Colorimetry evaluation supporting the design of LED projectors for paintings lighting: a case study

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The article describes metrological experiments performed for the development of a projector with a variables light output emission in terms of quantity and chromaticity. Based on LED light sources, the product is designed to emit light with a variable colour temperature ranging from 2700K to 10000K, depending on the arrangement of the LED, the aperture angle of the lens to and the current supply. It also describes the technique used for choosing the best mix of current to guarantee the value of the desired colour temperature and a high colour rendering index for the resulting light mixture.

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Introduction

LED stands for Light Emitting Diode, represents, from the technical point of view, one of the greatest and most promising technological breakthroughs in the lighting industry in recent years. In fact, when we speak of light-emitting diodes, or Solid State Lighting, very often, it refers to the term "intelligent lighting", particularly in view of the great deal of possibilities offered by the management and control devices that use this technology [1].

The LED is able to emit radiation only in the visible range of electromagnetic spectrum (for this reason it is considered a narrowband source) and its luminous flux is made proportional to the input current. LED introduces substantial innovations in the management of the colour of light: we can get white light by an additive synthesis of RGB (Red, Green, Blue) or by the AWB (Amber, White, Blue) system or even by combination of complementary colours (Blue, Yellow) or by conversion of ultraviolet or blue radiation into visible light using a phosphors coatings.

If the traditional light sources have the ability to reach a limited range of colour temperatures, the LED technology can carry out a separate adjustment being able to obtain different tones of white light, as well as a single colour. Taking as reference the Kruithof's studies [2], we emphasise the importance of the colour of light is not only a principle of perception and pleasantness, but above all, to ensure a good performance in the visual task area.

In fact, LEDs can contribute to stress a particular tone of colour in an environment that is free or just play on the aesthetics and the search for the well-being of the individual (psychological and physiological area) following the latest trends [3]. The innovations introduced by the LED contributes to the birth of research field due to the novelty of this technology and the need to develop new methods of measurement. In recent years, in fact, measuring instruments were limited to process photometric intensities data, a method which is now considered very simplistic in comparison of the great benefits that LEDs are able to offer. The market has greatly enhanced the number of products using colour for aesthetic and/or communication in order to achieve greater well-being of the human psycho-physiological [4].

Through the application LED technology, there are a great number of different options and possibilities in lighting application, and in this study several solutions for optical and colour mixing of LED sources, were tested and measured.

The aim of this research is an attempt to control the uniformity and chromaticity of the emitted light field and to allow the emitted light goes through the complete Planckian's locus by the use of adequate current supply for each light source. The ultimate goal of such experiments is to assess the ability to create new lighting systems with advanced performance, where, in real time, the colour of light is able to follow any scenario of colour temperature, but also hue and saturation.

Image-based colour measure

In addition to the one-dimensional processing signal acquired through the traditional process of measuring (point by point measurement), in recent years researchers have developed a new methodology called Image Based Measurement System (IBMs) that is used in many sectors: from industrial quality to robotics, medicine and biology.

IBMs techniques find their application in the field of lighting design, developing the ILMD (Imaging Luminance Measurement Devices) [5], better known as video-luminance photometers or CCD photometer. A ILMD is able to measure the levels of luminance of a real scene giving back a pseudo-colour or gray scale image relative to the photometric measured values. They are based on CCD (Charge-Coupled Devices) from 8 to 16 bits, similar to those devices used in digital cameras, where the values of irradiance measured in each cell of the CCD are converted into a digital value. Figure 1 shows an example of luminance map recovered by a ILMD instrument.

A 16-bit CCD sensor is able to acquire 65536 different luminance levels. Other types of ILMD, are equipped with low-dynamic CCD 8-bit and they are based on an automatic mechanism that captures a sequence of images with increasing exposure interval and then reassemble them in a high-dynamic image [6] which allows a greater range of luminance values than each single frame. ILMD instrument represent a real innovation for lighting designers because it can offer a quick and noninvasive measure of the values of uniformity, contrast and the spatial distribution of luminance produced by a particular lighting system. In addition, implementing a new measurement parameter on the light, you have the opportunity to properly assess, from a quantitative point of view, the real vision of the enlightened elements of the scene, as a function of perceptual adaptation typical of the human visual system.

