Accurate Prediction of Colours on Liquid Crystal Displays

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Abstract

The performance of two newly derived LCD-projector characterisation models has been tested for four liquid crystal based displays – two LC projectors and two LC flat panels. Data measured from a series of test colours, indicated that all LC-based displays showed similar characteristics, including an S-shaped tone characteristic curve and poor channel chromaticity constancy. It is proved that the new characterisation models based on a hyperbolic function fit the tone curve very accurately with only four coefficients per channel for any kind of LC displays. In addition it is shown that the first derivative of the function provides a means of accurate correction of the chromaticity variation.

Introduction

Liquid crystal displays (LCDs) are now widely used for image reproduction, both as flat-panel portable and desktop computer displays and as projection displays. To establish colour management systems, it is essential to understand characteristics such as the relationship between digital input values and output colours for display devices. Colour management systems do not always handle LCDs well, however, because LCD colour characteristics are significantly different from cathode ray tube (CRT) displays for which characteristics are well known. Studies by the authors of the salient colour characteristics of a Sanyo desktop LCD projector have demonstrated that two main characteristics have to be considered to predict LCD output colours according to input digital.[1] Those were S-shaped electro-optical transfer functions and the non-constancy of channel chromaticity, i.e. changes of chromaticity in primary colours and achromatic colours depending on the drive signal level of each channel.

The shape of the electro-optical transfer function of any LC-based monitor or projector is quite different from the conventional CRT monitor (see Figure 1). The CRT follows a power function (the 'gamma function') but the LCD is inherently a binary device that switches from an OFF state to an ON state, following an S-shaped curve, implying failure of the GOG model[3,4] for LC-based displays. To predict the measured curve, the S-Curve Model I was proposed[1].

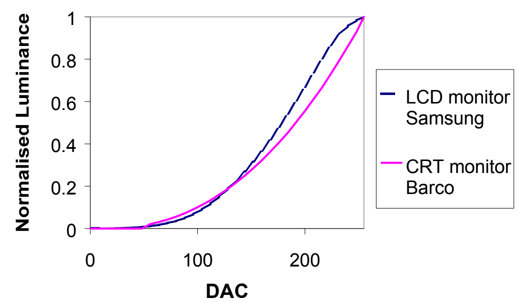

Figure 1 Electro-Optical Transfer Functions of CRT and LCD based monitors

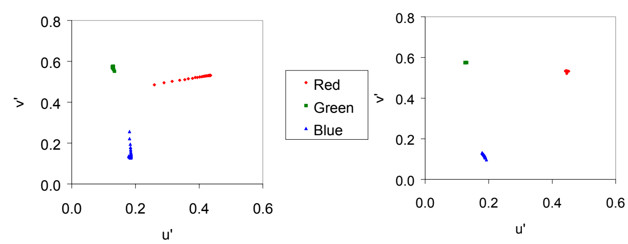

Figure 2 Colour Tracking, before (left) and after (right) Black Correction, for LCD projector, Sanyo PLC-5605B

S-Curve Model I assumes channel independence and constant chromaticity of each primary, in the same manner as GOG or PLCC models. However the LCD projector tested (Sanyo PLC-5605B) exhibited very poor chromaticity constancy, indicating the limitation of the S-Curve Model I.

Figure 2 shows the chromaticities of 32 steps per channel plotted on the CIE 1976 UCS diagram, (u′,v′). Left graph shows that the chromaticities of each channel approached that of black as the input level approached zero because the chromaticity of black arises from the leaked light through LC cells and this leaked light is always added to any colour. Therefore the chromaticities could be corrected by subtracting the black values. However, even after the black correction, some variation in chromaticity is evident, with blue exhibiting the largest variation, followed by green. Red showed the most stable chromaticity (see Figure 2 right).

An extended model, called S-Curve Model II, was therefore developed to account for this effect.

