Characterisation of a LED Panel

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ABSTRACT

A two-stage characterisation model between the input current values and the device CIE tristimulus values was derived for an LED panel. The first stage was a non-linear transformation to correlate normalised current values to device dependent RGB values. The second stage involved a polynomial transformation, where the device dependent RGB values were transformed to device independent CIE tristimulus values. By using the model, a colorimetric characterisation accuracy of less than 1 ΔE^*_{ab} unit was achieved.

1. INTRODUCTION

For many applications such as signals, displays, traffic lights or task lighting, especially where directional light sources are required, , the potential for Light Emitting Diodes (LEDs) appears to be promising. Compared to traditional light sources, LEDs have several significant advantages which include efficiency, small size, low voltage, durability and long life. Hence, several kinds of LED displays have been developed and for both indoor and outdoor use. In order to control such displays precisely, it is essential to understand the relationship between input lighting and output signals. The characterisation of LED displays is, however, quite different from cathode-ray tube (CRT) [1] and liquid-crystal display (LCD) [2] devices and is still not well established. The aim of this study is to build a relationship between the input current values to the LED panel and the device independent CIE XYZ values via device-dependent RGB values.

In practice, it is required not only a transform from input current values to *XYZ* but also from *XYZ* to input values. The former transform is called the Forward Model, the latter the Reverse Model. A polynomial transformation was also developed for the reverse model.

2. EXPERIMENTAL DESIGN

A LED panel for mixing monochromatic red, green and blue LEDs was built. The monochromatic red, green and blue LEDs were fixed symmetrically around the centre in the proportion of 3:1:2. LEDs with the same colours were built in the same cluster channel and each channel was controlled by adjusting the electrical current (i_v, v=r, g, b) to obtain output luminance signals (RGB). The panel was then placed inside an integrating sphere as shown in Figure 1. Chromaticity coordinates (x, y) and luminance (L) values of the LED colours controlled by electrical currents (i_r, i_g, i_b) were measured using a PhotoResearch PR650 telespectroradiometer. The measurement geometry was D/0 with a viewing field of 2°. The current, i_v, for each channel varies from 5-40 mA at a 5 mA interval. Therefore, 512 different tristimulus values were

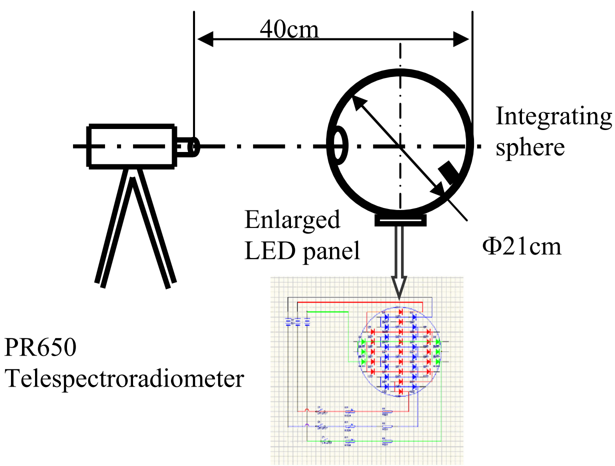

Figure 1 LED panel measured by PR650 telespectrophotometer

measured corresponding to the 512 sets of electrical currents (i_r, i_g, i_b). The x, y and L corresponding to the maximum current, 40 mA, for each channel were transformed to the tristimulus values X_W, Y_W and Z_W with Y_W normalised to 100.

Figure 2 shows the scaled RGB normalised values versus scaled currents i_r, i_g and i_b. The shape resembles a power function with an exponent of less than 1. Thus, the shapes of the curves are opposite to those of CRTs[1] and also different to LCDs[2]. For the CRT, the luminance output of each channel increases as a power function (with the power greater than 1) of the input voltage, which can be modelled very accurately. For the LCD, the curves often have an S shape and can be modelled very precisely by using an S-curve model. It is clear that neither the GOG model (which is commonly applied to CRT-based displays) nor the S-Curve model (used for LCD displays) can be applied to LED panels.

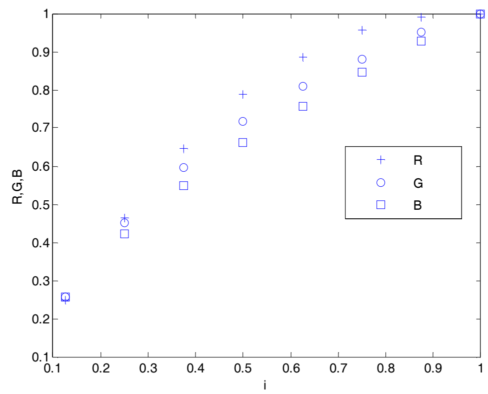

Figure 2 A graph of normalised RGB against electrical current

3. DEVELOPING FORWARD LED MODELS

The additivity properties of the LED panel was first examined by investigating the relationship between the luminous output (Lm) from a mixed colour and the sum of luminous outputs (Lr+Lg+Lb) from each individual channel. Figure 3 shows this relationship. It can be seen that all data points are consistently above the 45º line. This indicates a consistent deviation from channel additivity of about 2%. This is caused by the fact that when the three coloured LED clusters were combined together, there were cross effects between each channel and so some luminance was lost.

