Multispectral System for Recovering Near-Infrared Reflectance Spectra

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Abstract

In this paper, we analyze an experimental system for recovering the reflectance spectra of samples in the near-infrared region of the spectrum (NIR, 800-1000 nm). Recently, CCD cameras with improved response in the NIR have been manufactured. It is therefore possible to use this standard instrumentation to obtain information on samples in this region. The setup used in this work consisted of a conventional multispectral system of five acquisition channels with spectral bands that were equi-spaced in the NIR region. An automated objective lens was used to control the exposure over the CCD. By using different F-number exposure series, we obtained sets of camera responses corresponding to a group of reference samples and analyzed the dependence of the digital output levels on the lens aperture. The reconstructions obtained for a set of textile samples show that Wiener estimation and principal component analysis provide the best results. These mathematical methods provide percentages of reconstruction close to 99.8% and *RMSE* values close to 0.025.

Introduction

In this study, we analyzed the efficiency of an experimental multispectral system for recovering the reflectance spectra of samples in the NIR region. Since the spectral information included in this range is related to the chemical properties of certain materials,[1] knowledge of the spectral reflectance of samples in the NIR can be useful in several fields of application, such as agriculture and the food, chemical and textile industries. Often, the spectral properties of the objects in the NIR are measured with conventional spectroradiometers, which may be costly. Recently, CCD cameras with improved response in the NIR have been manufactured and it is therefore possible to use this standard instrumentation to obtain information on samples in this region.

In previous research,[2-4] we demonstrated by numerical simulation that multispectral imaging is a good alternative method for obtaining the spectral reflectances of samples in the NIR. This technique allows the reconstruction of the reflectance spectra using a small number of measurements carried out through the various channels of a conventional CCD camera. We studied various mathematical methods of reconstruction and determined that the best results in this region were given by the non-linear fitting method,[3,4] Wiener estimation[3] and principal component analysis (PCA).[2-4] We also determined the optimum spectral characteristics of the filters to be used in the various acquisition channels. In this work, we analyzed the performance of an experimental multispectral reconstruction system (8 bits) and compared the results obtained with previous simulations. An automated objective lens was included in the experimental system in order to control the exposure over the CCD. Using different F-number exposure series, we obtained sets of camera responses for each acquisition channel corresponding to a group of reference samples. We thus developed a correction method for removing the dependence of the digital output levels on the lens aperture[5]. The results obtained show that the methodology can be used, although the reconstructions were not as good as they were in the simulations. Wiener estimation and PCA provide better experimental results than the non-linear fitting method. In order to minimize the experimental errors present in the system, more than 8 bits might be necessary. This will be studied in further research.

Method

The experimental setup of the multispectral system used (Figure 1) consisted of a halogen lamp (Philips 15V 150W, T_c=3357 K) (Figure 2), which emitted a considerable amount of light in the NIR, connected to a Hewlett Packard 6642A DC power supply (for a stable illumination of the sample); a wheel with five interference filters (ThermoCorion) with equi-spaced transmittance peaks in the NIR (Figure 3(a)); two more filters (a cut-off IR filter and a cut-off VIS ThermoCorion filter, which was used to remove the radiation that did not fall into the 800-1000 nm range (Figure 3(b)); a CCD camera with improved response in the NIR (Hamamatsu C7500-51) (Figure 4) connected to an 8-bit frame grabber (Matrox IP8); and finally, an automated objective lens (Cosmicar Pentax) which provides control over the focus, zoom and iris (F-number).