The physical explanation for the chromaticity changes may be found in the changes in LC cell spectral transmission according to applied voltage, and hence according to grey level.[2]

Figure 3 indicates that greys will have bluish tint as the input level decreases, which also showed in the authors' study. The tendency for LCD colours to become more bluish at lower signal levels has also been noted in other studies.[5]

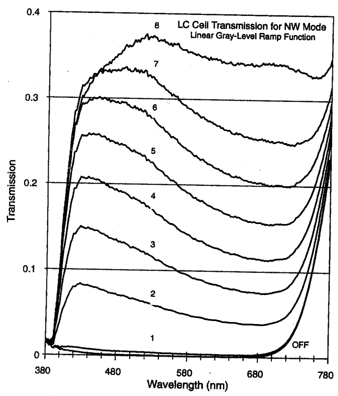

Figure 3 LC cell spectral transmission for the model NW LCD as a function of 8 linear grey levels and the off-state (Figure8 in ref. 2)

The new mathematical models S-Curve Model I and II were shown to be successful for the specific LCD projector Sanyo PLC-5605B. In this further study, they were applied to other LCD projectors and LCD monitors to demonstrate that the S-Curve Models have general validity for all LC-based displays.

S-Curve Model I and modified S-Curve Model II

The S-Curve model has same structure as the GOG model[2,3] but uses a different function for the non-linear relationship between DAC signal values and monitor *RGB* luminance levels.

These models consist of two stages – non-linear relationship between DAC signal values and monitor *R,G,B* luminance levels, followed by a linear transformation matrix where the *R,G,B* channel luminances are transformed to CIE tristimulus values *X,Y,Z.* The matrix and equations for S-Curve Model I are given below.

- ❑ Nonlinear Relationship between DAC Values and Monitor Luminance Values for S-Curve Model I

$$R = A_r \frac{d_r^{\alpha_r}}{d_r^{\beta_r} + C_r},\ G = A_g \frac{d_g^{\alpha_g}}{d_g^{\beta_g} + C_g},\ B = A_b \frac{d_b^{\alpha_b}}{d_b^{\beta_b} + C_b} \quad (1)$$

- ❑ Linear Transformation Matrix

$$\begin{bmatrix} X_{pixel} \\ Y_{pixel} \\ Z_{pixel} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\substack{ambient \\ flare}} + \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (2)$$

d_r, d_g and d_b represent the normalised input digital values for red, green and blue channels and *R, G* and *B* represent normalised monitor luminance levels computed using the spectral radiance of the red, green, and blue channels at maximum excitation as primaries. Even though S-Curve Model I was derived to fit an S-shaped curve, the function (below) has a very generalised form. When β is equal to 0, $f(x)$ becomes a power function, which can also be used to characterise a CRT-based monitor.

$$f(x) = A \frac{\chi^{\alpha}}{\chi^{\beta} + C} \quad (3)$$

S-Curve Model II is an extension of S-Curve Model I to correct errors caused by the dependencies between normalised monitor luminances *R*, *G* and *B*. For example, the input signal from the blue channel generates not only *B* values but also *R* and *G* values. This effect arises from the changes in channel chromaticity caused by input digital values. Equations for modified S-Curve Model II are shown below.

- ❑ Nonlinear Relationship between DAC Values and Monitor Luminance Values for modified S-Curve Model II

$$\begin{aligned} R &= A_{rr} \cdot f_{RR}(d_r) + A_{rg} \cdot f_{RG}'(d_g) + A_{rb} \cdot f_{RB}'(d_b) \\ G &= A_{gr} \cdot f_{GR}'(d_r) + A_{gg} \cdot f_{GG}(d_g) + A_{gb} \cdot f_{GB}'(d_b) \\ B &= A_{br} \cdot f_{BR}'(d_r) + A_{bg} \cdot f_{BG}'(d_g) + A_{bb} \cdot f_{BB}(d_b) \\ f(x) &= \frac{x^{\alpha}}{x^{\beta} + C}, \quad f'(x) = \frac{(\alpha - \beta)x^{\alpha+\beta-1} + \alpha \cdot C \cdot x^{\alpha-1}}{(x^{\beta} + C)^2} \\ & f'(x)\text{: first - order derivative of } f(x) \end{aligned} \quad (4)$$

In the original paper, f_{GR} and f_{BR} were supposed to be the same as f_{RR} (also $f_{GG} = f_{RG} = f_{BG}$, $f_{BB} = f_{RB} = f_{GB}$). However it has been found that using different functions produces better results, even though this requires more parameters.

Characteristics of LC-based Displays

In this study, the characteristics of two LCD projectors and two LCD monitors were compared. Table 1 lists the displays used.

