Color Balancing Experimental Projection Displays

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Abstract

Experimental, tiled displays made of commodity projectors provide a relatively easy and cost effective way to explore "on the wall" viewing and interaction. To color balance the display, each projector must be characterized and mapped to a common gamut. Projectors with three imaging elements and three filters can be characterized by a simple extension to the monitor calibration model. However, projectors with a single micro-mirror array and a color wheel may include a "white printer" to increase the system luminance. This makes the characterization more complex. This paper will discuss characterization of both forms of projectors in the context of color balancing the Stanford Interactive Mural.

Keywords
Display walls, color matching, projection displays

I. INTRODUCTION

Experimental, tiled displays made of commodity projectors are becoming common in computer graphics research.[8] They provide a relatively easy and cost effective way to explore "on the wall" viewing and interaction. Displays can be either front or back projected. Each "tile" is a single, projected image. To color balance such a display wall, we seek to characterize the projectors, then map them to a common gamut.

Such a display, called the Stanford Interactive Mural, has been constructed by tiling twelve Compaq MP1800 projectors, which are small, lightweight projectors based on the Digital Light Processing (DLP) imaging technology from Texas Instruments [5]. The mural is used for experiments in visualization and interaction, and is shown in figure 1

Projectors that use three imaging elements, one per separation, can be characterized using an extension of the monitor characterization model [3, 1, 2]. However, small DLP projectors use a single imaging element constructed from an array of micro-mirrors (DMD) and a color wheel. Along with the expected red, green and blue filters, there is a clear segment that is used to increase the maximum luminance of the system, much as a black printer is used to increase the density of a print. Therefore, characterizing these devices is not just a simple extension of the monitor characterization model.

This paper will first describe the process we propose for color balancing the Interactive Mural and similar displays. Then, it will present data demonstrating that three-element LCD projectors can be characterized like monitors as long as care is taken to compensate for their high black level. Finally, it will describe the effect of the white segment on the DLP projector gamut and characterization, and discuss possible strategies for compensating for it efficiently.

Figure 1: A 4x3 projection array, the Stanford Interactive Mural. Displayed are images, sketches, 3D models and a virtual desktop. The user interacts with the content using an eBeam pen

II. Process Overview

The process we propose is similar to any device-independent color management problem [4]. First, create an invertible characterization for each projector that maps from input RGB pixel values to a perceptually based space such as tristimulus values. Then, define the standard gamut for the display. Ideally, this would be contained within all the projector gamuts to avoid gamut mapping. For a homogeneous array of projectors, such a constraint should not be too limiting. Finally, compute the transformation that maps input RGB pixels for a specific projector to the standard gamut. That is, modify the RGB input colors so that "full red," for example, becomes the full red of the standard gamut instead of the full red of the device

If M_d is the transformation from a projector's color intensity values to tristimulus space represented as a square matrix, and M_s is the equivalent matrix for the standard gamut, then $M_s M_d^{-1}$ describes the transformation needed. This assumes, of course, that pixel values are correctly transformed to intensity values and back, which can be done with 1-D lookup tables.

For an interactive display wall, the color balancing must be performed in real time without degrading the system performance. Figure 2.shows the system architecture for the processor cluster that drives the Interactive Mural. Millefeuille acts as the window manager and handles input to the system. Rendering is done on a 32 processor graphics cluster[6]. These processors are connected by a high-speed network, the Myrnet. Twelve of these processors contain graphics cards and are connected to the projectors using a digital video interface (www.ddwg.org).

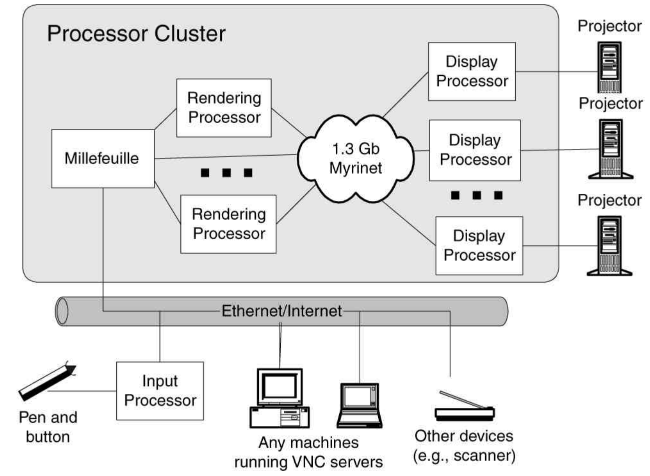

Figure 2: System architecture for the Interactive Mural. Color balancing would best be implemented in the display processors

