Estimation of Human Iris Spectral Reflectance Using a Multi-Spectral Imaging System

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Abstract

In this work we evaluate the performance of a multi-spectral system for the estimation of spectral reflectance curves associated to the iris of human eye. The aim of the study is to check the feasibility and the accuracy of the developed system in order to perform this kind of measurements, and to optimize the corresponding experimental set-up. In the experiment, twenty-six different subjects with different iris coloration were measured. We tested several sets of filters to be used as channels of the acquisition system, which consisted of a 12-bit depth cooled CCD monochrome camera. We also analyzed different reconstruction algorithms, specifically the pseudo-inverse technique and the principal component analysis, and several metrics such as the Root Mean Square Error and color difference equations were used in order to evaluate the obtained results. The final purpose of this study is to build in the near future a large and representative database of human iris spectral reflectances, which can be easily estimated from the images captured by the developed system. This database could be useful in several fields such as medical imaging and the cosmetics industry.

Introduction

With the assumption of the smoothness of spectral reflectances, it is possible to come up with multi-band imaging systems with 3 to 6 channels that can reconstruct spectral reflectance with reasonable accuracy [1].

Previous work studied the efficiency of a conventional multi-spectral system based on a trichromatic camera to measure the spectral reflectance in the visible range associated to the human iris[2]. However, this study was only testing feasibility and did not compare performance of the estimation method compared to a more conventional narrow-band method using interference filters. The goal of the study is to extend the previous study with a more thorough research of the potentialities by comparing its performance to the results obtained using a narrow-band image acquisition system. Thus, two imaging systems with different filter configurations are compared. This study also compares two different algorithms for spectral estimation. Furthermore, the study also contains reconstruction experiments carried out using subsets composed of few iris samples as training sets, in order to demonstrate the utility of the system with reduced training set.

The final purpose of the work is to build a representative spectral reflectance database with the performed measurements extending procedures developed for colorimetric measurements of human iris [3]. This work can be useful in some applications such as medical imaging and the cosmetics industry. In these areas, the spectral characterization of the iris could make easier the choice of materials and colorants used for instance to manufacture color contact lenses or prosthetics eye balls, etc.

This paper is structured as follows: in the following section the experimental method is presented. And in the following section, experiment is described. After that, the results obtained with the several configurations of the proposed system are summarized. Finally, in the last section the most relevant conclusions of the study are presented.

Method

The multi-spectral system developed [4] consisted of a 12-bit depth CCD monochrome camera, a zoom lens, an illumination system, and several sets of broadband filters, which covered the whole visible range of the electromagnetic spectrum, used as acquisition channels. Previous study [2] indicated the feasibility of human iris spectral reflectance estimation using broadband filters due to the smooth nature of the human iris spectral reflectance curves. In this study we evaluated two different filter configurations: on one hand an RGB tunable filter and an additional blue absorption filter were placed in front of the camera, allowing the acquisition of three or six images with only one or two exposures, respectively; on the other hand, a set of seven interference filters equi-spaced along the visible range which allowed the consecutive measurement of seven spectral images. Magnified images with high resolution of the entire iris of each subject could be acquired using the described configurations. Therefore, it was possible to obtain the digital signals associated to different parts of it, from which the corresponding spectral reflectances were estimated. The reference (ground-truth) spectral reflectances of the considered areas of the iris were also estimated from spectral radiance measurements taken with a tele-spectroradiometer placed next to the spectral system.

A flat-field correction was performed to every acquired images due to non-uniform spatial response of the imaging sensor and non-uniform distribution of luminance field across the imaging field [5]. The spatial non-uniformity correction used gain and offset matrixes in order to correct the individual pixel values, producing uniform digital output levels by imaging a reference white using the illumination system and the camera with the same geometry as in the performed experimental acquisitions.

From the acquired images, the reflectance curves of the irises were estimated using the following two linear mathematical methods: the pseudo-inverse technique (PSE) and the principal component analysis (PCA) [6][7]. These methods allow the reconstruction of spectral reflectances from the camera responses by means of an estimation matrix, which can be computed using the digital output levels corresponding to a training set of samples. These techniques also need *a priori* knowledge of the spectral reflectances associated to the training sample patches. In this study, we used different training sets in order to perform the reconstructions, such as the GretagMacbeth ColorChecker rending chart (CCCR) and different subsets of the experimental iris measurements. In order to evaluate the accuracy of the spectral estimations of the iris, several color accuracy metrics such as the spectral reflectance Root Mean Square Error (RMSE) and color difference equations (ΔE^*_{ab} , ΔE^*_{94}) were also used.

