Illuminant Influence on the Reconstruction of NIR Spectra

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Abstract

In order to recover spectral reflectances or transmittances using a multispectral imaging based technique, it is necessary to know the spectral radiance of the illuminant used to light the samples in the acquisition process. In this study, we analyzed the influence of the spectral distribution of the illuminant on the reconstruction of spectral reflectances in the near infrared region of the spectrum (NIR). We considered a set of 30 textile samples with different spectral reflectance in this region. We tested the performance of a principal component analysis (PCA) based method and a non-linear estimation method (NLE), which allow us to obtain the spectral reflectance of samples in the NIR region from a small number of measurements performed with a CCD camera. Using numerical simulation, we analyzed the number and shape of the optimum filters that need to be used in the acquisition channels in order to obtain good spectral reconstructions under several lighting conditions. Finally, we studied the quality of the reconstructions with a set of commercially available filters which are similar to the optimum filters obtained in the simulations. The results obtained show that the reconstruction does not depend heavily on the illuminant used. This indicates that, with the same set of filters, we can obtain good reconstructions for different types of illuminant.

Introduction

Conventional CCD cameras[1,2] have maximum spectral sensitivity in the visible region of the spectrum. Nevertheless, CCD cameras with improved response in the near infrared (NIR) are currently manufactured and their spectral sensitivity is clearly significant up to 1000 nm. Therefore, this standard instrumentation can be used in order to obtain spectral information of samples in the NIR region (800 – 1000 nm), which is not usually available with conventional spectrophotometers. Standard spectrophoto-meters normally have their response limited to the visible range and require additional sensors to detect energy coming from the NIR (for example, InGaAs), which can significantly increase their cost. The spectral information included in the NIR region is in general directly related to the constituents of a material. Therefore, it is used as an analytical tool in industry and research, and is known as NIR technology.[3] The applications include agriculture, the food industry, medical applications, military applications, the chemical industry etc.

Multispectral imaging[4-7] allows us to obtain the reflectance or transmittance spectra of samples using conventional CCD camera measurements. This technique uses different acquisition channels from which several images of the analyzed sample are obtained. Because of the different spectral response of the channels, the obtained images hold spectral information of the acquired scene. It is therefore possible to calculate the spectral reflectance or transmittance of the original measured sample. The multispectral imaging based methods need all the spectral variables involved in the acquisition process to be known. These variables are; the spectral radiance of the illuminant used, the spectral transmittance of the filters which define each of the acquisition channels and the spectral sensitivity of the CCD camera. After selecting the CCD camera, we can study which illuminants and filters may be used in order to obtain the best reconstruction results of the set of considered samples. Since the mathematical methods used perform approximations, the factors mentioned may yield different quality reconstructions.

In this work we studied the performance of two different spectral reconstruction methods, principal component analysis (PCA)[6,8-10] and a non-linear estimation method (NLE),[11,12] under several lighting conditions. The considered illuminants were of the blackbody type with color temperatures between 1000 K and 16000 K. By numerical simulation, we analyzed the shape of the optimum filters which must be placed in front of the camera in order to obtain good reconstructions of the reflectance spectra of different samples for the tested illuminants. After that, we studied the influence of the illuminant on the quality of the reconstruction using commercially available filters similar to the optimum filters used in the simulations.

Spectral Reconstruction Methods

The reconstruction process used in multispectral imaging based methods is summarized in Figure 1. A multi-channel image of an original object is acquired by placing a selected set of filters in front of the camera. After that, a spectral reconstruction method is applied and the reconstructed spectral reflectance of the sample is obtained.

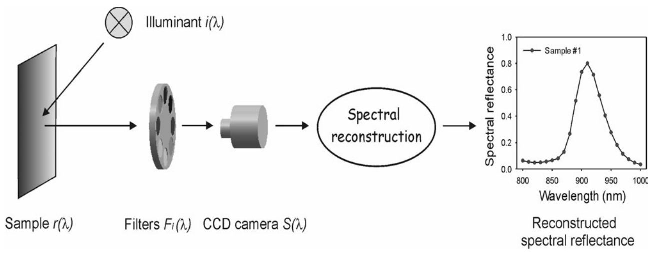

Figure 1. Schematic view of the acquisition system and the final spectral reconstruction step.

