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Characterization of Error Reduction in Mobile Liquid Crystal Display Using Distinct *XYZ* Electro-Optical Transfer Functions for Each Channel and Interchannel Components

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Abstract. *Most display characterization methods, such as the gain-offset-gamma model and S-curve model, generally assume that displays have two fundamental characteristics, channel-chromaticity constancy and channel independence. Consequently, based on the assumption of channel-chromaticity constancy, only one electro-optical transfer function (EOTF) is used for each channel to establish the relation between the digital input values and the output luminance levels. Meanwhile, based on the channel-independence assumption, the channel color values are simply summed to acquire mixed color values. However, these assumptions are not so applicable in the case of liquid crystal-based mobile displays. Accordingly, modifications are required to enable the application of conventional display characterization methods to mobile displays. Therefore, this study proposes the modeling of distinct EOTFs in terms of the X, Y, and Z values for each channel to consider the differences among the EOTFs resulting from channel-chromaticity inconstancy. In addition, to overcome the poor additivity property among the channels due to channel interaction, the proposed method also models and uses the EOTFs of the X, Y, and Z values for the interchannel components cyan, magenta, yellow, and gray. Experimental results confirm that the mobile display color values predicted by the proposed characterization method are more accurate than those predicted by other characterization methods due to considering the channel-chromaticity inconstancy and/or channel dependence of the display.* **©** *2006 Society for Imaging Science and Technology.*
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INTRODUCTION

The recent growth in display device technologies has been remarkable, including the commercial application of cathode ray tubes (CRTs), liquid crystal displays (LCDs), plasma display panels, and organic light emitting diodes. In particular, miniaturized and lighter display devices have been developed for mobile devices, such as cellular phones and PDAs. Yet, when compared with a monitor, mobile displays are unable to display images with a good color fidelity due to their smaller gamut, dimmer luminance, and inferior color reproduction ability related to their low power consumption. Thus, to reproduce accurate colors on mobile display devices, color management systems are required. In such color management systems, it is essential to establish a relationship between the device-dependent digital input values and the device-independent output color values for display devices.

In recent years, several methods of display characterization have been proposed and developed. The gain-offset-gamma (GOG) model[1–3] is a well-known and standardized method for characterizing the exponential electro-optical transfer function (EOTF) of displays like CRTs. This method is a simple yet accurate way of predicting color values for CRTs whose EOTFs for red, green, and blue channels are exponential features. However, for LCDs with S-shaped EOTFs, the GOG model is not suitable due to the shape of the EOTFs. As such, an S-curve model (version I)[4,5] using two gamma parameters as the numerator and denominator to model S-shaped EOTFs of LCDs has been proposed. Essentially, the two methods involve the same two-step procedure: first, linearization between the digital input values and the output luminance levels for the red, green, and blue (RGB) channels under a channel-chromaticity-constancy assumption, and second, linear summation using the output color values of the individual channels under a channel-independence assumption.[6,7] In LCDs, the channel-chromaticity-constancy assumption is not perfect due to the

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dispersion characteristic of liquid crystal (LC) materials. Thus, for better modeling, in the S-curve model (version II),[4,5] derivatives of the EOTFs have been used to model the chromaticity changes of the LCD channels. However, such EOTF derivatives do not fit well as regards the chromaticity changes for each channel. Therefore, another approach to the weak channel-chromaticity-constancy characteristic in LCDs is a model with nine independent EOTFs in the linearization step.[6] However, none of these models consider the poor channel-independence condition in LCDs. Consequently, to approximate the color variation caused by channel interaction, the masking model[8,9] uses cyan, magenta, yellow, and gray as well as the RGB primary colors. In addition, to minimize the error caused by a variation in the channel chromaticity, the CIEXYZ vectors are obtained using their first principal component vector. Yet, there is a limit to representing three-dimensional CIEXYZ vectors using only one principal component vector. Plus, the use of all three principal component vectors is inefficient when compared to the direct use of CIEXYZ vectors.

Accordingly, to consider the weak channel-chromaticity-constancy characteristic, this paper proposes the direct modeling of three distinct EOTFs for the X, Y, and Z values of each channel in contrast to the S-curve model, which use derivatives of the EOTFs, and the masking model, which only uses one principal component of the CIEXYZ vectors. In addition, for the weak channel-independence characteristic resulting from crosstalk between channels,[10,11] the proposed method models and uses three EOTFs for both the red, green, and blue channels and the interchannel components cyan, magenta, yellow, and gray, similar to the masking model. Experimental results demonstrate that the proposed method yields a better performance as regards predicting the color values on a LC-based mobile display compared to other conventional methods.