Experiments

The multi-spectral system developed consists of a 12-bit cooled CCD monochrome camera (QImaging QICAM Fast1394), an objective zoom lens (Nikon zoom AF Nikkor 28 to 105 mm), and different sets of broadband filters, some of them placed in a motorized wheel. The two different configurations of filters tested for the multi-spectral acquisitions were the following: a color RGB tunable filter (QImaging) attached to the CCD camera and an additional blue filter (GamColor Filter 720 Light Steel Blue) placed into the wheel (Configuration 1) (Fig. 1(a)), which permitted obtaining three or six images by performing only one or two exposures respectively, and also a set of seven interference filters (CVI F40) placed into the wheel with a full-width half maximum (FWHM) of approximately 40 nm (Configuration 2) (Fig. 1(b)), which allowed the consecutive measurement of seven images with different spectral information associated. The supplementary blue filter used in Configuration 1 was chosen in order to compensate the rather low sensitivity of the blue channel of the system [2].

Furthermore, an illumination system composed of an adjustable halogen lamp (Philips 15V 150W) attached to a stabilized DC power supply (Hewlett Packard 6642A) and a focusing lens, allowed to illuminate the analyzed iris with a 45º angle of incidence, obtaining a rather uniform luminous field on the eye. Finally, a tele-spectroradiometer (Photo Research PR-650) positioned beside the camera was also used in order to measure the spectral radiance associated to the areas of the iris. In order to obtain the reflectance values of the samples, a measurement of the radiance corresponding to a reference white placed at the same position as the eye was also necessary. Although the measurements with the camera and the tele-spectroradiometer were not performed with exact geometrical features, we checked that this mismatch did not introduce significant errors into the experimental values due to their small difference in position.

Magnified images with high resolution of the entire iris of each subject could be obtained through the various channels of the CCD and therefore it was possible to obtain the digital signals associated to different parts of it. Specifically, we measured the mean digital output levels corresponding to two square areas of approximately 2 by 2 mm on the iris (Fig. 2), which presented rather uniform coloration. At the same time, the corresponding averaged spectral reflectances of those zones were also measured using the tele-spectroradiometer. Twenty-six different subjects were used in order to perform the preliminary experiment with the developed system.

The irises belonging to the 26 subjects had very different colorations such as blue, brown and green. With the experimental system, we also measured the 24 patches corresponding to the ColorChecker rendition chart (CCCR). All the acquired images were spatially corrected by applying an optimized flat-field correction algorithm with the application of the gain and offset matrixes pixel by pixel. Subsequently, the mean digital output levels of the selected zones were calculated and the corresponding mean spectral reflectances were also determined by measurements taken using tele-spectroradiometer.

