Spectral synthesis of daylight using a digital CCD colour camera

J.L. Nieves[1], E.M. Valero[1], S.M.C. Nascimento[2], J. Hernández-Andrés[1], J. Romero[1]
[1]*Departamento de Óptica, Fac. de Ciencias, Universidad de Granada, 18071-Granada (SPAIN)*
[2]*Departamento de Física, Campus de Gualtar, Universidade do Minho, 4710-057 Braga (PORTUGAL)*
Corresponding author: J.L. Nieves (jnieves@ugr.es)

ABSTRACT

We investigated the quality of the spectral estimation of daylight-type illuminants using a commercial digital CCD camera coupled or not with a set of broadband coloured filters. Several recovery algorithms that did not need information about spectral sensitivities of the camera sensors nor eigenvectors to describe the spectra were tested. Tests were carried out both with virtual data, using simulated digital counts, and real data obtained from real measurements. It is found that it is possible to recover daylight spectra with high spectral and colorimetric accuracy with a reduced number of 3 to 9 spectral bands.

1. INTRODUCTION

Although intense research has been focusing in multispectral analysis of images, in particular in the area of accurate spectral characterization of artworks[1-4], multispectral analysis and synthesis of the spectral power distribution (SPD) of illuminants has been little explored.[5] Different computational approaches have been introduced to improve the colorimetric and spectral accuracy for channel selection in the spectral estimation of either the reflectance or the SPD using multi-channel devices.[1,3,6] The spectral techniques can be classified into two main categories accordingly to the way spectral images are captured. On one hand, techniques that use a large number of filters (generally a narrow-band set of more than 30 filters covering the visible spectrum). This is the most direct spectral method and is based on coupling a set of filters to a monochrome camera.[3] On the other hand, Imai and co-workers proposed a more indirect technique that assumes some a priori spectral analysis of the colour signals.[1] They have shown that a multiple-of-three channels through either multi-filter or multi-illuminant approach can be used to derive computationally efficient of low cost and colorimetrically and spectrally accurate spectral analysis.

The aim of the present work was to investigate the quality of the spectral estimation of daylight-type illuminants using a commercial digital CCD camera coupled or not with colored filters. Several recovering techniques based on different algorithms, number and type of colored filters were tested. Both virtual data using simulated digital counts and real measurements were carried out. It was found that it is possible to recover daylight spectra with high spectral and colorimetric accuracy with a reduced number of spectral bands.

2. METHOD

The digital camera used was a Retiga 1300, with a spatial resolution of 1280×1024 pixels and a digital resolution of 12-bits per channel. The camera was assumed pointing to a uniform white reference surface with spectral reflectance function $r_W(\lambda)$. The response of the kth sensor ρ_k is,

$$\rho_k = \sum_{\lambda=400}^{700} E(\lambda) r_W(\lambda) Q_k(\lambda) \tag{1}$$

where $Q_k(\lambda)$ is the spectral sensitivity of the kth sensor (Figure 1) and $E(\lambda)$ is the SPD of the illuminant impinging on the white reference surface (chip number 19 from the GretagMacBeth ColorChecker). The digital counts were computed for a set of 433 SPDs of daylight-type illuminants which were previously measured in our laboratory.[7] Simulation of digital counts was also carried out assuming the CCD camera coupled with different sets of broad-band colour filters. Thus, data were