Table 1 List of the displays used in the experiment

Type	Manufacturer	Model
LCD projector	Sanyo	PLC-5605B
LCD projector	ASK	Impression A10
LCD panel	Samsung	Sense 820 (Laptop computer display)
LCD panel	Sharp	LC-20VM2

All measurements were performed on a central uniform square patch (h/5xh/5, h: the effective screen height), with the remainder of the display filled with a black background represented by D_R, D_G, D_B digital counts of (0,0,0). A spectroradiometer (PhotoResearch PR-650) was used to measure the colours generated by the displays and experiments were conducted in a dark room to eliminate the effect of ambient light.

Additivity

As a first step, the additivity of the displays was checked because S-Curve Model I and II assume channel independence, i.e. the equivalence between white and the sum of three primary colours. Except for the Sharp LCD panel, the other three displays all showed good additivity (see Table 2).

Table 2 Additivity test result

	Reference White			Red+Green+Blue-2×Black			% Error		
	X_L	Y_L	Z_L	X_L	Y_L	Z_L	ΔX_L	ΔY_L	ΔZ_L
Sanyo	114.6	137.5	134.1	114.2	137.3	135.1	-0.39	-0.14	0.77
ASK	411.0	495.6	558.7	411.5	495.9	558.5	0.11	0.06	-0.04
Samsung	101.0	112.5	94.2	100.8	112.5	95.0	-0.15	-0.02	0.88
Sharp	181.5	175.1	311.8	192.4	185.3	324.5	6.02	5.83	4.08

Tone Characteristics

Tone characteristics were compared using the normalised output luminance for green channel (see Figure 4). Sanyo projector and Samsung panel both exhibited an S-shaped curve, which is the intrinsic character of the liquid crystal, but ASK projector and Sharp panel showed power function-like curve. This is presumably a deliberate design intention by the manufacturers to simulate CRT display behaviour.

Colour Tracking (Chromaticity Changes of Primaries)

Colour tracking characteristics were checked, i.e. the locus of chromaticity changes of primary colours corresponding to the input digital values of each channel. Chromaticities of 32 steps per channel were measured and plotted on the CIE 1976 UCS diagram (u′,v′). Figure 2 and Figure 5 show that all LC-based displays have poor channel chromaticity constancy.

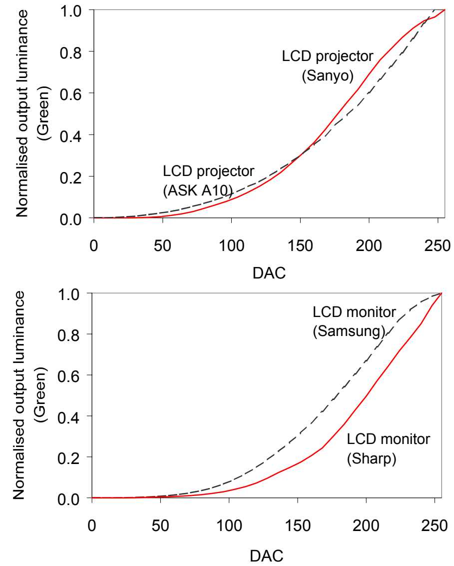

Figure 4 Tone characteristic comparison using the green channel data

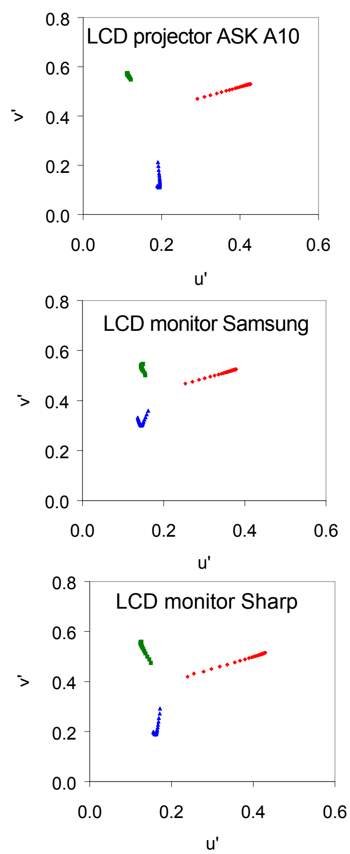

Figure 5 Colour tracking without black correction for LCD projector ASK A10, LCD monitor Samsung and Sharp

