardly perceptible and the maximum error was lower than any other method.

Table 2. Inverse Characterization Result for LCD Monitor.

	Regression 3X20		GOG model		Channel independent GOG model	
	ΔEavg	ΔEmax	ΔEavg	ΔEmax	ΔEavg	ΔEmax
216 patches	4.91	15.92	6.92	15.27	3.24	8.73

5. Conclusion

This paper proposed an effective channel-independent inverse characterization method through the simple modeling of channel-dependent values and nine channel-independent inverse interpolation TRCs with suitable black-level tri-stimulus values. In experiments, the results of the proposed method are simpler than those for the 3D-LUT method as regards the measurement process or complexity, plus the cost of characterization was low. The proposed method was also more accurate than the GOG model or regression method.

Acknowledgement

This work was supported by grant no. M1041200010204 J000003910 from the National Research Laboratory Program of the Ministry of Science & Technology.

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Biography

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