At the level of Millefeuille and the higher levels of rendering in the cluster, the Mural is treated as a single, large display surface (roughly 4000 x 1500 pixels). Logically, color balancing should occur in the display processors, as this is the point in the system where the image is split into individual projected tiles. Modern high-performance graphics card such as the NVidia G-Force 2 (www.nvidia.com) should have sufficient power and flexibility to implement the matrix multiply and table lookup described above

III. Characterizing LCD projectors

The previous version of the Interactive Mural used eight, NEC MT1030 projectors, which use three liquid crystal (LCD) imaging elements and a dichroic mirror to split the light in to red, green and blue separations. Such a projector can be characterized like a monitor except that the black level cannot be assumed to be negligible. This black value needs to be subtracted from all color measurements to reveal the basic additive system underneath. Figure 3 shows this effect. The data are the chromaticity coordinates of the three primaries measured at four levels of brightness, from 0.25 to 1.0. The raw measurements, shown as small crosses, shift significantly towards the black point. The open circles are the chromaticity coordinates computed from the same measurements after subtracting the tristimulus value for black (X: 0.657, Y: 0.695, Z: 0.765). These are nearly constant, as would be expected for an additive system.

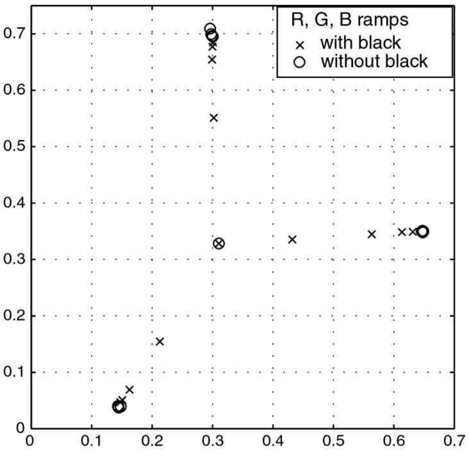

Figure 3: Comparison of RGB ramp data with and without subtracting the black value from the color measurements. Subtracting black produces a nearly constant color for each primary.

Most commercial projectors are optimized for displaying video, so a typical intensity transfer function will be a gamma curve, such as the ones shown in figure 4. These are the result of image processing hardware within the projector, as the native response of the LCD imaging element is nearly linear,

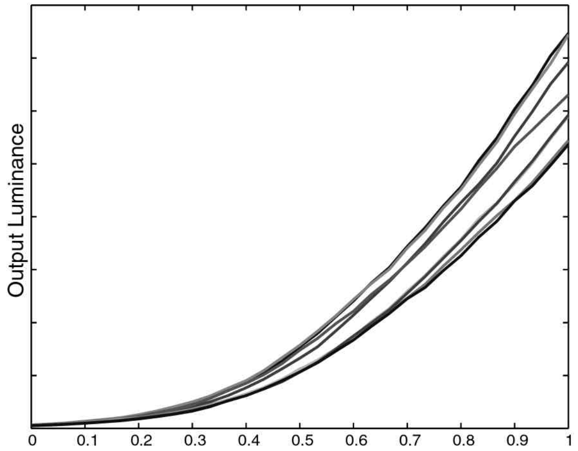

Figure 4: ITFs for eight NEC MT1030 LCD projectors. These curves can be changed by adjusting brightness (raises whole curve) and contrast (raises the maximum value) using the projector menus

More formally, if *p* is an input pixel value, there is a function *ITF*(*p*) that maps p to normalized intensity. Therefore,

$$\begin{aligned} R &= ITF_R(p_R) \\ G &= ITF_G(p_G) \\ B &= ITF_B(p_B) \end{aligned} \tag{1}$$

