End-User DLP Projector Colour Calibration

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ABSTRACT

We have analyzed different approaches to calibrating 4-segment Digital Light Processing (DLP) projectors from the perspective of an end-user. A modification is introduced to Wyble and Rosen's[1,2] model that improves its prediction of tristimulus values (XYZ) as a function of input RGB. Tests also show that Tamura, Tsumura, and Miyake's Masking model, which was originally introduced to compensate for channel interaction in LCD monitors, performs as well as the improved Wyble-Rosen model in the forward direction (RGB to XYZ). For predicting RGB values given XYZ input data (backward direction); however, we find that the Masking model is more accurate. All the models considered in this paper involve only basic look-up tables and matrix multiplication and as a result are computationally efficient.

1. INTRODUCTION

An end-user, as opposed to the manufacturer, may well wish to characterize and calibrate a DLP projector in order to control accurately the colours displayed. The end-user's task is complicated by the fact that the precise internal workings of the projector are unknown. This paper provides a method for end-user colour calibration of 4-segment colour wheel DLP projectors.

The primary goal of a colour characterization model is to establish a mapping from digital input values, RGB, to tristimulus values such as CIE XYZ and vice versa. A good characterization model should be fast, use a small amount of data, and allow for "backward" mapping from tristimulus values to RGB. Two common types of projector are Liquid Crystal Displays (LCD) and Digital Light Processing (DLP). A 3x3 linear model[4] is a common approach for calibrating CRT displays and has been shown to work well for LCD projectors as well[5, 6].

DLP projectors achieve increased luminance by adding a white channel to the usual RGB channels found in CRT displays[4]. Introducing the white-filter creates a non-linear relationship between digital input values and tristimulus values[7]. This means a linear model that applies a 3x3 matrix to linearized input values will not predict tristimulus values very accurately. Wyble and Rosen[1,2] introduced a model we will refer to as the WR model that uses a 4x3 matrix to predict XYZ values. In this paper we compare the performance of the WR model with the Masking model which uses a 7x3 matrix[3].

2. WYBLE-ROSEN MODEL

For the case of the forward mapping from RGB to XYZ, the WR model[1,2] starts with linearized (i.e., gamma=1) R, G, B and then introduces a fourth coordinate, W, defined as the minimum of R,G,B. Given RGBW, a 3x4 matrix, M_{3x4}, is used to transform to XYZ space, where the matrix is defined as:

$$M_{3x4} = \begin{bmatrix} X_R & X_G & X_B & X_W \\ Y_R & Y_G & Y_B & Y_W \\ Z_R & Z_G & Z_B & Z_W \end{bmatrix} \quad (1)$$

The entries of M_{3x4} are measured tristimulus XYZ values for full red (i.e., (255,0,0)), full green, full blue and white. The values are corrected for black by subtracting the contribution of the residual light when R=G=B=0 from the measured XYZ.

The inverse WR model, converting XYZ to RGB, is too detailed to explain here beyond the basic idea involved. The strategy is in the first stage to ignore W and simply use a 3x3 matrix M_2, which is the inverse of the first part of M_{3x4}, to map XYZ to RGB. Some of the resulting RGB are likely to lie outside the device's range because of the white filter effect. The second step is to assign a W component based on the minimum of the RGB values. The corresponding white component (W,W,W) is removed from the initial XYZ. These white-removed XYZ are modified using a look-up table and then mapped directly to the final RGB by again using M_2.

3. MODIFIED WYBLE MODEL

In the WR forward model, the matrix M_{3x4} is based on the 4 measured XYZ triples given the 4 RGB settings. A simple modification is to solve for M_{3x4} based on a least-squares fit between linearized RGBW and XYZ over a much larger set of measurements. Least-squares has previously been used to calculate transformation matrices for calibrating monitors[4]. In the Results section we show that this simple modification does reduce the error.

4. MASKING MODEL

The Masking model[3] was originally introduced to overcome the problems caused by the interaction between colour channels that is commonly found in LCD displays. The Masking model approach bears some similarity to under-colour removal when printing. The original digital input values d_i (i=1,2,3 for RGB) are converted to masked values m_i (i=1,2,3,4,5,6,7 for RGBCMYK). The masked values then are combined in a manner similar to that for the Linear Model[5, 6]. The masking operation involves 'primary' colours (R,G,B), 'secondary' colours (C,M,Y) and the 'under' colour (K) and is defined as follows:

$$\begin{aligned}
&\text{Set primary colour index } p \text{ such that } d_p = \max(d_1, d_2, d_3) \\
&\text{Set under colour index } k \text{ such that } d_k = \min(d_1, d_2, d_3)\ \&\ k \neq p \\
&\text{Set secondary colour index such that } s = k + 3 \\
&\text{Assign primary colour mask value } \ m_p = d_p \\
&\text{Assign secondary colour mask value } \ m_s = d_{6-p-k} \\
&\text{Assign under colour } \ m_7 = d_k \\
&\text{Zero remaining values } \ m_{q \notin \{p,s,7\}} = 0
\end{aligned} \qquad \textbf{(2)}$$