There are several spectral reconstruction methods based on interpolation or estimation methods.[4-7] The latter include linear methods, NLE or PCA methods. In this work we analyzed the performance of a PCA and an NLE method. In previous works[10,15] we showed how these methods yield the best spectral reconstruction results in the NIR region.

In order to use these methods, it is necessary to know a set of spectral reflectances similar to the curves that we want to reconstruct. The set of *n* known spectral reflectances is represented by a *n* x *p* matrix called **Or**.

The camera responses for the acquisition channels can be expressed in matrix notation as follows:

$$\mathbf{X} = \mathbf{Cr} \tag{1}$$

where **X** is a column vector which represents the *m* responses of the camera to a sample, **r** is a column vector (*n* components) representing the spectral reflectance of the sample, and **C** is a $m \times n$ matrix in which each row is the spectral sensitivity of a different acquisition channel, that is, $i(\lambda_l)F_i(\lambda_l)S(\lambda_l)$ with i=1,.., m and l=1,...,n, $i(\lambda_l)$ being the spectral radiance of the illuminant, $F_i(\lambda_l)$ the transmittance of the filters used, and $S(\lambda_l)$ the sensitivity of the CCD camera.

The PCA method associates the matrix **Or** to a vector space and its characteristic vectors can be calculated. Thus, each spectral reflectance curve can be obtained as a linear combination of the largest characteristic vectors:

$$\mathbf{r_{rec}} \approx \mathbf{r_M} + \alpha \mathbf{v_{r1}} + \beta \mathbf{v_{r2}} + ... + \xi \mathbf{v_{rq}}, \ q<n \tag{2}$$

where $\mathbf{r}_{rec}$ is the reconstructed spectral reflectance, $\mathbf{r}_M$ is the mean spectral reflectance of the curves belonging to **Or**, $\mathbf{v}_{r1}$, $\mathbf{v}_{r2}$,..., $\mathbf{v}_{rq}$ are the characteristic vectors and α, β,.., ξ are scalar coefficients. They can be experimentally determined relating the camera responses for each sample to the characteristic vectors, that is, combining Eqs. (1) and (2):

$$\mathbf{X} = \mathbf{Cr} \approx \mathbf{Cr_M} + \alpha \mathbf{Cv_{r1}} + \beta \mathbf{Cv_{r2}} + ... + \xi \mathbf{Cv_{rq}}, \ q<n \tag{3}$$

On the other hand, the NLE method used supposes that a matrix $\mathbf{D}_{NL}$ exists and that it provides the spectral reflectances from:

$$\mathbf{r_{rec}} = \mathbf{D_{NL}} \mathbf{X_{NL}} \tag{4}$$

where $\mathbf{X}_{NL}$ is a column vector which represents a complete second order polynomial calculated using the camera responses, that is,

$$\mathbf{X_{NL}} = \left[1 \ X_1 \ X_2 \ X_3 \ X_1^2 \ X_2^2 \ X_3^2 \ X_1 X_2 \ X_1 X_2 \ X_2 X_3 \right]^T \tag{5}$$

The matrix $\mathbf{D}_{NL}$ can be calculated using the pseudoinverse technique,[5,13,14] taking into account the reflectance spectra belonging to the matrix **Or**:

$$\mathbf{D_{NL}} = \mathbf{O_r} \mathbf{X_{NL}^T} (\mathbf{X_{NL}} \mathbf{X_{NL}^T})^{-1} \tag{6}$$

In order to evaluate the quality of the reconstruction of the analyzed spectra we use two different parameters :

Percentage of Reconstruction:

$$P_{rec} = \left[1 - \frac{\sum_{\lambda_{min}}^{\lambda_{max}} (r - r_{rec})^2}{\sum_{\lambda_{min}}^{\lambda_{max}} (r)^2} \right] \times 100 \tag{7}$$