The further aim is to support the lighting design which is not limited to the evaluation of illuminance and luminance, but also investigating the chromatic information, researching the perceptual quality in terms of contrasts, the direct and indirect glare, as a further parameter, the mechanism of vision and colour perception of light [7,8].

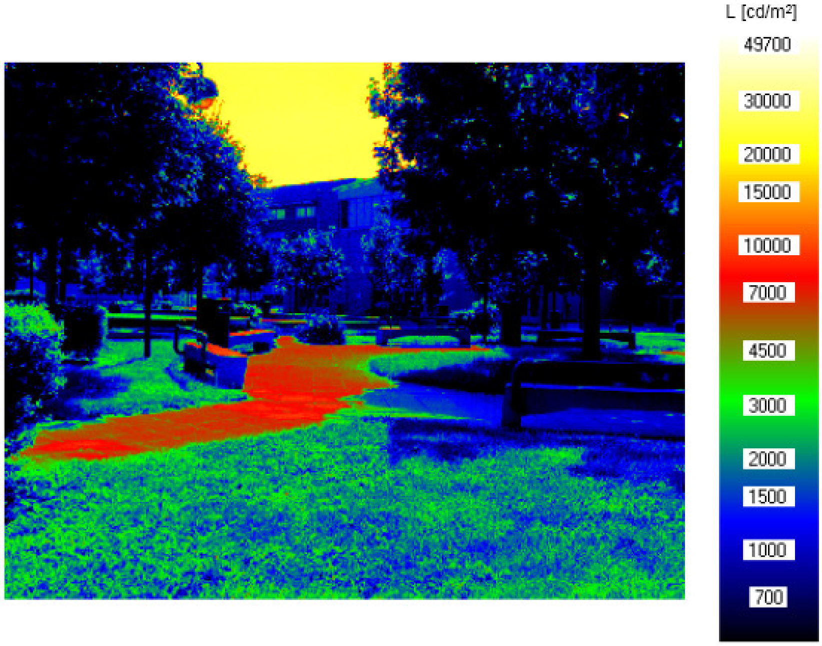

Figure 1: Using a video ILMD photometer for the evaluation of a natural image luminance (luminance is represented in logarithmic scale).

Our research has focused on the determination of “chromatic performance" of a projector prototype characterised by a five-channel LED system R, G, B, WW, NW (Red, Green, Blue, Warm White, Neutral White). The aim is to evaluate the colour distribution of the light field projected onto a screen (especially in terms of uniformity), changing of colour temperature (in the range between 10000K and 2700K) and the aperture beam of the optics associated with each LED. Usually, this kind of investigation is carried out at the design stage of the product through the use of ray tracing software systems: each source is connected whit a set of rays representing the light distribution in space of the product and the spectral distribution of light emitted.

The Minolta CA-2000 2D Colour Analyzer

Konica Minolta Sensing has developed the 2D Colour Analyzer CA-2000, an instrument hardware/software which can provide an accurate measurement (high resolution) on the two-dimensional colour distribution, and luminance uniformity of FPDs, projectors, backlights, or LCD or plasma display, auto-motive components such as car navigation system or other type of control panels. One of the most interesting instrument's features is the extreme speed of processing and evaluation of data obtained from the measurement process. Using XYZ filters and high-resolution monochrome CCD sensors, the instrument CA-2000 combines with a simple software included as a standard accessory, which is fast and efficient tool to provide data analysis and evaluation. The CA-2000 2D Color Analyzer is able to measure the colour distribution, uniformity, chromaticity and luminance up to a resolution of 980 × 980 measuring points [9]. The working principle of the instrument is described in the Figure 2.

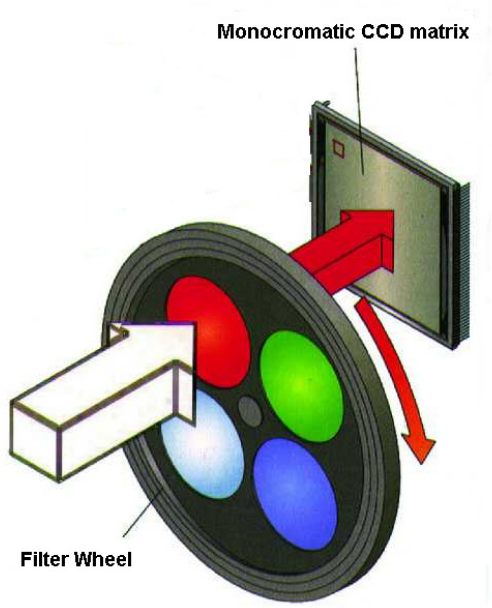

Figure 2: Working principle of an instrument for colour measuring using images.