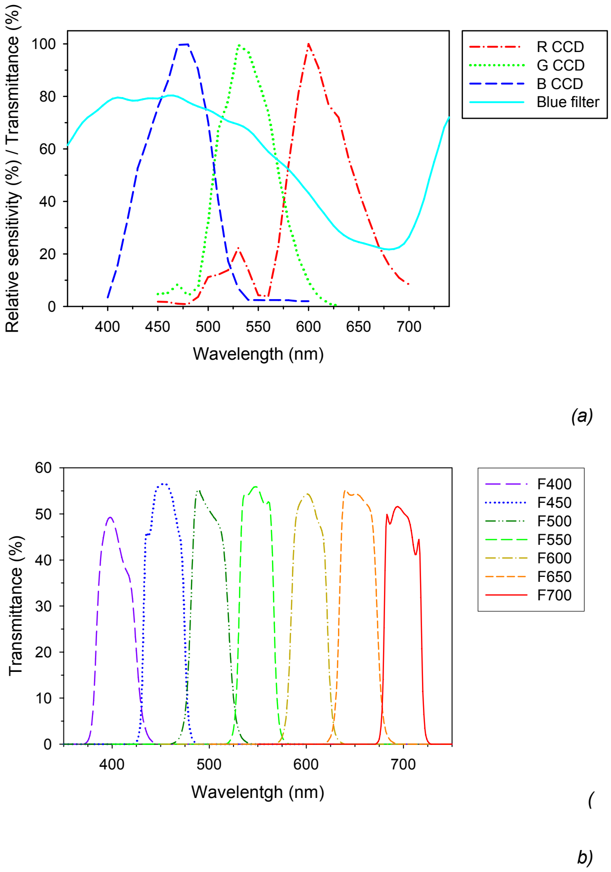

Figure 1. *(a) Configuration 1: Relative spectral sensitivities of the RGB channels of the system (Tunable filter and CCD camera) and transmittance of the additional blue filter and (b) Configuration 2: Transmittance of the seven interference filters .*

After these experimental measurements, we applied the pseudo-inverse algorithm (PSE) and the principal component analysis (PCA) in order to estimate the spectral reflectances from the digital output levels. In both filter configurations we used different number of channels to perform the reconstructions: in Configuration 1 we took into account reconstructions performed using only three channels (RGB) and six channels (adding the blue filter in front of the RGB channels to obtain three extra channels besides original RGB channels), and in Configuration 2 we carried out reconstructions using a subset of three interference filters (F450, F550, F650) apart from the complete set, that is, seven.

The reconstructions were also performed by using different training sets: first, the 24 color patches of the CCCR were used as training set and the 104 iris samples (26 subjects comprising both eyes for 2 areas as depicted in Figure 2) were considered as the test set.

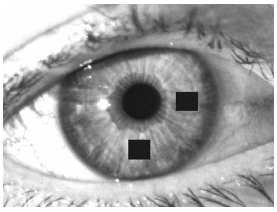

Figure 2. Image of an iris and corresponding analyzed areas.

Results

Results obtained when the PSE algorithm is used with Configuration 1 can be seen in Table 1. In this table, the mean and standard deviation of the color difference equations ΔE^*_{ab} and ΔE^*_{94} as well as the Root Mean Square Error *RMSE* of the spectral reflectances are shown. As can be seen from Table 1, the colorimetric and spectral accuracy is very poor, meaning that the ColorChecker chart is not an appropriate representation of the colors associated to the human iris. It can also be seen that the increase of channels produces worse results due to the error accumulation. The use of the same training and test sets with the PCA method and Configuration 2 also provides very inaccurate results.

Table 1: Colorimetric and spectral accuracy between the 104 measured and estimated iris spectral reflectances (Training: 24 CCCR, Test: 104 iris samples, Method: PSE, Configuration: 1)

Config. 1	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	26.1±3.1	25.4±3.1	17.4±5.8
6 channels	29.2±10.9	22.6±9.1	7.6±4.2

In order to improve these results, we also considered the complete 104 iris samples as training and test sets simultaneously. The results obtained in this case are shown in tables 2 and 3.

Table 2: Colorimetric and spectral accuracy between the 104 measured and estimated iris spectral reflectances (Training: 104 iris samples, Test: 104 iris samples, Method: PSE)

Config. 1	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	2.9±1.7	2.2±1.1	0.7±0.4
6 channels	2.9±1.6	2.2±1.0	0.7±0.4

Config. 2	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	3.7±2.4	2.7±1.4	0.7±0.4
7 channels	3.2±2.2	2.4±1.3	0.7±0.4

Table 3: Colorimetric and spectral accuracy between the 104 measured and estimated iris spectral reflectances (Training: 104 iris samples, Test: 104 iris samples, Method: PCA)

Config. 1	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	3.4±1.7	2.6±1.0	0.8±0.4
6 channels	2.9±1.6	2.2±1.0	0.7±0.4

Config. 2	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	4.3±2.2	3.2±1.3	0.8±0.4
7 channels	3.2±2.2	2.4±1.3	0.7±0.4