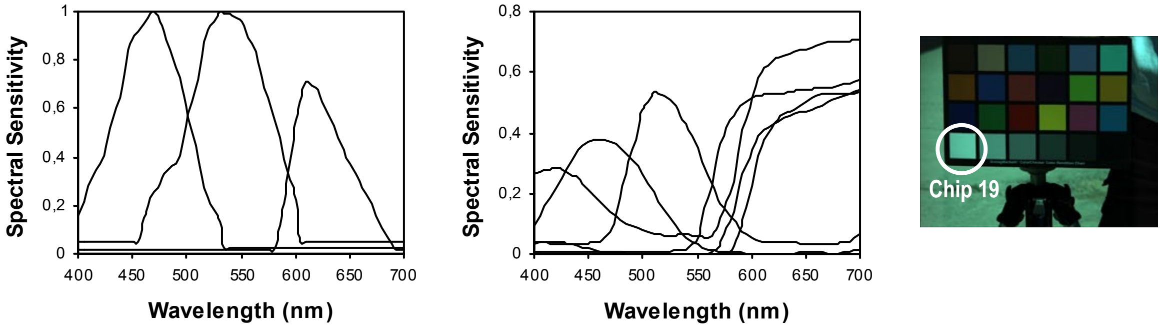

Figure 1: Spectral sensitivity functions of digital CCD and spectral transmittance curves (two leftmost figures) of the six colour filters used for the SPD synthesis. The experimental setup showing the achromatic chip captured by the camera is also shown on the right panel.

obtained with a single a set of k=3 sensors, the three native RGB channels of the camera, a set of k=6 sensors, with three filtered RGB channels, and a set of k=9 sensors with six filtered RGB (Figure 1).

2.1. Eigenvector analysis with pseudo-inverse transformation

It is possible to find square-integrable functions $V_i(\lambda)$ (i= 1,2,…m) such that for any SPD of the illuminant there is a single set of real numbers, ε_i, such[8,9] $E(\lambda)=\sum_{i=1}^{m}\varepsilon_i V_i(\lambda)$. Thus the response of the k sensors can be expressed in matrix notation as,

$$\overline{\boldsymbol{\rho}} = \Lambda\overline{\boldsymbol{\varepsilon}} \tag{2}$$

where,
$$\Lambda_{ki} = \sum_{\lambda} V_i(\lambda) r_W(\lambda) Q_k(\lambda) \tag{3}$$

and coefficients ε_i are calculated as usual by the orthogonal projection,

$$\varepsilon_i = \left\langle E(\lambda) \middle| V_i(\lambda) \right\rangle \tag{4}$$

If the number of sensors do not equal the number of eigenvectors a transformation can be derived by fitting the k simulated digital signals and the m eigenvector coefficients, ε_i. We have used the eigenvectors obtained by PCA from a set of 2,600 daylight spectra.[5,7] To obtain the estimated spectrum $\overline{\boldsymbol{E}}_e$ from the digital counts, let $\overline{\boldsymbol{G}}$ be the $m \times k$ matrix operating from the right hand,

$$\varepsilon_e = \overline{\boldsymbol{G}}\,\overline{\boldsymbol{\rho}} \tag{5}$$

where ε_e are the estimated m eigenvector coefficients. A relationship between ε_e and digital counts $\overline{\boldsymbol{\rho}}$ can be established by the usual pseudo-inverse calculation, and the matrix $\overline{\boldsymbol{G}}$ is expressed as,

$$\overline{\boldsymbol{G}} = \overline{\varepsilon}\,\overline{\boldsymbol{\rho}}^T \left[\overline{\boldsymbol{\rho}}\,\overline{\boldsymbol{\rho}}^T\right]^{-1} \tag{6}$$

Thus the estimated SPD of illuminants can finally be obtained from the matrix product,

$$\overline{\boldsymbol{E}}_e = \boldsymbol{V}\left(\overline{\boldsymbol{G}}\,\overline{\boldsymbol{\rho}}\right) \tag{7}$$

In general, the method requires an adequately choice of the k sensors, which determines the dimension of the base derived from PCA and influence spectral and colorimetric quality of the SPD estimation.

2.2. Direct pseudo-inverse transformation

This method consists on establishing a direct relationship between the digital counts and the spectra of the illuminants. It is based on a one-step transformation which minimizes the least square error between the original, $E(\lambda)$, and the estimated SPDs of the illuminants, $E_e(\lambda)$, from the k digital signals. This means that a transformation matrix is directly obtained from the spectra of the training set of 2,600 SPDs and the k digital signals. The error defined by $\left\| \overline{\boldsymbol{E}} - \overline{\boldsymbol{F}}\ \overline{\boldsymbol{\rho}} \right\|^2$ where $\overline{\boldsymbol{F}}\ \overline{\boldsymbol{\rho}}$ represents the estimated SPD, is minimized with respect to $\overline{\boldsymbol{F}}$, and the spectrum of the estimated illuminant is,

$$\overline{\boldsymbol{E}}_e = \overline{\boldsymbol{E}}\ \overline{\boldsymbol{\rho}}^T \left[\overline{\boldsymbol{\rho}}\ \overline{\boldsymbol{\rho}}^T \right]^{-1} \overline{\boldsymbol{\rho}} \qquad (8)$$