Description of our measurement technique

This research covered several prototype projector characterised by a LED five-channel system (R, G, B, WW, NW), which is carried out in collaboration with one major company in the Italian lighting market. The aim is to assess the distribution of the chromatic light field emitted by the device, which is made by applying different types of discrete micro-optic to each LED light source, through the variations of current supply in each branch circuit. By interpolation of a lookup table containing the current power supply values of the selected five primary colours, we have designed a system with a variable colour temperature in the range between 10000K and 2700K.

For the evaluation of LED's mixtures, the first step was the organisation of the measuring setup which is characterised by the placement of sources at a suitable distance (between 2.3m and 2.5m as function of the aperture beam optics used) from the surface to be illuminated (a perfectly diffuse white screen) and the placement of the measuring instrument CA-2000 which is associated with a control computer (see Figure 3 for details). The 2D colorimeter was oriented so that the optical axis was perpendicular to the screen size, as well as the maximum intensity of the beam emitted; the choice of the objective was determined by the distance between the instrument and the screen itself so that an adequate spatial resolution was been reached (in this case a standard objective is used).

Measurements were carried out under conditions of thermal equilibrium at a temperature of 25°±1°C, after completely turning on the unit for at least 45'. For the realisation of the mixture, all primary engine light were considered, which is more or less activation is connected with the requested colour temperature, and, if necessary, the value of the colour rendering index of interest. During the test, the currents were been adjusted using a numeric keypad and a slider control to achieve the desired configuration.

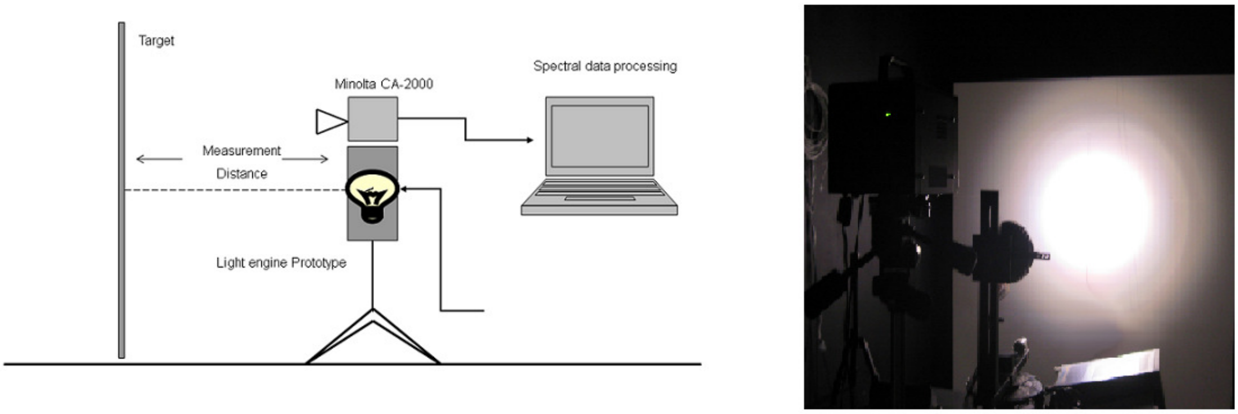

Figure 3: Setup for evaluating colour uniformity of a light engine.

For each device setting and for each set of lenses, the following parameters were been evaluated:

- CCT map (correlated colour temperature map);
- Spot map and the respective average values of CCT within the measurement spot;
- CIE 1931 diagram (2° observer) with superimposed the placement of the chromaticity coordinates detected within the test area.

