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Inverse Characterization Method of Alternate Gain-Offset-Gamma Model for Accurate Color Reproduction in Display Device

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Abstract. *Display characterization, deriving the relationship between the digital input values and the corresponding CIEXYZ tri-stimulus values, is necessary to reproduce accurate colors in a color management system. For colorimetric reproduction in a display device, an inverse characterization process is needed to input RGB corresponding to the desired tri-stimulus values. However, inverse display characterization using nine channel tone response curves (TRCs) cannot be directly inverted because the CIEXYZ values corresponding to each RGB value are inseparable. Inverse display characterization is usually implemented using the three-dimensional (3D)-look-up table (LUT) method, yet this requires a lot of memory space and a considerable amount of measurement data, although it provides a relatively accurate estimation. Accordingly, this paper proposes an inverse characterization method based on modeling channel-dependent values and a nine-channel inverse process using the gain-offset-gamma (GOG) model. First, the initially normalized luminance values for each RGB channel are computed using the inverse matrix. These normalized luminance values are then used to compensate the corresponding nine channel TRCs, thereby modifying the TRCs into input linearized values for the inverse process. Thereafter, each of the nine channel digital RGB values is estimated using the inverse GOG model based on the predetermined parameters from the forward characterization. Finally, three digital RGB values are deduced for each RGB channel based on the ratio of the maximum CIEXYZ values to reduce the interpolation error. Consequently, the proposed method enhances the accuracy of the display characterization and reduces both the complexity and the number of measurement data required. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

Despite the recent development of various types of display device, such as liquid-crystal displays (LCDs) and plasma display panels (PDPs), these devices still reproduce different colors to the same input signals they are sent. Thus, color fidelity remains a key issue for the image quality of display devices, covering device characterization,[1–4] gamut mapping,[5,6] and color appearance models.[7,8] In general, gamut mapping and color appearance modeling are performed in a device-independent color space to consider the characteristics of the human visual system. Then, these color signals have to be converted to a device-dependent color space, that is, display input values, to reproduce the image on a display device. However, accurate color reproduction requires estimating the relationship between the device-independent color space and the device-dependent color space, referred to as display characterization. Therefore, this paper focuses on the device characterization method of display to establish the relationship between the signals sent to a device and the colors it produces.

There are essentially two types of display characterization method. One uses various data measurements to implement the device characterization, such as a 3D LUT,[9] polynomial regression,[10] and neural network methods,[11] which improves the characterization accuracy, yet requires a lot of measurement data, an extensive memory, and is highly complex. Meanwhile, the other type of method uses a smaller number of data measurements to model the relationship between the device input and the output signals, such as a simple gamma model,[12] GOG model,[1,2] GOGO (gain, offset, gamma, offset) model,[12] masking model,[13] and S-curve model.[3] Thus, modeling methods are more effective for display characterization than large amounts of measurement data, as the algorithm can be easily generalized, thereby reducing the complexity. Also, the characterization accuracy is nearly imperceptible to the human visual system. The most recent modeling method developed for display characterization is the alternate model.[4] Conventional characterization methods for a CRT display only use the luminance values for each *RGB* channel to model the relationship. However, the fundamental assumptions of channel independence and channel chromaticity constancy do not apply to LCD and PDP displays. Accordingly, the alternate model uses all the CIE*XYZ* values for each of the nine *RGB* channels to enhance the characterization accuracy.

However, for practical use with a display, an inverse characterization method is also required for the color management of the display device to provide *RGB* values corresponding to the desired tri-stimulus values, like CIE*XYZ* values. The inverse characterization process is essentially a reverse of the forward characterization. Yet, inverse characterization is impossible in the case of the alternate model, as the CIE*XYZ* values corresponding to each *RGB* value are inseparable.[4] Nonetheless, forward characterization using the

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alternate model produces more accurate results than the conventional characterization methods, then a 3D LUT is generally used for the inverse characterization instead of simple modeling parameters and tone response correction. Accordingly, this paper proposes an inverse characterization method for the alternate model, involving the modeling of channel-dependent values as simple second-order polynomials and a reverse process based on additional TRCs to separate the nine channel TRCs. Experimental results show that the proposed inverse characterization method for the alternate model does not need additional measurement data, in contrast to the three-channel GOG model, and enhances the accuracy of the display characterization. The proposed method is also simpler than the 3D-LUT method as regards the measurement process and complexity.

FORWARD CHARACTERIZATION OF DISPLAY DEVICE

Display device characterization using just a few data measurements consists of two parts.[1–4,10,12] The first step involves a nonlinear transformation, where the normalized digital-to-analog converters (DAC) values are transformed into the TRCs of the display device, while the second step is a linear transformation, where the normalized luminance values are transformed into CIE*XYZ* values. The conversion from the display *RGB* values into the corresponding CIE*XYZ* values is defined as forward display characterization. In practice, the color calibration of a display device permits accurate display images where the pixel colors are specified in terms of their CIE*XYZ* values. Thus, the practical application of display characterization requires inverse display characterization, which provides a mapping from each desired color in CIE*XYZ* values to the corresponding display RGB values. Figure 1 shows a block diagram of forward and inverse display characterization.[4] Figure 1(a) represents forward display characterization, where the display signals are converted into CIEXYZ values using three channel TRCs and a 3×3 linear transformation matrix. Meanwhile, Fig. 1(b) represents inverse display characterization, which consists of the reverse process of forward display characterization. Inverse display characterization must be applied to each pixel color for an accurate color reproduction in the display device.

