Characterisation of LCD and DLP Projection Displays

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Abstract

Successful colour management of projection systems depends on knowledge of their characteristics. In this study, two typical portable projectors have been characterised. The two projectors are based on different technologies, Liquid Crystal Display (LCD) and Digital Light Processing (DLP). Measurements were made with a spectroradiometer.

The LCD projector showed good colour additivity. The luminance difference between the sum of primaries and white was 0.33% after correction of the black level. The corresponding value for the DLP projector was 56%. This is due to a non-filtering segment in the filter wheel.

The inter-channel dependency was calculated. The LCD projector showed good independence. For the DLP projector, the additional segment complicates the interpretation of the calculated values.

Measurements of the signal input-output relationship have been made. The LCD projector showed a power function response, while the DLP projector showed an S-shaped response. Neither of these are native responses of the projectors, so this is probably a deliberate design.

The chromaticity changes of primary colours and grey depending on the input signal were measured. The chromaticity constancy was poor for both projectors. It was shown that the relatively high black luminance is the dominant reason for this.

The spatial uniformity was surprisingly poor. Measurements revealed uniformities down to 20% and 30% for the DLP and the LCD projector, respectively.

Our tests showed that both the intensity and the colour of the background influenced the displayed colour. The average colour differences were found to be ΔE^*_{ab}=4.83 for the LCD and ΔE^*_{ab}=2.94 for the DLP projector.

1. Introduction

In recent years, rapid advancements for projection systems have been made. Improved image quality, especially higher resolution and luminance, along with size and weight reduction have widened the areas of application outside the traditional electronic presentation. Entertainment, advertising, and information are some new important areas.

Portable projection systems are typically based on either liquid crystal display (LCD) or digital light processing (DLP) technology. The heart of the DLP technology is the digital micromirror device (DMD); essentially a 2D-array of fast movable micromirrors. The LCD technology has been available for many years, whereas the more recent DLP technology was introduced by Texas Instruments in 1996.

The substantial increase in use of projection displays makes colour management of different types of projectors an important issue. For colour management to be possible, a consistent and standardised method of characterisation must be established. The International Electrotechnical Commission (IEC) has started this work and published a working draft for characterisation of LCD, DLP and cathode ray tube (CRT) based projection systems.[1] Relevant information has also been published by Video Electronic Standards Association (VESA).[2]

There have been few reported characterisations of LCD and DLP based projectors.[3, 4, 5] In the present study, an LCD and a DLP projector were characterised using mainly the methods suggested by the IEC draft.

The equipment and conditions used in this study are given in the following section. In Section 3 some key results are presented and commented, and in Section 4 conclusions are drawn.

2. Experimental setup

The two projectors tested in this study were the ASK C6 Compact and the DAVIS DP X16. The LCD projector from ASK has a panel of three polysilicon LCDs, and exhibits a luminance of 900 ANSI lumens. The DLP projector from DAVIS is a single-chip DMD, and uses a revolving wheel with filters to produce colours. It exhibits a luminance of 1000 ANSI lumens.

The choice of projection screen will have a large effect on the colour performance. A standard diffuse screen from Projecta was used. Using a perfect diffuser as a reference, the spectral reflectance of the screen at normal incidence was measured, see Figure 1. A reflectance larger than unity indicates that the screen is partially specularly reflecting, since the reflection coefficient of the screen is substantially lower than that of the perfect diffuser.

The measurement conditions given below were adopted from the IEC draft except otherwise noted.

The measurements were performed in a dark room with standard indoor conditions (temperature/humidity). A minimum of one hour warm-up time preceded any measurement and the projector was connected to a line voltage stabiliser.

Preset positions of contrast, brightness and other adjustable parameters were used. The image diagonal was set to 102 cm (40 inches) as recommended by Microsoft.[6] Colour patches of size $h/5 \times h/5$ (h is image height) prepared in PowerPoint were displayed at the centre of the screen. The distance between the screen and the spectroradiometer was about $3h$ as recommended by Kwak *et al.*[3]

The spectroradiometer used was a PR-650 from PhotoResearch.