CHANNEL-CHROMATICITY CONSTANCY

One of the important assumptions that allows the possibility of display characterization using the GOG model or S-curve model is the chromaticity constancy of the channels.[6,7] Based on this assumption, it is stated that the spectral radiances for a channel have the same basic shape, and can be represented by a function of the digital input value and wavelength as follows:

$$S_r(d_r,\lambda) = R(d_r)S_{r,\max}(\lambda), \quad (1)$$

$$S_g(d_g,\lambda) = G(d_g)S_{g,\max}(\lambda), \quad (2)$$

$$S_b(d_b,\lambda) = B(d_b)S_{b,\max}(\lambda), \quad (3)$$

where $S_{p,\max}(\lambda)$, $p=r$, g, and b, is the spectral radiance at the maximum digital input value for the red, green, and blue channels and $P(d_p)$, $P=R$, G, and B, is the scalar to scale basic spectral radiance for each channel that can be represented by the function of the digital input value d_p and referred to as the EOTF.

Also, the channel-chromaticity-constancy assumption can be represented in terms of the CIEXYZ tristimulus values resulting from the integration of the spectral radiance, which is weighted by the spectra of the color matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$, as follows:

$$I_r(d_r) = R(d_r)I_{r,\max}, \quad (4)$$

$$I_g(d_g) = G(d_g)I_{g,\max}, \quad (5)$$

$$I_b(d_b) = B(d_b)I_{b,\max}, \quad (6)$$

where $I_p(d_p)$, $I=X$, Y, and Z, and $p=r$, g, and b, represent one of the CIEXYZ values at an arbitrary digital input value d_p and $I_{p,\max}$ means the CIEXYZ values at the maximum digital input value for the red, green, and blue channels, respectively.

However, as shown in Fig. 1, the measured electro-optical transfer characteristics of the X, Y, and Z values for a LC-based mobile display differ from each other for the red, green, and blue channels. If the channel chromaticity is perfectly constant, the measured electro-optical transfer characteristics of the X, Y, and Z values should be identical for each channel, according to Eqs. (4), (5), and (6). As such, Fig. 1 shows that the characteristic of a LC-based mobile display as regards the channel chromaticity constancy is poor.

CHANNEL INDEPENDENCE

The other important assumption that needs to be guaranteed in display characterization models that use the respective EOTFs for each channel is the channel independence.[6,7] Under this assumption, the display characterization can be simply performed by modeling the EOTF for the red, green, and blue channels individually and summing them. The mathematical expression for the channel independence can be expressed as

$$S_{rgb}(d_r,d_g,d_b,\lambda) = S_r(d_r,\lambda) + S_g(d_g,\lambda) + S_b(d_b,\lambda), \quad (7)$$

where $S_{rgb}(d_r,d_g,d_b,\lambda)$ is the output spectral radiance of the display for the digital input values d_r, d_g, and d_b and $S_r(d_r,\lambda)$, $S_g(d_g,\lambda)$, and $S_b(d_b,\lambda)$ are the spectral radiance for the red, green, and blue channel, respectively. The expression of the channel independence relative to the CIEXYZ values can be written as

$$I_{rgb}(d_r,d_g,d_b) = I_r(d_r) + I_g(d_g) + I_b(d_b), \quad (8)$$

where $I_{rgb}(d_r,d_g,d_b)$, $I=X$, Y, and Z, represent one of the CIEXYZ values for the digital input values d_r, d_g, and d_b, while $I_r(d_r)$, $I_g(d_g)$, and $I_b(d_b)$ are the CIEXYZ values for the red, green, and blue channel, respectively. Namely, $I_r(d_r)$, $I_g(d_g)$, and $I_b(d_b)$ mean $I_{rgb}(d_r,0,0)$, $I_{rgb}(0,d_g,0)$, and $I_{rgb}(0,0,d_b)$, respectively.

However, the channel independence property is not ideal for a LC-based mobile display, as shown Table I, which presents the average and maximum color differences of the X, Y, Z, and CIELAB values between measured colors for