The GOG model[1,2,12] based on a CRT display is a common display characterization method that uses three channel TRCs. The S-curve model[3] is then a mathematical generalization of the GOG model for application to an LCD or LCD projector, which has a different electro-optical transfer function to a CRT display. The masking model,[13] which is similar to the under color removal (UCR) method in printing technology, was developed to take account of the channel interaction in an LCD. In addition, the alternate GOG model[4] using nine channel TRCs for an LCD, which does not satisfy the fundamental assumptions of the GOG model,[1,2] has been proposed to enhance the accuracy of device characterization.

Although the color characteristics of an LCD device usually differ from those of a CRT display, the color characteristics of some LCD monitors have recently been fitted

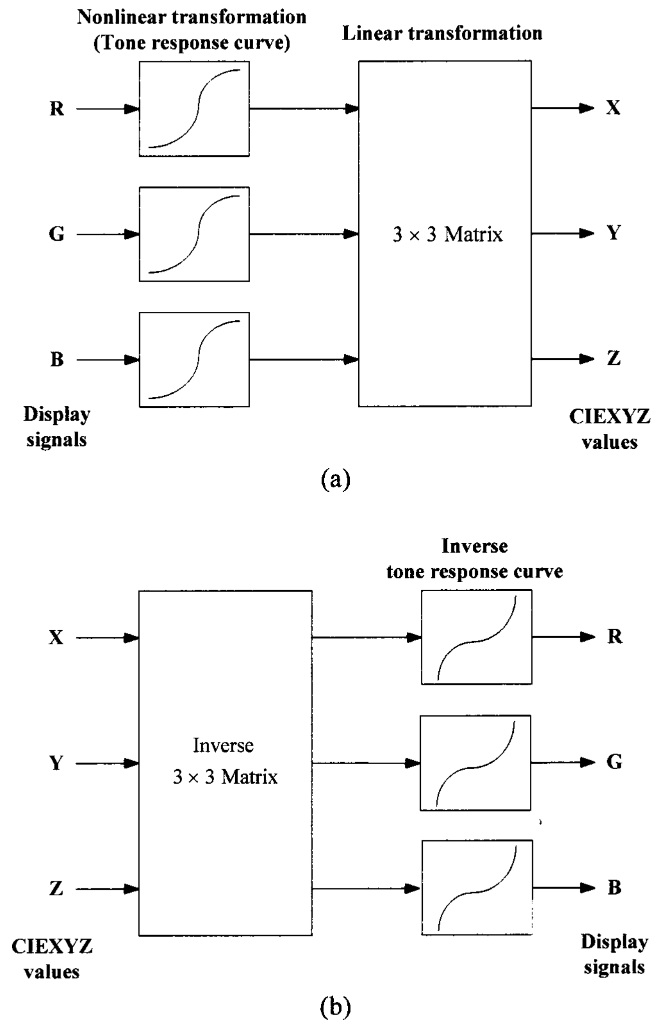

Figure 1. Block diagram of display characterization (Ref. 4); (a) forward display characterization, (b) inverse display characterization.

with the color characteristics of a CRT display, in which case the characterization result of the GOG model is similar to that of the S-curve model. Also, the masking model increases the complexity, as additional data measurements (cyan, magenta, yellow, gray) are needed for display characterization. Therefore, the present study applies the alternate model[4] using nine channel TRCs based on the GOG model with no additional data measurements. In the case of the GOG model based on three channel TRCs, when the TRCs for the display RGB values are modeled using only the luminance *Y* values, the TRCs for the *X* and *Z* channels are different from those for the luminance *Y* channels. However, the alternate model using nine channel TRCs can consider the difference between the channel TRCs. A block diagram of the alternate model[4] for display characterization is shown in Fig. 2. The estimated nine channel TRCs for the CIE*XYZ* values for each *RGB* channel in an LCD (Samsung SyncMaster Magic CX171T) are presented in Fig. 3. Figure 3(a) shows the TRCs for the normalized *X* values, Fig. 3(b) shows the TRCs for the normalized *Y* values, and Fig. 3(c) shows the TRCs for the normalized *Z* values for each *RGB* channel. In the

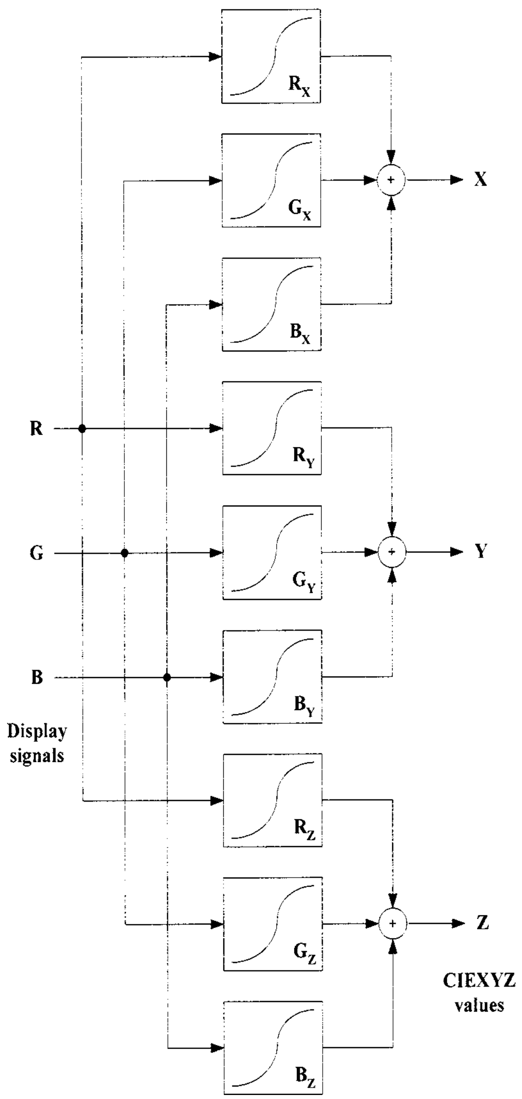

Figure 2. Block diagram of alternate display characterization (Ref. 4).