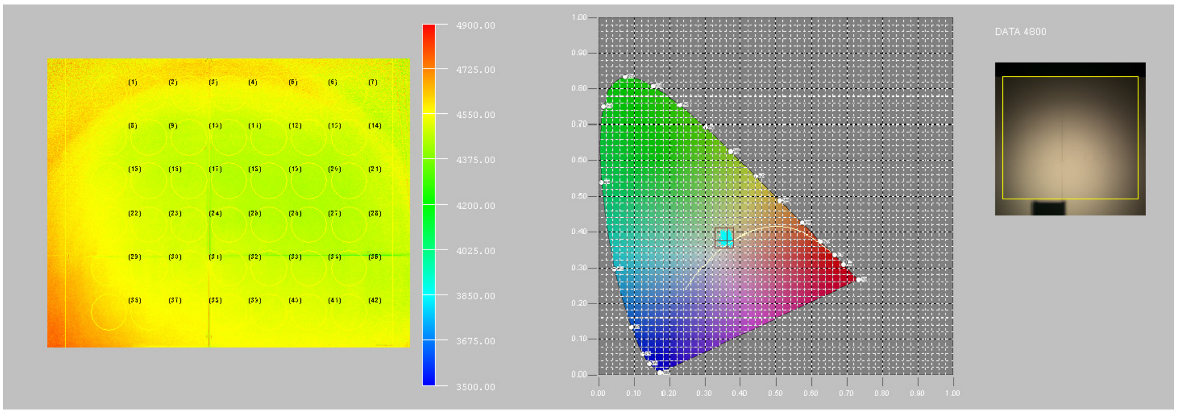

Figure 4: Output example (on the left) and possible data processing of collected data (on the right).

Figure 4 shows the screen image measurement: the yellow circles represent the measurement spot, the green rectangle is the measurement's area within the CCT map is evaluated. At the center of the frame is shown the light beam produced by the projector. The instrument was set to acquire a matrix of 980 × 980 pixels, with a standard focal length.

Measurements were performed on two different prototypes to evaluate the performance obtained by different optical solutions (type of optics available, aperture beam, etc.).

First prototype

The considered luminaire (Figure 5) consists of five channels light engine (Red, Green, Blue, WW, NW) where you can vary the current power supply of individual circuit between 12÷15mA and 450mA.

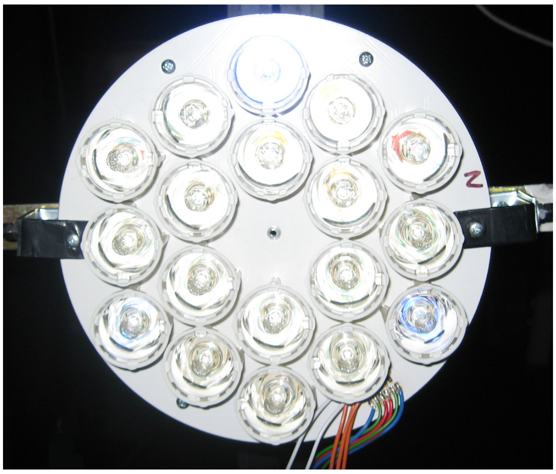

Figure 5: First LED prototype projector used for measurements.

The lenses used for testing are manufactured by FRAEN and they are suitable for CREE XR-E LED with following beam aperture:

- Narrow lens (beam angle between 6° and 8° depending on the size of the die, which is function of the LED's colour);
- Medium lens (open 21°, regardless of LED's colour).

The first step was to set the mixing of the currents in 5 channel of the unit (for each of the two openings of the lenses considered), in order to obtain a variable correlated colour temperature in the range 2700K÷10000K. For this purpose, it was also provided a measurement set-up as shown in Figure 6, and spectral irradiance produced by the light beam emitted on-axis was determined (at a distance that the projector could be considered point source) properly adjusting the current in each channel, so that light mixture emitted reaches the desired CCT value.