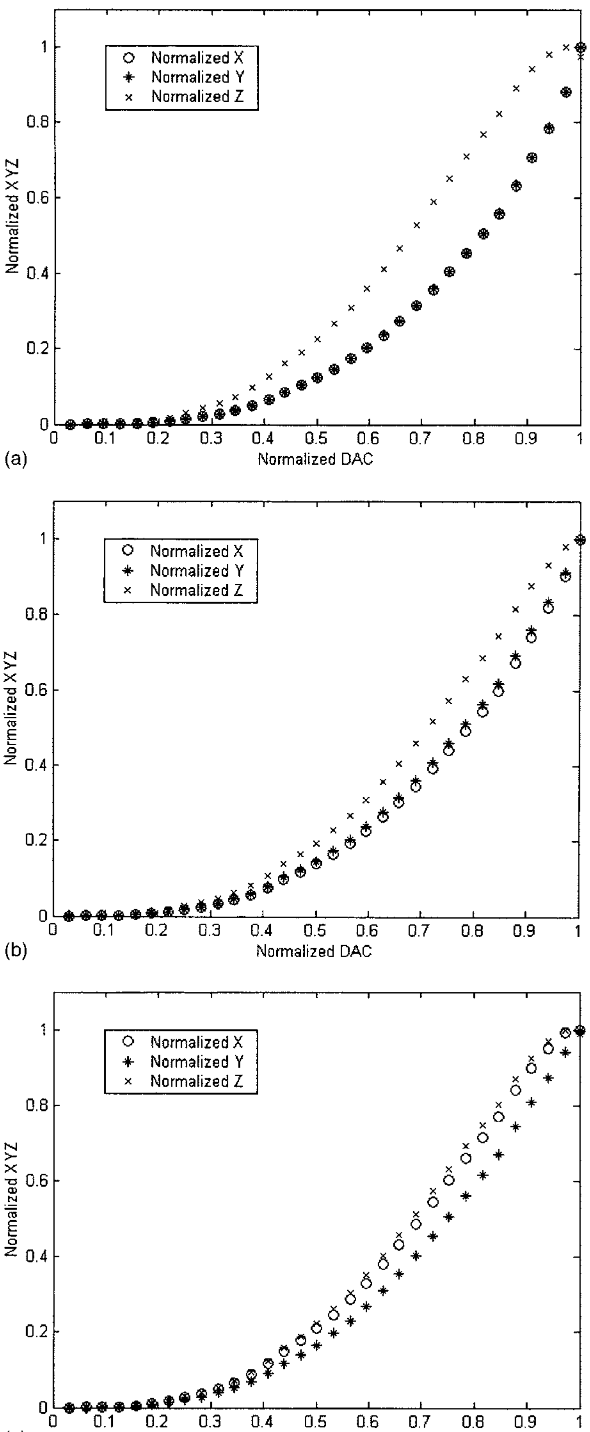

Figure 1. Electro-optical transfer characteristics of *X*, *Y*, and *Z* values for red, green, and blue channel in mobile LCD: (a) electro-optical transfer characteristics for red channel, (b) electro-optical transfer characteristics for green channel, and (c) electro-optical transfer characteristics for blue channel.

200 patches mixed using at least two pure colors and the sum of the measured pure colors for the corresponding patches of each channel. All the colors were chosen from among 216 ($6\times6\times6$) colors equally spaced in a RGB cube. All the measured color values in Table I represent values

Table I. Color differences between mixed colors and sum of pure colors.

200 ($6\times6\times6-16$) patches	Between $I_{rgb}(d_r,d_g,d_b)$ and $I_r(d_r)+I_g(d_g)+I_b(d_b)$			
	$\lvert\Delta X\rvert$	$\lvert\Delta Y\rvert$	$\lvert\Delta Z\rvert$	ΔE_{ab}
Average	2.81	3.07	2.80	3.29
Maximum	9.99	11.33	10.62	7.81

where black level values have already been subtracted from the measured original values. Note that the average ΔE_{ab} color difference was higher than 3 and the maximum ΔE_{ab} color difference was beyond 7.

S-CURVE MODEL

The GOG model[1–3] is a well-known method that models the exponential EOTF of displays like CRTs, while the S-curve model[4,5] models the S-shaped EOTF of displays like LCDs used for most mobile displays. Like the GOG model, the S-curve model consists of two steps: establishing a parametric mathematical model for the nonlinear relationship between the digital input values and the display luminance levels for the red, green, and blue channel, respectively, and a linear transformation from display luminance levels to CIEXYZ values using a 3×3 matrix whose elements are the CIEXYZ values at the maximum digital input value for the red, green, and blue channel, respectively. The shapes of the nonlinear relationship curves with the S-curve model differ from those with the GOG model as follows:

$$R(d_r)=A_r\frac{[d_r/(2^N-1)]^{\alpha_r}}{[d_r/(2^N-1)]^{\beta_r}+E_r},\tag{9}$$

$$G(d_g)=A_g\frac{[d_g/(2^N-1)]^{\alpha_g}}{[d_g/(2^N-1)]^{\beta_g}+E_g},\tag{10}$$

$$B(d_b)=A_b\frac{[d_b/(2^N-1)]^{\alpha_b}}{[d_b/(2^N-1)]^{\beta_b}+E_b},\tag{11}$$

where d_r, d_g, and d_b are the digital input values for the red, green, and blue channel, respectively, and N is the bit number. Namely, 2^N-1 becomes the maximum digital input value and is used to normalize the other digital input values. $R(d_r)$, $G(d_g)$, and $B(d_b)$ are the normalized display luminance levels corresponding to certain digital input values d_r, d_g, and d_b for the red, green, and blue channel, respectively, and A_p, α_p, β_p, and E_p, $p=r$, g, and b, are the model parameters to be calculated. To estimate the optimal parameters A_p, α_p, β_p, and E_p, 32 patches are created with equally spaced digital input values for each channel, then the CIEXYZ values are measured and the X values for the red channel, the Y values for the green channel, and the Z values for the blue channel used to define the normalized display luminance levels as follows:

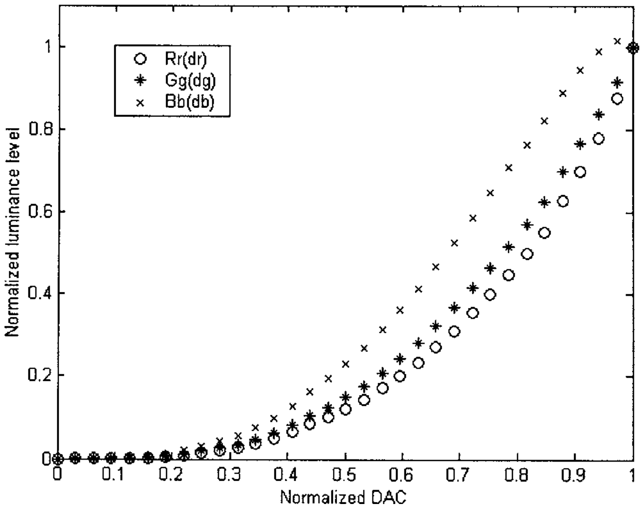

Figure 2. Electro-optical transfer characteristics between normalized digital input values and normalized output luminance levels for red, green, and blue channels.

$$R(d_r) = X_r/X_{r,\max}, \tag{12}$$

$$G(d_g) = Y_g/Y_{g,\max}, \tag{13}$$

$$B(d_b) = Z_b/Z_{b,\max}. \tag{14}$$

Thereafter, the normalized display luminance levels and corresponding digital input values are used, while an optimization process is applied to calculate the optimal parameters A_p, α_p, β_p, and E_p.

After modeling the EOTFs, normalized display luminance levels corresponding to arbitrary digital input values for each channel can be estimated using the modeled functions with the optimal parameters. Finally, the estimated $R(d_r)$, $G(d_g)$, and $B(d_b)$, which correspond to arbitrary d_r, d_g, and d_b, respectively, are used to estimate the CIEXYZ values as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix}, \tag{15}$$

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

Moreover, to account for the unstable chromaticity of a channel, the S-curve model is updated by dividing the display luminance levels for each channel into self-channel components, as shown Fig. 2, and other channel components, as shown Fig. 3, using the following equation:

$$\begin{bmatrix} R_p(d_p) \\ G_p(d_p) \\ B_p(d_p) \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix}^{-1} \begin{bmatrix} X_p(d_p) \\ Y_p(d_p) \\ Z_p(d_p) \end{bmatrix}, \tag{16}$$

where $X_p(d_p)$, $Y_p(d_p)$, and $Z_p(d_p)$, $p=r, g$, and b, are the measured CIEXYZ values at an digital input value d_p for the red, green, and blue channel individually, $R_r(d_r)$, $G_g(d_g)$, and $B_b(d_b)$ mean the self-channel luminance level components of the red, green, and blue channel, respectively, and $G_r(d_r)$ and $B_r(d_r)$, $R_g(d_g)$ and $B_g(d_g)$, and $R_b(d_b)$ and $G_b(d_b)$ mean the

