Reconstruction of CIE Standard Illuminants with an LED-based Spectrally Tuneable Light Source

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ABSTRACT

Solid-state lighting is reaching a really good position on the market and replacing traditional light sources. For this reason, a LED-based spectrally tunable source with high spectral resolution has been developed. The aim of this light source is the generation of spectra of CIE standard illuminants (D65, D50, A, E, F2, F11 and HP1) in the visible range (400-700nm) by means of 31 spectral channels. First, Gauss's equations were applied for finding the weighting values for each LED. This method shows very good results in terms of goodness of fit coefficient (GFC) and root-mean square error (RMSE). In addition, the colorimetric properties, such as correlated colour temperature (CCT), colour rendering indexes (Ra and Rb) and the colorimetric coordinates in the CIE-xy system are quite similar to CIE standard illuminants. Secondly, a minimization routine designed for offering transferable (positive) weights to the light source was applied. The fitting and colorimetric parameters are not as good as in Gauss's equations but, despite that, they are experimentally better. In conclusion, a minimization method which is able to simulate spectra of standard illuminants by means of a LED-based light source has been developed but it needs further work to reach higher levels of accuracy.

1. INTRODUCTION

LED technology has been growing very fast in last years and, nowadays, is one of the branches of optics with a higher prediction of development. This work is focused on one of the most versatile applications: generation of CIE standard illuminants. The main advantage of generating standard illuminants by using a LED-based light source lies on the fact that it allows to reproduce different illuminants with only one source. Generally, recent researches apply minimization methods in order to adjust as maximum as possible the generated spectrum by LEDs to the spectrum of the illuminant (Park et al. 2009, Mackiewicz 2012). These methods started being used as an alternative to lengthy convergence procedures (Fryc et al. 2005).

Consequently, the model for reconstructing illuminants that we propose it is placed inside minimization procedures but, in this case, we use a light source with 31 spectral bands in the visible range (400-700nm), more than usual in this kind of devices. For this reason, we expect to reach better adjustment than others works that use fewer channels.

2. METHOD

The first prototype of the light source is composed of 62 LEDs, two for each channel. Peak wavelengths are spread between 400 and 700nm, with a mean gap of 10.06nm and a mean

FWHM of 22.51nm (Figure 1). This spectral characterization was performed by the PR-655 tele-spectroradiometer of Photo Research, Inc.

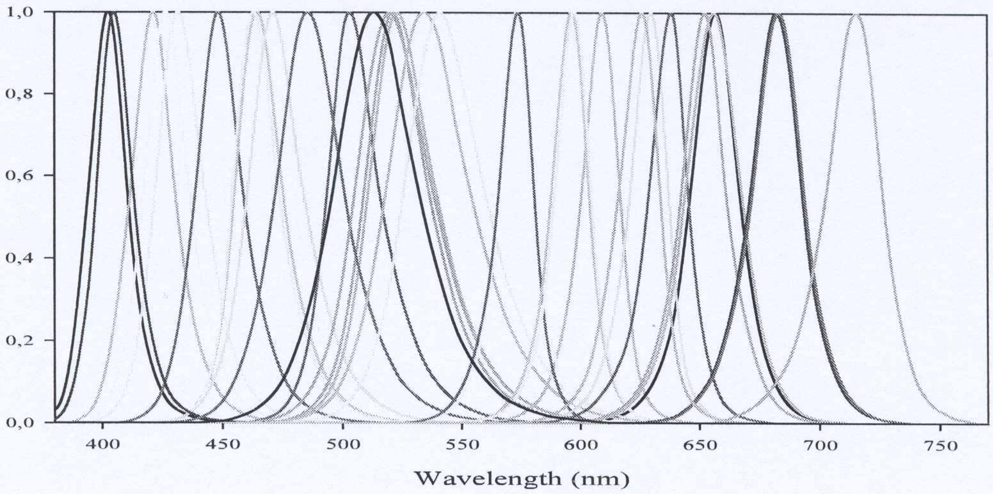

Figure 1. Spectral power distribution with normalized spectral radiance.

After this previous evaluation, we proceed to the development of the mathematical model that would allow us to know the intensity needed from each LED for reconstructing the followings illuminants: D65, D50, A, E, F2, F11 and HP1. The result of this method should be a weighting matrix that relates the spectrum of standard illuminant to the set of LED spectra, both expressed by radiance:

$$I_m = p_n L_{m,n}, \qquad \text{(Eq. 1)}$$

where I_m represents standard illuminant spectrum, $L_{m,n}$ contains spectra of the 31 LEDs and p_n is the weighting matrix that encompasses the weights of each LED which are used to match target spectrum. The spectral resolution that set for the reconstruction was 1nm, in this way, the model should simulate the spectrum of each illuminant over 301 wavelengths (m) and 31 channels (n).