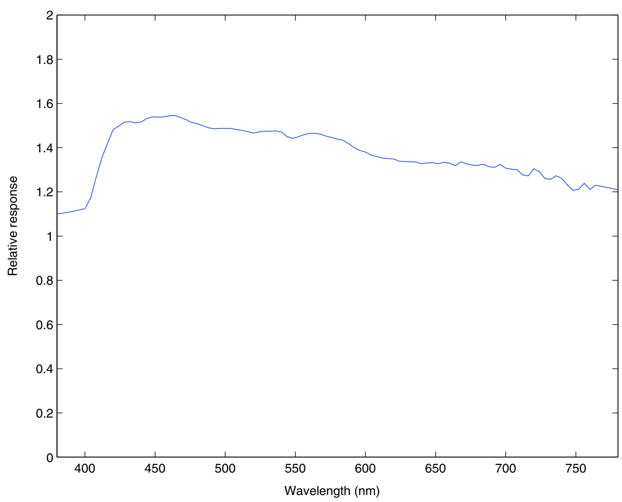

Figure 1: Relative spectral reflectance of the screen at normal incidence compared to a perfect diffuser.

3. Experimental results and discussion

The IEC draft suggests assessment of a total of nine different properties for an LCD projector, spectral characteristics and the intensity of the primary and white colours, basic colorimetric characteristics, inter-channel dependency, tone characteristics, colour tracking characteristics, spatial non-uniformity, dependency on background, temporal stability and viewing angle characteristics. It also gives an outline of how to present the results. All properties except viewing angle dependency were measured in this study. A complete presentation in this paper would be too comprehensive, but the main findings are presented in the following sections.

3.1. Spectral and basic colorimetric characteristics

The spectral radiance distributions for full primary colours and full white are shown in Figure 2. Table 1 shows absolute tristimulus values and chromaticity coordinates for the same colours and black, and also the correlated colour temperature for white.

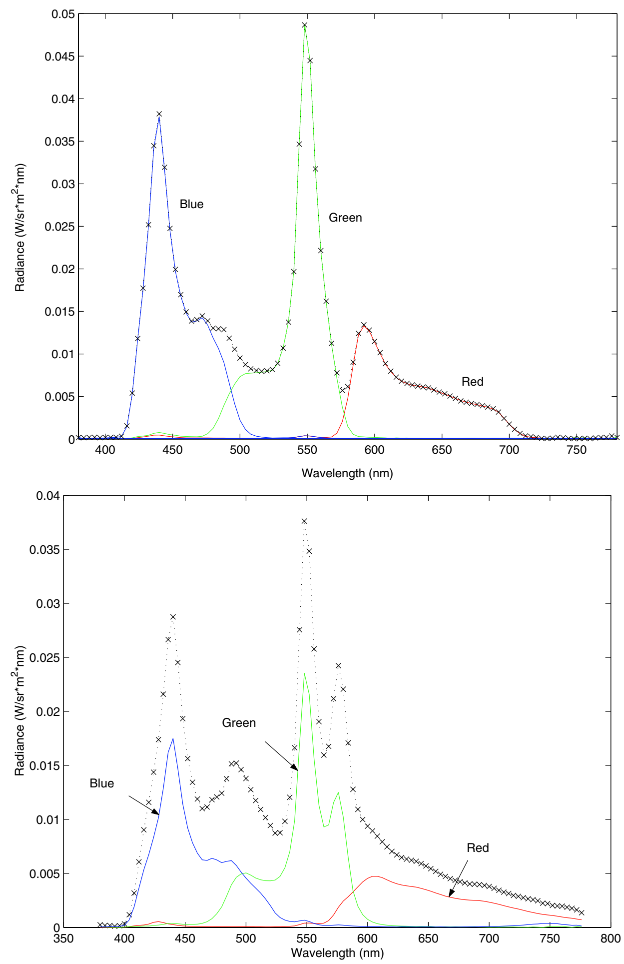

Figure 2: Spectral radiance distributions for full colours red, green and blue for the LCD (top) and the DLP projector (bottom). The lines with cross markers represent white.

For the LCD projector the primary colours approximately add up to white. The luminance difference is 1.8%, and if we correct for the black level, which contributes three times to the sum of the primaries and only once to white, we get a difference of 0.33%, which is comparable with results found elsewhere.[3,4] The difference remaining after correcting for the black level is caused by interchannel dependency. However, for the DLP projector the

Table 1: *Absolute tristimulus values, chromaticity coordinates and correlated colour temperature for white for the LCD (top) and the DLP projector (bottom).*

Colour	X	Y(cd/m^2)	Z	x	y
Red	373.0	226.2	16.21	0.6061	0.3676
Green	357.4	829.2	84.73	0.2812	0.6522
Blue	248.4	66.09	1321	0.1519	0.0404
White	960.2	1101	1392	0.2781	0.3188
Black	7.923	8.413	14.96	0.2532	0.2688
Correlated colour temperature for white: 8906 K					

Colour	X	Y(cd/m^2)	Z	x	y
Red	181.2	109.1	14.35	0.5948	0.3581
Green	310.9	561.5	69.08	0.3302	0.5964
Blue	132.6	77.42	672.5	0.1503	0.0877
White	1002	1154	1198	0.2988	0.3442
Black	3.982	4.428	5.783	0.2816	0.3120
Correlated colour temperature for white: 7111 K					

corresponding value is about 56% after correction of the black level. This is due to a non-filtering segment in the filter wheel which increases the overall system luminance.[5] This makes characterisation and colour management more complicated.