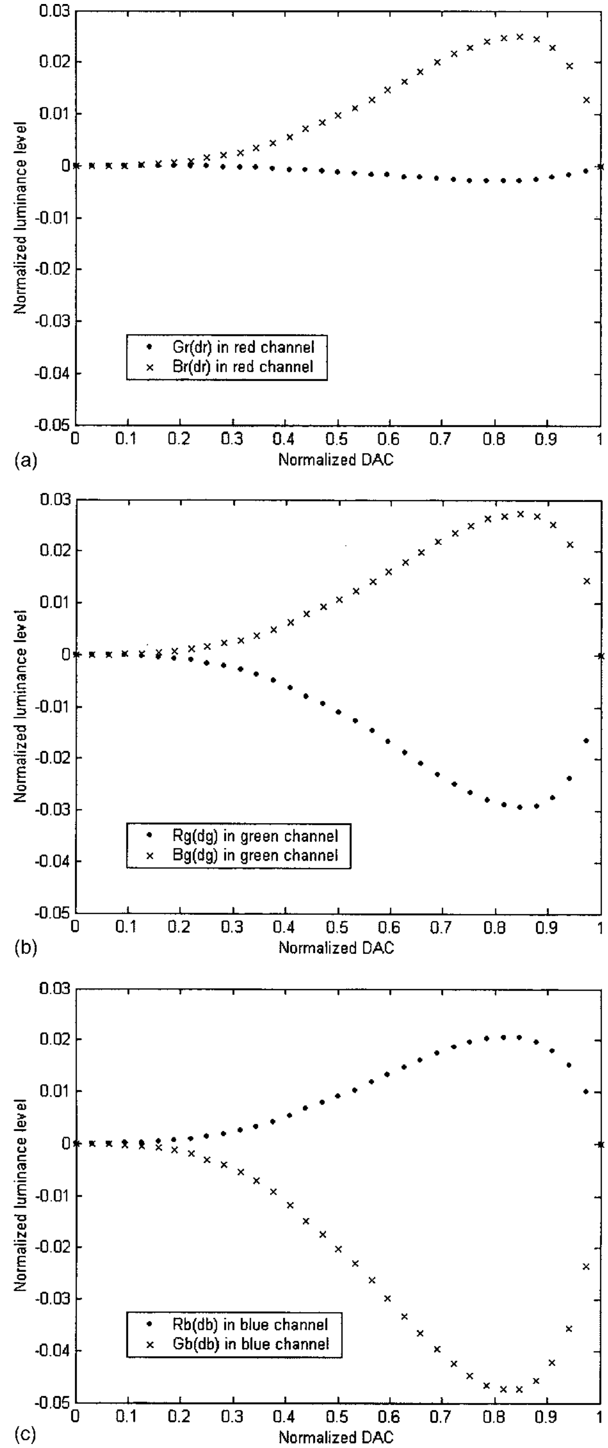

Figure 3. Chromaticity fluctuations of channel colors: (a) representation of chromaticity fluctuation of red channel colors with normalized luminance level components of green and blue channels, (b) representation of chromaticity fluctuation of green channel colors with normalized luminance level components of red and blue channels, and (c) representation of chromaticity fluctuation of blue channel colors with normalized luminance level components of red and green channels.

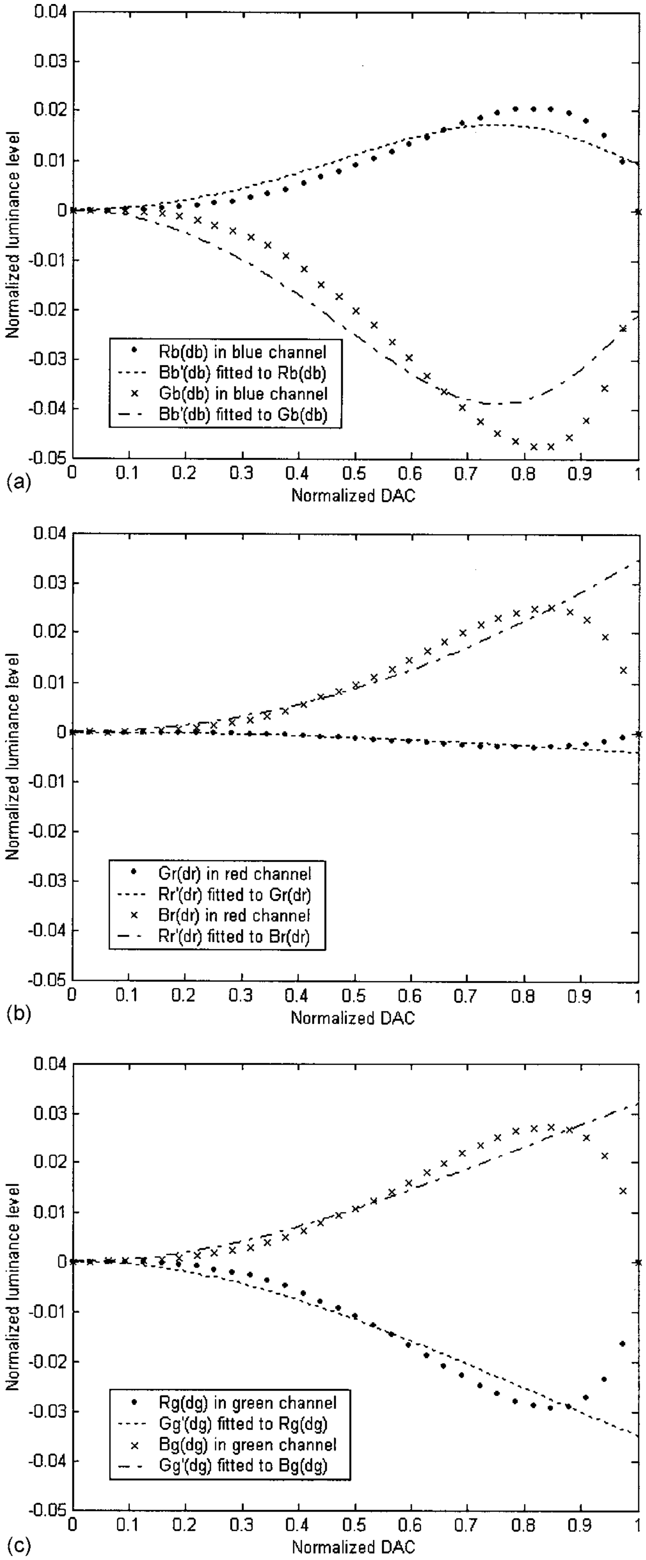

Figure 4. Modeling luminance level components of other channels using derivative of EOTF of self-channel for each channel: (a) red channel, (b) green channel, and (c) blue channel.