Thus, using this method, the SPD of illuminants does not need to be described in any mathematical base.

3. RESULTS

3.1. Results with simulated digital counts.

Figure 2 shows examples of the 99th percentile for GFC and the different sets of double colored filters used (k=9) with simulated digital counts; the results for the pseudo-inverse transformation are for an equal number of sensors and eigenvectors. As expected, accuracy is better than that obtained for the camera without filter or with one single coloured filters. Spectral accuracy for both methods is similar with average GFC (±SD) of 0.99985±0.00005 and 0.99987±0.00004, respectively, indicating very good spectral fits.

3.2. Results with measured digital counts.

To estimate the quality of the spectral recovery in real conditions the achromatic patch number 19 of the GretagMacBeth ColorChecker was imaged outdoors using the Retiga 1300 camera. Simultaneously, the colour signal from this patch was measured with a telespectroradiometer PR-650. The *magenta2* and the pair *magenta2-orange* were the filter and filter combinations selected. In each measurement the achromatic patch was recorded with 3, 6 and 9 digital signals, corresponding to the filter configurations described. The ColorChecker was held at a 45º angle and 50 cm above the floor. Transformation matrix $\overline{\boldsymbol{G}}$ was derived from a sub-set of 20 SPDs, and additional set of 10 SPDs was used to test the multispectral synthesis algorithms.

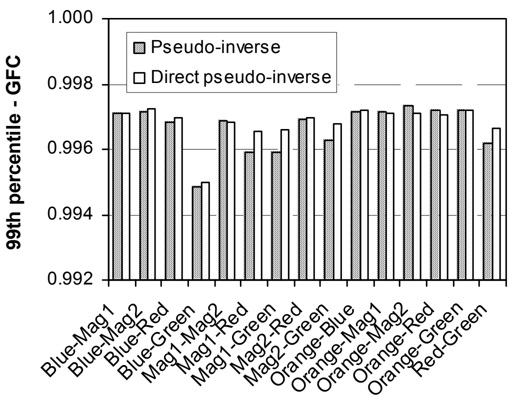

Figure 2: The 99th percentile for GFC for the two estimation algorithms and for the different sets of double coloured filters used, k=9.

Direct pseudo-inverse gives better spectral and colorimetric accuracy than pseudo-inverse SPD synthesis method (average GFC value of 0.9999 versus 0.9970). The colorimetric accuracy increases on average from ΔEab=0.7330 for pseudo-inverse, to 0.1794 for the direct-pseudo-inverse method. Also increasing the number of sensors reduces the errors in the estimated SPDs, although the colorimetric accuracy is slightly better for 6 than for 9 bands.

4. DISCUSSION AND CONCLUSIONS

Results suggest that direct pseudo-inverse surpass eigenvector analysis with simple inversion and pseudo-inverse transformation for both virtual data using simulated digital counts and real measurements (see figure 3). The differences obtained for spectral and colorimetric accuracy between pseudo-inverse and direct pseudo-inverse methods shortens particularly for 6 and 9 sensors and measured digital counts. Even with 6 sensors the colorimetric accuracy is close and slightly better than for 9 sensors. Thus, the spectral estimation of daylight-type illuminants using a tri-chromatic digital camera and a priori analysis of spectral properties is plausible not only for reflectances but for SPD of illuminants also.