3.2. Inter-channel dependency

A model for the relationship between input data and tristimulus values of the displayed colours is defined in Equation (1).

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \mathbf{ST} \begin{pmatrix} 1 \\ R' \\ G' \\ B' \\ R'G' \\ G'B' \\ B'R' \\ R'G'B' \end{pmatrix} \qquad (1)$$

The 3×3 matrix $\mathbf{S}$ gives the dominant relation, and the 3×8 matrix $\mathbf{T}$ gives the cross-channel relations among the primaries. The terms in $\mathbf{T}$ contain contributions from each individual channel (1^{st} order), from the combination of two channels (2^{nd} order) and from the combination of all three channels (3^{rd} order). The prime symbolises that the values are normalised.

A set of 32 colour patches containing grey levels, primary and mixed colours were measured to find the inter-channel dependency using regression as described by the IEC draft,[1] and the results are presented in Equation (2).

The elements in $\mathbf{T}_{\mathrm{LCD}}$ seem reasonable with values close to unity along the 1^{st} order diagonal. The calculation was repeated with the black level subtracted from all measurements. This gave significantly smaller values for the inter-channel elements than those reported in Equation (2). The $\mathbf{T}_{\mathrm{DLP}}$ matrix is more difficult to interpret. It is not clear whether the method used here for calculation of inter-channel dependency is relevant for projectors with a non-filtering segment.

3.3. Tone characteristics

The relationship between input and output signal was found for the three primary colours by measuring a set of 32 patches, equally stepped in PowerPoint, for each colour. The results are presented in Figure 3. The IEC draft suggests that the plots should be presented with logarithmic scales for the LCD projector, but following Kwak *et al.*[3] our data is shown on a linear scale. Logarithmic plots are convenient for CRT displays which show a power function-like response, and although some projectors are implemented to resemble CRT displays, this is not always the case.

Looking at Figure 3 we see that the LCD projector has approximately a power function response. The intrinsic response of the liquid crystal is S-shaped, so this is interpreted as being due to internal processing intended to give the projector CRT-like tone characteristics.[4] The responses are dissimilar for the different channels. This means that the grey scale is not neutral, i.e. a grey colour specified with equal amounts of R, G, and B, exhibits varying hues at varying intensity levels. The primaries reach their luminance maxima before their corresponding the RGB values. This might imply that the preset brightness is set too high.

We note that for the DLP projector, the curves in Figure 3 appear to be S-shaped. The DLP projector has a linear intrinsic signal to light relationship,[7] so this is again a manufactured response. The S-shape response is sometimes implemented in DLP devices since stretching of the mid-range values gives higher detail contrast.[8]

3.4. Colour tracking

The chromaticity changes of the primary colours and grey resulting from different driving levels were found by measuring 8 equi-stepped patches for each primary colour and grey. The results are plotted in $u'v'$ diagrams.

Both projectors show poor chromaticity constancy for the primaries, with the LCD projector being the poorer. This is a common problem for LCD and DLP devices.[5, 9] The chromaticity coordinates drift towards the system black as the drive signal decreases. The reason for this is that unlike CRT devices, LCD and DLP devices have

$$\mathbf{S}_{\mathrm{LCD}} = \begin{pmatrix} 0.3326 & 0.3188 & 0.2206 \\ 0.2017 & 0.7396 & 0.0587 \\ 0.0145 & 0.0756 & 1.1733 \end{pmatrix} \quad \mathbf{S}_{\mathrm{DLP}} = \begin{pmatrix} 0.2862 & 0.3992 & 0.1827 \\ 0.1723 & 0.7211 & 0.1066 \\ 0.0227 & 0.0877 & 0.9262 \end{pmatrix}$$