alternate display characterization process based on the GOG model, nonlinear transformations relating the normalized DAC values to the TRCs of the display device are estimated using the gain, offset, and gamma as follows:

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

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

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

where $d_j(j=r,g,b)$ are the digital input values for each RGB channel, N is the number of bits, 2^N-1 is the maximum digital input value, and R_i, G_i, and B_i are normalized i ($i=X,Y,Z$) values from 0 to 1 for the red, green, and blue channel, respectively. To estimate the optimal gain, offset, and gamma parameters, k_{gji}, k_{oji}, and γ_{ji} ($j=r,g,b$, *and* $i=X,Y,Z$), respectively, 32 patches are created with equally spaced digital values, then the CIEXYZ values for each patch are measured. After modeling the TRCs, the estimated R_i, G_i, and B_i values are used to estimate the CIEXYZ values,

$$X = [X_{r,\max} \quad X_{g,\max} \quad X_{b,\max}] \begin{bmatrix} R_X \\ G_X \\ B_X \end{bmatrix}, \tag{4}$$

$$Y = [Y_{r,\max} \quad Y_{g,\max} \quad Y_{b,\max}] \begin{bmatrix} R_Y \\ G_Y \\ B_Y \end{bmatrix}, \tag{5}$$

$$X = [Z_{r,\max} \quad Z_{g,\max} \quad Z_{b,\max}] \begin{bmatrix} R_Z \\ G_Z \\ B_Z \end{bmatrix}, \tag{6}$$

where the $X_{j,\max}$, $Y_{j,\max}$, and $Z_{j,\max}(j=r,g,b)$ values are the maximum CIEXYZ values for each red, green, and blue channel.

Table I shows the results of the forward display characterization. 216 patches($6\times6\times6$ RGB cube) were tested to compare the average and maximum CIELAB color difference for an LCD (Samsung SyncMaster Magic CX171T). The results showed that using the alternate model as the display characterization method produced the smallest color difference, except for the 3D LUT method based on a tetrahedral interpolation. However, the polynomial regression using 21 coefficients and 3D LUT method using 216 sample data required a lot of data measurements to derive an unperceivable color difference, thereby increasing the complexity. Also, the color difference results when using the S-curve model and three-channel GOG model were similar to each other, indicating that the S-curve model is not always effective for an LCD, since some manufacturers transform the S-curve characteristic into the gamma characteristic on an integrated circuit (IC).[13] Therefore the alternate display characterization method based on the GOG model was shown to be effective, especially considering the accuracy of the display characterization and complexity. However, even though the display characterization result for the alternate model was good, the alternate model cannot be directly inverted to obtain an inverse model, as the CIEXYZ values corresponding to each of the normalized luminance values are inseparable. The initial luminance values cannot be directly used for each of the nine channel TRCs, as the nine channel TRCs are different from each other. Accordingly, an inverse characterization method based on nine channel TRCs is proposed to reduce

