Multispectral imaging system with multiplexed LED illumination for spectral and color measurements

Jorge HERRERA-RAMIREZ, Meritxell VILASECA and Jaume PUJOL
Centre for Sensors, Instruments and Systems Development (CD6), Technical University of Catalonia (UPC)

Abstract

This paper shows the characterization of a multispectral system that uses a cluster of light-emitting diodes (LEDs) as illumination source to perform reflectance measures. The system has two modules. The first module covers the range of wavelengths from 350 to 950nm and the second one from 950 to 1650nm. The spectral emission and temporal behavior of the LEDs are experimentally measured. Furthermore, the spatial non-uniformity of the illumination field together with the imaging sensors is evaluated and corrected. The performance of the system for the reconstruction of spectral reflectances is analyzed by simulating ideal conditions and realistic ones adding noise. The results show that a rather good performance of the setup is expected. However, they also reveal a difference in the performances of the two modules, being that of the second one poorer due to the fact that it has a lower number of LEDs with a wider spectral emission covering the near-infrared range.

1. Introduction

Multispectral imaging is a field with a wide range of applications because of its capacity of offering spectral information with high spatial resolution; it extends over industrial problems as well as biological ones passing by arts, pharmaceutical and many others, Sheth et al. (2009); Vilaseca et al. (2008) . A multispectral system can be implemented in different ways and recently the development and accessibility to LED technology has become an attractive alternative to be used in these systems, Brydegaard et al. (2009). Colored LED elements have narrow-spectral emission and are available in several wavelengths over the different spectral ranges of ultraviolet (UV), visible (VIS) and near-infrared (NIR). Therefore, they allow lighting the sample with a large number of specific wavelengths or customized combinations of them in a fast way and in synchrony with the imaging sensors used. Following this idea, this work shows the characterization of a multispectral system with LED illumination. This characterization was carried out with experimental measurements of the temporal behavior of the LED emissions; with the correction of the spatial non-uniformity in the illumination; and the evaluation of the system performance in spectral reflectance estimation through simulations of ideal and real noise conditions of operation, for which the pseudo-inverse method has been used, Vilaseca et al. (2006). Different metrics were used to quantify the system performance in the simulations of reflectance reconstruction.

2. Experimental setup

The experimental implementation of the multispectral system has two different modules. The first module consists of a monochrome CCD camera with 12 bit depth, 1392 x 1040 pixels and 16 groups of LEDs where each group, consisting of four LEDs which were equi-spaced along a ring, has a specific central wavelength of emission. They cover the wavelength range from 350nm to

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950nm. In a similar fashion, the second module has an InGaAs based camera with 14 bit depth, 320 x 246 pixels and 7 groups of LEDs. This module covers the range of wavelengths from 900nm to 1650nm. Table 1 contains the measured spectral descriptive data for each LED element (Peak wavelength and full width at half maximum [FWHM]). Figure 1 shows one of the modules of the system.

Table 1. Spectral data for the LED elements comprising the illumination source (Peak wavelength and full width at half maximum [FWHM]). All data are given in nanometers (nm).

Module 1				Module 2	
Peak wavelength	**FWHM**	**Peak wavelength**	**FWHM**	**Peak wavelength**	**FWHM**
373	9.5	404	15	955	51
432	17	461	22	1071	53
500	32	535	34	1202	88
593	15	634	16.5	1297	89
665	21	693	23.5	1451	122
728	24	761	26	1540	126
801	28	835	31	1630	111
874	45	903	41		

3. Methods

3.1 Temporal characterization

The emission of all groups of LEDs was characterized as a function of the time in order to establish the necessary time to obtain a constant and stationary illumination over the samples.

3.2 Spatial characterization

The aim of the spatial characterization was the correction of the spatial non-uniformity of the imaging sensor together with the light source used, in our case the ring of LEDs. For it we used a flat field algorithm based on an offset and gain matrices proposed by de Lasarte et al. (2007), which takes into account a dark image and a base correction image with a mean digital level placed in the middle of the linear response range of the cameras to correct the raw image acquired.

3.3 Pseudo-inverse model to estimate reflectances and metrics for spectral evaluation

There are several methods to estimate spectral reflectances in multispectral systems. One of them is the widely spread pseudo-inverse method. This method relates the camera responses of the system through the different acquisitions channels with the estimated reflectances by means of a transformation matrix. This mapping matrix minimizes the least-squares-error for a training set of known reflectances with the correspondent camera responses and does not use prior knowledge of the acquisition system characteristics,Vilaseca et al. (2006).

Reconstructions were carried out for two different conditions in the simulations: under ideal conditions (IC) and under noise conditions (NC), where a 2% additive random noise and the quantization error of the imaging sensors were included.

To evaluate the performance of the system three different metrics were used. Two metrics serve to compare the estimated spectral curves with respect to the original spectra: the root mean square error (RMSE), which is a widely used metric for spectral evaluation, and the goodness-of-fit coefficient (GFC) proposed by Hernández-Andrés et al. (2001). GFC $\geq$ 0.999 and GFC $\geq$0.9999 are required for respectively good and excellent matches. The third metric is the CIEDE2000 formula (DE00) used over the reconstructions in the VIS range as a colorimetric evaluation, Sharma et al. (2005).

