Colorimetric Characterization Model for DLP™ Projectors

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Introduction

The widespread use of data projectors in more demanding imaging applications has emphasized the need for accurate methods of their color control. Projectors are relied upon in settings where color reproduction is increasingly important, such as digital cinema, and business applications including advertising and presentations using such color-critical items as corporate logos. We have measured and characterized a set of 12 such data projectors, using both liquid crystal display (LCD) and Digital Light Processing™ display technologies. (DLP™, trademarked Texas Instruments.) LCD projectors are successfully modeled using established techniques[1,2,3,4] for LCD projectors and display screens as typically found in laptop computers. For the DLP devices, the LCD model is extended using a previously-proposed[5] model in combination with a new method for calculating the amount of white channel addition. Colorimetric results are presented for both types of display technology for a series of projectors, with the more complex DLP modeling performing as well as the simpler LCD modeling.

Background

The LCD projectors we tested each use a similar color and optical configuration. The lamp output is split into RGB channels using reflective and selective optics such as dichroic mirrors. These channels are directed through polarizing elements and then through the LCD itself. The three channels are then recombined and imaged through final focus and zoom optics. This configuration is shown in Fig. 1a.

DLP devices use an entirely different system,[6] incorporating a Digital Micromirror Device™ (DMD™, also trademark Texas Instruments throughout). These projectors use sequential imaging system, where each color is imaged in turn as a filter wheel rotates through red, green, blue, and white segments. The lamp output is imaged directly onto the DMD, which either directs **on** pixels towards the filter wheel or diverts **off** pixels to a light trap. The DMD is refreshed at least four times per rotation of the wheel, so that each separation can be individually imaged. The DLP process is shown schematically in Fig. 1b, although the figure shows an RGB system with only three filters in the wheel. The DLP model described in this paper apply to four-color DLP systems.

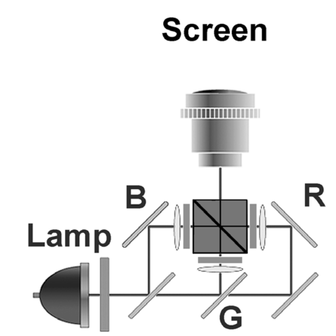

Figure 1a. Typical light path for liquid crystal display projectors. (Original image courtesy TI).

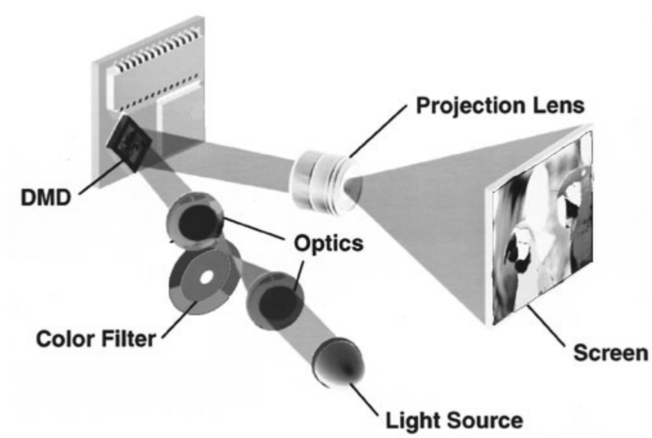

Figure 1b. Typical light path for DLP projectors. Note that the color wheel shown here is RGB only. (Courtesy TI)

Characterization Measurements

All projectors were measured in same fashion, using an LMT 1210 colorimeter controlled by Matlab™ scripts which produced the images, triggered the colorimetric measurements, and stored the data. The LMT is an extremely sensitive and accurate device, designed to measure light sources directly. It is placed inline between the projector and the screen. The projectors therefore image directly onto the diffusing element of the LMT sensor. No screen or other reflective surface is affecting the measurement.

The projector characterization can be accomplished with the typical red, green, blue, and white ramp data. We measured the tristimulus values every five digital counts for the center for the range, and every digital count for the shadows and highlights. This was to ensure that we were accurately understanding the behavior at these critical brightness levels.