The great advantage of this synthesis algorithm by comparison with other algorithms using CCD cameras[6] is that it does not need information about spectral sensitivities of the camera sensors. Thus, the performance of the direct pseudo-inverse method does not depend neither on possible illconditioness of the transformation matrices derived from eigenvector analysis with simple inversion methods (see equation (2)) nor on the selected illuminant spectral used to do the eigenvector analysis. The method proposed here is optimized with appropriate selection of the training set SPDs; the larger the set of different SPDs of illuminants, including different atmospheric conditions, hours of the day and seasons, the better spectral and colorimetric accuracy will be.

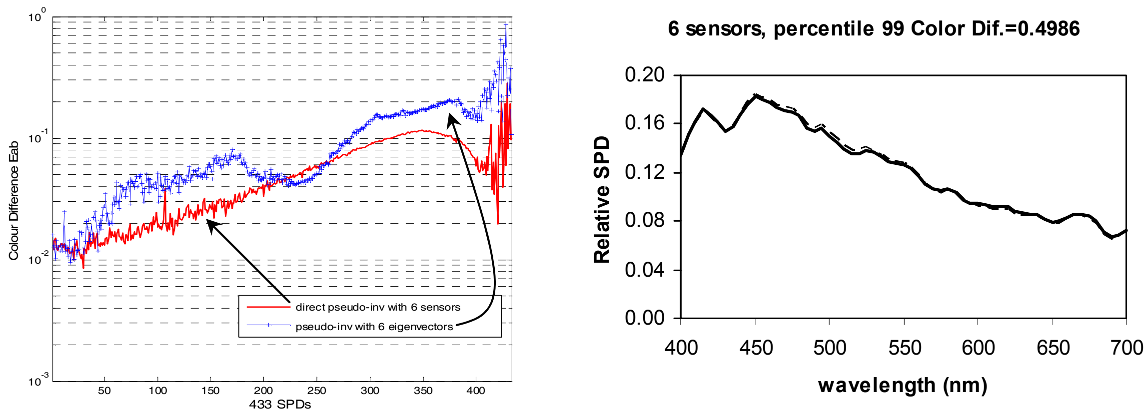

Figure 3: Colour differences (left) derived from the two synthesis methods with simulated digital counts and 6 sensors. Example (right) of the recovered spectrum using the direct pseudo-inverse method with 6 sensors and real measurements.

References

1. F.H. Imai and R. Berns, “Spectral estimation using trichromatic digital cameras”, in International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives (Society of Multispectral Imaging of Japan, 1999), pp. 42-49.
2. F.H. Imai, R. Berns and Di-Y. Tzeng, “A comparative analysis of spectral reflectance estimated in various spaces using a trichromatic camera system”, J.Imaging Sci. Technol. 44, 280-371 (2000).
3. J. Hardeberg, F. Schmitt and H. Brettel, “Multispectral color image capture using a liquid crystal tunable filter“, Opt. Eng. 41, 2532-2548 (2002).
4. F. H. Imai and R. S. Berns, Spectral estimation of oil paints using multi-filter trichromatic imaging, in Proc. of the 9th Congress of the International Colour Association, Rochester (NY, 2001), pp. 504-507.
5. J. Hernández-Andrés, J.L. Nieves, E. Valero and J. Romero, “Spectral-daylight recovery by use of only a few sensors”, J.Opt.Soc.Am. A 21, 13-23 (2004).
6. C.-C. Chiao, D. Osorio, M. Vorobyev and T.W. Cronin, “Characterization of natural illuminants in forests and the use of digital video data to reconstruct illuminant spectra”, J. Opt. Soc. Am. A 17, 1713-11721 (2000).
7. J. Hernández-Andrés, J. Romero, J.L. Nieves and R.L. Lee, Jr., “Color and spectral analysis of daylight in southern Europe”, J. Opt. Soc. Am. A 18, 1325-1335 (2001).
8. L.T. Maloney and B. Wandell, “Color constancy: a method for recovering surface spectral reflectance”, J. Opt. Soc. Am A 3, 23-33 (1986).
9. J. Romero, A. García-Beltrán and J. Hernández-Andrés, “Linear bases for representation of natural and artificial illuminants”, J. Opt. Soc. Am. A 14, 1007-1014 (1997).