Automated Control of The Color Rendering Index for LED RGBW Modules in Industrial Lighting

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Abstract

In this article the method of automatic brightness components control of RGBW LED module using pulse-width modulation is proposed. The method allows the value of color rendering index Ra with values of chromaticity and overall brightness fixed to be adjusted. It enables control of visually perceived saturation of green and red colors of reflecting objects. Experimental verification of the method has shown linearity Ra changes depending on brightness of the white LED.

1 Introduction

The development of systems providing lighting control options is becoming a matter of interest due to continuing spread of lighting devices, based on light-emitting diodes (LEDs). It has recently been impossible to achieve while using prior element basis. One natural light control parameter is defined as brightness, the other as correlated color temperature (CCT), which is related to the feeling of “cold” or “warm” light and determines its color.

LED lighting makes it possible to implement wide range brightness control. It also makes possible to control the chromaticity of lighting in systems with blending emissions. However, LED possibilities are far from being limited to this. In some cases, the color perception of reflecting objects can be controlled through clarification effect [1].

The influence of light source spectrum on visually perceived color of objects should be characterized by color rendering index. General color rendering index (Ra) is the indicator of recommended lighting sources quality [2]. Calculation of Ra is based on the definition of average color samples deviated from a standard set in uniform color space W*U*V* (CIE 1960 UCS), which is caused by the change of standard lighting source compared with tested. The index is measured in dimension of less conventional units, and the greatest possible value equal 100 corresponds to color rendition without deviations.

Since the beginning of widespread introduction of LED lighting, the concept of Ra is constantly being criticized [3–5]. The reason, in our opinion, is the lack of compliance of visually observed color rendering with the method of Ra calculating (color ratios distortion while changing lighting). However, it cannot be demanded from the index represented by a single number. Considering the fact, that saving color ratio of object is more important for observer, comfortable perception of real scenes illuminated with low Ra is possible under certain conditions. For example, the implication of colorimetric RGB-lighting [6] can lead to clarification effect, that can have an equal increase of mutually contrasting green and red color saturation. In this case, visual discomfort is not perceived and Ra reduction may characterize the increase of saturation level. Thus, Ra can be regarded as one more parameter of lighting control, responsible for the value of clarification effect, i.e., color saturation.

The purpose of this work is to develop LED devices management method, enabling the adjustment of such visually perceived parameters as “brightness of lighting”, “lighting tint (CCT)”, “illuminated objects color saturation (Ra)”.

2 Method of RGBW Module Spectrum Management

The RGBW combination of LEDs proves to be the most suitable for achieving the goal. The spectra of individual components, applied in the research and possible results of their mixing are shown in Fig. 1.

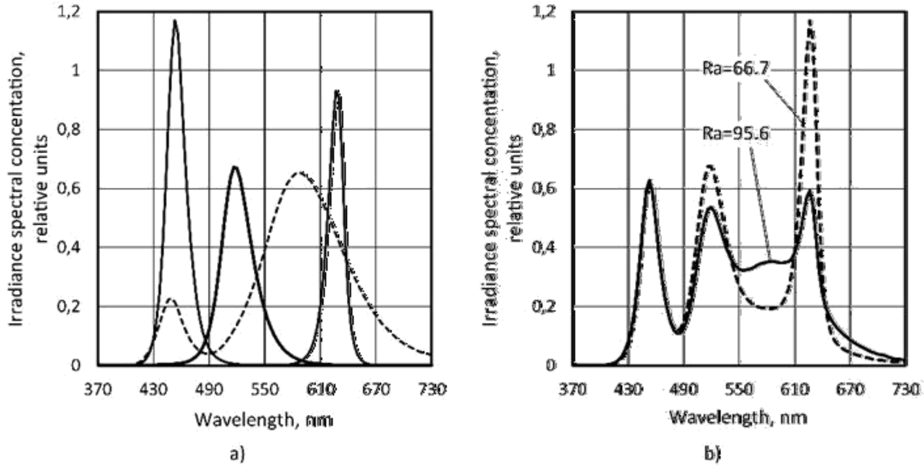

Figure 1: The emission spectra: a) – separate components of RGBW LEDs, used in work; b) – options for mixed emission with identical chromaticity and brightness, but various Ra

The use of four LEDs provides a variety of light spectrum options in a single color. More uniform spectrum is closer to the standard and should have a higher Ra (Fig. 1, b), so, the color adjustment can be performed by changing the emission output of white LED as the main control parameter. The adjustment is performed with the help of pulse-width modulation (PWM), preventing the displacement of dominant wavelength.