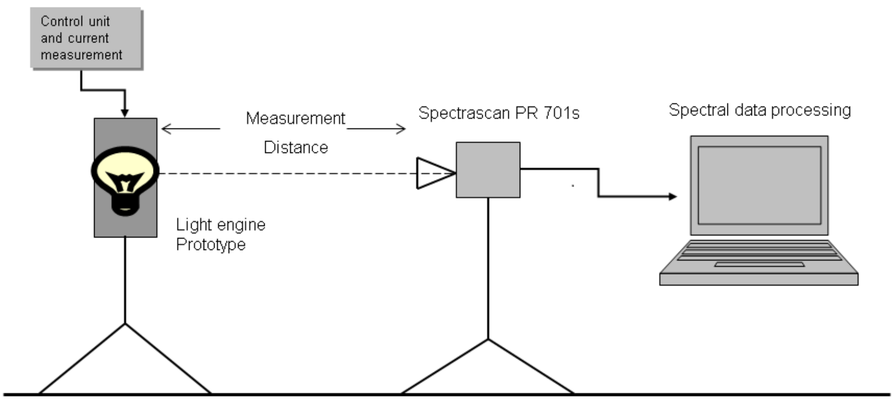

Figure 6: Setup for determination of the current in the 5 channels of the projector.

Figure 7 shows the evolution of estimated currents in each branch of the circuit as a function of CCT and the trend of light intensity on axis as a function of CCT (medium beam lenses).

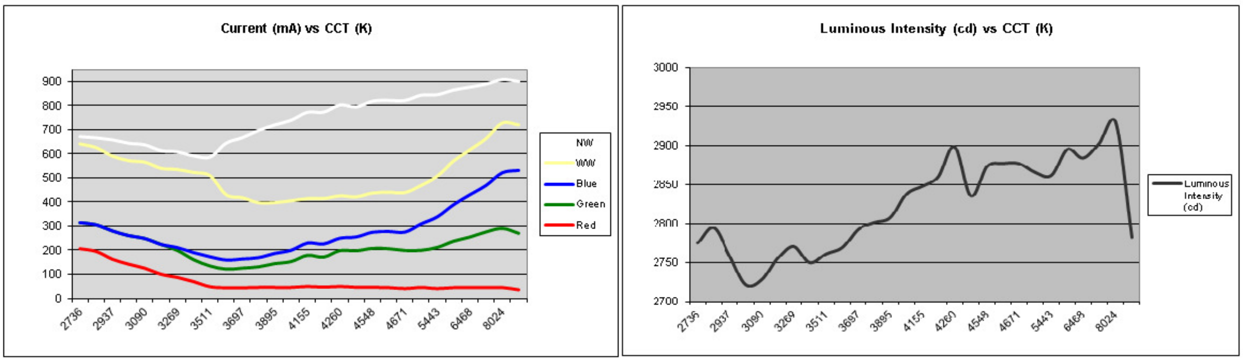

Figure 7: The left part of the figure shows current trends in each of 5 channels for the prototype with medium beam lenses, while the right one shows the value of luminous intensity in candles, emitted on-axis.

The choice of the 5 primary was determined by a process of constrained optimisation providing a value of CRI better than 87 for the achieved light mixture (CRI index was calculated over an average of the standard Munsell 14 colour samples). The desired spectrum resulting from the mixing was set equal to the linear combination of the spectra of the primary colour thought proper weighting factor which are related to the current power supply of each channel. The results obtained in measuring the near field, are shown on Figures 8 and 9 for values of colour temperature between 2800K and 5000K. On the left it shows the map of the prototype CCT (mixture at 2800K) with medium lenses, and the right size the result obtained from a light mixture at the same colour temperature, but with narrow beam aperture lens. In CCT maps, the gray areas represent part of the measuring screen where is not defined the colour temperature, for example points where the chromaticity of the test source differs more than ΔC = 0.05 from the ideal Planckian's Radiator.

$$\Delta C = \left[\left(u_t' - u_p'\right)^2 + \frac{4}{9}\left(v_t' - v_p'\right)^2 \right]^{1/2} \qquad (1)$$

where u'_p and v'_p are the chromaticity coordinates of the Planckian radiator and u'_t and v'_p represent the chromaticity coordinates of the test source.

