Colorimetric characterization of liquid crystal display using an improved two-stage model

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An improved two-stage model of colorimetric characterization for liquid crystal display (LCD) was proposed. The model included an S-shape nonlinear function with four coefficients for each channel to fit the Tone reproduction curve (TRC), and a linear transfer matrix with black-level correction. To compare with the simple model (SM), gain-offset-gain (GOG), S-curve and three-one-dimensional look-up tables (3-1D LUTs) models, an identical LCD was characterized and the color differences were calculated and summarized using the set of $7 \times 7 \times 7$ digital-to-analog converter (DAC) triplets as test data. The experimental results showed that the model was outperformed in comparison with the GOG and SM ones, and near to that of the S-curve model and 3-1D LUTs method.

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Nowadays the colorimetric characterization for liquid crystal display (LCD) have been extensively studied and many methods were developed[1]. These methods were summarized into two catalogs: one-stage and two-stage models. The three-dimensional look-up table (3D LUT)[2], neural network[3,4], and two-primary crosstalk (TPC) models[5] represented the former, which consisted of one-stage conversion to deal with three channels simultaneously. These methods required large numbers of data to be measured, which increased the time and costs of the characterization. The latter detached three channels by a simple linear transformation with the assumption of channel independence and chromaticity invariability of three primary colors, and then utilized Tone reproduction curve (TRC) function or one-dimensional (1D) LUT to describe the electro-optical characteristic of each channel. The representatives were the simple model (SM)[6], gain-offset-gain (GOG)[7], S-curve[8], and three-one-dimensional (3-1D) LUTs models. Although the 3-1D LUTs model was accurate, utilizing the TRC function to approximate the nonlinear relationship was meaningful to make the model efficient. The SM and GOG models were often used for cathode ray tube (CRT), while the S-curve model was testified to be appropriate for the desktop LCD projector.

A new two-stage model, named S-shape model, was proposed to improve the accuracy of LCD characterization while not to reduce the efficiency. The model had different mathematic representations, with the advantage that the optimal coefficients were easily converged and insusceptible to the initial values, from the S-curve model. A LCD monitor was characterized with several two-stage models including the SM, GOG, S-curve, 3-1D LUTs and S-shape. Their performances were evaluated by the CIELAB color differences[9].

Considering the black-level correction, the linear transformation was described by

$$\mathbf{X} = \mathbf{AR} + \mathbf{X}_k, \tag{1}$$

where $\mathbf{X} = [XYZ]^{\mathrm{T}}$ was the vector containing the resulting tristimulus values at a pixel, $\mathbf{R} = [R'G'B']^{\mathrm{T}}$ represent the vector composed of the linearized channel data, and $\mathbf{X}_k = [XYZ]_k^{\mathrm{T}}$ was the tristimulus values vector of the black point. The linear transfer matrix $\mathbf{A}$ could be defined by the tristimulus values after black-level correction of the peak primary colors:

$$\mathbf{A} = \begin{bmatrix} X_{\mathrm{R,max}} & X_{\mathrm{G,max}} & X_{\mathrm{B,max}} \\ Y_{\mathrm{R,max}} & Y_{\mathrm{G,max}} & Y_{\mathrm{B,max}} \\ Z_{\mathrm{R,max}} & Z_{\mathrm{G,max}} & Z_{\mathrm{B,max}} \end{bmatrix}_{\text{black}-\text{level correction}}, \tag{2}$$

where the suffix R represented the red channel, and the suffixes G and B corresponded to the green and blue channels respectively. The matrix also could be obtained by multiple regression using characterization data for more accurate results.

The electro-optical fitting functions of the models were listed in Table 1. The S-shape model with coefficients a, b, c, and k was proposed originally in this paper, R' was the linearized channel data. $R = D_{\mathrm{R}}/(2^N - 1)$ represented the normalized signal level, the superscript N was the bit-depth of image driver card and D_{R} was input digital data. For the other two channels, the TRC functions had similar forms except that R' was replaced by G', B' and R by G, B. It was the same case for the other models. For convenience, the function was presented only for red channel except for the S-curve II model. The S-curve II model was extended from S-curve I with the identical coefficients A_1, α, β and C. It was more complicate because of the additional items considering the inter-channel effect by the first-order derivative of the base driver function of influencing channel.

