Multispectral system for the reflectance reconstruction and color visualization of natural and manufactured objects in the near-infrared region

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ABSTRACT

In this study we analyze the performance of a multispectral system that works in the near-infrared region of the electromagnetic spectrum (NIR, 800-1000 nm). This system, which uses a conventional CCD camera with five acquisition channels as a sensor, is capable of reconstructing the NIR spectral reflectances of the samples analyzed and also provides pseudo-colored images of the scenes registered. The system was tested using a wide range of samples, which included natural and manufactured objects, with different spectral reflectance curves in the NIR. The results show the potential of the system developed in this study for obtaining information relating to spectral reflectance curves. Furthermore, the pseudo-colored images provided permit one to obtain a visualization of the region considered carrying spectral information or maximizing the color differences in order to discriminate between samples with the same appearance in the visible range but different spectra in the NIR.

1. INTRODUCTION

In this work we perform a complete study of the operation of a multispectral system that works in the near-infrared region, as a continuation of work undertaken in previous studies[1-4]. The sensor included in the system consists of a conventional CCD camera with a zoom lens, whose spectral sensitivity is significant up to 1000 nm, although its maximum response corresponds to the visible range. The system permits one to obtain five multispectral images, which correspond to the channels that have different spectral transmittance profiles in the NIR. From these images, the system is capable of reconstructing the NIR spectral reflectances of the samples and also provides a pseudo-colored image of the scene registered. The spectral information included in the NIR region may be of interest because it is related to certain chemical properties of the materials; In this range, some absorption peaks correspond to specific vibrations of molecules, such as biological substances (moisture, proteins, fibers, etc.) or other chemical constituents (present in fabrics, plastics, etc.) that make the objects reflect and absorb differently at different wavelengths. Therefore, these components can be identified from the spectral reflectance of the samples, using an analytical tool known as NIR technology[5].

In order to reconstruct the spectral reflectance curves, five multispectral images are acquired of the samples analyzed. Subsequently, a luminance adaptation model[3,6] is applied, which frees these images from dependency on the exposure time of the camera and the F-number of the lens used. Finally, several mathematical methods of reconstruction, such as the Wiener estimation, principal component analysis and a non-linear method[2], are used to reconstruct the spectral reflectances. This reconstruction system was applied to a set of 80 different samples that had different reflectance spectra in the NIR, some of which were natural and others of which were manufactured. The samples included fabrics and plastics of different compositions, samples of marble, different kinds of wood and paper, plants, leather and food (cheese, bread, crackers, meat, vegetables, fruit, etc.).

Apart from providing a spectral reflectance reconstruction of the samples described above, the system also provides a pseudo-colored image of the captured scene by combining the multispectral images. The system uses different color space representations or pseudo-coloring methods[4,7] so as to associate the camera responses of the spectral bands of the system with the color channels of a calibrated CRT monitor[8] in order to display the images. Some of these methods use the properties of human color vision translated into the NIR and others just attempt to increase the colorimetric discrimination between the objects present in the scene. With the pseudo-colored images, an intuitive representation of the NIR is achieved and samples with the same appearance, that is, with the same spectral reflectance in the visible range, can be discriminated between. In order to test the color visualization system developed, it was applied to a wide range of samples.