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4. Results and discussion

Figure 2 contains the temporal stabilization curve for one of the LEDs used in the system (λ=535nm). The change in percentage between the peak of intensity and the stabilization zone for the different LEDs tested ranged between a maximum of 9.19% and a minimum of 2.12%, with a 5.43% for the case shown. In general, stabilization times longer than 40 sec were necessary to achieve a percentage of variation below 2%. Although we have a good control of the current in the system, a higher stability is not reached because of the temperature influence in the LEDs emission.

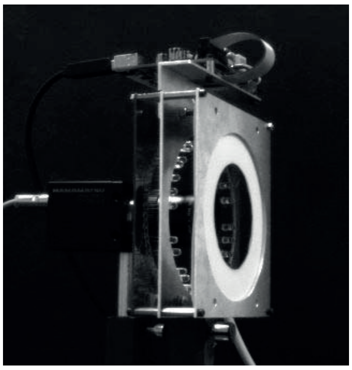


Figure 1. Multispectral system

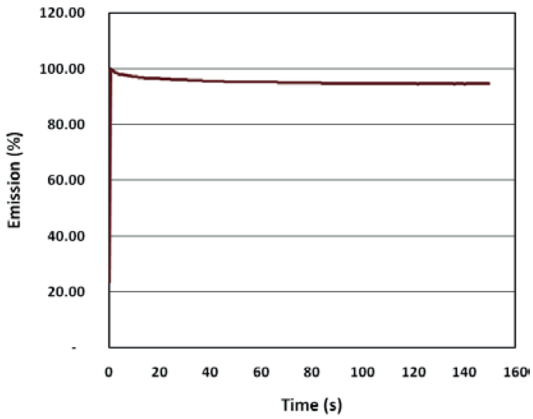
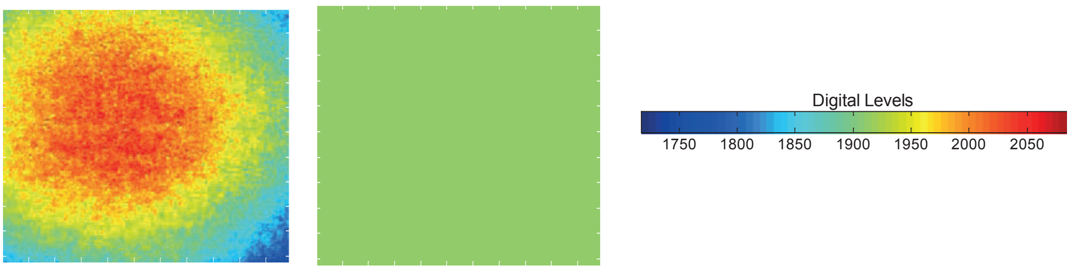


Figure 2.Curve of temporal stabilization of LED emission

Figure 3 shows the result of applying the flat field correction to the system in terms of spatial non-uniformity percentage: SNUP = 100 × σ(mean)/mean, de Lasarte et al. (2007). This parameter changed from a value of 2.83% to a 0.012% with the application of the correction. A similar behavior was found in the different channels of the system. Table 2 shows the comparison of the implemented metrics for the evaluation of the reflectance estimation with and without noise. The results demonstrate that the system performs rather well even under noise conditions. Although the second module has poorer results than the first one, probably due to the lower number of LEDs and their wider spectral emission, its performance is still reasonably good.



a) b)

Figure 3. Spatial non-uniformity correction. a) Original image and b) corrected image.

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Table 2. Comparison of metrics for the evaluation of the reflectance estimation for two different conditions: ideal conditions (IC) and under noise conditions (NC).

	Module 1						Module 2			
	DE00		RMSE (%)		GFC		RMSE (%)		GFC	
	IC	NC	IC	NC	IC	NC	IC	NC	IC	NC
Mean	0.017	1.016	0.16	1.17	1.0000	0.9995	0.96	2.11	0.9991	0.9976
Min	1.2e-3	0.208	3.7e-3	0.11	0.9991	0.9962	0.04	0.10	0.9899	0.9790
Max	0.098	3.039	0.81	3.11	1.0000	0.9999	4.16	9.45	1.0000	0.9997

5. Conclusions

This paper shows the evaluation through simulations and the characterization of a multispectral system intended for its future use in the study of artwork. The temporal behavior in emission of the LED elements was measured showing good stability after 40 sec. A flat field algorithm was implemented for the correction of the spatial non-uniformity and simulations of the system in reflectance estimation were also carried out. Regarding the metrics for the evaluation of the reflectance estimation, the system performs very accurately for the two modules under ideal conditions. For the noise condition, the performance of the system decays but it is still good. Comparatively, the second module has less accuracy than the first module and that fact is closely related to the minor availability of LED elements in the range of wavelengths comprised by this module.

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Address: Jorge Herrera, Centre for Sensors, Instruments and Systems Development (CD6), Technical University of Catalonia (UPC). Rambla Sant Nebridi, 10, TR11/CD6, 08222 Terrassa, Spain
E-mails: Jorge.alexis.herrera@cd6.upc.edu, mvilasec@oo.upc.edu, pujol@oo.upc.edu

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