A 15-inch IBM LCD monitor was measured in a dark room using the spectral telephotometer PR650, which was perpendicular to and about one meter far from the center of screen. The brightness was set to maximum and the contrast was not varied because the control was not open to the end-user. The display and the measurement devices were warmed up over 1 hour beforehand. According to the conditions of measurement defined for LCD (IEC 61966-4), the test images were square center color patches with the remainder of the screen filled with black, as shown in Fig. 1. The measurement results were

Table 1. TRC Functions and the Results of the Optimization of Models

Model	Function	Coefficient (Initial Value)	Red	Green	Blue
SM	$R' = k_g(R)^\gamma$	k_g (1.0)	1.05239	1.06102	1.09662
		γ (2.0)	3.01121	2.74541	2.42182
GOG	$R' = \begin{cases} (k_g R + k_o)^\gamma, & k_g R + k_o > 0 \\ 0, & k_g R + k_o \le 0 \end{cases}$	k_g (1.0)	0.93561	1.03026	1.18497
		k_o (0.0)	0.08131	−0.00843	−0.14406
		γ (2.0)	3.36009	2.71456	2.00129
S-Curve I	$R' = A_1 \frac{(R)^\alpha}{(R)^\beta + C}$	A_1 (5.0)	13.17749	10.69101	5.61710
		α (2.0)	3.10383	2.86081	2.67855
		β (18.0)	53.6132	36.64567	18.43493
		C (4.0)	12.19107	9.70917	4.64479
S-Curve II	$R' = A_1 f_R(R) + A_2 f'_G(G) + A_3 f'_B(B)$	A_2 (0.0)	−0.09290	−0.00548	0.06196
		A_3(0.0)	0.03360	−0.06114	0.07926
S-Shape	$R' = \begin{cases} \frac{a}{(1+\exp(-k(R-b)))} - c, & \frac{a}{(1+\exp(-k(R-b)))} - c > 0 \\ 0, & \frac{a}{(1+\exp(-k(R-b)))} - c \le 0 \end{cases}$	a (1.0)	1.85292	1.66113	1.37318
		b (1.0)	0.95455	0.90384	0.80258
		c (0.0)	0.00937	0.01361	0.01218
		k (1.0)	5.56491	5.49435	5.95734

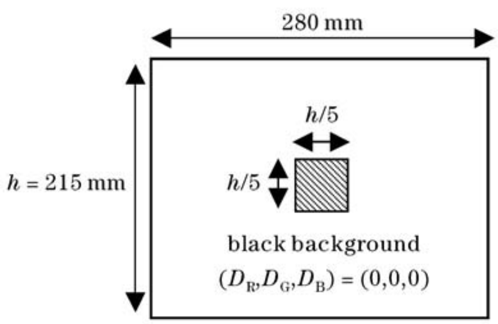

Fig. 1. Test image.

collected by the SpectraWin software provided with the PR650.

The tristimulus values and the chromaticies of black, white, and the three primary colors were given in Table 2. The linear transfer matrix **A** was calculated using Eq. (2). For each channel, 52 steps measured data from digital counts from 0 to 255 with interval of 5 were used as characterization data. The linearized channel data R', G', and B' were calculated by

$$R' = X_R/X_{R,\max},\ G' = Y_G/Y_{G,\max},\ B' = Z_B/Z_{B,\max}. \quad (3)$$

The nonlinear relationship of TRCs was fitted using the GOG, S-shape, S-curve I, S-curve II, and S-shape functions. The coefficients of models were obtained by the Levenberg-Marquardt nonlinear fitting method and listed in Table 1.

To obtain the optimal coefficients of S-curve I model needed great effort. In the beginning, with unsuitable initial values and no constraints for the coefficients the TRC data also could be fitted, but the predicted errors of the coefficients were larger, which implied that the coefficients could not be predicted accurately. After many trials, the initial values $A_1 = 5.0$, $\alpha = 2.0$, $\beta = 18.0$, $C = 4.0$, and the constraints of $\alpha > 0$ and $\beta > 0$ were found appropriately for the optimization of S-curve I model. The other models were optimized easily with the initial values shown in Table 1. The reduced chi-square, Chi^2/DoF, and the coefficient of determination, R^2, for nonlinear fit were reported in Table 3. It was obvious that the S-curve and S-shape models fit the electro-optical characteristics of LCD more accurately than the SM and GOG ones. The colors corresponding to the 343 ($7 \times 7 \times 7$) DAC triplets containing all the combinations from 0, 12, 81, 195, 226, 250, and 255 were measured. These colors were also predicted by the models with different TRC functions and the 3-1D LUTs method. The linear transfer matrix **A** was constituted by the tristimulus values of the peak primary colors with black-level correction, and also calculated by multiple regression method using the characterization data. The CIELAB color differences between the predicted and