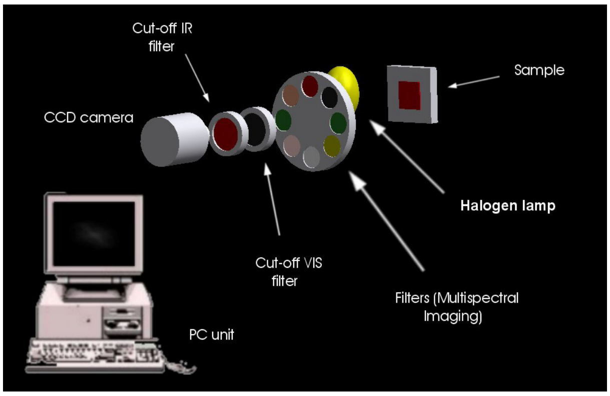


Figure 1. Experimental setup of the multispectral reconstruction system

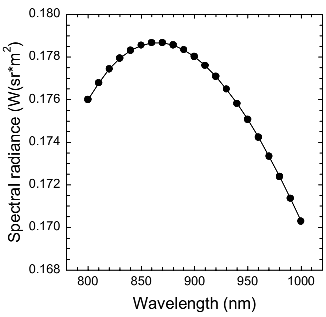
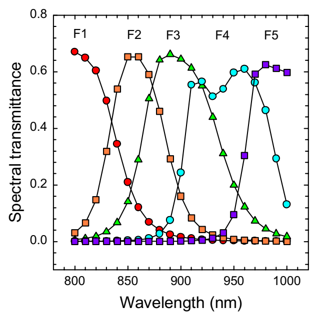
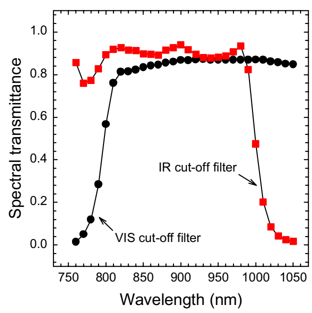


Figure 2. Spectral emission of the halogen lamp



(a)



(b)

Figure 3. Spectral transmittance of the filters used in the multispectral system: (a) five equi-spaced filters and (b) cut-off VIS and IR filters

The variability of the F-number or aperture of the lens is very useful since it allows us to adapt the dynamic range of the CCD camera to the amount of light reflected by the samples. Each sample can be measured using different F-number values, which provides digital output levels or camera responses within the linear range. Thus, by using different F-number exposure series, we obtained sets of camera responses for each acquisition channel corresponding to a group of reference samples. From each set of measurements associated with a channel and a specific aperture of the objective lens, it is possible to remove the dependence of the camera responses on the F-number. This is accomplished by fitting the digital output levels measured with the theoretical camera responses. The theoretical camera responses are independent of the F-number and may be expressed as follows:

$$X_i = \int_{\lambda_{min}}^{\lambda_{max}} i(\lambda) r(\lambda) F_i(\lambda) S(\lambda) \, d\lambda \tag{1}$$

where X_i is the theoretical camera response obtained for a certain channel (i = 1, ..., m), $i(\lambda)$ the spectral radiance of the illuminant, $r(\lambda)$ the spectral reflectance of the sample, $F_i(\lambda)$ the spectral transmittance of the filters placed between the camera and the sample, and $S(\lambda)$ the spectral sensitivity of the CCD camera used.

The details of the transformations that must be applied to the digital output levels for each channel and F-number are shown in the subsequent section (Results).

Finally, once the corrected camera responses were obtained, several mathematical reconstruction methods (non-linear method, Wiener estimation and PCA) were applied to recover the spectral reflectance of a set of nineteen textile samples with different spectral reflectances. In order to evaluate the quality of the reconstructed spectra, we used the following two parameters:

Percentage of reconstruction

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

Root Mean Square Error

$$RMSE = \left[\frac{1}{N_\lambda} \sum_{\lambda_{min}}^{\lambda_{max}} (r - r_{rec})^2 \right]^{1/2} \tag{3}$$

where r are the experimentally measured components of the original reflectance curves, r_{rec} the reconstructed values and N_λ the number of wavelengths where the measurements were taken.

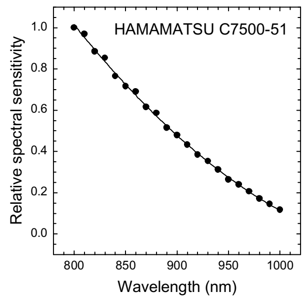


Figure 4. Spectral sensitivity of the CCD camera

Results

In all the cases analyzed, linear correction was necessary in order to eliminate the dependency of the digital output levels on the lens aperture. For each acquisition channel and F-number, a different transformation was needed. The slope value (m) corresponds to a scale factor that was not considered in the experiment. This factor is necessary to readjust the responses and to treat them in absolute terms of energy. This is because we considered the spectral radiance of the illuminant and not the exposure that reaches the CCD sensor: the spectral sensitivity of the camera was expressed in relative terms, etc. The offset value (n) is an uncontrollable correction factor due to experimental errors and existing noise. The numerical values for the two parameters (m, n) are shown in Table 1, as is the regression value r for each fitting carried out. Cases with no fitting values correspond to the series of digital output levels outside the linear range of the camera. An example of the linear correction for Channel F1 and an F-number value of 1570 is given in Figure 5. The F-number value provided corresponds to a specific position of the motor that controls the automated iris. These positions may vary from 0 (equivalent to an F-number of 1.4) to 1750 (equivalent to an F-number of 22).