The proposed method is based on vector-matrix representation of spectra light sources and colorimetric calculations. Measured spectra are usually represented as discrete sets of emission power for a pre-fixed number of spectral bands N, and should be viewed as vectors of N-dimensional space S. If in the processes considered the mutual influence of spectral zones is excluded, the system of N basis vectors, corresponding to the spectral zones, can be roughly assumed orthonormal.

In the space of spectra S the subspace V (three-dimensional hyperplane) can be determined with the basis of the color matching functions (CMF) of some colorimetric system, for example, XYZ (CIE 1931). According to the hypothesis of Wyszecki [7, 8], vector, corresponding to illuminant D, as well as any vector of S, can be represented as a sum of two vectors:

$$S_d = S_{dv} + b$$

where vector S_{dv} – is orthogonal projection of S_d to V, which is called the fundamental stimulus (or metamere), b – is orthogonal vector to V, or metameric black. Later, Cohen [9] propose an explicit form of the projection operator of S to V named R-matrix:

$$R = X(X^T X)^{-1} X^T \quad (1)$$

Spectra sl, obtained from the RGBW LED, can be found in the subspace L with the basis of spectra components s_r, s_g, s_b, s_w:

$$s_l = h_1 s_r + h_2 s_g + h_3 s_b + h_4 s_w \tag{2}$$

where h_i – is standard brightness of LED components R, G, B, W, ranging from zero to one and being proportional to PWM pulse ratio of LEDs power supply.

Thus, the control problem can be solved by finding a subset of vectors in L, whose projection on V coincides with S_{dv}:

$$Rs_l = Rs_d \tag{3}$$

By considering (1), the expression (3) can be greatly simplified and represented as:

$$X^T(s_l - s_d) = 0 \tag{4}$$

It refers to the fact, that the difference of vectors s_d and s_l must be orthogonal to V, i.e. not perceived by the observer.

By considering (2), the expression (4) can be rewritten as:

$$X^T\left(S_{rgbw}a - s_d\right) = X^T S_{rgbw}[h_1 h_2 h_3 h_4 h_5]^T = X^T S_{rgbw} h = 0 \tag{5}$$

where $S_{rgbw} = \left[s_r s_g s_b s_w - s_d\right]$ – is the matrix, composed of the listed vectors-spectra, h is a vector containing brightness of components, which can be used to obtain the desired PWM pulse ratio. The addition of extra component h_5 in vector h has not essentially modified the task of finding it because of homogeneity. Spectral power distribution in the spectrum s_d of standard light source is vital as it defines its chromaticity. The brightness of a standard source, determined by the value h5, may be considered arbitrary, as the equation (5) determines only the ratio of hi component, but not its absolute value.

From (5) follows that the desired vector $h*$ must belong to the kernel of a linear operator, defined by the matrix $X^T S_{rgbw}$ whose size is 3×5 elements and the rank is 3. Thus, the dimension of the kernel is 2, and the general solution $h*$ of the equation (5) can be represented as basis expansion:

$$h^* = b_1 \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ 1 \\ 0 \end{bmatrix} + b_2 \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \\ 0 \\ 1 \end{bmatrix} = b_1\alpha_1 + b_2\alpha_2 \tag{6}$$

where a_{ij} values can be easily found applying standard algorithms, and the coefficients b_1 and b_2 can be arbitrary.