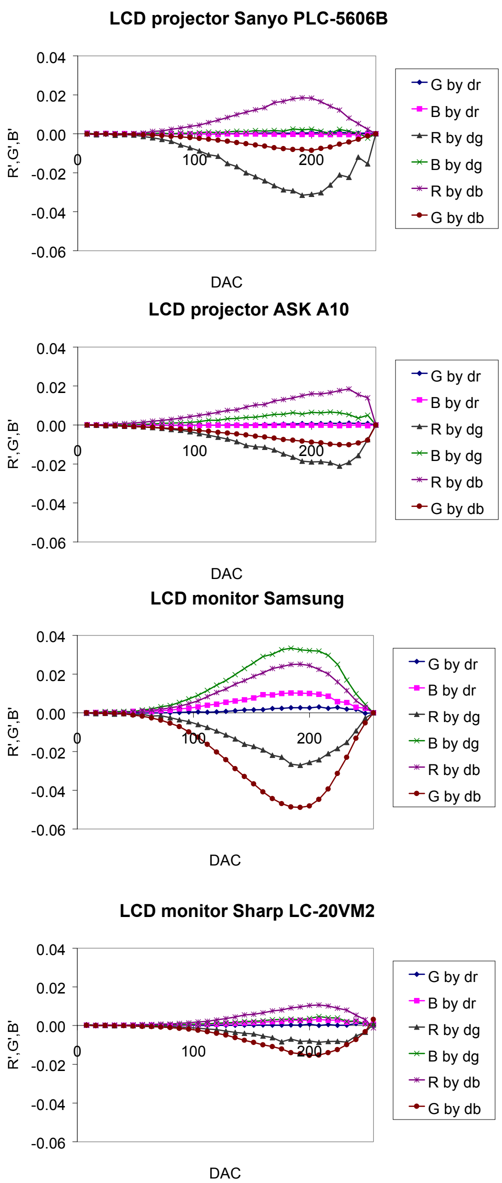

Figure 6 Normalised monitor luminance level generated by input signal from other channel. R by dg means R value generated by green channel input signal.

To prove the necessity of the S-Curve Model II, normalised monitor luminance levels generated by input signal from other channels were calculated and presented as graphs.

Figure 6 represents the following six functions of each device:

$$R\ by\ dg = A_{rg} \cdot f_{RG}'(d_g),\quad R\ by\ db = A_{rb} \cdot f_{RB}'(d_b)$$
$$G\ by\ dr = A_{gr} \cdot f_{GR}'(d_r),\quad G\ by\ db = A_{gb} \cdot f_{GB}'(d_b)$$
$$B\ by\ dr = A_{br} \cdot f_{BR}'(d_r),\quad B\ by\ dg = A_{bg} \cdot f_{BG}'(d_g) \quad (5)$$

Note that these graphs provide another means of quantifying the channel chromaticity constancy. The normalised monitor luminance level driven by another channel appears to be small when it is considered that the vertical axis has a scale from 0 to 1. However, to predict the chromaticity changes accurately and to improve the tone characterisation performances, these components must be included in the characterisation model. It is observed from Figure 6 that all curves have a similar form, which appears to follow the gradient of the S-Curve function. That is the reason why S-Curve Model II uses the first derivative of the primary function of S-Curve Model I for the cross-product terms.

Comparison of Model Performances

The performances of S-Curve Model I and II were tested and compared with GOG model[3,4] to check the effectiveness of new models. For the GOG model, Eq. 6 is used for the non-linear relationship between signal voltage and luminance. (Eq. 6 shows equation for Red channel. Analogous equations can be set up for Green and Blue channels.) Gain k_g, offset k_o and gamma γ are constants determined by experimental data. d_r means normalised digital input value.

$$R = \begin{cases} \left[k_{g,r} \cdot d_r + k_{o,r}\right]^{\gamma_r}, & \left[k_{g,r} \cdot d_r + k_{o,r}\right] \geq 0 \\ 0, & \left[k_{g,r} \cdot d_r + k_{o,r}\right] < 0 \end{cases} \quad (6)$$

To calculate parameters of the S-Curve and GOG models, measurement data of equally spaced 32 steps between 0 to 255 per channel were used as training data set.