The parameters were determined by minimising the value of S as given in equation (1):

$$S = \sqrt{((L_r + L_g + L_b) - Lm)^2} \qquad (1)$$

where L_r, L_g, L_b are the luminance output values of the red, green and blue LED clusters respectively. Lm is the luminance output value of the mixed colours, calculated according to equation (2):

$$\text{Lm} = L_r + 0.97\,L_g + 0.85\,L_b \qquad (2)$$

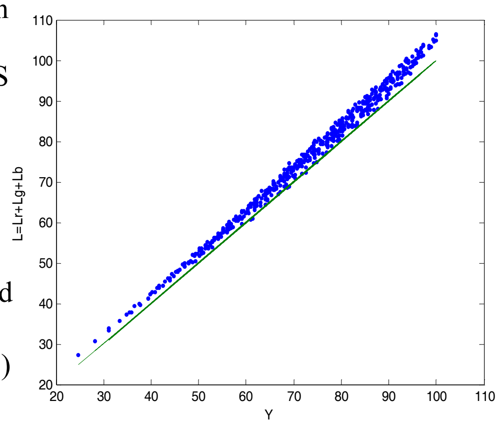

Figure 3 The sum of luminance output of each channel against that of mixed colour

Furthermore, for the Forward Models, similar to the CRT and LCD displays, three two-stage models were developed to transform the normalised electrical currents (i_r, i_g, i_b) via normalised (*RGB*) to CIE tristimulus values. The first stage was a non-linear transform to convert normalised current values to device dependent *RGB* values. The second stage was a transform where the device dependent *RGB* values were transformed to device independent CIE XYZ.

Three models were developed and are displayed below:

Model I:
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}, \quad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} i^{\alpha_r} \\ i^{\alpha_g} \\ i^{\alpha_b} \end{bmatrix} \qquad (3)$$

Here, motivated by the shapes of the curves in Figure 2, the normalised RGB values were determined from the normalised electrical current values i_r, i_g and i_b using a power function with the factors α_r, α_g and α_b less than 1. Model I is based on the assumption that the ultimate output from the LED panel is simply the mixture of the outputs from each channel, i.e. the three channels have no cross effects.

Model II: $$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}, \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} i^{\alpha_r} \\ i^{\alpha_g} \\ i^{\alpha_b} \end{bmatrix} + \begin{bmatrix} b_{14} \\ b_{24} \\ b_{34} \end{bmatrix} \quad (4)$$

Compared to Model I, the cross effects were observed in Model II according to equation 2. The b_{ij} coefficients were determined by using the least-squares method.

Model III: $$\begin{aligned} X &= \sum_{0 \le j_1+j_2+j_3 \le n} a_{X,j_1,j_2,j_3} R^{j_1} G^{j_2} B^{j_3} \\ Y &= \sum_{0 \le j_1+j_2+j_3 \le n} a_{Y,j_1,j_2,j_3} R^{j_1} G^{j_2} B^{j_3} \\ Z &= \sum_{0 \le j_1+j_2+j_3 \le n} a_{Z,j_1,j_2,j_3} R^{j_1} G^{j_2} B^{j_3} \end{aligned} , \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} i^{\alpha_r} \\ i^{\alpha_g} \\ i^{\alpha_b} \end{bmatrix} + \begin{bmatrix} b_{14} \\ b_{24} \\ b_{34} \end{bmatrix} \quad (5)$$

Model III was derived based on a polynomial characterisation model,[1] where n is the polynomial order. Once the coefficients of $a_{X,j_1,j_2,j_3}, a_{Y,j_1,j_2,j_3}, a_{Z,j_1,j_2,j_3}$ are determined, then for any given RGB signals, the corresponding CIE tristimulus values XYZ can be found using equations (5).

To determine the coefficients of $a_{X,j_1,j_2,j_3}, a_{Y,j_1,j_2,j_3}, a_{Z,j_1,j_2,j_3}$, the measured 512 data pairs were divided into two sets. One was the training set, and the other the testing set. For Model III, different orders of the polynomial were tried to obtain the best results. The optimum result with less than 1 ΔE^*_{ab} unit can be obtained when n is 3.

In this research, Models I, II and III were used to predict the tristimulus values XYZ which corresponded to a set of input current values. CIELAB colour differences between the measured and predicted colours were employed to evaluate the performance of different models.

Table 1 gives the maximum, mean and median colour differences from models I and II; Table 2 gives the maximum, mean and median colour differences from model III using different orders.