other channel luminance level components of the red, green, and blue channel, respectively. Then, to model the EOTFs, the S-curve model uses Eqs. (9)–(11) for the self-channel luminance level components and the derivative of those equations for the otherchannel luminance level components in each channel. Finally, to obtain the EOTFs considering an unstable chromaticity for each channel, the EOTF from the self-channel and those from the other channels for each channel are summed as follows:

$$R(d_r) = R_r(d_r) + R_g(d_g) + R_b(d_b), \tag{17}$$

$$G(d_g) = G_r(d_r) + G_g(d_g) + G_b(d_b), \tag{18}$$

$$B(d_b) = B_r(d_r) + B_g(d_g) + B_b(d_b). \tag{19}$$

MASKING MODEL

To approximate the color variation caused by channel interaction, the masking model[8,9] also uses the colors cyan, magenta, yellow, and gray, as well as the primary colors red, green, and blue. The CIEXYZ values of the arbitrary digital input value are then calculated using the red, green, blue, cyan, magenta, yellow, and gray characteristics. The same amount of red, green, and blue is replaced with gray according to the digital input value, which is equal to the smallest digital input value among the red, green, and blue colors. Similarly, the remaining colors are also replaced with the primary or secondary colors. Let $\mathbf{I}(d_r,d_g,d_b)$ be the three-dimensional CIEXYZ vector that corresponds to the digital input values (d_r,d_g,d_b). Then, the CIEXYZ vector for the arbitrary digital input values (d_r,d_g,d_b) can be approximated as follows:

$$\mathbf{I}(d_r,d_g,d_b) = \mathbf{I}(d_b,d_b,d_b) + [\mathbf{I}(d_g,d_g,0) - \mathbf{I}(d_b,d_b,0)] + [\mathbf{I}(d_r,0,0) - \mathbf{I}(d_g,0,0)], \quad d_b < d_g < d_r. \tag{20}$$

Equation (20) is a more accurate approximation in comparison with the method that only uses $\mathbf{I}(d_r,0,0)$, $\mathbf{I}(0,d_g,0)$, and $\mathbf{I}(0,0,d_b)$, since the channel interaction is considered by introducing $\mathbf{I}(d_k,d_k,d_k)$ and $\mathbf{I}(d_y,d_y,0)$.

Also, to minimize the error caused by a variation in the channel chromaticity, the masking model applies a principal component analysis to the measured CIEXYZ vectors of each channel. As a result, the measured CIEXYZ vectors are represented by a single vector with a minimum error as follows:

$$\mathbf{I}_i(d_i) = C_i(d_i)\begin{bmatrix} X_{i,PCA} \\ Y_{i,PCA} \\ Z_{i,PCA} \end{bmatrix}, \tag{21}$$

where i denotes r, g, b, c, m, y, and k, respectively, and $[X_{i,PCA}, Y_{i,PCA}, Z_{i,PCA}]^T$ means the first principal component of the measured data that was normalized as the unit length. $C_i(d_i)$ for the digital input value d_i can then be calculated as follows:

Table II. Color differences between mixed colors and mixture of pure colors and interchannel colors.

200 ($6 \times 6 \times 6-16$) patches	Between $I_{rgb}(d_r, d_g, d_b)$ and $I_p(d_1)-I_p(d_2)+I_s(d_2)-I_s(d_3)+I_k(d_3)$			
	$\|\Delta X\|$	$\|\Delta Y\|$	$\|\Delta Z\|$	ΔE_{ab}
Average	0.98	1.16	1.36	1.84
Maximum	3.62	4.83	8.11	5.33

$$C_i(d_i) = \mathbf{I}_i(d_i)^T \begin{bmatrix} X_{i,PCA} \\ Y_{i,PCA} \\ Z_{i,PCA} \end{bmatrix}. \tag{22}$$

Plus, $C_i(d_i)$ for an arbitrary digital input value is calculated by interpolating the calculated $C_i(d_i)$ using Eq. (22).

PROPOSED CHARACTERIZATION METHOD FOR MOBILE LCD

The S-curve model attempts to consider the unstable channel chromaticity by dividing the luminance levels for each channel into those of the self-channel and other channels, and modeling the luminance level components of the other channels using the derivative of the EOTF of the self-channel for each channel. However, as shown Fig. 4, the derivative of the EOTF of the self-channel does not fit well with the luminance level components of the other channels for each channel. Moreover, the S-curve model assumes the channel-independence of displays and does not consider the violation of additivity, resulting from the crosstalk effect[10,11] among channels, in LCDs. Meanwhile, to consider the violation of additivity, the masking model uses cyan, magenta, yellow, and gray, as well as the RGB primary colors. Plus, to consider the inconstancy of the channel chromaticity in displays, the masking model calculates the CIEXYZ vectors using a single principal component vector extracted from measured CIEXYZ values for each color. However, approximating the three-dimensional CIEXYZ vectors into a single vector can produce a large characterization error if the linearity among the CIEXYZ vectors is weak. Also, if all three principal component vectors are used, there is no reason to use the comparatively complex principal component analysis algorithm to calculate the exact CIEXYZ vector. Rather, it is more effective to use the CIEXYZ vector directly. Therefore, a method is proposed for directly modeling the distinct EOTFs of the X, Y, and Z values for each channel and interchannel components for mobile LCDs.