First of all, equation 1 was theoretically solved by normal or Gauss equations due to that $L_{m,n}$ is not an square matrix:

$$p = (L^T L)^{-1} L^T I, \qquad \text{(Ec. 2)}$$

Unfortunately, this technique solves this system of equation without taking into account that the weight of an LED cannot be negative, therefore another method was applied. As we said previously, this new method is classified as a minimization routine; especially, the Matlab's (version 7.11) function *fmincon* was applied. Its goal is to minimize the distance between target spectrum (SPD_illum_i) and the one generated by LEDs (SPD_LEDs_i):

$$f = \sum_{i=400}^{700} (SPD\_illum_i - SPD\_LEDs_i)^2 \qquad \text{(Eq. 3)}$$

Thanks to this method, positive weighting values were obtained between 0 and 1.

Quantitative evaluation of the reconstructions was realised through goodness of fit coefficient (GFC), root-mean-square error (RMSE), correlated colour temperature (CCT), colour rendering indexes (Ra and Rb) and chromatic coordinates CIE-xy.

3. RESULTS AND DISCUSSION

Figure 2 shows four comparisons between of the generated spectra and the real ones. In addition, in Table 1 there are CCT, Ra, Rb, CIE-xy, GFC and RMSE values for D65, A, E and F2 illuminants.

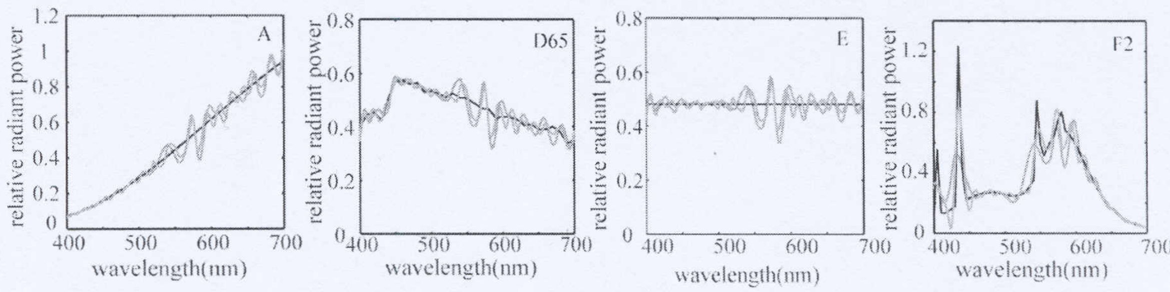

Figure 2. Comparison between the generated spectra (green line: Gauss's equations method; red line: minimization routine) and the real ones (black line).

Table 1. CCT, Ra, Rb, CIE-xy, GFC and RMSE parameters.

		CCT (K)	Ra	Rb	x	y	GFC	RMSE
CIE standards	D65	6505	99.55	99.50	0.3127	0.3293	-	-
	A	2864	99.47	99.23	0.4472	0.4077	-	-
	E	5457	95.31	93.84	0.3333	0.3338	-	-
	F2	4230	64	50.61	0.3721	0.3751	-	-
Gauss's equations	D65	6557	99.06	98.89	0.3118	0.3286	0.9984	2.6466
	A	2867	98.66	98.37	0.4467	0.4072	0.9980	3.4059
	E	5496	94.39	92.71	0.3325	0.3331	0.9983	2.7809
	F2	4261	63.48	51.32	0.3708	0.3751	0.9846	7.0262
Minimization routine	D65	6615	98.32	98.04	0.3108	0.3281	0.9966	3.8852
	A	2875	97.31	96.89	0.4461	0.4069	0.9957	4.9892
	E	5541	93.46	91.65	0.3315	0.3325	0.9964	4.0655
	F2	4423	70.07	59.08	0.3649	0.3726	0.9543	12.0390

Theoretical model offers more accurate reconstructions in both fitting and colorimetric values, as it can be seen in Figure 2 and Table 1, but experimentally unacceptable. Despite the fitting achieved by the minimization routine is not as accurate as the theoretical method, the obtained weights for each LED are totally transferable to the light source. The best reconstructions were found for D65, D50, A and E standard illuminants.

The spectral range where fitting is worse is the one placed between 550 and 600nm, the well-known *green gap*. This phenomenon is due to the fact that, nowadays, LED technology is not able to generate higher values of radiance like it does in other spectral regions.

4. CONCLUSIONS

In this work, a minimization routine able to reproduce the spectrum of standard illuminants based on an LED-based spectrally tuneable light source has been developed but further work is needed to reach higher levels of accuracy. Moreover, new LEDs in the green region of the visible spectrum (500-600nm) will be searched in order to increase the spectral sampling in this zone. Consequently, the performance of the algorithm will be improved, which is considered a solid and applicable method to any set of quasi-monochromatic light sources (LEDs or any other future technology).

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