To achieve this goal, from the set $\{h^*\}$ of all solutions of the equation (5) it is necessary to select the only thing, corresponding to set values of the controlled parameters. This solution should correspond to the set values of controlled parameters. It should be noted, that one of these parameters called “lighting hue” is already implicitly incorporated in (6) as CCT, because the calculation of vector S_d is based on it. For the accounting of “brightness” and “color saturation of illuminated objects (Ra)” it is necessary to address to the meaning of vectors α_1 and α_2 from (6).

Consider the situation, where $b_1 = 0$, $b_2 \neq 0$. In this case, the emission of white LED in the spectrum of RGBW LEDs will not exist, as the fourth element in α_2 is equal to zero. Therefore a_{12}, a_{22}, a_{32} are the brightness of RGB LEDs, which ratio provides a fit to S_d on chromaticity, while their absolute values coincide with the brightness of S_d . In this case, to adjust the brightness of RGB LEDs, the change of coefficient value b_2 in (6) should be used. This change must occur within the allowable pulse ratio range. If the capacity of quantized pulse ratio is excluded and its maximum value is equal to one, then:

$$0 \leq b_2 \leq \frac{1}{max\{a_{12}, a_{22}, a_{32}\}} \quad (7)$$

Next, consider the vector α_1. It should be noted that a_{12}, a_{22}, a_{32} are always negative. Therefore, their values indicate how much should the RGB LEDs brightness be reduced to avoid visually perceptible change of lighting when a unit brightness W LED is added. Therefore, b_1 value should be used to adjust the "uniformity" of RGBW LED spectrum, which would correspond to a change in Ra and "color saturation of illuminated objects".

The variation limits of b_1 can easily be followed from the obvious non-negativity constraint of the components of h^* solution in (6), at a given level of b_2:

$$0 \leq b_1 \leq min\left\{-b_2\frac{a_{12}}{a_{11}}, -b_2\frac{a_{22}}{a_{21}}, -b_2\frac{a_{32}}{a_{31}}\right\} \quad (8)$$

The final decision is as follows:

$$\begin{bmatrix} h_r \\ h_g \\ h_b \\ h_w \end{bmatrix} = A_{rgbw}b = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \quad (9)$$

where h_i is a normalized value of RGBW LEDs brightness, varied from 0 to 1, A_{rgbw} is a matrix of a_{ij} elements from the solution (6) of equation (5), b_1 and b_2 are parameters, arbitrarily varied within the constraints (7–8), managing Ra and general lighting brightness.

3 Experimental Verification

Experimental stand, which can be described as a lightproof box with neutral gray walls, was assembled to verify the proposed method (Figure 2).

Figure 2: Experimental stand. 1 - operating computer; 2 - lightproof boxing; 3 - lightproof curtains; 4 - light source; 5 - spectrophotometer; 6 - Color Checker target; 7 - block of variable resistors for CCT management b_1 and b_2; 8 - stabilized power supply unit

The spectral coefficient of walls' reflection is controlled by spectrophotometer and amounts 20%. The light source used as a LED module, is made of RGB segments and "warm white" LED strip, designated inside the box on the upper wall.

High frequency n-channel FETs (IRLML2502), controlled by PWM outputs of ATmega 328P controller take over the power supply of R, G, B, W channels. PWM frequency is about 500 Hz, the pulse ratio adjustment step equals 1/256, that corresponds to 8-bit quantization scale. The controller's work is implemented under the control of monitoring program (software package of ArduinoIO). It allows the controller to interact with the outputs from MATLAB environment, installed on the host computer. Variable resistors are connected to three analog inputs of a controller and used to adjust CCT, b_1 and b_2 .

Spectral irradiance laying in the range of 370–730 nm with a pitch of 3.33 nm, is recorded with the help of spectrophotometer i1-Pro (X-Rite) integrated with ArgyllCMS software package. While conducting all measurements, a spectrophotometer in the box is fixed in the same position, the front part of the box is closed by an opaque curtain, and all the colored objects are removed from the box. The data obtained are expressed in mW/(m2·nm). Random measurement error is 0.24 mW/(m2·nm) for p = 0.95. Systematic device errors, unfortunately, can not be specified.

