Display Characterization for Mobile LCD Based on Modeling Electro-Optical Transfer Functions for Channels and Inter-Channels

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Abstract

Most display characterization methods 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 (LC)-based 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 inter-channel components cyan, magenta, yellow, and gray. 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.

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 (PDPs), and organic light emitting diodes (OLEDs). 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] is a well-known 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. However, for LCDs with S-shaped EOTFs, the GOG model is not suitable. As such, an S-curve model (version I) [2] 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 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 [3]. However, the channel-chromaticity-constancy assumption is not perfect in LCDs. Thus, in the S-curve model (version II) [2], derivatives of the EOTFs have been used to model the chromaticity-changes of the LCD channels. Yet, such EOTF derivatives do not fit well as regards the chromaticity-changes. Another approach to the weak channel-chromaticity-constancy characteristic in LCDs is a model with 9 independent EOTFs [3]. 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 [4] 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 cross-talk between channels [5], [6], the proposed method models and uses three EOTFs for both the red, green, and blue channels and the inter-channel 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 allow the possibility of display characterization using the GOG model or S-curve model is the chromaticity constancy of the channels [3]. This assumption can be represented in terms of the CIEXYZ tristimulus as follows:

$$I_r(d_r) = R(d_r)I_{r,\max} \tag{1}$$

$$I_g(d_g) = G(d_g)I_{g,\max} \tag{2}$$

$$I_b(d_b) = B(d_b)I_{b,\max} \tag{3}$$

where $I_p(d_p)$, $I = X, Y$, and Z and $p = r, g$, and b, represents 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 Figure 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 equations (1), (2), and (3). As such, Figure 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 [3]. 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 expression of the channel independence relative to the CIEXYZ values can be written as:

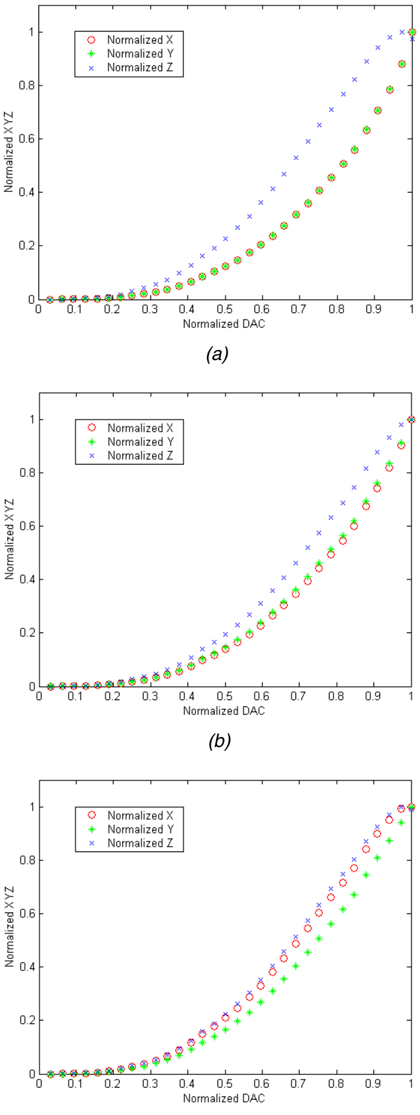
$$I_{rgb}(d_r, d_g, d_b) = I_r(d_r) + I_g(d_g) + I_b(d_b) \tag{4}$$

where $I_{rgb}(d_r, d_g, d_b)$, $I = X, Y$, and Z, represents 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 $I_b(d_b)$ means $I_{rgb}(d_r, 0, 0)$, $I_{rgb}(0, d_g, 0)$, and $I_{rgb}(0, 0, d_b)$, respectively.

However, the channel independence property is not ideal for an LC-based mobile display, as shown Table 1, which presents the average and maximum color differences of the X, Y, Z, and CIELAB values between measured colors for 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 (6×6×6) colors equally spaced in an RGB cube. All the measured color values in Table 1 represent values 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.

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.



(a)

(b)

(c)

***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.*

Table 1. Color differences between mixed colors and sum of pure colors.