Root Mean Square Error:

$$RMSE = \left[\frac{1}{N_\lambda} \sum_{\lambda_{min}}^{\lambda_{max}} (r - r_{rec})^2 \right]^{1/2} \tag{8}$$

Data

In order to perform the simulations and the optimization process we considered a matrix $\mathbf{O}_r$ composed of 30 spectral reflectance curves corresponding to textile samples (Figure 2). We considered the spectral data between 800 and 1000 nm in 10 nm steps. Therefore, each curve was made up of 21 components. The CCD camera used was a JAI CV-M10 progressive scan camera (Figure 3).

The analyzed illuminants were blackbody or Planckian type (specifically graybody radiators) with the following color temperatures: 1000, 1500, 1800, 1850, 1900, 2000, 2852, 3371, 4000, 5000, 6000, 7000, 8000, 9000, 12000, 13000, 14000 and 16000 K (Figure 4). 2852 and 3371 K correspond to the color temperatures of commercial available sources. The total emission of the illuminants was normalized to a specific value of radiance (10^5 W/sr*m^2) in order to obtain simulated lamps with the same radiant flux. In the case of the PCA method, it can be seen that the reconstruction results only depend on the relative emission of the illuminant, that is, its color temperature. Unlike PCA, the results provided by the NLE method have a dependency on the absolute emission of the illuminant as well as the color temperature. In order to take into account this dependency we have also analyzed the NLE method under the influence of some illuminants with color temperature Tc = 3371 K but different radiance values (specifically 10^3, 10^4, 10^6 and 10^7 W/sr*m^2).

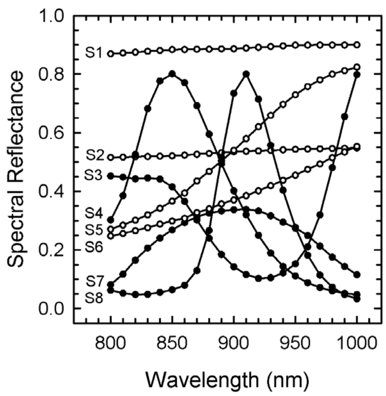

Figure 2. Spectral reflectance curves of 8 representative samples belonging to the matrix ***Or****.*

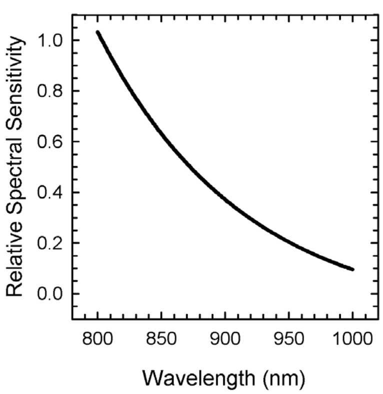

Figure 3. Experimental relative spectral sensitivity of the camera JAI CV-M10.

In the first part of the numerical simulation we used five equi-spaced Gaussian filters in the 800-1000 nm region with variable spectral bandwidth, in order to obtain simple transmittance profiles and therefore available commercial filters. In a previous work we demonstrated that five filters were enough to achieve good reconstructions in the NIR region[10,15]. The transmittance of each simulated filter was:

$$T(\lambda) = T_{MAX}\ \exp\left[-4\ln 2\left(\frac{\lambda-\lambda_0}{FWHM}\right)^2\right] \qquad (9)$$

where T_{MAX} (considered 1 in this study) is the maximum height of the Gaussian peak, λ_0 is the wavelength corresponding to the maximum (center) of the Gaussian and FWHM is the full width at half maximum of the Gaussian. The parameter FWHM was considered the optimization parameter. In order to determine the shape of the optimum filters, it was increased progressively in the same way for all the channels and the value providing the best reconstruction for the spectral curves belonging to $\mathbf{O_r}$ was chosen.