To test the model performances, arbitrary colours were generated and measured. Then measured values of output colours were compared with the values predicted by each model by calculating CIELAB colour difference. In this study 94 test colours were used for this task. Table 3 shows the test results, where Test means the results derived from 94 colours made by a mixture of the three primary colours, and Red, Green, Blue mean those of 32 colours per channel, which are training data set.

Modified S-Curve Model II showed a much improved performance compared to others, implying that correction of chromaticity changes is important for predicting output colours of the LC-based displays. The Sharp panel had worst performance, probably related to its poor additivity. Note that all three models assume the additivity of three channels. The GOG model showed very poor performances for the S-shaped tone curve (Sanyo, Samsung), and S-Curve Model I worked better than GOG even for power function-like curve (Ask, Sharp). None of the devices had a zero value for the parameter β implying that even power function-like curves were not real power functions.

Table 3 Performance results of the characterisation models. (Numbers represent average CIELAB colour differences between measured and predicted values of test colours and training colours.)

ΔE^*_{ab}	**Modified S-Curve Model II**			
	Test	Red	Green	Blue
Sanyo	1.46	0.88	1.12	2.01
ASK	1.60	0.80	1.14	2.14
Samsung	1.22	0.78	0.68	0.54
Sharp	2.36	1.01	1.38	0.70
ΔE^*_{ab}	**S-Curve Model I**			
	Test	Red	Green	Blue
Sanyo	2.21	0.99	2.31	4.79
ASK	2.56	0.82	2.87	6.87
Samsung	3.78	2.66	4.10	6.99
Sharp	3.25	1.56	1.98	3.93
ΔE^*_{ab}	**GOG model**			
	Test	Red	Green	Blue
Sanyo	11.3	4.77	8.48	11.3
ASK	3.05	1.52	4.88	6.87
Samsung	7.85	4.75	7.11	9.87
Sharp	6.56	3.04	5.52	6.93

Conclusion

Colour characteristics were examined for four liquid crystal displays: two LCD projectors, Sanyo PLC-5605B and ASK A10, and two LCD monitors Samsung Sense820 and Sharp LC-20VM2. The results showed that all displays had poor channel chromaticity constancy and half of them exhibited S-shaped tone characteristics while others exhibited power function-like curves. To predict the output colours, three mathematical characterisation models: S-Curve Model I, modified S-Curve Model II and GOG model were tested. Modified S-Curve Model II showed the best performance and S-Curve Model I showed better performance than GOG model, even for power function-like curves. From these results, we have demonstrated that S-Curve Model I and II can be generally used for any liquid crystal display.

This is an important result because it offers a precise mathematical means of modelling the colorimetric performance of any LCD display, and therefore opens the way for colour management systems to control image output on LCD displays with more precise and consistent results. To implement this within the ICC framework, however, would require a new display profile format, because the present specification for display profile (which is based primarily on CRT behaviour) assumes channel chromaticity constancy.[6]

In spite of the rapid growth of the LCD market, colour management systems for LC-based displays are not well established yet. It is believed that authors' study could be used to generate more efficient colour management profiles for LC-based displays.

Acknowledgement

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References

1. Y. Kwak, L. MacDonald, Characterisation of a desktop LCD projector, *Displays* **21** 179-194 (2000)
2. L. D. Silverstein, T. G. Fiske, Colorimetric and Photometric Modeling of Liquid Crystal Displays, *Proc. IS&T/SID First Color Imaging Conference*, pg. 149 (1993)
3. R.S. Berns, R J. Motta, M E. Gorzynski, CRT colorimetry, part I: theory and practice, *Col. Res. Appl*. **18**, 299 (1993)
4. R.S Berns, Methods for characterizing CRT displays, *Displays*, **16**, 173 (1995)
5. S.L. Wright, K. Ho, A. Lien, Status of TFTLCD color and Metrology, *Proc. 8th IS&T/SID Color Imaging Conf.*, pg. 301-304 (2000)
6. Specification ICC.1:1998-09, File Format for Color Profiles, http://www.color.org/ICC-1_1998-09.PDF