200 (6×6×6-16) 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

However, 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 cross-talk effect [5], [6] 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, in the proposed characterization method, the EOTFs of the X, Y, and Z values, which have different shapes from each other, as shown in Figure 1, are modeled directly using the same parametric mathematical models as the S-curve model for the red, green, and blue channels as follows:

$$R_I(d_r) = A_{r_I} \frac{\left[d_r / \left(2^N - 1\right)\right]^{\alpha_{r_I}}}{\left[d_r / \left(2^N - 1\right)\right]^{\beta_{r_I}} + E_{r_I}} \tag{5}$$

$$G_I(d_g) = A_{g_I} \frac{\left[d_g / \left(2^N - 1\right)\right]^{\alpha_{g_I}}}{\left[d_g / \left(2^N - 1\right)\right]^{\beta_{g_I}} + E_{g_I}} \tag{6}$$

$$B_I(d_b) = A_{b_I} \frac{\left[d_b / \left(2^N - 1\right)\right]^{\alpha_{b_I}}}{\left[d_b / \left(2^N - 1\right)\right]^{\beta_{b_I}} + E_{b_I}} \tag{7}$$

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, are the model parameters to be calculated. To estimate the optimal parameters, 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.

Also, for the inter-channel components cyan, magenta, yellow, and gray (CMYK), 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:

$$C_I(d_c) = A_{c_I} \frac{\left[d_c / \left(2^N - 1\right)\right]^{\alpha_{c_I}}}{\left[d_c / \left(2^N - 1\right)\right]^{\beta_{c_I}} + E_{c_I}} \tag{8}$$

$$M_I(d_m) = A_{m_I} \frac{\left[d_m / \left(2^N - 1\right)\right]^{\alpha_{m_I}}}{\left[d_m / \left(2^N - 1\right)\right]^{\beta_{m_I}} + E_{m_I}} \tag{9}$$

$$Y_I(d_y) = A_{y_I} \frac{\left[d_y / \left(2^N - 1\right)\right]^{\alpha_{y_I}}}{\left[d_y / \left(2^N - 1\right)\right]^{\beta_{y_I}} + E_{y_I}} \tag{10}$$

$$K_I(d_k) = A_{k_I} \frac{\left[d_k / \left(2^N - 1\right)\right]^{\alpha_{k_I}}}{\left[d_k / \left(2^N - 1\right)\right]^{\beta_{k_I}} + E_{k_I}} \tag{11}$$

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 inter-channel 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 inter-channel 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:

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

$$P = \begin{cases} R, & d_1 = d_r \\ G, & d_1 = d_g \\ B, & d_1 = d_b \end{cases} \text{ and } S = \begin{cases} C, & d_3 = d_r \\ M, & d_3 = d_g \\ Y, & d_3 = d_b \end{cases} \tag{12}$$

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, inter-channel, and the gray component, respectively.

Experimental result

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 inter-channel, 224 (32×7) red, green, blue, cyan, magenta, yellow, and gray patches were used. Also, to evaluate the performance of the characterizations in predicting arbitral colors, 216 (6×6×6) patches equally spaced in the RGB cube were used.

Table 2. Characterization errors in mobile LCD when using conventional characterization method and proposed method.

Methods	Patches	32 Red	32 Green	32 Blue
S-curve model I	ΔE_{avg}	5.059	4.246	8.469
	$\Delta E_{\max}$	9.362	7.183	14.58
S-curve model II	ΔE_{avg}	1.284	1.176	3.331
	$\Delta E_{\max}$	10.39	5.984	8.612
9 EOTF Modeling	ΔE_{avg}	0.639	0.607	0.851
	$\Delta E_{\max}$	3.806	2.334	3.018
Masking model	ΔE_{avg}	3.294	2.523	4.670
	$\Delta E_{\max}$	6.145	4.387	8.725
Proposed Method	ΔE_{avg}	0.639	0.607	0.851
	$\Delta E_{\max}$	3.806	2.334	3.018

Table 2 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 (6×6×6) 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 inter-channel 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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