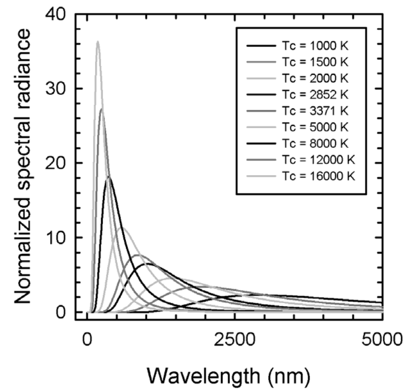

*Figure 4. Spectral radiance of the analyzed illuminants normalized to 10^5 W/sr*m^2.*

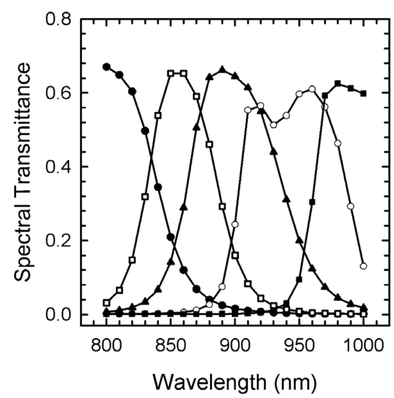

Figure 5. Spectral transmittance of the real interference filters.

After the optimizations with simulated Gaussian filters, we used real commercial filters (Thermo Corion interference filters) in order to evaluate the influence of the illuminants in the reconstructions. These filters were chosen taking into account the shape of the optimum Gaussian filters obtained. According to the results, the FWHM of the filters should be approximately 70 nm. The transmittance of the five real interference filters is shown in Figure 5.

Results

1. Reconstructions with the Simulated Gaussian Filters

In order to determine the shape of the optimum equi-spaced Gaussian filters and therefore to obtain the best reconstruction results under all the analyzed lighting conditions, we performed a numerical simulation using the two proposed reconstruction methods. The best filters were determined by searching for the minimum mean *RMSE* of the curves belonging to the matrix **Or**. Table 1 and Table 2 show the obtained results for the PCA and the NLE methods using illuminants with different color temperatures and radiance 10^5 W/sr*m^2. The obtained reconstruction results using the NLE method and illuminants of color temperature Tc = 3371 K with different radiance values are shown in Table 3.

In the PCA method, the optimizations using illuminants with higher temperature yield optimum filters with smaller FHWM. The parameter P_{rec} decreases with the color temperature, and *RMSE* increases. Using the NLE method, there is no clear relationship between the color temperature and the FHWM of the optimum filters. Similarly, the simulations performed with illuminants of color temperature Tc = 3371K with different radiance values provide results that do not bear any relationship to the emitted radiance.

In both methods there is a stabilization of the optimum spectral bandwidth of the filters for illuminants of color temperature Tc = 5000 K – 6000 K or more. This can be explained by the spectral emission of the illuminants in the NIR region. Because the illuminants with large color temperature have the maximum emission peak located at short wavelengths, they have a similar decreasing spectral distribution between 800 and 1000 nm.

The results obtained can be explained as follows. The PCA method is a linear method whose simulation results are described by equation (3). The explicit form of this equation is:

$$\sum_{\lambda} i_{\lambda} F_{i\lambda} s_{\lambda} r_{\lambda} = \sum_{\lambda} i_{\lambda} F_{i\lambda} s_{\lambda} r_{M\lambda} + \alpha \sum_{\lambda} i_{\lambda} F_{i\lambda} s_{\lambda} v_{1\lambda} + \ldots \qquad (10)$$

Table 1. Reconstruction results using the PCA method, the simulated Gaussian filters and illuminants with different color temperatures.