In the proposed characterization method, the EOTFs of the X, Y, and Z values, which have different shapes from each other, as shown in Fig. 1, are modeled directly using the same parametric mathematical models as the S-curve model for the red, green, and blue channels as follows:

$$R_I(d_r) = A_{r_I} \frac{[d_r/(2^N-1)]^{\alpha_{r_I}}}{[d_r/(2^N-1)]^{\beta_{rI}} + E_{r_I}}, \tag{23}$$

$$G_I(d_g) = A_{g_I} \frac{[d_g/(2^N-1)]^{\alpha_{g_I}}}{[d_g/(2^N-1)]^{\beta_{g_I}} + E_{g_I}}, \tag{24}$$

Table III. Characterization errors in mobile LCD when using conventional characterization method and proposed method.

Methods	Patches	32 Red	32 Green	32 Blue	Other 216
S-curve model I	ΔE_{avg}	5.059	4.246	8.469	5.986
	ΔE_{max}	9.362	7.183	14.58	14.73
S-curve model II	ΔE_{avg}	1.284	1.176	3.331	4.225
	ΔE_{max}	10.39	5.984	8.612	10.47
9 EOTF Modeling	ΔE_{avg}	0.639	0.607	0.851	3.233
	ΔE_{max}	3.806	2.334	3.018	8.090
Masking model	ΔE_{avg}	3.294	2.523	4.670	6.583
	ΔE_{max}	6.145	4.387	8.725	12.31
Proposed Method	ΔE_{avg}	0.639	0.607	0.851	2.241
	ΔE_{max}	3.806	2.334	3.018	5.483

$$B_I(d_b) = A_{b_I}\frac{[d_b/(2^N-1)]^{\alpha_{b_I}}}{[d_b/(2^N-1)]^{\beta_{b_I}} + E_{b_I}}, \quad (25)$$

where $R_I(d_r)$, $G_I(d_g)$, and $B_I(d_b)$ are the normalized I values, $I=X$, Y, and Z, corresponding to certain digital input values d_r, d_g, and d_b for the red, green, and blue channel, respectively, and A_{p_I}, α_{p_I}, β_{p_I}, and E_{p_I}, $p=r$, g, and b and $I=X$, Y, and Z,are the model parameters to be calculated. To estimate the optimal parameters A_{p_I}, α_{p_I}, β_{p_I}, and E_{p_I}, 32 patches are created with equally spaced digital input values, then the CIEXYZ values for each patch are measured and normalized for each channel. Thereafter, the normalized CIEXYZ values and digital input values for the patches are used, while an optimization process is applied to calculate the optimal parameters A_{p_I}, α_{p_I}, β_{p_I}, and E_{p_I}.

Also, for the interchannel components cyan, magenta, yellow, and gray, the EOTFs of the X, Y, and Z values are modeled to consider the additivity violation between channels, resulting from the channel interactions, as follows:

$$C_I(d_c) = A_{c_I}\frac{[d_c/(2^N-1)]^{\alpha_{c_I}}}{[d_c/(2^N-1)]^{\beta_{c_I}} + E_{c_I}}, \quad (26)$$

$$M_I(d_m) = A_{m_I}\frac{[d_m/(2^N-1)]^{\alpha_{m_I}}}{[d_m/(2^N-1)]^{\beta_{m_I}} + E_{m_I}}, \quad (27)$$

$$Y_I(d_y) = A_{y_I}\frac{[d_y/(2^N-1)]^{\alpha_{y_I}}}{[d_y/(2^N-1)]^{\beta_{y_I}} + E_{y_I}}, \quad (28)$$

$$K_I(d_k) = A_{k_I}\frac{[d_k/(2^N-1)]^{\alpha_{k_I}}}{[d_k/(2^N-1)]^{\beta_{k_I}} + E_{k_I}}, \quad (29)$$

where d_c, d_m, d_y, and d_k represent the digital input values of two or three channels, such as $(0,d_c,d_c)$, $(d_m,0,d_m)$, $(d_y,d_y,0)$, and (d_k,d_k,d_k) and C_I, M_I, Y_I, and K_I are the normalized I values, $I=X$, Y, and Z, for the interchannel components cyan, magenta, yellow and gray, respectively.