2. METHOD

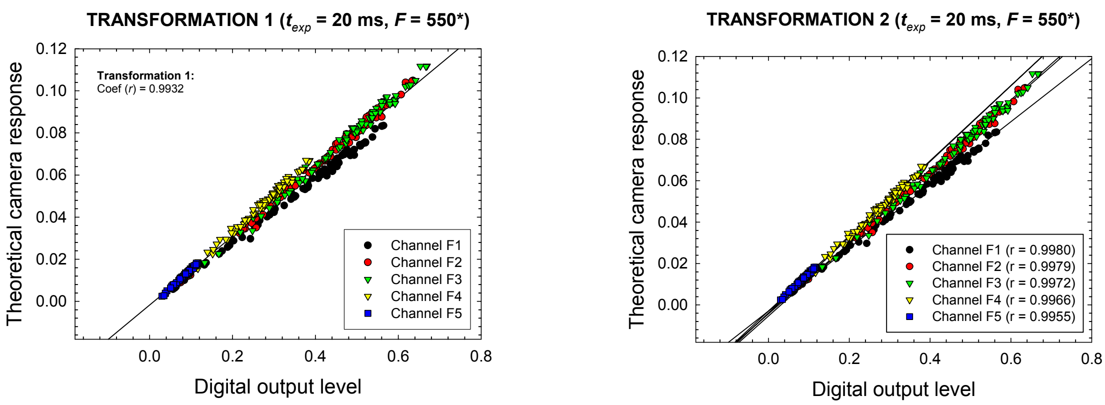
The system developed comprises a CCD camera (Photometrics Sensys KAF0400-G2) with 12-bit depth, an automated zoom lens (Cosmicar Pentax C6Z1218M3-1 12.5-75 mm), a wheel with the five multispectral interference filters (Thermo Corion) whose peaks are equispaced in the NIR (Channel F1: 800, F2: 860, F3: 890, F4: 960, F5: 980 nm), a cut-off IR filter and a cut-off VIS filter to ensure that the radiation that reaches the sensor comes only from the NIR range considered, a halogen lamp (Philips 15V 150 W) connected to a Hewlett Packard 6642A DC power supply (for a stable illumination of the samples), and lastly, a PC with a calibrated CRT monitor.

This system allows us to obtain five multispectral images of the samples analyzed through the different acquisition channels using different exposure time values for the camera (t_{exp}) and different F-number values for the zoom lens (F). These parameters permit one to adapt the dynamic range of the camera to the incident light, which is highly dependent on whichever channel is used because of differences in sensitivity and in the amount of light reflected by the samples. A luminance adaptation model, which was calculated using samples of known spectral reflectances, transforms the measured camera responses or digital output levels for each t_{exp} and F value into theoretical responses (Transformation 1), which are independent of the F-number and may be calculated as follows:

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

where X_i is the theoretical camera response obtained for a certain channel (i = 1, ..., 5), $i(\lambda)$ is the spectral radiance of the lamp, $r(\lambda)$ is the spectral reflectance of the sample, $F_i(\lambda)$ is the spectral transmittance of the filters (multispectral + cut-off), and $S(\lambda)$ is the spectral sensitivity of the CCD camera used.

In all the cases analyzed, the transformations obtained for each t_{exp} and F value were linear and subsequent reconstructions were more accurate if the corrections were performed independently for each acquisition channel (Transformation 2), as some systematic errors present in the system and which have different effects on the multispectral bands were better compensated, as can be seen in Figure 1.



(a) (b)

Figure 1. Examples of the luminance adaptation model obtained for t_{exp} = 20 ms and F = 550 (*550 corresponds to a specific position of the motor that controls the aperture diaphragm). In (a) the transformation is performed using a linear fitting that includes all the acquisition channels together (Transformation 1), while in (b) each channel is considered independently (Transformation 2).

Once the multispectral images of all the samples analyzed were acquired and corrected using the luminance adaptation model, the mathematical methods of reconstruction could be applied. In this study we used the Wiener estimation (WIE), a non-linear variation of this method (NLE) and principal component analysis (PCA), which provide the best reconstructions, as had been demonstrated in previous studies[1]. In order to evaluate the quality of the reconstructed spectra, we used two parameters: the percentage of reconstruction (P_{rec}) and the Root Mean Square Error (*RMSE*):

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

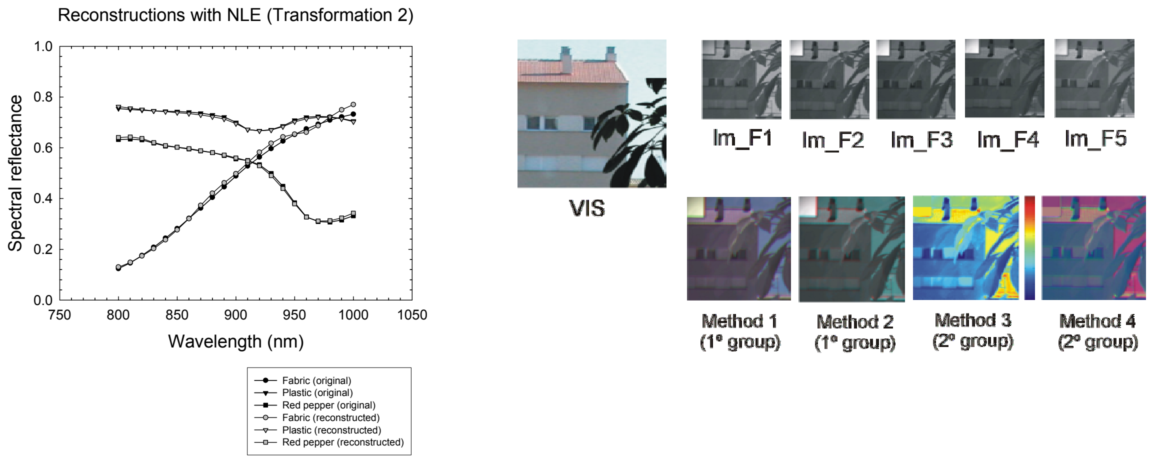
where r are the real components of the reflectance, measured with an Instrument Systems SP320 IR1 spectrophotometer, r_{rec} are the reconstructed values and N_λ are the number of wavelengths where the measurements were taken.