Tc (K)	*FWHM*	Mean P_{rec}	Mean (*RMSE**100)
1000	122	99.996	0.170
1500	97	99.996	0.183
1800	87	99.995	0.191
1850	85	99.995	0.193
1900	82	99.995	0.194
2000	80	99.995	0.197
2852	66	99.995	0.215
3371	61	99.994	0.223
4000	59	99.994	0.229
5000	56	99.994	0.237
6000	75	99.994	0.242
7000	54	99.994	0.245
8000	54	99.993	0.248
9000	54	99.993	0.250
12000	54	99.993	0.253
13000	54	99.993	0.254
14000	52	99.993	0.255
16000	52	99.993	0.256

Table 2. Reconstruction results using the NLE method, the simulated Gaussian filters and illuminants with different color temperatures.

Tc (K)	*FWHM*	Mean P_{rec}	Mean (*RMSE**100)
1000	66	100	0.032
1500	92	100	0.014
1800	38	100	0.014
1850	89	100	0.014
1900	38	100	0.013
2000	82	100	0.015
2852	80	100	0.016
3371	78	100	0.016
4000	80	100	0.016
5000	103	100	0.016
6000	103	100	0.017
7000	97	100	0.016
8000	99	100	0.016
9000	97	100	0.016
12000	101	100	0.016
13000	103	100	0.016
14000	99	100	0.016
16000	101	100	0.016

Table 3. Reconstruction results using the NLE method, the simulated Gaussian filters and illuminants of Tc = 3371K with different radiance values.

Radiance (W/sr*m^2)	*FWHM*	Mean P_{rec}	Mean (*RMSE**100)
10^3	45	100	0.025
10^4	80	100	0.016
10^5	78	100	0.016
10^6	49	100	0.020
10^7	96	100	0.024

In order to obtain similar results in the optimization process of the filters for any sample, it is necessary to have similar values of the term $i_{\lambda}s_{\lambda}r_{\lambda}$ for the different analyzed illuminants (or, by extension, the terms $i_{\lambda}s_{\lambda}r_{M\lambda}$ and $i_{\lambda}s_{\lambda}v_{1\lambda}$, $i_{\lambda}s_{\lambda}v_{2\lambda}$ etc.). Figure 6 shows these spectral products for a particular sample belonging to the matrix **Or**. While spectral products with different shape, corresponding to specific illuminants, have different optimization results, similarities in these spectral curves are translated to similar spectral bandwidths of the obtained optimum filters.

On the other hand, the shape of these products does not explain the behavior found in the NLE method. This method uses the pseudoinverse technique which computes the inverse of a nonsquare matrix and which, in general, has singularities. The method searches for a least squares solution. Therefore, the obtained results are very sensitive to input variations and may present considerable oscillations.

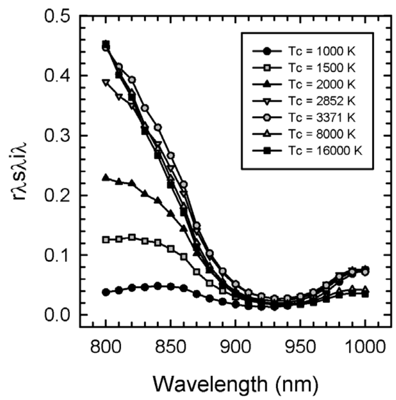

Figure 6. Spectral curve $r_\lambda s_\lambda i_\lambda$ of the sample S3 belonging to $\mathbf{O}_r$.

2. Reconstructions with the Real Filters

In the last section we have presented optimizations performed with five simulated Gaussian filters. We have seen that the spectral bandwidth of the optimum filters depends on the considered illuminant for both analyzed methods. Taking into account that incandescent or halogen lamps, which are used in many devices, have color temperatures within the 2800–3100 K range, we can consider the results obtained for the illuminants with color temperatures 2852 K and 3371 K as optimum. Using the PCA method, the spectral bandwidth of the optimum filters for these two illuminants are 66 nm and 78 nm respectively. In the case of the NLE method, the FWHM values are 80 nm and 78 nm. When ones uses the illuminants of color temperature 3371 K with different radiance values, the optimum filters have an FWHM of between 45 nm and 96 nm. In conventional commercial catalogues of various manufacturers we can find common interference filters with the following spectral bandwidths (FWHM): 1.5, 3, 10, 25, 40 and 70 nm. In almost all the cases considered, the one most similar to those obtained in the simulation process is the filter with a FWHM value of 70 nm. We acquired five filters with these spectral features included in the analyzed range (Thermo Corion interference filters), that is, the NIR region. The transmittance of these filters is presented in the data section (Figure 5). We can now consider how the reconstructions use these filters under the influence of the different illuminants. Table 4 shows the reconstruction results obtained for the PCA method with some illuminants of different color temperatures, and the results for the NLE method are presented in Table 5. Table 6 shows the reconstruction results for the NLE method under the influence of the illuminants of color temperature 3371 K with different radiance values.