$$\mathbf{T}_{\mathrm{LCD}} = \left(\begin{array}{r|rrr|rrr|r} -0.0199 & 1.0372 & -0.0074 & -0.0055 & 0.0495 & -0.0007 & 0.0290 & -0.0799 \\ -0.0003 & -0.0086 & 1.0268 & -0.0087 & 0.0106 & -0.0062 & 0.0055 & -0.0286 \\ -0.0052 & -0.0106 & -0.0096 & 1.0521 & 0.0000 & -0.0134 & -0.0086 & 0.0078 \end{array} \right) \tag{2}$$

$$\mathbf{T}_{\mathrm{DLP}} = \left(\begin{array}{r|rrr|rrr|r} 0.1567 & -1.0563 & -1.3939 & -1.9743 & 1.2096 & 1.2249 & 0.2448 & -3.5225 \\ -0.0663 & 1.1288 & 1.4608 & 1.3843 & -0.7151 & -0.7534 & -0.2003 & 3.1490 \\ -0.0857 & 0.0106 & 0.4094 & 0.6455 & -0.5367 & -0.5218 & -0.0868 & 0.8219 \end{array} \right)$$

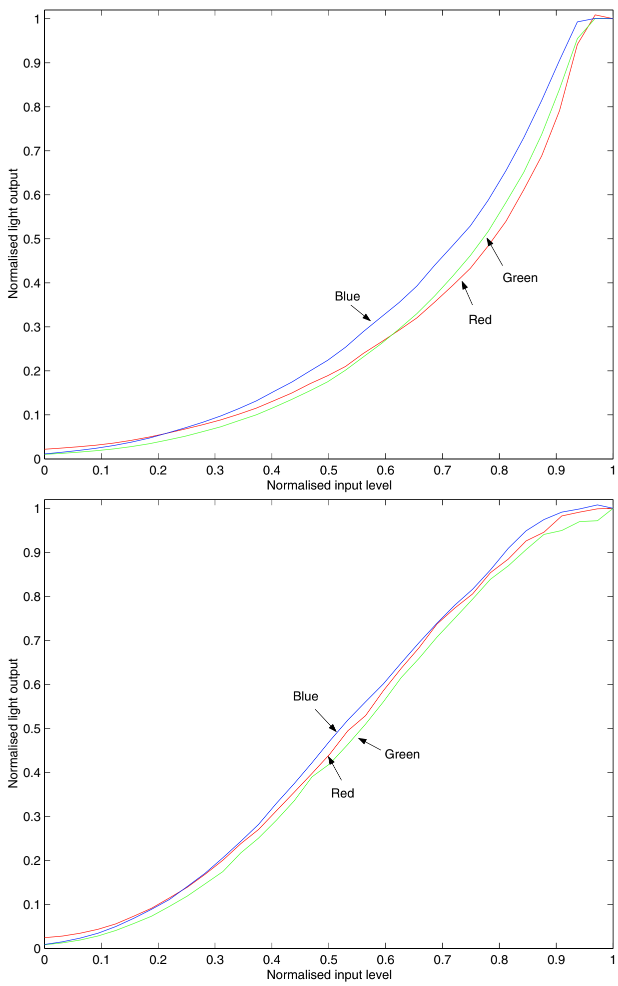

Figure 3: *Output response of the primary colours as a function of the RGB input level for the LCD (top) and DLP projector (bottom).*

relatively high luminance of black. This is caused by leakage of light through the LCD cells for the LCD projector,[4] and by scattering from the mirrors and the substrate between the mirrors for the DLP projector.[7] Subtracting the black level from all measurements significantly improves the chromaticity constancy, as seen in Figure 5. Although the contribution from the black level dominates, there are still some small chromaticity changes present after the correction. Possible explanations may be found in References 4, 11, and 12.

As foreseen in the previous section, there is a shift in the chromaticity coordinates of grey for the LCD projector. The DLP projector has quite similar channel responses giving almost constant grey coordinates.

3.5. Spatial non-uniformity

The spatial non-uniformity was considered by displaying a full white image and measuring the tristimulus values at 25 equally spaced points over the image. The tristimulus values were converted into $\Delta u'$, $\Delta v'$, ΔL^*, ΔC^*_{ab}, and ΔE^*_{ab} using the central point of the image as reference. The average absolute differences are shown in Table 2.