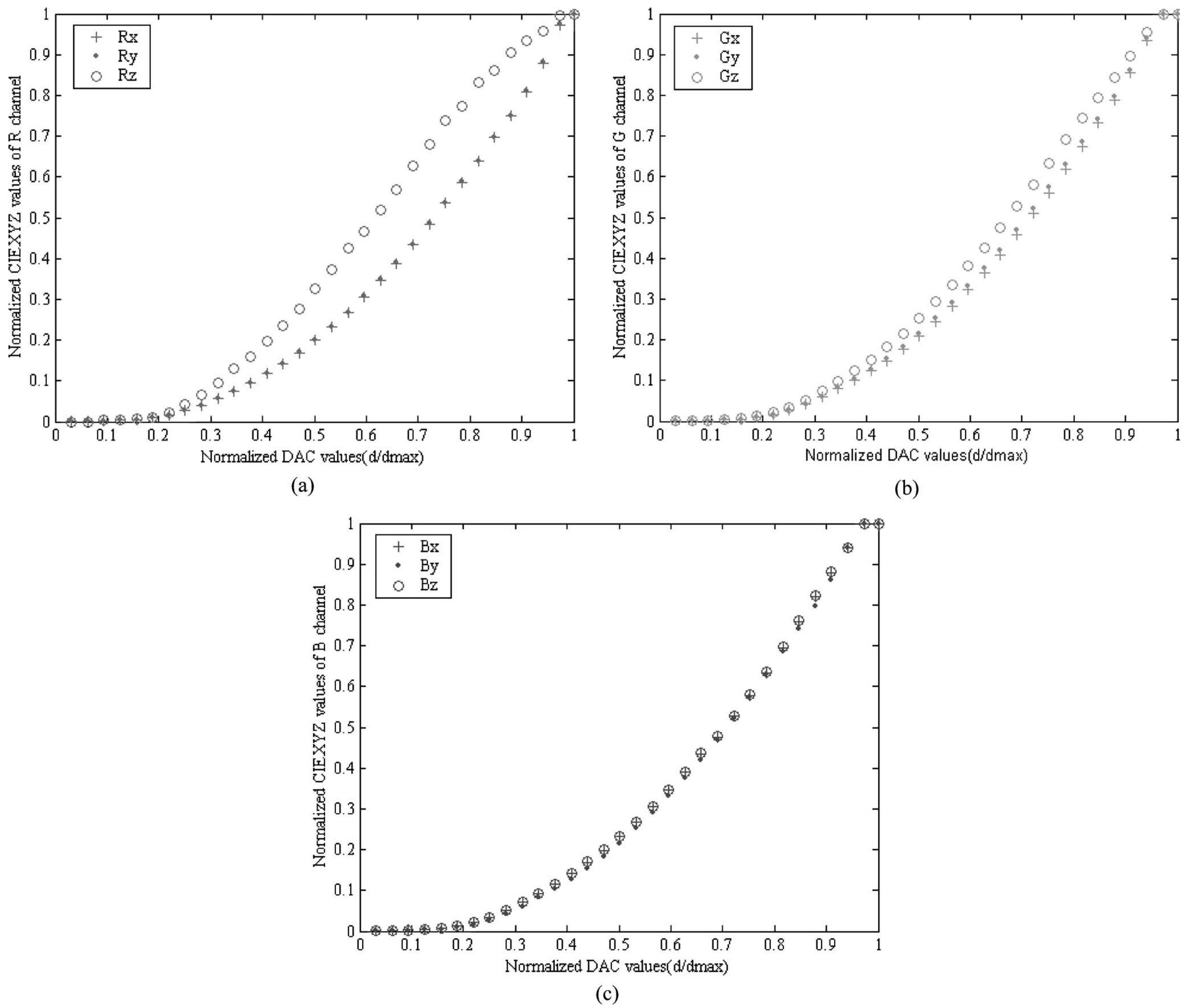

Figure 3. Alternate display characterization for LCD monitor (SAMSUNG SyncMaster Magic CX171T): (a) TRCs for normalized *X* values, (b) TRCs for normalized *Y* values, and (c) TRCs for normalized *Z* values.

Table I. Result of forward characterization methods for LCD monitor.

Polynomial Regression (3 × 21 matrix)		3D LUT		Three channel GOG model		Three channel S-curve model		Alternate GOG model	
E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}
4.02	20.68	1.08	4.28	5.63	19.50	5.54	18.95	3.07	12.61

the characterization complexity and enhance the characterization accuracy.

INVERSE DISPLAY CHARACTERIZATION OF ALTERNATE MODEL

The inverse process of the alternate model is performed based on the GOG model. Figure 4 shows a block diagram of the inverse model for the alternate display characterization. First, tri-stimulus values for the black-level emission[14] are subtracted from the input CIE*XYZ* values to correct the black-level offset values of the display device. Three initially normalized luminance values are computed for each *RGB* channel using the inverse matrix of Eqs. (4)–(6). The inverse matrix is the combined form of Eqs. (4)–(6), which is generally used in the three channel display characterization method. The inverse matrix is composed of the maximum CIE*XYZ* values. Then, each of the initially-normalized lumi-