Table 2. Tristimulus Values and Chromaticies of Black, White, and the Three Primary Colors

	D_R	D_G	D_B	X	Y (cd/m^2)	Z	x	y
Black	0	0	0	0.296	0.285	0.465	0.283	0.272
White	255	255	255	112.200	113.800	113.200	0.331	0.335
Red	255	0	0	48.330	28.320	7.117	0.577	0.338
Green	0	255	0	41.060	64.470	18.420	0.331	0.520
Blue	0	0	255	18.590	16.180	85.070	0.155	0.135
CCT for White	5573 K							

Table 3. Chi^2/DoF and R^2 of TRC Functions Nonlinear Fit

	SM			GOG			S-Curve			S-Shape		
	R	G	B	R	G	B	R	G	B	R	G	B
Chi^2/DoF ($\times$ 0.0001)	1.8	1.9	5.4	1.6	1.9	4.6	0.9	0.5	0.4	0.7	0.6	1.1
R^2(%)	99.82	99.82	99.53	99.83	99.82	99.61	99.91	99.95	99.95	99.93	99.94	99.91

Table 4. Model Performance Comparison Using Test Colors

Model	ΔE^*_{ab}				ΔE^*_{ab} (with Regressive Matrix)			
	Avg.	Std.	Max.	Min.	Avg.	Std.	Max.	Min.
SM	4.034	2.210	10.003	0.224	3.755	1.602	8.709	0.224
GOG	4.181	2.167	9.802	0.305	3.700	1.529	8.383	0.324
S-Curve I	3.365	2.042	9.662	0.093	2.810	1.258	6.440	0.098
S-Curve II	2.684	1.553	9.142	0.191	2.976	1.352	6.771	0.187
S-Shape	3.461	2.058	9.808	0.224	2.960	1.183	6.135	0.224
3-1D LUTs	3.241	2.048	10.439	0.165	2.669	1.156	7.025	0.224

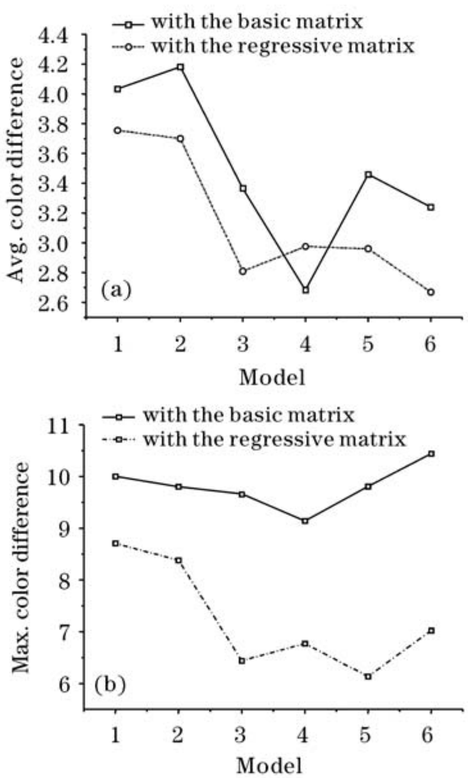

Fig. 2. Color differences of each model for the 343 test colors. (a) Average; (b) maximum. 1: SM; 2: GOG; 3: S-curve I; 4: S-curve II; 5: S-shape; 6: 3-1D LUTs.

measured colors, ΔE^*_{ab}, were calculated in Table 4.

The average and maximum CIELAB color differences of the 343 test colors for each model were plotted in Fig. 2. With the basic matrix, the performance of S-curve II model was the best, the SM and GOG models produced the maximum average color difference.With the regressive matrix, the maximum color difference reduced for all models and that for the S-shape model was the least. The average decreased for all models but the S-curve II. The reason might be that the regressive matrix and the S-curve II model contained the channel independence effect repeatedly. The performance of 3-1D LUTs was the best, the S-curve I, S-curve II and S-shape models were next with average color difference less than 3.0, which were outperformed compared with the SM and GOG models.

The GOG model accurately revealed the gamma characteristics of cathode ray tube (CRT), so it was excellent for CRT characterization. But for LCD, the relationship between the radiant luminance and the driver digital values was much different. Therefore, the S-shape model could accurately describe the TRC characteristics of LCD, and was easier to use for the mathematical expression of TRC functions, which was easier to be nonlinear fit than that of the S-curve model. The colorimetric characterizations for the identical LCD were carried out. The experimental results showed that the S-shape model gave more accurate characterization than the SM and GOG models, and was more convenient than the S-curve and 3-1D LUTs models with the comparative accuracy.

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