To compute the matrix, let *c* be the color intensity vector computed from the *ITFs*, $[X_R, Y_R, Z_R]$, $[X_G\ Y_G\ Z_G]$, and $[X_B\ Y_B\ Z_B]$ be the tristimulus values for the primaries, and $t_K = [X_K\ Y_K\ Z_K]$ be the tristimulus values for black. Then the tristimulus values *t* corresponding to c can be computed from:

$$cM + t_K = t$$

$$M = \begin{bmatrix} X_R - X_K & Y_R - Y_K & Z_R - Z_K \\ X_G - X_K & Y_G - Y_K & Z_G - Z_K \\ X_B - X_K & Y_B - Y_K & Z_B - Z_K \end{bmatrix} \tag{2}$$

To convert from CIEXYZ to RGB, invert the matrix and rearrange, giving:

$$c = (t - t_K)M^{-1} \qquad (3)$$

These transformations can be defined as a single 4x4 homogeneous transformation matrix as shown in equation 4, and its inverse.

$$\begin{bmatrix} R & G & B & 1 \end{bmatrix} \begin{bmatrix} X_R - X_K & Y_R - Y_K & Z_R - Z_K & 0 \\ X_G - X_K & Y_G - Y_K & Z_G - Z_K & 0 \\ X_B - X_K & Y_B - Y_K & Z_B - Z_K & 0 \\ X_K & Y_K & Z_K & 1 \end{bmatrix} = \begin{bmatrix} X & Y & Z & 1 \end{bmatrix} \qquad (4)$$

This convenient representation is commonly used in graphics systems and hardware, and can be applied to the process described in the previous section.

IV. Characterizing DLP projectors

DLP projectors, like the Compaq MP 1800 (www.compaq.com) used in the Interactive Mural, are not simple RGB systems because they include a “white” filter on the color wheel. This makes the white about 145% of the sum of the RGB primaries. This can be seen in figure 5 which plots output luminance for an 11-step gray ramp. The input values have been normalized to the summed RGB luminance. This is equivalent to applying the pixel to luminance ITF’s for each primary

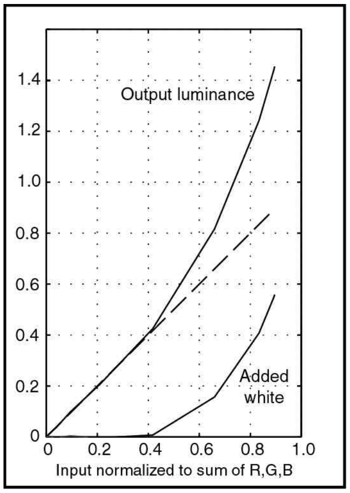

Figure 5: Plot of output luminance vs. summed RGB luminance. The added white increases the output luminance 43%

The algorithm for applying the white filter was published by Texas Instruments in 1998 [6]. The white filter is added in 3 fixed amounts, as shown in figure 6, which was taken from the paper. At each transition point, the RGB values are modified to maintain a smooth luminance ramp without hue shifts. The R, G and B values are not subtracted uniformly. There is a calibration step where the balance of the RGB values is determined to maintain a constant color that matches the sum of the white filter plus the full-on RGB filters. The published specs are variation under 3 ΔE in u*v*, and ΔE in L*.

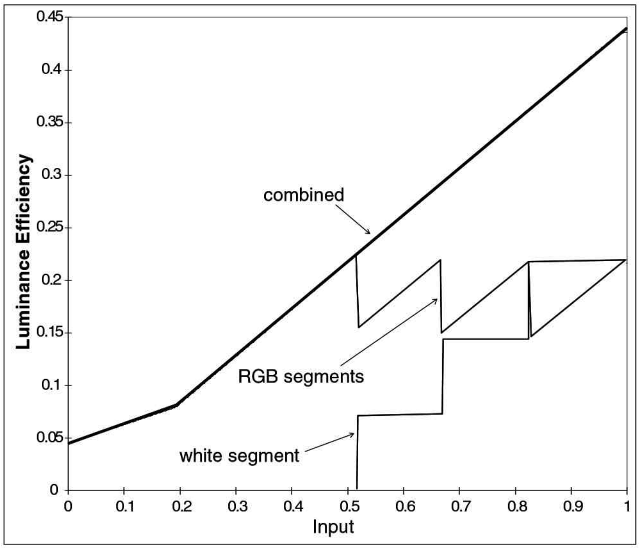

Figure 6: From [6], showing how the white filter is added in steps as the RGB luminance increases

Figure 7 shows an XYZ scatter plot of a full gamut of an MP1800. Each edge of the color cube has been highlighted by overlaying a line plot of the colors at the edge. The white point that would be achieved by summing R, G and B is shown as dashed black lines. The scatter plot is a 9x9x9 array, but the line plots come from an 11x11x11 set of data. The effect of the white segment is clearly visible as an extension of the white point.