Model Overview

The models presented for the LCD and DLP projectors are not necessarily intended to be representative of the underlying physical processes of the devices. However, we use them because they perform with sufficient accuracy for general use.

The LCD Model

The model for the LCD projectors is a simple one: a lookup table (LUT) for linearization of the digital counts followed by a 3x3 rotation matrix. The matrix is composed of the black-corrected tristimulus values of the full-on RGB primaries The matrix transforms the linearized digital counts into tristimulus values. For some projectors, sufficient linearization can be accomplished with a gamma (power) function. In practice the LUT is a better selection since the gamma is not a built-in physical property of the system, but a behavior imposed by the system designers. Since such a design can be arbitrarily shaped, the LUT make more sense for the general case. The LUTs are derived directly from the black-corrected XYZ values of the separation ramps. Example LUTs for one LCD projector are shown in Fig 3. Note that these LUTs are normalized to unity.

Mathematically, the complete forward model is:

$$\begin{bmatrix} X_R - X_K & X_G - X_K & X_B - X_K \\ Y_R - Y_K & Y_G - Y_K & Y_B - Y_K \\ Z_R - Z_K & Y_G - Z_K & Z_B - Z_K \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} X_K \\ Y_K \\ Z_K \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (1)$$

The K subscripts indicate the measured black values. The primed values are radiometric scalars, which are the input digital counts after linearization by the LUTs.

Similar models have been proposed for LCD displays[1-4] and LCD projection systems.[3,7] These have typically included cross terms in the matrix, indicating an interaction between the channels. We include this simplified form of the established models to provide a framework from which to extend the DLP model. Various display models have included the dark correction. These date back to early CRT[8] and LCD[1] colorimetric characterization. More recently, Katoh *et al*[9,10] provided a good description of the use of flare and offset terms.

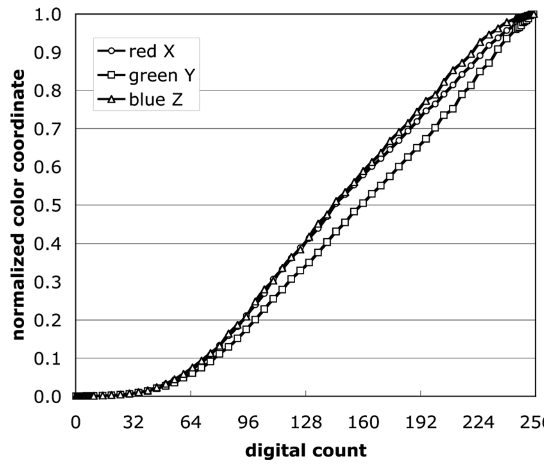

Figure 3. Example LUTs for one LCD projector. These are the black-corrected XYZ values for the separation ramps.

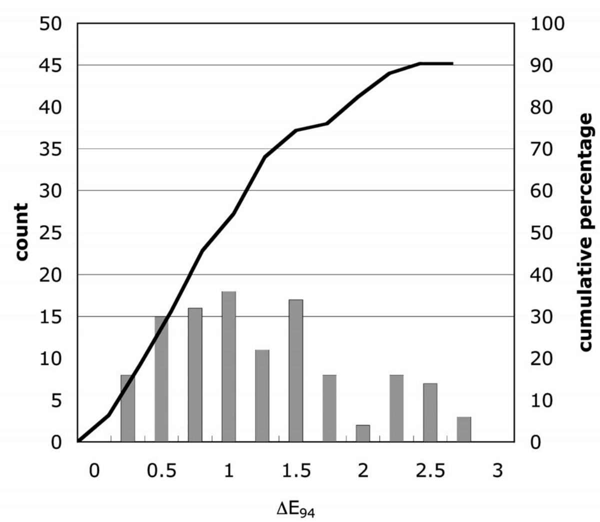

Figure 4. Color difference performance of the example LCD projector model. Data were uniformly-sampled 5x5x5 in RGB space.