While, with the PCA method, the *RMSE* parameter increases when the color temperature is increased (as we found in the case of the Gaussian filters), the results are almost constant for the different illuminants analyzed with the NLE method (except for the illuminant with color temperature 1000 K). Using the NLE method and illuminants of color temperature 3371 K with different radiance values, the results obtained for the *RMSE* parameter are almost the same in all the analyzed cases, except for the illuminant with a radiance value of 10^7 W/sr*m^2, for which a worse *RMSE* was found.

Table 4. Reconstruction results using the PCA method, the five real interference filters and illuminants with different color temperatures.

Tc	Mean P_{rec}	Mean (*RMSE**100)
1000	99.995	0.184
2000	99.992	0.238
2852	99.988	0.280
3371	99.985	0.302
5000	99.979	0.351
16000	99.966	0.443

Table 5. Reconstruction results using the NLE method, the five real interference filters and illuminants with different color temperatures.

Tc	Mean P_{rec}	Mean (*RMSE**100)
1000	100	0.044
2000	100	0.016
2852	100	0.016
3371	100	0.017
5000	100	0.017
16000	100	0.018

Table 6. Reconstruction results using the NLE method, with five real interference filters and illuminants of Tc = 3371K with different radiance values.

Radiance (W/sr*m^2)	Mean P_{rec}	Mean (*RMSE**100)
10^3	100	0.018
10^4	100	0.017
10^5	100	0.017
10^6	100	0.017
10^7	100	0.024

In general, even when there are variations in the results, they are not significant. All the performed reconstructions have $P_{rec} > 99.9$ % and $RMSE < 1$. In a previous work it was demonstrated that these values guarantee acceptable reconstructions of the samples in the NIR region[10,15]. Therefore, the set of commercial analyzed filters can be used to obtain spectral reflectance curves under the influence of all the analyzed illuminants.

Conclusion

In this work, we studied the influence of the illuminant on the reconstruction of NIR spectra using multispectral imaging methods. We used principal component analysis (PCA) and a non-linear method (NLE) based on a second order polynomial in order to obtain reflectance spectra in the NIR region using CCD camera measurements under several lighting conditions. The analyzed illuminants were graybody radiators with color temperatures between 1000 K and 16000 K with the same radiant flux for both methods and illuminants with color temperature 3371 K and different radiance values in the case of the NLE method. In the first part of the study, we used five equi-spaced Gaussian filters in order to reconstruct the spectral reflectance of 30 textile samples. We determined the optimum spectral bandwidth of the filters in order to obtain the best possible reconstruction for each analyzed case, that is, for each illuminant and tested method. According to the results obtained, we analyzed a set of commercially available interference filters (Thermo Corion) and analyzed the quality of reconstruction achieved with these filters under different lighting conditions. The results obtained show that $P_{rec} > 99.9$ % and *RMSE* < 1 in all the analyzed cases. This indicates that, with the same set of filters, we can obtain good reconstructions for all the considered illuminants in the NIR region.

Acknowledgments

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Biography

Meritxell Vilaseca completed her BSc Degree in Physics at the Autonomous University of Barcelona in 2000. She completed her Degree in Optics and Optometry at the Technical University of Catalonia in 1996. She is currently enrolled on the PhD program in Optical Engineering at the Technical University of Catalonia. Her work focuses on camera calibration and characterization, industrial colorimetry, color management and imaging.
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