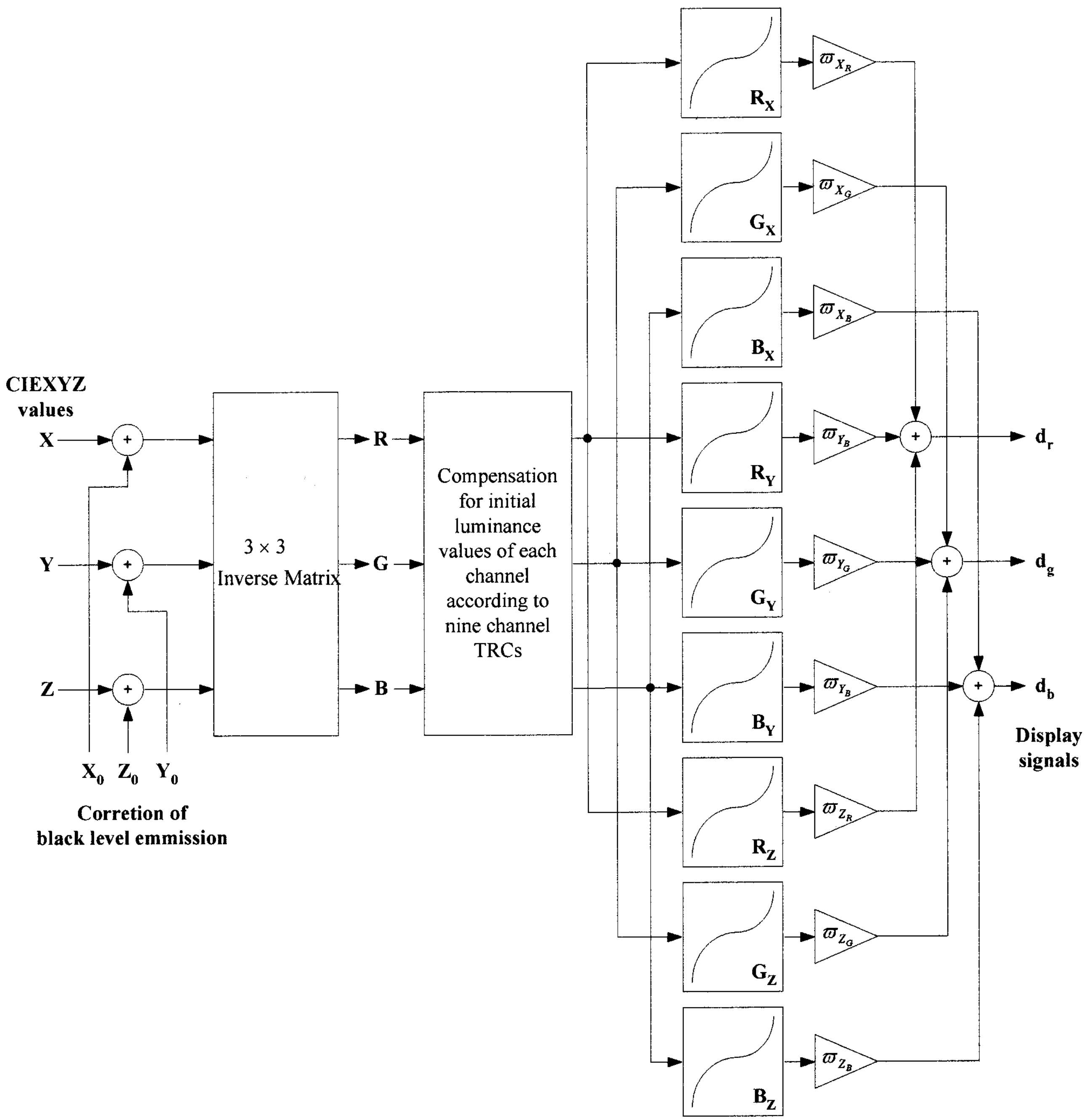

Figure 4. Block diagram of inverse model for alternate display characterization.

nance values is compensated according to the corresponding nine channel TRCs, thereby modifying the TRCs to input linearized values in the inverse process. The digital *RGB* values for the nine channel TRCs are estimated using the inverse GOG model, and the final three digital *RGB* values are determined using the ratio of the maximum CIE*XYZ* values for each *RGB* channel. Since the red channel is highly correlated to the *X* channel, rather than the *Y* and *Z* channel, the green channel is correlated to the *Y* channel, and the blue channel is correlated to the *Z* channel, the ratio of the maximum CIE*XYZ* values is used as a weighting factor to reduce the interpolation error.

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 values of a primary color are concentrated to a point for a linear transformation, an appropriate black-level emission measurement can improve the characterization accuracy. 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,[14] which is formed based on the variance of each chromaticity value. Figure 5 presents the chromaticity values for each

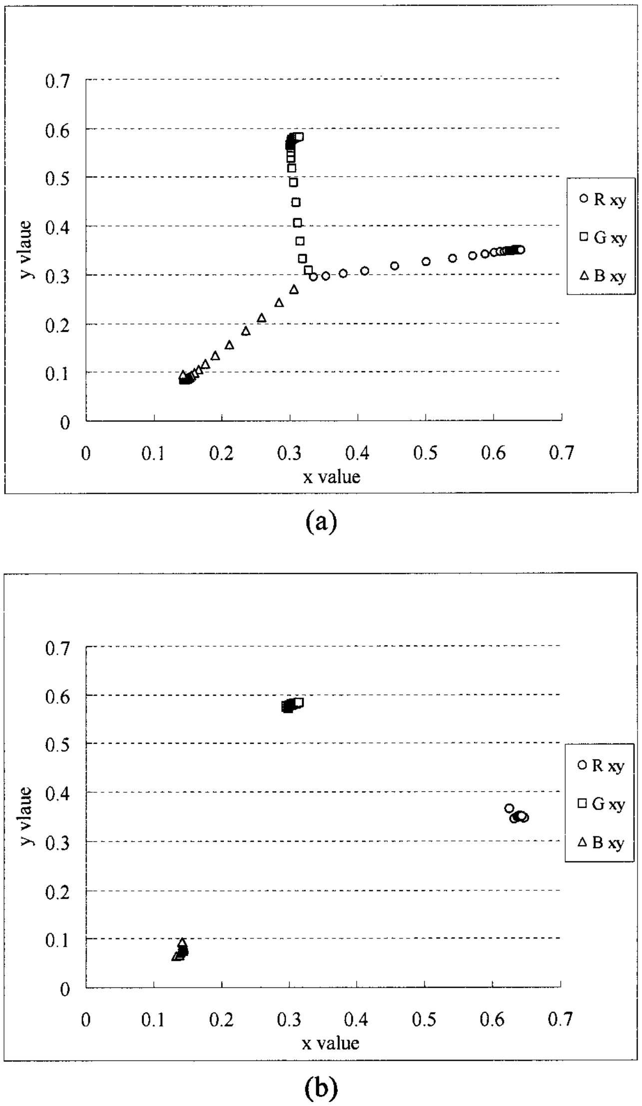

Figure 5. Estimating black level tri-stimulus values: (a) Chromaticity values for each *RGB* channel varying in digital value between 0 and 255 and (b) chromaticity values for each *RGB* channel varying in digital values after subtraction of estimated black-level emission.

RGB channel, where Fig. 5(a) shows the chromaticity values for each *RGB* channel varying in digital value between 0 and 255 and Fig. 5(b) shows the chromaticity values for each *RGB* channel after subtracting the estimated black-level emission.