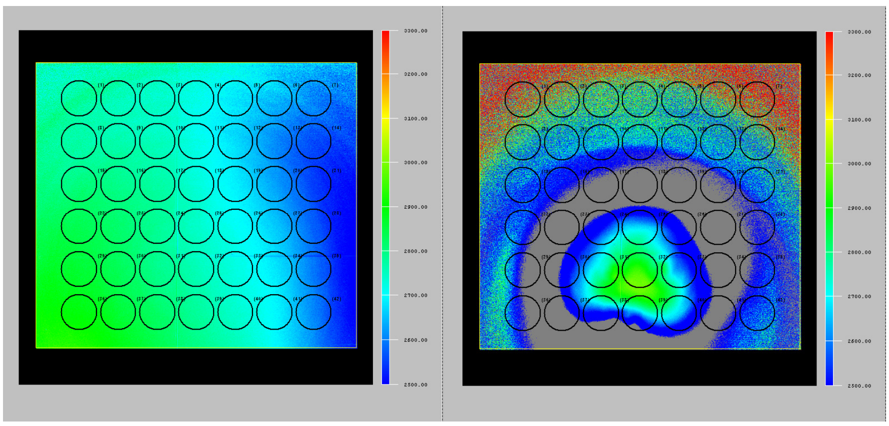

Figure 8: Mixture at correlated colour temperature of 2800K obtained by medium lenses (left) and by narrow lenses (right).

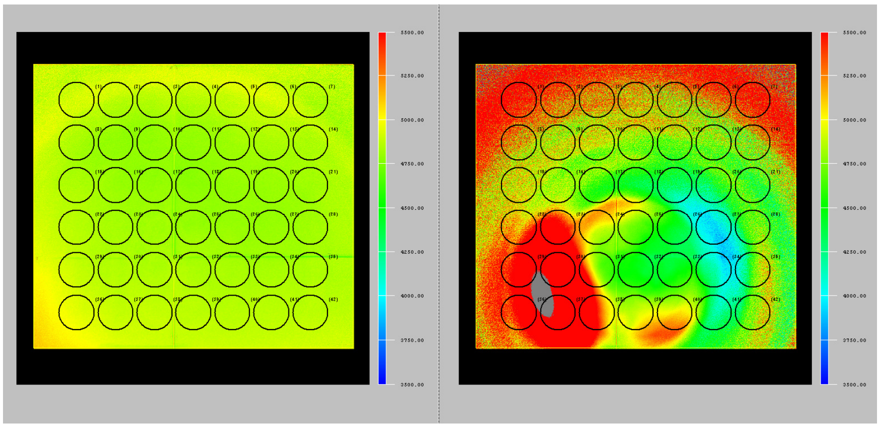

Figure 9: Mixture at a correlated colour temperature of 5000K obtained by medium lenses (left) and by narrow lenses (right).

Second prototype

The second prototype uses a system consisting of 5 independent channels and a multi lenses suitable to host up to four LEDs, which produces a medium beam on the target screen (Figure 10).

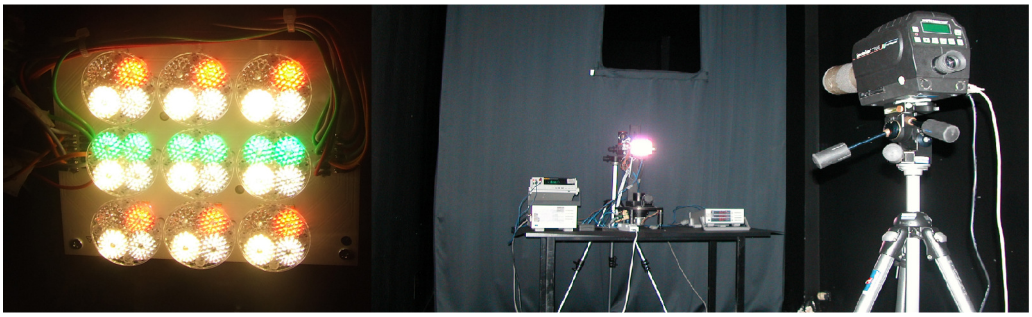

Figure 10: Projector prototype with multi lenses.

Again, the first step performed was to determine the combination of the currents in 5-channel unit in order to obtain a correlated colour temperature variable in the range of 2700K÷10000K, in the manner already described in previous paragraph.