The result of the masking operation is to set p to the index of the maximum primary colour (R, G, or B), and map to the input value for that colour. It assigns s to index the secondary colour (C, M, or Y) that contains none of the minimum colour, and assigns m_s to the middle one of the original values. Finally, it sets the under colour value m_7 to the minimum of the original R, G, and B. For example, if the original input is RGB=(200,100,50), the primary colour will be red, with a value of 200. The secondary colour will be yellow (which does not contain blue) with a value of 100, and the grey (under) colour will have a value of 50. The masked input array becomes m=[200,0,0,100,0,0,50].

Once the inputs have been converted into masked values m_i, a linearization function $C_i(m_i)$ for each input channel i is determined to linearize individual R, G and B counts as a function of tristimulus values. The transformation from masked input RGBCMYK to XYZ output can then be written as follows:

$$XYZ_{est} = \begin{bmatrix} P_p & P_s & P_7 \end{bmatrix} \cdot \begin{bmatrix} C_p(m_p) - C_p(m_s) \\ C_s(m_s) - C_7(m_7) \\ C_7(m_7) \end{bmatrix} \quad (3)$$

The backward mapping from XYZ to RGB requires knowledge of the primary and secondary colour indices *p* and *s*. There is no way to know these values, so all six possible (*p, s*) combinations are tested (RM, RY, GC, GY, BC, BM) and any combination that satisfies the following conditions will yield the correct result.

$$255 \geq m_p \geq m_s \geq m_7 \geq 0 \quad (4)$$

5. RESULTS

The error in predicting XYZ from RGB will be described in terms of the ΔE_{94} difference between the measured and predicted XYZ values. The test data set is based on measuring the XYZ output corresponding to 2700 distinct RGB inputs. Two DLP projectors were measured. All data used in this study was collected using a Photo Research SpectraScan 650 Spectrometer in a dark room with the spectrometer aimed perpendicularly at the center of the screen from a distance of 2 meters. The data collection was performed automatically in large, randomized test suites. For each RGB setting, the XYZ was recorded as the average of a total of 25 measurements taken in 5 randomly scheduled bursts of 5 measurements each.

The left hand part of Table 1 shows the forward RGB-to-XYZ error for the three models. Both the modified WR model and the Masking model are quite accurate. Since modified WR requires a smaller matrix transformation (3x4 rather than 3x7), it is perhaps more desirable over all.

The backward (XYZ-to-RGB) errors are also compared in Table 1. The Masking model outperforms the WR model in the backward direction. Calculation of the backward error is complicated by the fact that since we cannot step through XYZ values in the way we can step through RGBs to send to a device, we do not have direct XYZ-to-RGB measurements. To make use of the available RGB-to-XYZ pairs in computing the backward error, we first do the XYZ-to-RGB prediction, then apply the forward model to the predicted RGB to get new XYZ. The ΔE_{94} difference between the input and predicted XYZ is calculated and then adjusted by subtracting the average error caused by forward model.

		Forward			**Backward**	
		WR	**Modified WR**	**Masking**	**WR**	**Masking**
	Mean	3.27	1.04	1.01	2.12	.354
DLP-Toshiba	**Max**	11.57	3.44	3.53	9.53	4.45
	Std	3.42	.63	.774	6.05	.584
	Mean	4.18	.814	.871	4.14	.3264
DLP-Infocus	**Max**	12.00	3.34	3.376	26.12	2.75
	Std	4.54	.453	.998	5.73	.346

Table 1: Forward (RGB-to-XYZ) and backward (XYZ-to-RGB) prediction error expressed in ΔE94 for two DLP projectors based on 2700 RGB-XYZ measurements. Mean, Max and Std represent the average, maximum, and standard deviation of the ΔE94 errors.

From the above results, we conclude that both the modified WR and Masking models are accurate forward models, while the Masking model is the better choice as a backward model.

6. CONCLUSIONS

We compared possible spaces in which DLP calibration could be applied and we found that the RGBW and RGBCMYK spaces derived from RGB space can predict tristimulus values well. The WR model[1,2] uses a 4x3 matrix to predict XYZ from RGB. A simple modification to this model improves its accuracy significantly. The Masking model[3], which was originally designed for LCD characterization, uses a 7x3 matrix and results in roughly the same performance as the modified WR model in terms of predicting XYZ from RGB. Although it has the disadvantage of being based on more parameters, the Masking model has the advantage that its error appears to be distributed more uniformly than the modified WR model. Furthermore, in the reverse direction—predicting RGB from XYZ—the Masking model performs much better than the WR model.

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