INVERSE MATRIX OF TRI-STIMULUS VALUES

The inverse matrix is determined based on the forward characterization matrix and composed of the maximum CIE*XYZ* values

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

MODELING OF CHANNEL-DEPENDENT VALUES

The GOG characterization method assumes that each channel only generates one kind of scalar.[1,2] In other words, the measurement data for the red channel should only generate R values and it is assumed that G and B are not generated. This assumption is based on channel independence. Therefore, the assumption can be investigated by calculating all the scalars produced by each *RGB* channel. Figure 6 shows the resulting channel-dependent values according to each primary channel, where the ordinate axis presents the normalized luminance values from 0 to 1, while the horizontal axis presents the input digital values from 0 to 255. The green and blue channels exhibited larger changes rather than the red channel, indicating that these values should be considered in the characterization process to improve the modeling performance.[3] All the channel-dependent values for the primary *RGB* are estimated using a second-order polynomial. For example, the non-zero values for the G and B channels corresponding to R_{primary} are computed as follows:

$$R_{G,\mathrm{error}} = a_{r,g}(R_{\mathrm{primary}})^2 - a_{r,g}(R_{\mathrm{primary}}),$$

$$R_{B,\mathrm{error}} = a_{r,b}(R_{\mathrm{primary}})^2 - a_{r,b}(R_{\mathrm{primary}}), \tag{8}$$

where $R_{G,\mathrm{error}}$ and $R_{B,\mathrm{error}}$ are the green and blue channel-dependent values for the primary R channel and a is the

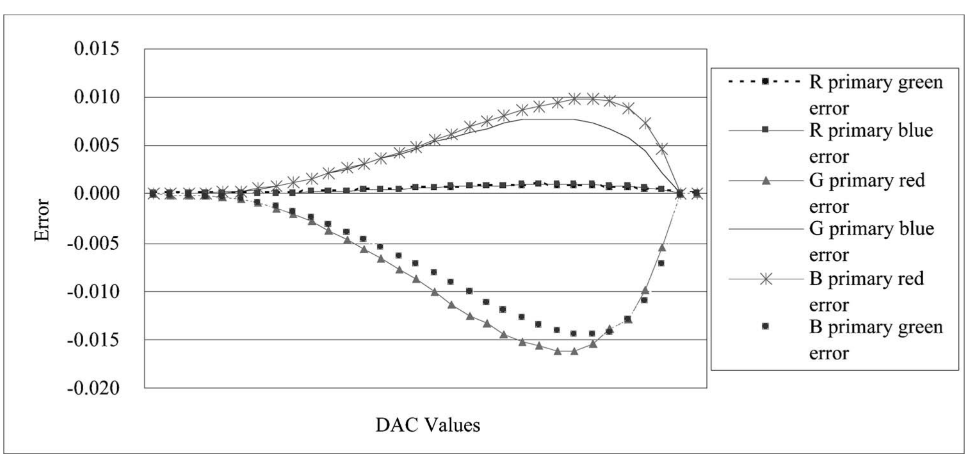

Figure 6. Channel dependent values for each *RGB* primary channel.

modeling parameter for the channel-dependent values based on an optimization method. The channel-dependent values for the G and B channels are also estimated using the same equation [Eq. (8)]. Accordingly, the initially normalized luminance values for each RGB channel are denoted by

$$R = R_{\text{primary}} - R_{G,\text{error}} - R_{B,\text{error}},$$

$$G = G_{\text{primary}} - G_{R,\text{error}} - G_{B,\text{error}},$$

$$B = B_{\text{primary}} - B_{G,\text{error}} - B_{R,\text{error}}. \quad (9)$$

COMPENSATION FOR THE NINE CHANNEL TRCs

After subtracting the channel-dependent values, the initially normalized luminance values (R,G,B) have to be separated into the nine channel TRCs. In this case, the input R,G,B values cannot be directly inverted to acquire the $R_X,G_X,B_X,R_Y,G_Y,B_Y,R_Z,G_Z,B_Z$ values. Thus, the proposed method uses additional TRCs based on d_r,d_g,d_b, along with the initially normalized luminance values. The additional TRCs are estimated by

$$\begin{aligned} R &= \{d_r(2^N-1)\}^{\gamma_{r_T}}, && \text{if } \{d_r(2^N-1)\} \geqslant 0 \\ &= 0, && \textit{otherwise} \end{aligned}, \quad (10)$$

$$\begin{aligned} G &= \{d_g(2^N-1)\}^{\gamma_{g_T}}, && \text{if } \{d_g(2^N-1)\} \geqslant 0 \\ &= 0, && \textit{otherwise} \end{aligned}, \quad (11)$$

$$\begin{aligned} B &= \{d_b(2^N-1)\}^{\gamma_{b_T}}, && \text{if } \{d_b(2^N-1)\} \geqslant 0 \\ &= 0, && \textit{otherwise} \end{aligned}, \quad (12)$$

where $\gamma_{j_T}(j=r,g,b)$ are the gamma values for the R,G,B channels. To reduce the complexity, only the gamma values are used to estimate the TRCs.

As the shape of the estimated additional TRCs is different from that of the nine channel TRCs, the additional TRCs have to be modified according to the nine channel TRCs, which were pre-determined in the forward display characterization. Figure 7 shows a graphical representation of the TRC modification in the case of the R channel. The same method is also applied to the G and B channels. If it is assumed that the gain and offset values are the same between (R and R_X,R_Y,R_Z), (G and G_X,G_Y,G_Z), and (B and B_X,B_Y,B_Z), each of the nine channel values can be determined by linearization of the TRCs using only the gamma values:

$$R_i = R^{\frac{\gamma_i}{\gamma_T}}, \quad (13)$$

$$G_i = G^{\frac{\gamma_i}{\gamma_T}}, \quad (14)$$

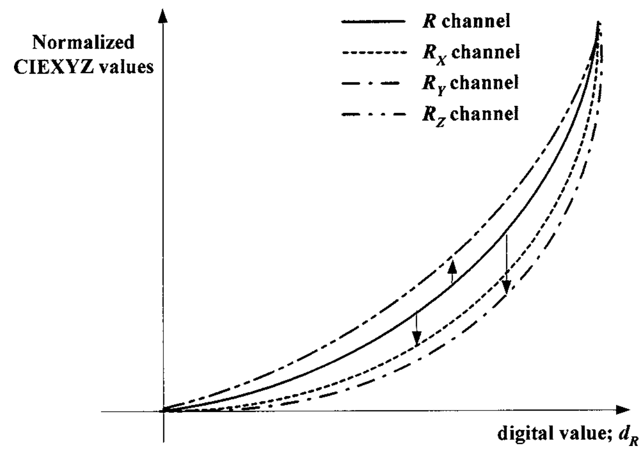

Figure 7. Graphical representation of TRC modification in case of R channel.

$$B_i = B^{\frac{\gamma_i}{\gamma_T}}, \quad (15)$$

where i is X,Y,Z. As the gain and offset values are small, using the same gain and offset values for each of the nine channel TRCs does not affect the compensation of the TRCs. Therefore, the input R,G,B values are changed to each of the nine channel TRCs. Estimating only the additional TRCs, specifically the gamma values, means that the $R_X,G_X,B_X,R_Y,G_Y,B_Y,R_Z,G_Z,B_Z$ values can be deduced from the R,G,B values, because the nine channel TRCs have already been estimated in the forward display characterization process.

INVERSE GOG MODEL

The nine channel digital RGB values are determined using the inverse GOG model, which corresponds to the TRCs of the display. The estimated display luminance levels have nine parameter sets as a result of the forward characterization method and these values are applied to the inverse GOG model to acquire the digital RGB values.

$$d_{ri} = [(2^n-1)/k_{g,ri}](R_i^{\frac{1}{\gamma_{ri}}} - k_{o,ri}), \quad \textit{if } 0 \leqslant R_i \leqslant 1, \quad (16)$$

$$d_{gi} = [(2^n-1)/k_{g,gi}](G_i^{\frac{1}{\gamma_{gi}}} - k_{o,gi}), \quad \textit{if } 0 \leqslant G_i \leqslant 1, \quad (17)$$

$$d_{bi} = [(2^n-1)/k_{g,bi}](B_i^{\frac{1}{\gamma_{bi}}} - k_{o,bi}), \quad \textit{if } 0 \leqslant B_i \leqslant 1. \quad (18)$$

The inverse GOG model is the reverse process of the forward GOG model, so the same gain, offset, and gamma values are used, as estimated using Eqs. (1)–(3) in the forward display characterization process.

DETERMINING d_r, d_g, d_b VALUES BY WEIGHTING FACTOR

The three DAC values (d_r, d_g, d_b) are determined using the ratio of the maximum CIE*XYZ* values for the red, green, and blue channels. A large maximum CIE*XYZ* value is insensitive to errors, while a small value is sensitive. The spectrum for the red channel is highly correlated to the X values, the green channel is correlated to the Y values, and the blue channel is correlated to the Z values. Thus, the X value is used to deduce the d_r value, the Y value to deduce the d_g value, and the Z value to deduce the d_b value. Therefore, the ratio of the maximum CIEXYZ values is used as a weighting factor, defined by

$$\omega_{i_r} = \frac{i_{r,\max}}{X_{r,\max} + Y_{r,\max} + Z_{r,\max}}, \tag{19}$$

$$\omega_{i_g} = \frac{i_{g,\max}}{X_{g,\max} + Y_{g,\max} + Z_{g,\max}}, \tag{20}$$

$$\omega_{i_b} = \frac{i_{b,\max}}{X_{b,\max} + Y_{b,\max} + Z_{b,\max}}, \tag{21}$$

where $\omega_{i_r}, \omega_{i_g}, \omega_{i_b}$ $(i = X, Y, Z)$ are the weighting factors for each *RGB* channel. Then, to reduce the interpolation error, the final three digital values for each *RGB* channel are as follows:

$$d_r = \sum d_{ri} \times \omega_{i_r}, \tag{22}$$

$$d_g = \sum d_{gi} \times \omega_{i_g}, \tag{23}$$

$$d_b = \sum d_{bi} \times \omega_{i_b}, \tag{24}$$

where d_{ji} $(j = r, g, b$ and $i = X, Y, Z)$ are the estimated digital values for the nine channel TRCs.

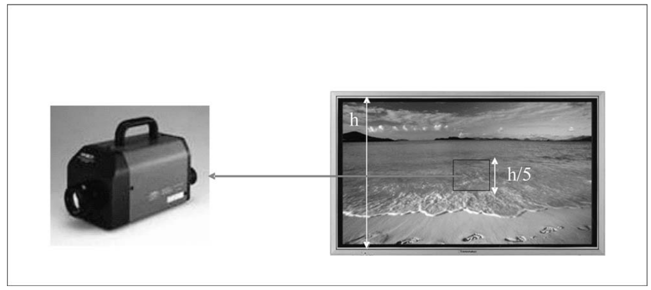

Figure 8. Measurement environment for display characterization.