Table 2: *Average absolute colour and luminance differences compared to the centre of the image.*

	$\Delta u'$	$\Delta v'$	ΔL^*	ΔC^*_{ab}	ΔE^*_{ab}
LCD	0.0007	0.0017	12.88	3.474	13.97
DLP	0.0017	0.0039	19.96	2.993	20.13

The poorest luminance uniformity of two compared spots was about 30% for the LCD projector and 20% for the DLP projector. The luminance uniformity is claimed by the manufacturer to be to 85% centre-to-corner for the DLP projector. No such specification could be found for the LCD projector. There is apparently a disagreement between the measured and specified uniformity, but indeed the centre-to-corner specification is very inaccurate. The best centre-to-corner measurement for the DLP projector made in this study was 70%, which agrees much better with the specification.

There may be several reasons for the poor luminance uniformity. In addition to the inevitable system non-uni-

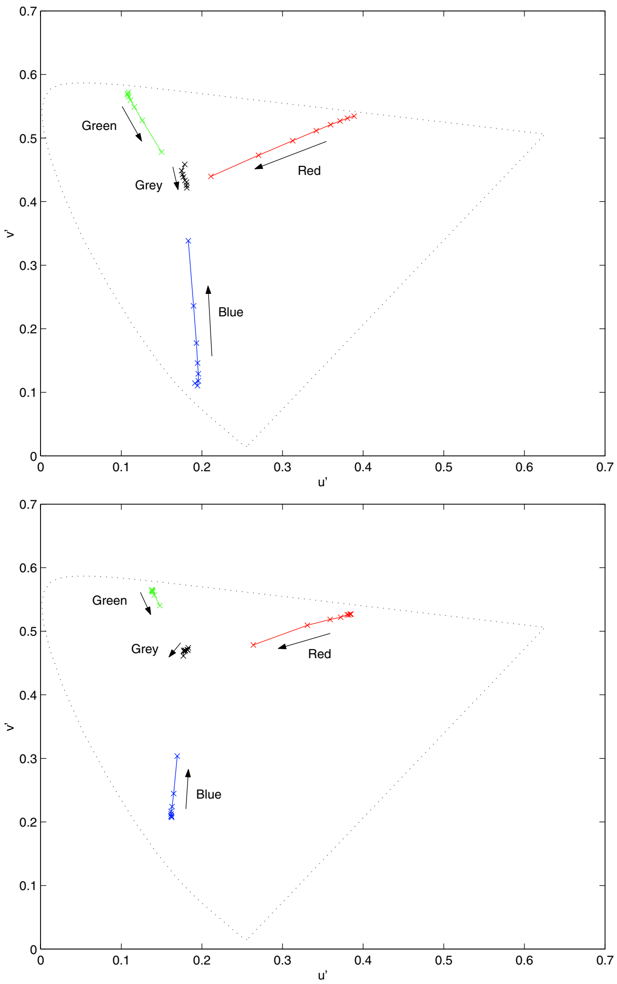

Figure 4: *Changes in colour coordinates of the primary colours and grey due to different driving levels for the LCD (top) and the DLP projector (bottom). The arrows indicate the direction of change with decreasing driving level.*

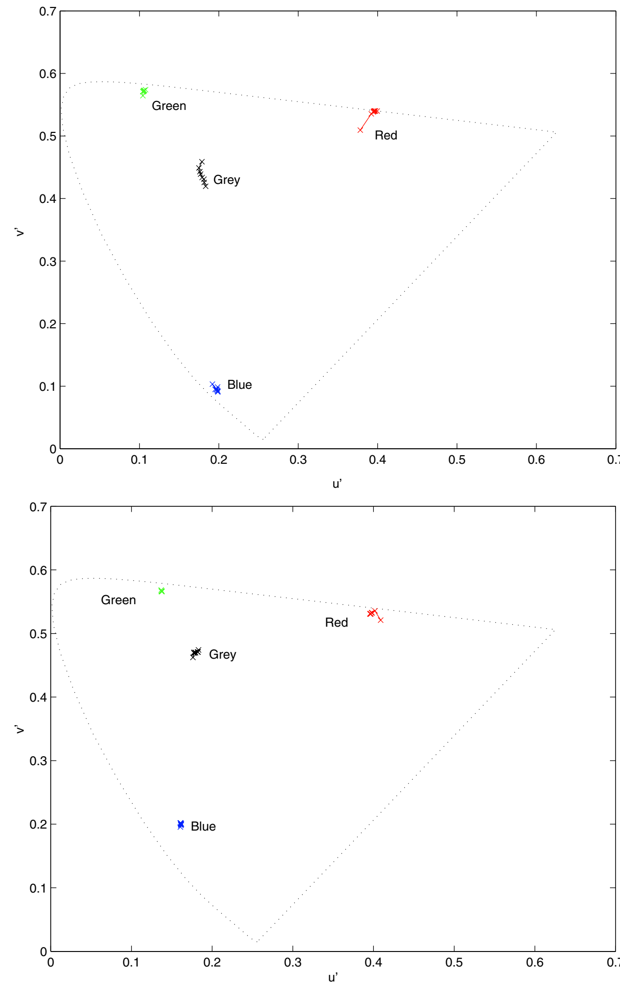

Figure 5: *Changes in colour coordinates of the primary colours and grey due to different driving levels for the LCD (top) and the DLP projector (bottom) after black correction.*