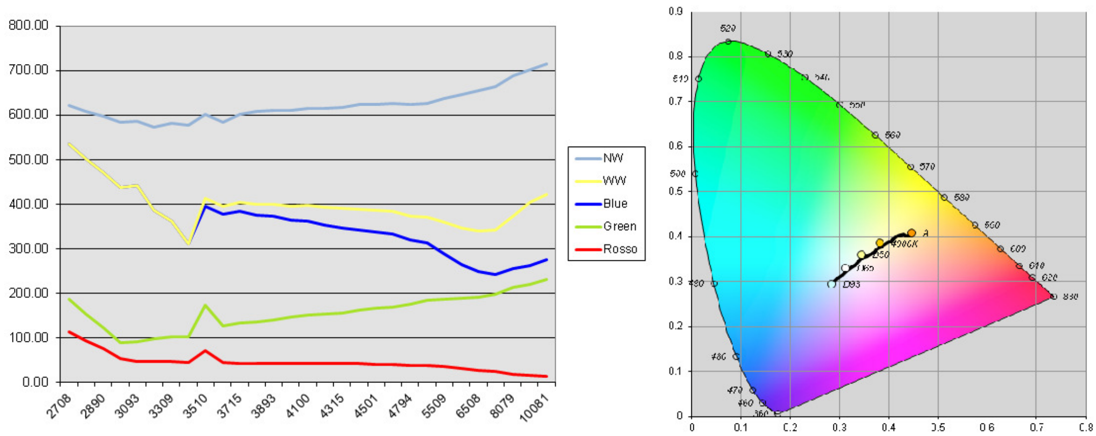

Figure 11: On the left it is showed the current trend in each circuit branches, on the right chromatic coordinates of the different mixtures obtained at different CCT compared to some reference illuminants used in photometry.

Figure 11 (left) represents the current trends in the five channels related to the change of CCT between 2700K and 10000K, while the right side of the same figure shows the CIE 1931 chromaticity coordinates measured on the target screen for different processed light mixture, compared to some illuminating reference in the range between 2700K and 10000K. With the use of this particular type of lens you can get light mixtures with related colour temperatures very closely to the Planckian's locus. Figures 12 and 13 show the distribution on the screen of colour temperature for a light mixture with colour temperature between 2800K and 5000K respectively; from analysis of these two images we can observe that the mixing on the target is satisfactory in both analysed conditions.

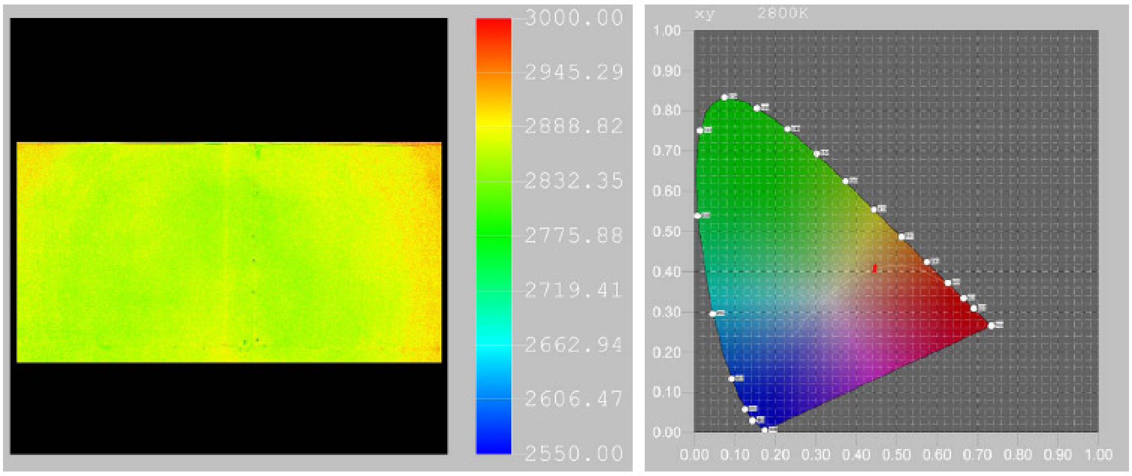

Figure 12: On the left it shows the CCT map for a light mixture at 2800K and to the right it shows the distribution of the corresponding coordinates x, y in CIE 1931 colour space.

