Colour matches using RGB LEDs

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Abstract

Visual and instrumental colour matches between broad band lights and lights composed of the additive mixture of R, G, and B LEDs differ considerably. Previously we have shown that using the primaries suggested by Vos or those now under consideration by the CIE TC 1-36 will diminish the differences between visual and instrumental matches.

In a new experiment also the question of the spectral power distribution of the RGB LED primaries has been investigated. We tested LEDs for which the dominant wavelengths were near to the prime colours suggested by Thornton, and as far as possible from these chromaticities, thus near to Thornton's anti-prime colours.

Characteristic differences were found for the two sets of primaries, showing that colorimetric settings using the anti-prime colours does not provide acceptable colorimetric description. This has been shown by colouring images in the following way: A hyper-spectral image was taken, where the reflection spectrum was known for every pixel, and in a simulation this image was irradiated by two RGB LED lights of equal correlated colour temperature, one using the prime colours, the other using the anti-prime colours. Comparing the two simulations showed far larger differences then could be expected from interaction of the broad band reflection spectra and the narrow band LED spectra.

Introduction

That the CIE 2° observer is in error was known for a log time [1], but up the last decade of the 20th Century little efforts were taken to correct this discrepancy, as for most material samples with broad reflection bands the CIE 1931 system worked well, or the 10° observer was used that did not suffer from the error in the CIE 1924 photometric observer. In 1992 Thornton published his three part paper [2] drawing the attention to the fact that colour matches might be in huge errors if the primaries are not selected properly (Thornton's original conclusion was different, and the CIE technical committee set up to investigate these questions [3] has still not solved all the outstanding questions). Subsequent papers have shown, see e.g. [4] that for most practical applications CIE colorimetry can be used without major errors. Later, among others, Borbély and Schanda [5] has shown that in case of using LEDs as primaries some errors might occur and the use of the colour matching functions (CMFs) proposed by Vos [6] provide better agreement between visual match and instrumental match.

$$\begin{bmatrix} \bar{x}_F(\lambda) \\ \bar{y}_F(\lambda) \\ \bar{z}_F(\lambda) \end{bmatrix} = \begin{bmatrix} 1.910988 & 1.394658 & 0.389317 \\ 0.643151 & 0.395946 & 0.000000 \\ 0.000000 & 0.000000 & 1.919339 \end{bmatrix} \begin{bmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{bmatrix} \quad (1)$$

Our intention was to investigate this question in more detail, considering also the LMS cone fundamental CMFs proposed by CIE TC 1-36 [7] and their transformation into a CIE-XYZ like system of colour matching functions, using the matrix transformation tentatively recommended by the CIE TC 1-36 [8] shown in Eq. 1.

Experiments

Two experiments were carried out,

1. a real colour matching experiment between broad band test lights produced as filtered incandescent light and the additive mixture of three narrow band lights (Red, Green and Blue LEDs). LEDs were selected because LEDs become more and more widespread in practical applications and colorimetric errors – if such errors should be observed – will influence the use of CIE colorimetry considerably; and
2. colour rendering type visual experiments, as it is well known that the CIE colour rendering test method [9] fails considerably in case of white LED light illumination (actually both for blue + phosphor and RGB-LEDs)[10].

Colour matching experiments

A visual colorimeter was built that enabled binocular colour matches practically as Maxwell matches. Into one half of a 2° bipartite field the additive mixture of the three LEDs was projected, into the other half of the visual field the light of an incandescent lamp could be projected, where in the light path one could insert broad-band glass colour filters. First we selected LEDs with dominant wavelengths close to Thornton's prime colours (with dominant wavelengths in the vicinity of 452 nm, 533 nm and 607 nm), and in a second round LEDs with dominant wavelength at 476 nm, 525 nm and 626 nm were used (the Thornton anti-prime wavelengths are 497 nm, 579 nm and 653 nm, we hope that still before the oral presentation we will be able to perform tests with LEDs with dominant wavelengths nearer to the anti-prime wavelengths). The LEDs were fed by a computer driven current supply that enabled the change of the mixed light along the co-ordinates of hue, saturation and luminance. This enabled intuitive visual colour matches, as it was much easier for the observer to adjust along hue, saturation, lightness co-ordinates as it would have been by selecting the intensity of the red, the green and the blue LED to achieve a match.

In the other light path a well stabilized incandescent lamp was placed, the colour of the light was changed using broad band colour filters, so that test lights were produced around the white point of the lamp. Two sets of experiments were conducted, with a white point at 2856 K and one near to D65 (the latter was achieved by filtering a Solux 4700 K incandescent lamp to achieve good spectral match in the visible part of the D65 spectrum).

Ten young observers participated in the investigation whose colour vision was tested using a Munsell-Farnsworth 100 hue test and a special variant of the pseudo-isochromatic tables.