formity, dirt on the lens, screen irregularities, and wear of the projector lamp may influence the uniformity. It is also possible that moving the spectroradiometer for measurements at different places on the screen may give inaccurate measurements ($< 10\%$). Single-chip DMD projectors as the one tested in this study normally uses an Abbe configuration which images the arc source directly onto the DMD.[11] The uniformity performance of this configuration is therefore sensitive to changes in the source caused by wear.

3.6. Dependency on background

The IEC working draft suggests finding the colorimetric change resulting from different brightnesses of the background by measuring white on a black background and white on a white background. This does not give a full description of the chromaticity changes, since the chromaticity of a colour patch will depend on the colour of the background as well as the brightness. The test suggested by Kwak *et al.*[3] was therefore used in this study. Black, grey, white as well as medium and full primary colours were measured on the same set of backgrounds. The average colour difference ΔE^*_{ab} was 4.83 for the LCD and 2.94 for the DLP projector. Kwak *et al.*[3] found an average colour difference of 6.10 for an LCD projector. For the DLP projector the white background gave the largest colorimetric changes (reasonable, since the non-filtering segment makes white much brighter than the sum of RGB), whereas for the LCD projector the full green and blue background in several cases gave larger colorimetric changes than full white.

3.7. Temporal stability

The short time temporal stability was tested by measuring full white and medium grey every two minutes for two hours. Both projectors stabilised after approximately 40 minutes.

3.8. Colour management

The characterisations have shown that it should be possible to perform colour management for the LCD projector by employing the calibration model commonly used for CRT displays.[12] This model makes two assumptions, channel-independence and chromaticity-constancy for the primaries. These properties were acceptable for the LCD projector when the black level was accounted for. By using this calibration model we found an average ΔE^*_{ab}=3.40 between predicted and measured colour for a set of ten random colours. This is comparable with results found for LCD displays,[13] and is good enough for most applications. It is possible that this calibration model may also be employed for the studied DLP projector by including a separate channel for the non-filtering segment.

The model described above can be a valuable tool for colour management of projectors, but it does not consider colour differences due to spatial non-uniformity and dependency on background. These properties were found to be significant for both projectors, and a truly successful colour management model would also have to include these effects.

4. Conclusions and further studies

Two projector systems were characterised in accordance with the methods suggested by the IEC draft. It is important to stress that the screen is part of the system, and that it is the combination of the projector and screen that was characterised.

Measurements of full primaries and white indicated good additivity for the LCD projector. For the DLP projector the luminance of white was 56% higher than the sum of primaries. This is due to a non-filtering segment in the filter wheel which is used to increase the luminance of the projector.

The inter-channel dependency was calculated. The LCD projector showed good channel independence, especially when taking the black level into account. This is in agreement with the result of the additivity test, which is an alternative method of testing inter-channel dependency. The method used for calculation of inter-channel dependency does not seem to be directly applicable to the tested DLP projector due to the non-filtering segment.

The two projectors showed power function-like and S-shape responses for the LCD and the DLP projector, respectively. The intrinsic responses of the projectors are S-shaped for the former and linear for the latter. The actual responses therefore seem to be related to deliberate internal processing.

The chromaticity changes of the primaries resulting from changes in the input signal were found to be significant. It is the relatively high black level that is the dominant reason for this.

Measurements of 25 spots over the image revealed poor spatial luminance and colour uniformity. The brightest and dimmest spot had a uniformity of about 20% for the DLP and 30% for the LCD projector.

Tests showed that both the intensity and the colour of the background influenced the displayed colour. A set of nine colour patches, each patch displayed on the same set of backgrounds, gave a significant average colour difference of ΔE^*_{ab}=4.83 for the LCD and a more moderate difference of ΔE^*_{ab}=2.94 for the DLP projector.

The characterisations have shown that there is potential for great improvements of colour reproduction through colour management.

5. References

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