Finally, combining the five multispectral monochromatic images of the scene analyzed, three new signals (R_{NIR}, G_{NIR} and B_{NIR}) were defined and they permitted us to obtain a pseudo-colored image by associating them with the color channels of a calibrated CRT monitor. The monitor must be calibrated to generate a final pseudo-colored image independently of the visualization device used. In order to obtain the color signals, we used two different groups of pseudo-coloring methods[4]: the methods belonging to the first group simulated human color vision translated into the NIR region and the second group increased the color differences between the objects present in the captured scene. The first group ranged from simple linear combinations of the multispectral images to more complex methods, which provided color signals that accounted for some color models defined in the visible range and which were adapted to the NIR. In this way, we defined a standard observer by compressing and translating the color matching functions of the *RGB* CIE-1931 standard observer into the NIR and by applying adapted models (LMS, ATD, CIELAB, etc.). However, the methods included in the second group were decorrelation methods, such as principal component analysis, which were used to remove the high correlation often present between NIR spectral bands and therefore to increase the color differences between the samples. In order to achieve this, PCA was applied over the multispectral images and different associations were performed. Examples of this include the following: the first principal component was associated with a color palette, and the three principal components were associated with the R_{NIR}, G_{NIR} and B_{NIR} signals. Using these kinds of associations, it was possible to assign very different colors to samples that had similar NIR reflectance spectra. The different color representations possible were applied over different scenes and were evaluated in terms of colorimetric discrimination using parameters such as CIELAB color differences.

3. RESULTS

The method described was used to analyze 80 different samples and the results of reconstruction showed the potential of the system, which yielded differences between the original and reconstructed spectra of less than 0.02 (*RMSE*). Equivalently, this entailed a percentage of reconstruction greater than 99.8%. These results corresponded to reconstructions performed using the luminance adaptation model with Transformation 2, that is, each channel was taken into account independently. The three different mathematical methods tested (WIE, NLE and PCA) yielded very similar results. Some examples of reconstruction are shown in Figure 2 (a).

Furthermore, the NIR multispectral images obtained for different captured scenes were combined in order to obtain pseudo-colored images using the different methods proposed (Figure 2 (b)). The best results in terms of visual discrimination were achieved by the second group, that is, PCA-based methods, because of the correlation present in the NIR. The maximum values for the CIELAB color differences were obtained when these methods were used, basically with the method that associated the first principal vector with a color palette (Method 3 in the figure). On the other hand, though the methods that simulated human color vision did not exhibit large CIELAB color differences, they did convey NIR spectral information of the samples present in the scene, and as such could be useful in certain applications.



(a) (b)

Figure 2. (a) Examples of reconstruction for three specific samples using the non-linear method and the luminance adaptation model with Transformation 2, and (b) visible image, five NIR multispectral images, and pseudo-colored images of a landscape obtained using different pseudo-coloring methods.

4. CONCLUSIONS

This study focused on the evaluation of a multispectral system for the reflectance reconstruction and color visualization of samples in the near-infrared region. The reconstructions carried out on a range of 80 different samples and using five acquisition channels demonstrate the efficiency of the system. Moreover, as the system permits one to display a pseudo-colored image of the captured scene on a CRT monitor, we were able to view the NIR region of the electromagnetic spectrum in color. This feature permits one to discriminate between samples that have the same spectral reflectance in the visible range but different spectral reflectances in the NIR.

5. ACKNOWLEDGMENTS

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