The forward model for the example LCD projector performed quite well, with mean and maximum color difference of 0.6 and 1.6 respectively, for a 5x5x5 matrix of test data. (These and all subsequent color differences are ΔE_{94}.) The histogram of the color difference distribution is shown in Fig. 4. These test data uniformly sample the RGB input space.

The DLP Model

Previous studies describing DLP systems have explored the difficulties in adding white in a colorimetrically-smooth method[11,12] or considered three-color DLP only.[13] Stone[5] and Sieme and Hardeberg[14] discuss four-channel DLP characterization, but did not provide a specific method for white channel addition. What follows will fully describe a method for incorporating the white channel into a colorimetric model.

As with the LCD model, the RGB lookup tables in this study are derived from the black-corrected separation ramp data. However, the white LUT cannot be measured directly, since a ramp of R=G=B will contain some contribution of light passing through the RGB filters. The white LUT is calculated by subtracting the sum of the RGB ramp XYZ values from the XYZ values of the white ramp. This will result in three curves, one for X, Y, and Z. We use the Y-derived curve for the white LUT although in practice all three are nearly identical after normalization. The resultant LUTs are shown in Figure 5. There is a significant amount of noise present in the upper end of figure 5, especially for the white LUT. This could be improved with additional measurements or smoothing.

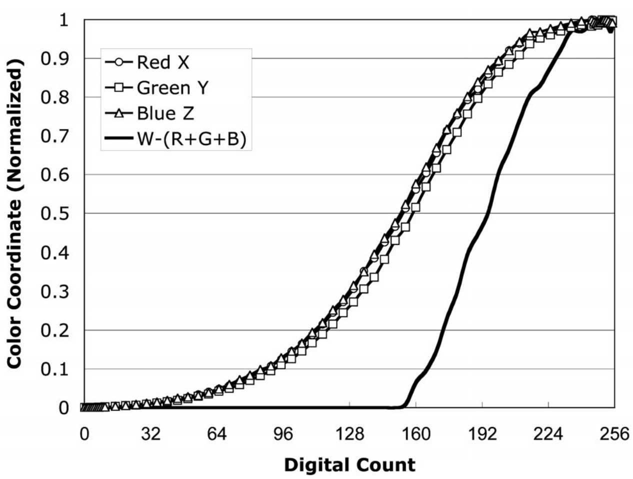

Figure 5. Normalized LUTs for an example DLP projector. Note that no white is not added until a digital count of about 150.

The most important consideration between the LCD and DLP characterizations is the amount of added white. (Note that we expect the three-color DLP systems to behave similarly to the LCD systems describes above.) This will be explored by examining some carefully-selected ramps. The critical data to examine are various ramps with two fixed separations, and one separation varying from 0 to 255. Figure 6 shows three ramps, in which red and green separations are constant and the blue is varied. These mixture curves are corrected for the amount of light that was contributed by the RGB ramps. What is left is assumed to be from the white channel. We first note that all three curves are zero up to a digital count of about 150. This indicates that the RGB primary ramps can fully account for all of the light. After a count of 150, the curves begin to climb, indicating that some of the white separation is being added. The triangle and square curves stop increasing at digital counts of 190 and 225, respectively. This is the important behavior that must be considered when modeling the DLP systems. Once the varying digital count exceeds the minimum value of the other two separations, no further white is added separations, no further white is added. For example, the triangles in Fig. 6 show that once the blue digital count exceeds 190, the green is now the minimum value. Hence the white contribution is fixed at 190 for the remainder of this ramp.