These data were taken with an X-Rite DTP92 colorimeter, which is designed to measure monitors. Therefore, the various bumps and wiggles in the figure probably should not be taken as significant. However, the general shape of the gamut reflects what the model predicts: an additive gamut with an extrusion at the white point

Because the clear filter simply adds another additive component, the transformation from RGB to XYZ can be characterized as follows:

$$\begin{bmatrix} R' & G' & B' & W & 1 \end{bmatrix} \begin{bmatrix} X_R - X_K & Y_R - Y_K & Z_R - Z_K & 0 \\ X_G - X_K & Y_G - Y_K & Z_G - Z_K & 0 \\ X_B - X_K & Y_B - Y_K & Z_B - Z_K & 0 \\ X_W - X_K & Y_W - Y_K & Z_W - Z_K & 0 \\ X_K & Y_K & Z_K & 1 \end{bmatrix} = \begin{bmatrix} X & Y & Z & 1 \end{bmatrix} \qquad (5)$$

However, the input R, G and B must be modified using logic that compares the summed luminance to the target luminance, which is indicated by R’, G’ and B’ in equation 5. The logic is published, and is conceptually simple. But, there are parameters that are calibrated for each projector.

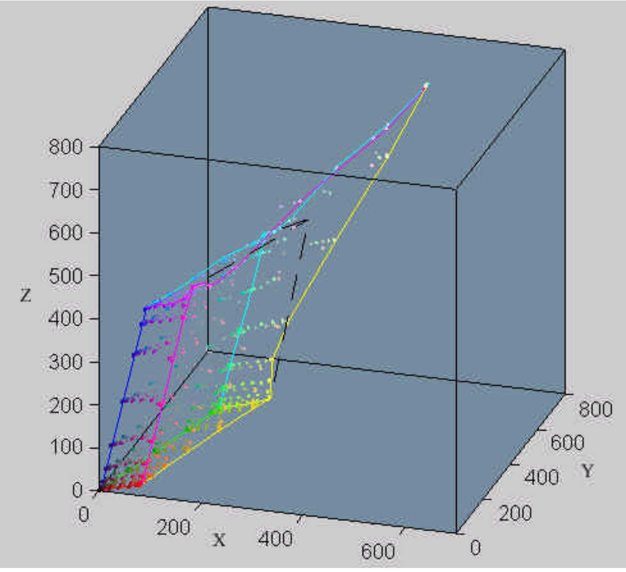

Figure 7: A scatter plot in CIE XYZ tristimulus space of data taken from a Compaq MP1800 projector. The extended white point is clearly visible

Typical ITF's for the MP1800 are shown in figure 8. These are basically gamma curves that roll off at the bright end. Again, these are manufactured curves. Grayscale in a DLP projector is created by pulsing the mirrors, which are binary devices.

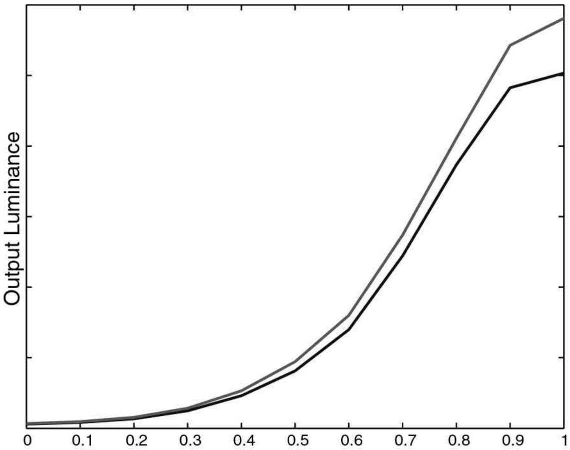

Figure 8: ITFs for two Compaq MP1800 DLP projectors.