Table 1. Parameters of the linear corrections (*m*, *n*) for each acquisition channel (*Ch*) and F-number (*F*)

Ch	*m* *(F:1570)*	*n* *(F:1570)*	*r* *(F:1570)*	*m* *(F:1489)*	*n* *(F:1489)*	*r* *(F:1489)*
F1	2.739e-3	0.010	0.9941	1.299e-3	-4.877e-3	0.9933
F2	3.049e-3	-3.223e-4	0.9941	1.506e-3	-0.024	0.9903
F3	3.170e-3	-0.015	0.9923	1.449e-3	-0.018	0.9859
F4	3.257e-3	3.561e-3	0.9867	1.439e-3	-3.051e-3	0.9868
F5	-	-	-	-	-	-
Ch	*m* *(F:1408)*	*n* *(F:1408)*	*r* *(F:1408)*	*m* *(F:1246)*	*n* *(F:1246)*	*r* *(F:1246)*
F1	9.295e-4	7.041e-3	0.9965	4.529e-4	6.825e-3	0.9993
F2	1.009e-3	5.042e-3	0.9975	-	-	-
F3	1.013e-3	1.761e-3	0.9940	-	-	-
F4	1.084e-3	-5.481e-4	0.9869	5.236e-4	2.256e-3	0.9936
F5	1.127e-3	2.812e-3	0.9657	5.332e-4	1.205e-3	0.9839
Ch	*m* *(F:1084)*	*n* *(F:1084)*	*r* *(F:1084)*			
F1	-	-	-			
F2	-	-	-			
F3	-	-	-			
F4	-	-	-			
F5	2.942e-4	-2.278e-3	0.9808			

The slope values (m) for every F-number position can be fitted as a different quadratic function for each acquisition channel (Figure 6). In the case of this study, the most fitting quadratic function can be expressed as follows:

$$m = 1/(a + b(F - number) + c(F - number)^2) \qquad (4)$$

The values of the fitting parameters a, b, c and r obtained for all the cases analyzed are detailed in Table 2.

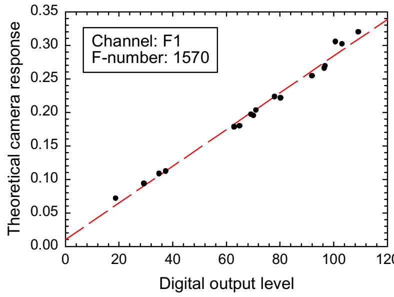


Figure 5. Linear correction for Channel F1 and F-number 1570 (m = 2.739e-3, n = 0.010)

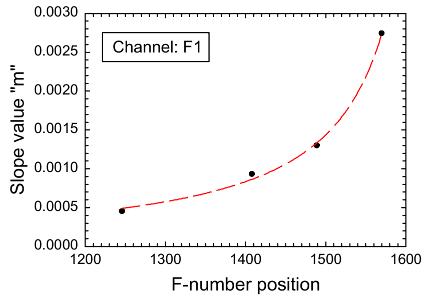


Figure 6. Relationship between the slope value (m) and the F-number position for Channel F1

We have not found a simple fitting function for the offset parameter (n) and the F-number position. This is due to the fact that this parameter is related to experimental errors. It has a random value for each F-number and each channel, and therefore it cannot be modeled. Figure 7 illustrates the results obtained for this parameter.

Table 2. Fitting parameters *a*, *b*, *c* and *r* for each acquisition channel

Ch	*a*	*b*	*c*	*r*
F1	11874.1689	-10.0552	0.0017	0.9988
F2	-13115.6250	22.3271	-0.0088	0.9985
F3	-20980.3756	33.0484	-0.0124	0.9992
F4	17826.7487	-18.4897	0.0047	0.9989
F5	27352.6996	-33.1430	0.0102	1.0000

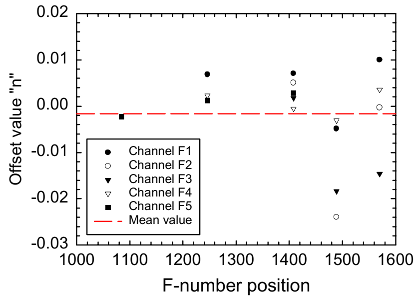


Figure 7. Offset values (n) obtained for the different channels (the dashed line represents the mean value).