Now, the color differences obtained and the corresponding spectral accuracy are in general very satisfactory, as expected since there is no distinction between training and verification sets. With three channels, the results obtained by means of the PSE algorithm are slightly better than when the PCA is used, due to the fact that this number of principal components is probably not enough to describe the variability of colors associated to the human iris. However, the results are almost exactly the same when six or seven channels are used. In Figure 3, the cumulative proportion index associated to the components of the PCA analysis performed over the 104 iris samples is shown. It is possible to see that more than three or four eigenvectors can theoretically reconstruct very well the reflectance curves. This can be stated with the experimental results obtained using PCA, in which an improvement is found when more than three channels are taken into account. Due to the easier implementation of PSE, this algorithm is preferred. Although using this method a slight improvement of the results is also observed when more than three channels are used, the accuracy obtained with three spectral bands is already acceptable.

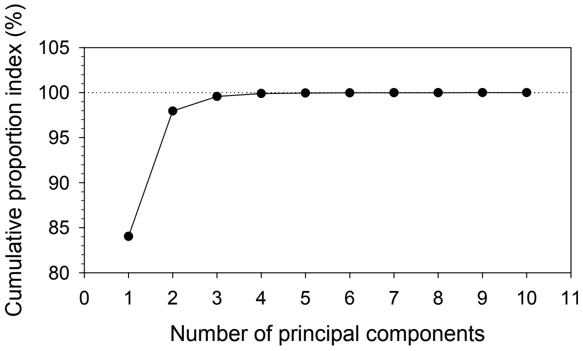

Figure 3. Cumulative proportion index (%), that is, percentage explained by different numbers of principal components of the PCA analysis performed on the 104 iris samples.

Regarding the set of filters used in the acquisitions, it can be seen that Configuration 1 provides slightly better colorimetric parameters than Configuration 2, even though the spectral accuracy achieved is similar or even worse. Because of the resemblance of the results, Configuration 1 is preferred due to its easier implementation. This configuration only involves two acquisitions meanwhile Configuration 2 consists of seven exposures, what can increase significantly the acquisition time and therefore, can become more uncomfortable for the subject. During the acquisitions, the movements of the eye can cause the measurement of slightly different regions on the iris. Furthermore, because of the narrowness of the interference filters and the use of only one focus position for the central channel (F550), the images corresponding to the extreme channels can appear fuzzy. These facts may introduce some additional errors in the calculations.

In order to take advantage of any multi-spectral system, this must be trained with a limited set of samples, that is, using a training set smaller than the test one. Therefore, the 104 iris samples (26 subjects) were reconstructed again but in this case using smaller training sets, specifically with subsets of the measurements. Due to the results previously shown, in order to perform the reconstructions we only took into account the PSE algorithm and Configuration 1. In this context, we used as training sets a subset of 56 iris samples (14 subjects) and another one composed of 32 (8 patients). In both cases the considered subsets included varied reflectance curves, which constituted a wide representation of the whole set of measured iris spectral reflectances. The results obtained are shown in table 4. As it can be seen, the reconstructions are not as good as before. However, the colorimetric and spectral accuracy obtained is still very satisfactory, mainly when 56 irises are used to train the system. With the 104 and 56 training sets, the mean color differences are close to 3 (ΔE^*_{ab}) and 2 (ΔE_{94}) units, and the mean (*RMSE*) is approximately 0.7%, meanwhile there is a slightly worsening of the results with the subset composed of 32 samples, basically when 6 channels are used. The use of more than three channels does not guarantee an improvement of the results, probably due to the fact that more errors are included in the calculations because of the smaller size of the training sets. However, the good reconstructions still obtained with these subsets could be explained by the relatively small variability of the colors associated to the human iris. Therefore, using only a relatively small amount of spectral basis curves could be enough to estimate a great amount of different iris samples.

Figure 4 shows the ΔE^*_{94} histogram corresponding to different sample size used in the training sets. As can be stated, with the training set composed of 56 samples, the color differences obtained practically remain at the same value intervals as when the whole set was used (104). With the sample set with 32 values, the peak of color accuracy histogram shifts presenting higher errors although the results can be considered still very acceptable. Moreover, the distributions obtained with three and six channels are quite similar, so that it can be stated that a simple RGB image can be used in order to predict the spectral reflectance of the irises in some applications.