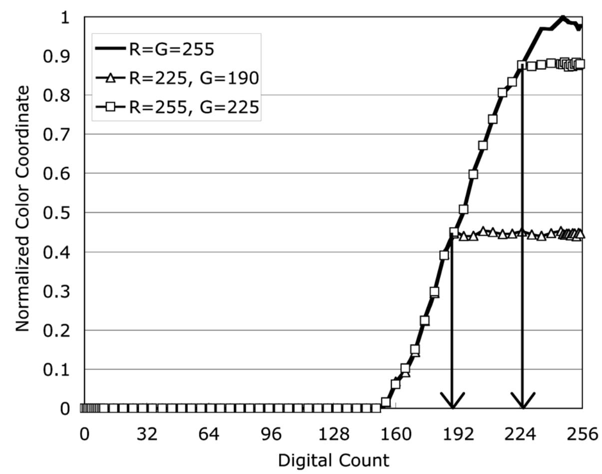

Figure 6. Behavior of DLP system for three mixtures. Each have constant red and green, and varying blue. These show how the white separation is added only up to the level of the minimum RGB value (shown by arrows).

The DLP model is implemented in the following steps:

- Dark correct the RGB tristimulus values:

$$\begin{bmatrix} X_R^c & X_G^c & X_B^c \\ Y_R^c & Y_G^c & Y_B^c \\ Z_R^c & Z_G^c & Z_B^c \end{bmatrix} = \begin{bmatrix} X_R - X_K & X_G - X_K & X_B - X_K \\ Y_R - Y_K & Y_G - Y_K & Y_B - Y_K \\ Z_R - Z_K & Z_G - Z_K & Z_B - Z_K \end{bmatrix}, \quad (2)$$

- Dark correct the white tristimulus values and subtract the dark-corrected RGB separation ramps:

$$\begin{bmatrix} X'_W \\ Y'_W \\ Z'_W \end{bmatrix} = \begin{bmatrix} X_W - X_K \\ Y_W - Y_K \\ Z_W - Z_K \end{bmatrix} - \begin{bmatrix} X_R^c & X_G^c & X_B^c \\ Y_R^c & Y_G^c & Y_B^c \\ Z_R^c & Z_G^c & Z_B^c \end{bmatrix}, \quad (3)$$

- Calculate the white scalar:

$$W = \min(R, G, B), \quad (4)$$

- Run RGB scalars through the lookup tables (with equivalent forms for G and B):

$$R' = rLUT(R), \tag{5}$$

- Apply the matrix to the scalars:

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} X_R^c & X_G^c & X_B^c & X'_W & X_K \\ Y_R^c & Y_G^c & Y_B^c & Y'_W & Y_K \\ Z_R^c & Z_G^c & Z_B^c & Z'_W & Z_K \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \\ W \\ 1 \end{bmatrix} \tag{6}$$

The obvious addition is the fourth channel, $[X'_W \quad Y'_W \quad Z'_W]$ and the corresponding linear scalar *W*. An equivalent model form has been published,[5] although the calculations for the white LUTs and scalar were not specified. The colorimetric performance of the set of DLP projectors had a mean and maximum of 0.7 and 4.6, respectively. Complete results for a 5x5x5 matrix of test data for all projectors are listed in table I.

In most color imaging applications, it is the inverse model that is most useful. In this case, an inverse model requires us to take colorimetric coordinates (CIEXYZ or CIELAB) as input and predict the RGB coordinates that would produce that input color. In practice this inversion is a difficult process with this model. Established techniques, such as lookup table-based inversion, can be employed. Such techniques are beyond the scope of this paper, but are well documented in the literature. Kang[15] describes implementation details for LUT creation and inversion.

Table I: Model Results for 5x5x5 Test Matrix

Projector Type	Colorimetric Error (ΔE_{94})	
	mean	max
LCD 1	1.1	3.7
LCD 2	0.4	1.1
LCD 3	1.0	3.4
LCD 4	1.3	4.8
LCD 5	0.6	1.6
LCD 6	2.2	7.8
DLP 1	0.3	4.9
DLP 2	1.8	6.0
DLP 3	0.6	3.6
DLP 4	0.6	3.0
DLP 5	0.5	4.3
DLP 6	0.5	5.2
DLP 7	0.8	5.4
LCD average	1.1	3.7
DLP average	0.7	4.6