After modeling the EOTFs, the normalized CIEXYZ values corresponding to arbitrary digital input values for each channel and interchannel are estimated using the modeled functions with the optimal parameters. Finally, the estimated $R_I(d_r)$, $G_I(d_g)$, $B_I(d_b)$, $C_I(d_c)$, $M_I(d_m)$, $Y_I(d_y)$, and $K_I(d_k)$, $I=X$, Y, and Z, are used to estimate the CIEXYZ values as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathrm{diag}\left(\begin{bmatrix} X_{p,\max} & X_{s,\max} & X_{k,\max} \\ Y_{p,\max} & Y_{s,\max} & Y_{k,\max} \\ Z_{p,\max} & Z_{s,\max} & Z_{k,\max} \end{bmatrix}\begin{bmatrix} P_X(d_1)-P_X(d_2) & P_Y(d_1)-P_Y(d_2) & P_Z(d_1)-P_Z(d_2) \\ S_X(d_2)-S_X(d_3) & S_Y(d_2)-S_Y(d_3) & S_Z(d_2)-S_Z(d_3) \\ K_X(d_3) & K_Y(d_3) & K_Z(d_3) \end{bmatrix}\right),$$

$$P = \begin{cases} R, & d_1 = d_r \\ G, & d_1 = d_g \\ B, & d_1 = d_b \end{cases} \quad \text{and} \quad S = \begin{cases} C, & d_3 = d_r \\ M, & d_3 = d_g, \\ Y, & d_3 = d_b \end{cases} \quad (30)$$

where d_1 represents the largest, d_2 represents the middle, and d_3 represents the smallest digital input value among the d_r, d_g, and d_b values and $I_{p,\max}$, $I_{s,\max}$, and $I_{k,\max}$, $I=X$, Y, and Z, correspond to the maximum CIEXYZ values for the corresponding channel, interchannel, and the gray component, respectively.

However, it should be noted that this characterization method, as shown in Eq. (30), cannot be directly inverted to obtain an inverse model that transforms CIEXYZ values to digital input values. Therefore, for arbitrary CIEXYZ values, the corresponding digital input values should be estimated using an optimization procedure with appropriate initial values or complete three-dimensional look-up table with interpolation.

EXPERIMENTAL RESULTS

The LC-based mobile display used in the experiments was from a Samsung cellular phone, model SCH-S200. A Minolta CS-1000 spectroradiometer was used to measure the CIEXYZ values for the patches on the display. To estimate the EOTFs for each channel and interchannel, 224 red, green, blue, cyan, magenta, yellow, and gray (32×7) patches were used. Also, to evaluate the performance of the characterization methods in predicting arbitral color values, 216 ($6\times6\times6$) patches equally spaced in the RGB cube were used.

Table II shows the average and maximum color differences in terms of the X, Y, and Z values and CIELAB values between the colors measured for the 200 patches, which were mixtures of at least two pure colors, and the sum of the pure colors and interchannel colors measured for the corresponding patches for each channel and interchannel. All the colors were chosen from among the 216 ($6\times6\times6$) patches equally spaced in the RGB cube. Here, all the measured color values in Tables I and II are the result of subtracting the black level values from the originally measured values. When compared with Table I, the average ΔE_{ab} color difference was reduced to below 3 and the maximum ΔE_{ab} color difference reduced to 5.33 in Table II, demonstrating that the use of the interchannel colors as well as the pure colors was efficient in compensating the poor channel-independence characteristic resulting from the crosstalk effects between the channels.

Table III presents the forward characterization errors for the LC-based mobile display when using the conventional characterization models and the proposed characterization method, including the average and maximum color differences in CIELAB color space between the measured and estimated color values for the 32 patches for each channel and 216 ($6\times6\times6$) patches equally sampled from all over RGB color space. Overall, the errors for the proposed characterization method were smaller than those for the conventional methods.

CONCLUSION

The conventional GOG and S-curve models both assume channel-chromaticity constancy and channel independence in displays, thereby allowing the display characterization procedure to be simplified. However, although the performance of the GOG model is excellent for CRTs and has been standardized by ICC, the assumption of channel-chromaticity constancy and channel independence is not as applicable to mobile displays. Namely, in mobile displays, the EOTFs of the X, Y, and Z values differ from each other and the additivity characteristic among the channel color values is inadequate to yield mixed color values based on summing the individual channel color values. Accordingly, this study modeled 21 EOTFs for mobile LCD characterization. To consider the weak channel-chromaticity-constancy characteristic, the distinct EOTFs of the X, Y, and Z values were all modeled for the red, green, blue channels, rather than a single EOTF. Plus, to compensate the poor channel-independence characteristic, the EOTFs of the X, Y, and Z values were also all modeled for the interchannel components cyan, magenta, yellow, and gray, as well as for the three red, green, and blue channels. The experimental results for the mobile display characterization confirmed the effectiveness of the proposed method. However, the considerable complexity of this approach does impose limitations on direct inversion for the inverse characterization of mobile displays.

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