	Maximum ΔE^*_{ab}	Mean ΔE^*_{ab}	Median ΔE^*_{ab}
Model I	27.70	8.92	7.82
Model II	33.72	7.93	6.20

Table 1: CIELAB colour difference for Model I and Model II

	Training Data			Testing Data		
n	Maximum ΔE^*_{ab}	Mean ΔE^*_{ab}	Median ΔE^*_{ab}	Maximum ΔE^*_{ab}	Mean ΔE^*_{ab}	Median ΔE^*_{ab}
1	15.64	5.11	4.52	17.47	5.26	4.85
2	4.66	1.97	1.83	12.29	2.30	1.99
3	2.61	0.79	0.63	11.55	1.13	0.91
4	2.01	0.52	0.43	103.94	15.14	12.22

Table 2: CIELAB colour difference for $3 \times$ n polynomial transfer matrices

Among the three models, Model I is considered to be the worst. However, Model II is better than Model I mainly because it took into consideration the cross effect between each channel. It is obvious that Model III performed better than both model I and model II in respect of the CIELAB colour differences, since those colour differences are much smaller than those of models I and II. Furthermore, the performance of the method improved with an increase in order n, and the largest improvement was found when the n was 3. The average CIELAB colour differences can be as small as 0.79 and 1.13 for training and test data respectively.

Despite this, many parameters can affect the performance of the polynomial models such as the number and distribution of reference and test samples.

4. REVERSE LED MODEL

In practice, transformations are needed not only from input current to *XYZ* values but also from *XYZ* to input values. Given tristimulus values, *XYZ*, we seek to find the normalised input current values i_r, i_g, i_b. In this research, polynomial transformation was also employed for the reverse model:

$$
\begin{aligned}
R &= \sum_{0\le j_1+j_2+j_3\le n} a_{X,j_1,j_2,j_3} X^{j_1} Y^{j_2} Z^{j_3} \\
G &= \sum_{0\le j_1+j_2+j_3\le n} a_{Y,j_1,j_2,j_3} X^{j_1} Y^{j_2} Z^{j_3} \\
B &= \sum_{0\le j_1+j_2+j_3\le n} a_{Z,j_1,j_2,j_3} X^{j_1} Y^{j_2} Z^{j_3}
\end{aligned}
,\quad
\begin{bmatrix} f_r(i) \\ f_g(j) \\ f_b(k) \end{bmatrix} = A^{-1} * \left[\begin{bmatrix} R \\ G \\ B \end{bmatrix} - \begin{bmatrix} b_{14} \\ b_{24} \\ b_{34} \end{bmatrix} \right],\quad
\begin{cases} i_r = R^{-\alpha_r} \\ i_g = G^{-\alpha_g} \\ i_b = B^{-\alpha_b} \end{cases}
\qquad (6)
$$

Here matrix A has been determined using the coefficients b_{ij} in Model II, and α_r, α_g and α_b have been determined from Model I. Then, for any required XYZ values, the corresponding input electrical current values i_r, i_g, i_b can be calculated according to equation (6).

The performance of the Reverse Model was tested using the same strategy as before. The calculated electrical current values i_r, i_g and i_b were used to predict the corresponding XYZ values via Model III. CIELAB colour differences between the measured and predicted colours were employed to evaluate the performance of the reverse model. As with the Forward Model, the best performance of the Reverse Model was achieved when n was 3. This time, the colour difference was 1.78, which is considered as not very satisfactory.

	Maximum ΔE^*_{ab}	Mean ΔE^*_{ab}	Median ΔE^*_{ab}
Reverse Model (n=3)	8.77	1.78	1.53

Table 3: CIELAB colour difference for the Reverse Model (n=3)

5. CONCLUSIONA LED panel for mixing monochromatic red, green and blue LEDs was built. The chromaticity coordinates (x, y) and luminance (L) values of the colours of the LED panel were measured using a PR650 telespectroradiometer for input currents ranging from 5-40 mA at intervals of 5mA. For the Forward Model, three two-stage models were considered for transforming the normalised electrical currents values (i_r, i_g, i_b) to the CIE tristimulus values (XYZ). Each model was evaluated by calculating CIELAB colour differences between the measured and predicted colours. It was found that the polynomial models had the best performance compared to the other two models, especially when the order, n, was 3. For the Reverse Model, the polynomial transformation was also employed and it had the best performance when the order was 3.

References

1. R.S. Berns, RJ Motta and ME Gorzynski, "CRT colorimetry, part I:, theory and practice," Color Research and Application 18(1993), 299-314.
2. Y. Kwak and L. MacDonald, "Characterization of a desktop LCD projector," Displays 21(2000), 179-194.
3. C.J. Li, G.H. Cui and M.R. Luo, "The accuracy of polynomial models for characterizing digital cameras," AIC conference, Bangkok, Thailand, 2003.