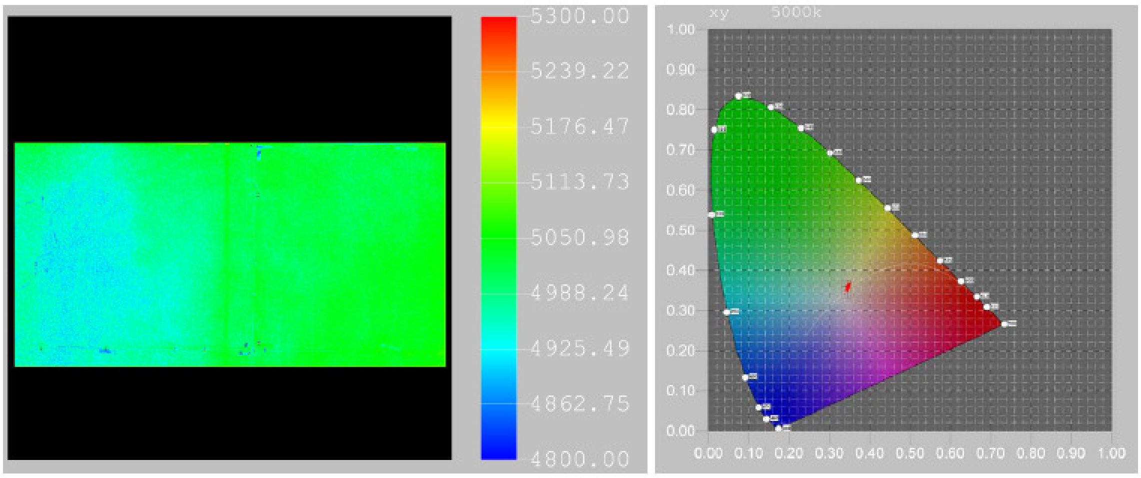

Figure 13: On the left it shows the CCT map for a mixture at 5000 K and to the right it shows the distribution of the corresponding coordinates x, y CIE 1931 space.

An examination of the maps shows that CCT uniformity is good enough until the colour temperature is below 6500K. Beyond this limit the correlated colour temperature distribution on the screen appears to be strongly unbalanced respect to the vertical axis of symmetry. In particular, we note a change of colour temperature in the lower left side, a colour temperature close to the target value in the center and clearly cooler temperatures in the right-field range (Figure 14).

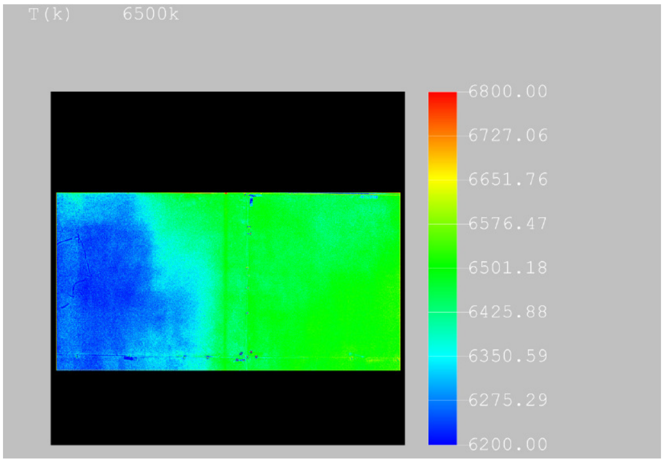

Figure 14: CCT map at 6500K: it represents the limit beyond which the mixing is no longer guaranteed in a satisfactory way.

Above 6500K the colour temperature has been obtained through the appropriate mix of channels WW and NW, and blue, the latter channel in increasing quantities. The choice has proved to be compelled by the fact that the colour temperatures of the two white LEDs are very close together (WW in 2978K and NW in 3954K) and the proposed solution is the one that best meets the constraints of the optimisation previously set (closeness of chromaticity coordinates x, y to the Planckian's locus and colour rendering index greater than 87). This has led to power the two white LEDs with two different current values and thus it has resulted in the decrease of colour consistency on the screen.

Conclusions

Using the described methodology a series of images were acquired to verify the uniformity of the projected beam of some LED projector prototypes, in accordance with the colour temperature changes depending on the distribution of currents in the circuit branches. The comparison between the correlated colour temperature values obtained in correspondence to the theoretically expected values of current power supply and the reference value, has improved the lookup table stored inside the product.

The system has allowed us to evaluate the degree of uniformity of the mixture on a screen for different arrangement of the LEDs, the lens aperture, the combination of current power supply. Further investigations are in progress using a 5-channel system based on multi-chip LED (R, G, B, WW, NW) with a suitable colour mixing system, to improve the performance obtained by the second prototype.

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