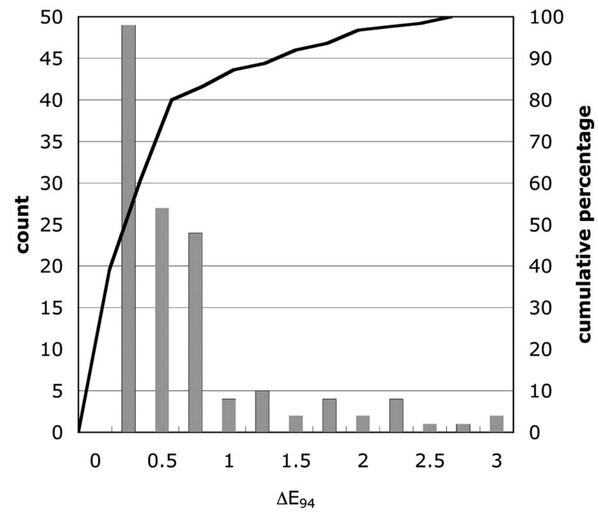

Figure 7. Color difference performance of the example DLP projector model.

Conclusions

We have demonstrated an accurate colorimetric model for DLP-based data projection systems. The model performs as well as established models for LCD projectors. Given all of the variables involved in the viewing of these in practical situations (ambient light, screen flare, viewing angle and distance) we feel that these results are quite satisfactory.

Acknowledgements

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References

1. M.D. Fairchild, D.R. Wyble, Colorimetric Characterization of the Apple Studio Display (Flat Panel LCD), Munsell Color Science Laboratory Technical Report (July 1998).
2. J.E. Gibson, M.D. Fairchild, Colorimetric Characterization of Three Computer Displays (LCD and CRT) Munsell Color Science Laboratory Technical Report (January 2000).
3. L. Seime and J.Y. Hardeberg, Characterisation of LCD and DLP Projection Displays, IS&T Tenth Color Imaging Conference 277-282 (2002).
4. Y. Kwak and L. MacDonald, Accurate Prediction of Colours on Liquid Crystal Displays, IS&T Ninth Color Imaging Conference 355-360 (2001)
5. M. Stone, Color Balancing Experimental Projection Displays, IS&T Ninth Color Imaging Conference 342-347 (2001).
6. For an extensive list of DLP and DMD references, see L. Yoder, The Digital Display Technology of the Future, INFOCOMM '97, Los Angeles (1997), or www.dlp.com.

7. Y. Kwak and L.W. MacDonald, Method for characterising an LCD projection display, Projection Displays VII, Proceedings of SPIE V 4294, 110-118 (2001).
8. R.S. Berns, R.J. Motta, and M.E. Gorzinski, CRT Colorimetry Part I: Theory and Practice, Color Res and Appl 18 299-314 (1993).
9. N. Katoh, T. Deguchi, R.S. Berns, An accurate characterization of CRT monitor (I) verification of past studies and clarifications of gamma. Optical Review 8: 305-314 (2001).
10. Katoh N, Deguchi T, Berns RS. An accurate characterization of CRT monitor (II) proposal for an extension to CIE method and its verification. Optical Review 8: 397-408 (2001).
11. A. Kunzman and G. Pettitt, , White Enhancement for Color Sequential DLP, SID Digest, San Diego, CA (1998).
12. S. Lee, C. Kim, Y. Seo, C. Hong, Color Conversion from RGB to RGB+White While Preserving Hue and Saturation, IS&T Tenth Color Imaging Conference 287-291 (2002).
13. O. Packer, L.C. Diller, J. Verweij, B.B. Lee, J. Pokorny, D.R. Williams, D.M. Dacey, D.H. Brainard, Characterization and use of a digital light processing projector for vision research, Vision Research 41, 427-439 (2001).
14. L. Sieme and J.Y. Hardeberg, Characterization of LCD and DLP Projection Displays, IS&T Tenth Color Imaging Conference 277-282 (2002).
15. H.R. Kang, Color Technology for Electronic Imaging Devices, SPIE Press, Bellingham, WA (1997).