Figure 9 is a plot of the spectral distribution for the red, green, blue, black and white light of a DLP projector. The dashed lines show the sum of the R, G, B spectra, plus the difference between this sum and white. Given the similarity between the summed and measured curves, the spectrum of the xenon bulb must be relatively flat.

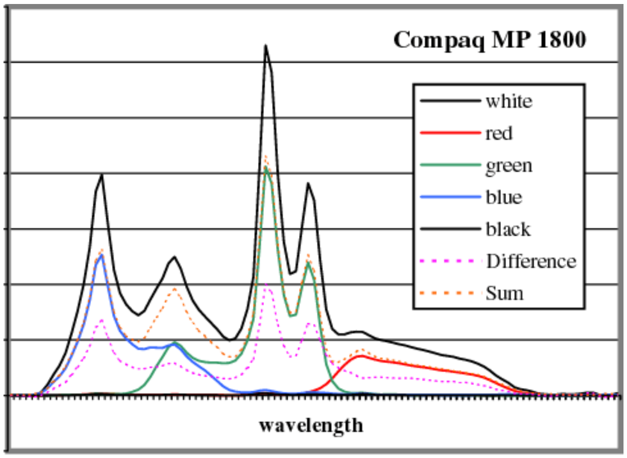

Figure 9: Spectral distribution curves for the Compaq MP 1800

V. Colorimetric Comparison

Figure 10 shows the red, green, blue primary colors plus white plotted on the 1931 CIE chromaticity diagram for both the NEC (small crosses) and the Compaq projectors (small dots). The primary variation in these colors is probably the bulb color, though anecdotally, there is also variation in the filter colors, especially in the red.

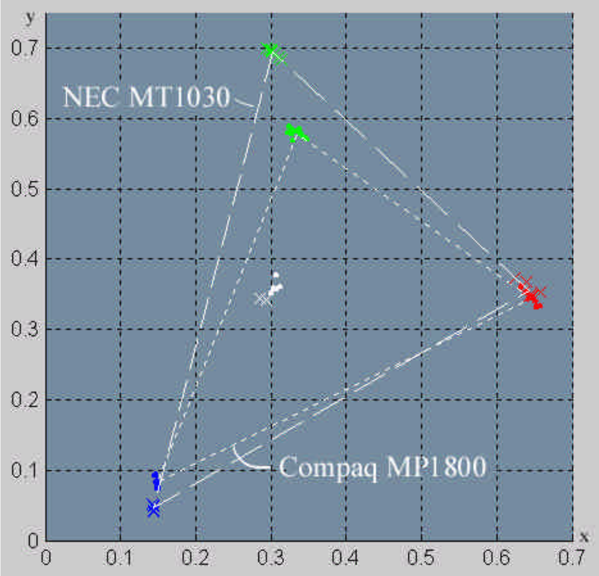

Figure 10: Chromaticity plot of full red, green, blue and white for eight NEC LCD projectors (crosses) and twelve Compaq DLP projectors (dots). The triangles show the average gamuts.

Table 1shows the average deviation for the red, green and blue primaries and white for both types of projectors.

Table 1: Average deviation of the chromaticity coordinates of the primaries and white for both types of projectors.

	Compaq MP1800		**NEC MT1030**	
	x	y	x	y
red	0.0054	0.0057	0.0069	0.0075
green	0.0075	0.0047	0.0054	0.0045
blue	0.0008	0.0049	0.0002	0.0039
white	0.0028	0.0056	0.0039	0.0055

VI. Discussion

The 4x4 matrix model for the LCD projectors is well supported by data. Unfortunately, we were not able to implement it in the previous version of the Mural as there was not enough processing power in the graphics cards of the time. We did balance the R, G, B curves for each projector to give a consistent black and white luminance, and this greatly improved the appearance of the system.

There exist DLP projectors with three imaging elements and dichroic filters like the LCD projectors, though these tend to be much larger than the ones we used in our system. These can be characterized with the monitor model also.[9]

The DLP projectors clearly present more of a challenge. Even if we could accurately implement the model in equation 5, the inverse is not uniquely defined. Also, the white point contains substantial amounts of the bulb color, therefore rebalancing the red, green and blue components may not change it much. Put another way, the gamut is narrow around white. It may be difficult to find a common white point in this narrow region. However, given the small variation between projectors, it might be worth applying the matrix model to provide a first level correction.