Table 3. Parameters of reconstruction of the spectral reflectance for the nineteen textile samples using the various mathematical methods

WIENER ESTIMATION				
Number of filters	2	3	4	5
Mean P_{rec}	99.699	99.722	99.583	99.768
Std. Dev. P_{rec}	0.645	0.392	0.490	0.257
Max P_{rec}	99.989	99.989	99.947	99.971
Min P_{rec}	97.291	98.255	97.807	99.092
Mean (*RMSE100)**	2.207	2.675	3.116	2.494
Std. Dev. (*RMSE100)**	1.317	1.285	1.761	1.166
Max (*RMSE100)**	4.999	5.474	6.437	5.822
Min (*RMSE100)**	0.604	0.597	1.337	0.983
PRINCIPAL COMPONENT ANALYSIS (PCA)				
Number of filters	2	3	4	5
Mean P_{rec}	99.842	99.757	99.674	99.752
Std. Dev. P_{rec}	0.202	0.300	0.411	0.277
Max P_{rec}	99.984	99.985	99.957	99.970
Min P_{rec}	99.210	98.672	98.176	98.958
Mean (*RMSE100)**	2.103	2.586	3.061	2.587
Std. Dev. (*RMSE100)**	1.130	1.228	1.748	1.151
Max (*RMSE100)**	4.842	5.476	6.385	5.866
Min (*RMSE100)**	0.741	0.705	1.276	1.002
NON- LINEAR METHOD (2nd order polynomial)				
Number of filters	2	3	4	5
Mean P_{rec}	99.833	99.792	99.743	97.589
Std. Dev. P_{rec}	0.260	0.237	0.369	8.882
Max P_{rec}	99.988	99.986	99.980	99.965
Min P_{rec}	98.870	98.973	98.377	62.013
Mean (*RMSE100)**	1.989	2.477	2.512	3.954
Std. Dev. (*RMSE100)**	0.943	1.312	1.059	2.806
Max (*RMSE100)**	4.580	6.273	5.556	14.032
Min (*RMSE100)**	0.629	0.685	0.828	1.086

Using the experimental system described above and taking into account the corresponding F-number corrections for the digital output levels of the camera, we performed reconstructions of the spectral reflectance for a set of nineteen textile samples using the three mathematical methods proposed (non-linear, Wiener estimation and PCA). The results obtained, using different numbers of channels or filters, are shown in Table 3. For two channels, the filters used were F2 and F4. For three channels, they were F2, F3 and F4. For four channels, F1, F2, F3 and F4 were used. Finally, for five channels F1, F2, F3, F4 and F5 were used.

Wiener estimation and PCA yielded very similar results. In both cases, the reconstructions were worse using three and four channels than they were using two channels. This can be explained by the consideration of experimental errors in the measurements. This behavior is eliminated when five channels are used, because the errors are compensated by the additional information. Conversely, with the non-linear method, the reconstruction results always deteriorate with the number of filters used. This is even the case with five filters. This is because, in the non-linear method, second-order polynomials of the measurements are used. The errors are therefore amplified considerably. For this reason, the first two methods are more advisable when recovering the reflectance spectra of samples.

PCA and Wiener estimation yielded P_{rec} values close to 99.8% and *RMSE* values close to 0.025, using the five existing channels. As expected, these results were worse than they were in the numerical simulations (P_{rec} values greater than 99.9% and *RMSE* values smaller than 0.01). Since the experimental errors were minimized in the multispectral system, more than 8 bits of digitalization may be necessary in order to obtain more accurate results. This will be discussed in further research.

Conclusion

In this study, we used an experimental multispectral system for recovering the reflectance spectra of textile samples in the NIR region. Basically, the system consists of a CCD camera with improved response in the NIR range, connected to an 8-bit frame grabber, an automated objective lens which provides control over the focus, zoom and iris (F-number) and finally, a wheel with five interference filters which define the different acquisition channels. We developed a method for removing the influence of the measurements on the F-number used and performed the reconstructions of the samples using three mathematical methods: Wiener estimation, PCA and a non-linear fitting method. Using the first two methods, which yielded the best results, the P_{rec} values obtained for a set of nineteen textile samples were close to 99.8% and the *RMSE* values were close to 0.025. In order to further improve the reconstruction results, more than 8 bits of digitalization can be used to minimize experimental errors in the measurements.

Acknowledgements

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Biography

Montserrat Arjona was awarded an MSDegree in Physics by the University of Barcelona in 1980 and a PhD in Physics by the Autonomous University of Barcelona in 1994. Since 1987, she has worked at the Optics and Optometry Department of the Technical University of Catalonia, where she teaches Optical Instrumentation and Physiological Optics. Her work focuses primarily on Vision Science and Color Imaging. E-mail: arjona@ oo.upc.es