The stand calibration involves the consequent measurement of s_r, s_g, s_b, s_w ranges while applying a continuous power (PWM level - 255) to the relevant channels of a light source. Spectrum of standard illuminant of series D, which is calculated during the experiment as a function of CCT given, is taken as a reference S_d . Matrix X is composed of CMF from XYZ system (10° CIE 1964), then the matrix $X^T S_{rgbw}$ from (5) is formed. Further, the matrix A_{rgbw}, used for generating PWM levels from (9), is defined. As brightness h_i in (9) varies from 0 to 1, to obtain levels of PWM, in our case, it should be multiplied by 255.

The experiment involved consistent measurements of illumination spectra, depending on b_1 coefficient at various fixed CCT levels and total brightness (b_2 ratio). Chromaticity and Ra were determined by spectrum. The values of b_1 coefficient were set as a percentage of maximum allowable, complying with certain constraints (8). The experimental results are presented in Fig. 3.

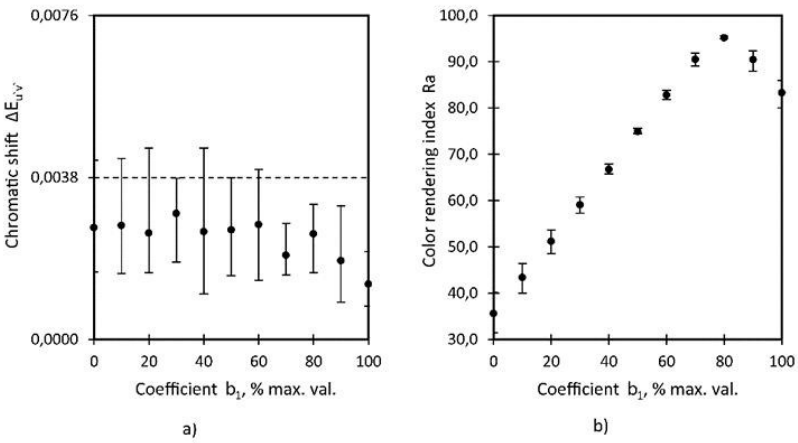

Figure 3: Change in luminous flux of RGBW LEDs characteristics depending on coefficient b_1: a) – chromatic shift $\Delta E_{u'v'}$ (10° CIE 1964); b) - color rendering index Ra. The graphs show the spread of values observed during experiment

As b_1 coefficient was changing under the experiments conducted, visually noticeable chromaticity deviations were observed for both experimental devices. While calculated from the spectra change of chromaticity (Fig. 3, a), they do not exceed the conventional threshold value of legibility (0.0038 on the chart u'v' 10° CIE 1964) in general. First we tried to explain this by the fact of CMF CIE 1964 imperfection, by analogy with [10]. However, the substitution in (5) CMF for the newer, obtained in accordance with the suggestions of CIE Technical Committee 1-36 in 2006, has not led to the significant improvement.

Fig. 3, b shows the dependence of Ra on the value of b_1 coefficient. It's obvious that b_1 coefficient (9) is perfectly correlated with Ra value. When b_1 values are about 80% of the maximum, the highest value of Ra is observed, then it begins to decline and the further increase of white LED proportion in spectrum is meaningless. The visual control of color reflective objects, placed in the box, has showed the decrease of intensity with the increase of Ra and vice versa.

4 Conclusions

RGBW LED management method has been developed and tested. It allowed the CCT, brightness, and color rendering index Ra to be adjusted. The Ra adjustment allows visually perceived color saturation of reflecting objects to be changed in a lighting zone due to the management of clarification effect.

Optimum limits for the operating parameter are set. The change of b_1 coefficient in (9) should be restricted within the range of 0 to 80 % of the maximum, specified by expression (8).

During the experiments, a significant change in chromaticity of lighting has been obtained. This is contrary to the predicted theoretical results. The explanation of this fact requires further research.

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