A few notes on measurement

The easiest way to measure a back projection display like the Interactive Mural is to use an instrument that can be attached to the screen. The brightness of projection displays varies both spatially and with viewing angle, so an instrument with a lens must be positioned precisely in front of each tile to ensure accurate comparison between each tile. Over a 6’ by 4’ display, this is difficult to achieve without special alignment hardware.

Most instruments that attach to the screen, however, are designed for calibrating monitors. Projection displays are much brighter (around 1000 cd/m2 for the Compaq projectors as we use them) and are spectrally quite different than monitors, as can be seen in figure 9. Comparing the X-Rite DTP92 monitor colorimeter with a PhotoResearch PR-650 spectroradiometer, we have seen errors as large as 50% in the X and 100% in the Z measurements of the colorimeter with respect to the spectroradiometer. The normalized luminance measurements, however, are accurate within 5% over most of the range. Since chromaticity doesn’t vary with viewing angle, we can combine luminance measurements from the colorimeter with chromaticity measurements from the spectroradiometer when comparing projectors.

For most of the measurements needed to characterize the projectors, relative measurements are sufficient. That is, first measure the tristimulus values for black, then subtract that value from all subsequent measurements. This also eliminates any contributions from extraneous light as long as the measurement conditions are kept constant. This is especially convenient for research displays, which are not usually sealed into light-tight “cubes” like commercial systems.

The black measurement in the characterization, however, is an absolute measurement. It is an interesting question what is “correct” for the black in this characterization. The most stable measurement is to measure only the light leaking from the projector when it is displaying “black.” This is achieved by eliminating all ambient light, included that generated by adjacent projectors, before measuring. However, it might be perceptually better to measure the black for normal viewing conditions, possibly even including typical room lighting.

VII. Conclusions

Using small DLP projectors results in a smaller gamut and the characterization problems introduced by the white filter. However, they have superior contrast and substantial size advantages over similarly priced LCD projectors. The smallest DLP projectors are approaching 3 pounds, and advertise a 400:1 contrast ratio. The image is crisp and bright and can easily be viewed with the lights on. Their small size makes it easy to build structures to hold and align them. There is substantial brightness variation, as in all projection displays, but no visible hue variation across the image.

LCD projectors have larger gamuts and a simple characterization model. However, they emit polarized light. If there are any other polarizing elements in the system, this polarization will create visible artifacts. Figure 11 shows a white “X” on a supposedly uniform gray background. The picture exaggerates the colorization slightly, but this problem was clearly visible on the old Mural. This problem is particularly noticeable in our application, where we concentrate the image into a 21” diagonal to achieve near-monitor resolutions. Most projection systems use a 30” to 40” diagonal, and this effect is much less visible.

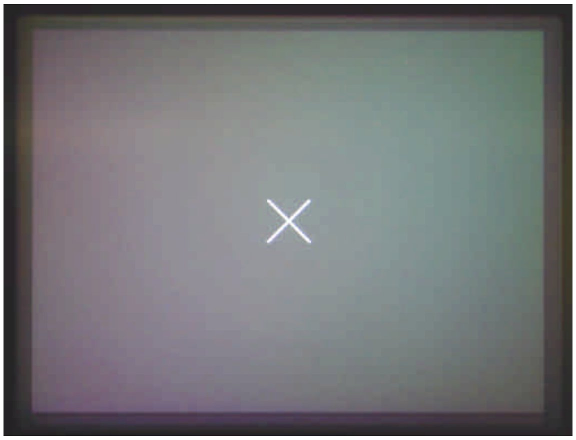

Figure 11: Polarized color “mottle” seen in LCD imaging systems.

The applications of projection displays is growing as digital projectors become smaller, cheaper, and higher quality.

Understanding their color characteristics will become more important as their uses multiply. The best way to characterize single-element DLP projectors is not solved. For the Interactive Mural, we propose to try a variety of partial solutions that would correct the strictly additive portion of the gamut, that is scale and transform the RGB primaries and hope that the white addition doesn't introduce too much error. It is not practical to use a sampled and interpolated representation for the gamut in the imaging pipeline. However, those involved in profile definition and construction may need to investigate more accurate solutions.

VIII. Acknowledgements

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