EXPERIMENTAL RESULTS

The measurements were all performed using a central uniform square patch[10] as the DVI signal values in a dark room. Figure 8 shows the measurement environment for the display characterization. All 32 patches were created with equally-spaced digital *R*, *G*, and *B* values. The target display device was a SAMSUNG SyncMaster Magic CX171T LCD and the measurement instrument to acquire the CIE*XYZ* values was a Minolta CS-1000 spectro-radiometer. To evaluate the characterization result effectively, 216 sample patches were used. Figure 9 shows a block diagram comparing the inverse characterization results based on the CIELAB color difference. The input CIE*XYZ* values were inverted into digital RGB values using a polynomial regression, the 3D LUT method based on a tetrahedral interpolation, the three-channel inverse GOG model, and the proposed inverse alternate GOG model. The values were then reconverted into CIE*XYZ* values using the 3D LUT method, which has the lowest color difference among the forward display characterization methods. The inverse S-curve model was not simulated in this study, as its results for the forward display characterization of an LCD are nearly the same as those with the GOG model, plus the S-curve model cannot be directly inverted.[3] Table II shows the results of the inverse characterization based on the CIELAB color difference. The average

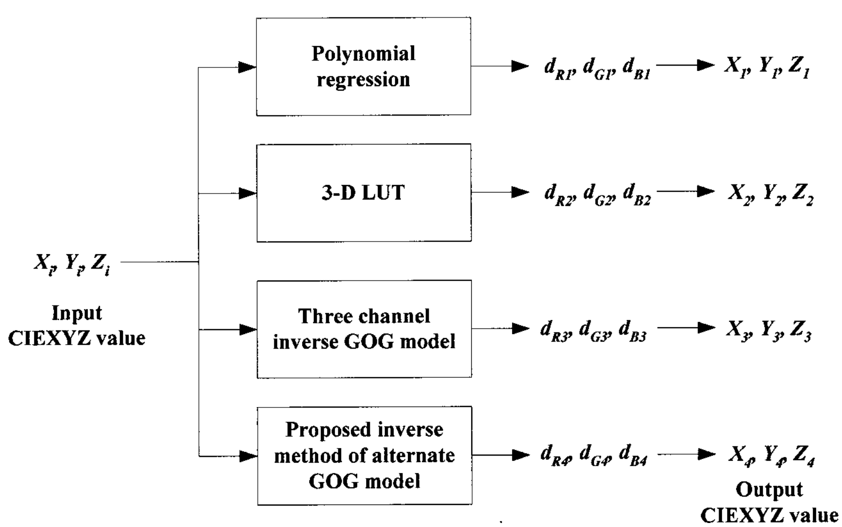

Figure 9. Block diagram comparing inverse characterization result.

Table II. Result of inverse characterization methods for LCD monitor.

Polynomial Regression (3×21 matrix)		3D LUT		Three channel GOG model		Proposed inverse method of alternate GOG model	
E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}
4.91	15.92	1.01	3.19	6.92	15.27	3.24	8.73

Table III. Result of color difference according to number of sampling data with 3D LUT method.

27 sampling data (3×3×3 *RGB* cube)		64 sampling data (4×4×4 *RGB* cube)		125 sampling data (5×5×5 *RGB* cube)		216 sampling data (6×6×6 *RGB* cube)	
E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}
8.91	13.49	5.83	9.09	4.15	7.17	1.01	3.19

Table IV. Result of color difference according to number of sampling data with proposed inverse method of alternate GOG model.

24 sampling data (8 data for each of RGB channel)		48 sampling data (16 data for each of RGB channel)		96 sampling data (32 data for each of RGB channel)	
E_{avg}	E_{max}	E_{avg}	E_{max}	E_{avg}	E_{max}
4.38	10.53	3.56	9.86	3.24	8.73

color difference for the proposed inverse characterization method was hardly perceptible and the maximum error was lower than with any other method, except for the 3D LUT method. Nonetheless, even though the 3D LUT method produced the smallest color difference, this method requires a lot of measurement data and is highly complex, in contrast to the characterization models that use relatively few data measurements. Table III shows the color difference with the 3D LUT method according to number of sampling data used, while Table IV shows the color difference when using the proposed inverse alternate GOG model according to the number of sampling data used. The average color difference with the proposed inverse method when using 48 sampling data (16 data for each *RGB* channel) was smaller than that with the 3D LUT method when using 125 sampling data. Furthermore, the 3D LUT method required about 125 sampling data to produce an appropriate result, yet the proposed inverse method only needed about 24 sampling data to deduce a similar result. While the proposed inverse characterization method can be constructed using only 1D LUT for each channel, the 3D LUT method based on a tetrahedral interpolation increases the complexity, which consists of finding the nearest tetrahedron from the input data and interpolating it based on the tetrahedron points.[9] Therefore, the proposed inverse characterization method of the alternate GOG model does not need additional measurement data, in contrast to the three-channel GOG model, and enhances the accuracy of the display characterization.

CONCLUSION

An inverse characterization method was proposed using the alternate GOG model based on estimating channel-dependent values and additional TRCs. Channel-dependent values for the primary *RGB* are estimated and optimized using a second-order polynomial function. Additional TRCs for the initially normalized luminance values are then used to separate the initially normalized luminance values into nine channel TRCs. Thereafter, the nine channel digital RGB values are estimated using the inverse GOG model based on the pre-determined parameters from the forward characterization process. In addition, to reduce the interpolation error, the ratio of the maximum CIE*XYZ* values is applied as a weighting factor to determine the digital *RGB* values. In experiments, the average and maximum color differences when using the proposed inverse characterization method were smaller than those with the three-channel inverse GOG model and polynomial regression method. While the 3D LUT method needs a lot of measurement data for accuracy, the proposed inverse characterization method requires less measurement data, making it simpler than the 3D-LUT method as regards the measurement process and complexity.

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