In the match situations the spectral power distributions of the test and reference fields were measured with a well calibrated (and for LED light colour corrected) PhotoResearch Pritchard PR 705 spectroradiometer.

Colour rendering experiments

For the colour matching experiments first a simulation experiment was set up, similar to the experiment described by Madár and Schanda at the CIE Beijing conference [11]. The reflectance spectrum of a hyper-spectrum image was pixel by pixel multiplied with the spectral power distribution of the test light sources (in this case the RGB-LEDs were the test light sources, together with some other commercial lamps) and the CIE standard illuminants A and D65 as reference sources, respectively. Tristimulus values were then calculated using both the CIE 2° standard observer and the CMFs based on cone fundamentals. Both versions were then transformed using the chromatic adaptation transform of the CIECAM02 colour appearance model to the white point of the display used in the visual experiments.

The visual tests were made to compare whether the cone fundamental based CMFs under the test light sources reproduced the colours of the image more similar to that of the image where the CIE CMFs and the CIE standard illuminants were used. The basic question in this experiment was: do the cone fundamental based CMFs render the pictures differently than the standard ones do, i.e. could the big difference between the visual and objective colour rendering observed in case of LED lights be ascribed to the use of wrong CMFs.

As a control experiment some pictures were visually tested in a double booth experimental chamber, where in one booth once an incandescent lamp set to the correlated colour temperature of 2856 K, and in a second experiment the modified Solux lamps adjusted to near D65 illumination illuminated the picture and in the other booth the two sets of RGB-LEDs (near prime and near anti-prime) irradiated the pictures, once setting equal irradiation chromaticity according to the CIE CMFs and in a second experiment using the CMFs derived form the cone fundamentals.

Results

The colour matching experiments showed explicitly that using the cone fundamental CMFs a better agreement with visual matches can be obtained. Figure 1 and 2 shows such an example:

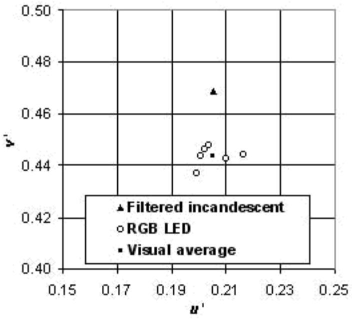

Figure 1. *Enlarged view of the u', v' chromaticity diagram in the vicinity of white sample: CIE 2° standard observer*

Differences between using the prime, and the anti-prime dominant wavelength LEDs showed some differences too, only in case of the anti-prime primaries the colour triangle became too small to perform experiments at higher number of chromaticity points.

Colour rendering type experiments showed too that there is an improvement in colour description: if the cone fundamental based CMFs are used.

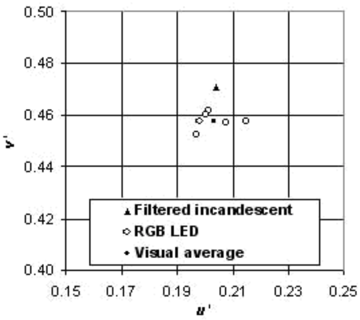

Figure 2. *Enlarged view of the u', v' chromaticity diagram in the vicinity of white sample: cone fundamental based 2° CMFs*

For the illumination of the pictures with the anti-prime primaries in the simulation experiment the difficulty – similarly to the colour matching experiment with the AP primaries – occurred that more pixels became outside of the gamut of the CRT monitor.

Conclusion

Experiments have shown that in case of RGB LED colorimetry and colour rendering studies the use of the CIE 2° standard observer leads to differences between the visual and instrumental colour match, and the use of the cone fundamental based CMFs provide a better description of LED colorimetry.

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Author Biography

Péter Csuti is a PhD student at the Virtual Environments and Imaging Technologies Laboratory at the University of Veszprém (now University of Pannonia), Hungary. He graduated in 2002; Master of Science in Informatics. His research fields are: colour matching experiments, V(λ) fitting of photometer detectors, photometrical measurement of LEDs, development of LED applications, bandpass error of spectrometers, colour rendering of LEDs, calibration of array spectroradiometers.

László Beke obtained his M.Sc. degree in informatics at the University of Veszprem (Hungary) in 2004. Recently, he has been working on his Ph.D. thesis at the University of Pannonia (former University of Veszprem). His research interest is primarily focused on vision modelling, colour appearance, vision related image processing and digital displays. He participated in several research projects in the field.

János Schanda is Professor Emeritus of the University of Pannonia, Hungary. He graduated in physics at the Loránd Eötvös University in Budapest. He worked the Research Institute for Technical Physics of the Hungrian Academy of Sciences, held different positions at the International Commission on Illumination (CIE), where is presently Vice President Technical. His main interest is in colorimetry and colour rendering, especially of LEDs.