In Figure 5, examples of reconstruction obtained with the system using different number of acquisition channels and training sets are illustrated, specifically for a brown iris. As it can be seen, the reconstructions are in general rather good. Only in the case of using 6 channels and the training set composed of 32 samples, the reconstructed curve starts to present some mismatches with respect to the original one.

Table 4: Colorimetric and spectral accuracy between the 104 measured and estimated iris spectral reflectances (Test: 104 iris samples, Method: PSE, Configuration: 1)

Train. : 56 iris	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	3.0±1.9	2.3±1.2	0.7±0.5
6 channels	3.1±1.8	2.3±1.1	0.7±0.4

Train. : 32 iris	ΔE^*_{ab}	ΔE^*_{94}	***RMSE (x100)***
3 channels	3.1±1.8	2.4±1.2	0.8±0.5
6 channels	3.3±1.8	2.6±1.2	0.8±0.5

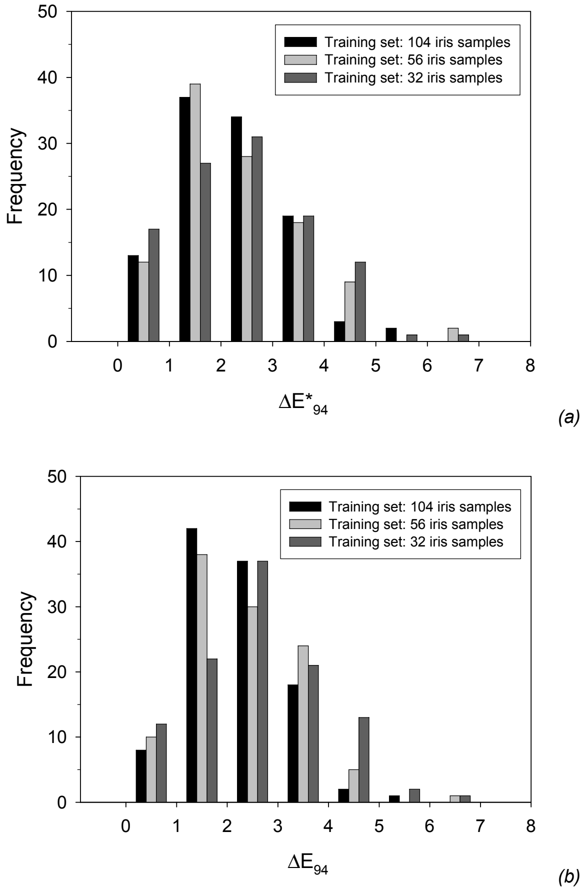

Figure 4. *ΔE^*_{94} histogram between the 104 measured and estimated iris spectral reflectances obtained using 3 channels (a) and 6 channels (b) (Test: 104 iris samples, Method: PSE, Configuration: 1).*

Conclusion

In this work we show the feasibility of a multi-spectral system to be used as a tool to estimate the spectral reflectance associated to the human iris. The used system consists of a 12-bit cooled CCD camera, an objective zoom lens with great magnification, several broadband filters, and a halogen lamp used to light the analyzed iris. The whole system is spatially corrected using a flat-field algorithm in order to obtain a uniform response across the imaging field. The system permits to perform a spectral reflectance estimation of the iris by acquiring only some images of the eye and applying linear algorithms such as the pseudo-inverse (PSE) and the principal component analysis (PCA). In this study we evaluate different configurations of the system in order to examine dependency of performance on filter design. This is accomplished by using a configuration composed of an RGB tunable filter and a supplementary blue filter, which allowed obtaining three and six images respectively. The application of PSE and PCA algorithm achieve similar results although the PSE is preferred for its simplicity. The mean CIELAB color differences obtained are close to 3 ($\Delta {*E}_{ab}$) and 2 (ΔE_{94}), and the mean spectral accuracy is approximately 0.7% (*RMSE*) when the optimal configuration is used. We also tested different training sets for the system and demonstrated that a reduced subset of samples is acceptable to obtain reasonable results of reflectance reconstruction. With the present study, we show the possibility to estimate the spectral reflectances of irises from simple RGB images. Future work is oriented to build a comprehensive database of spectral reflectances associated to the human iris, jointly with other color researching groups (mainly, University of Granada, in Spain).

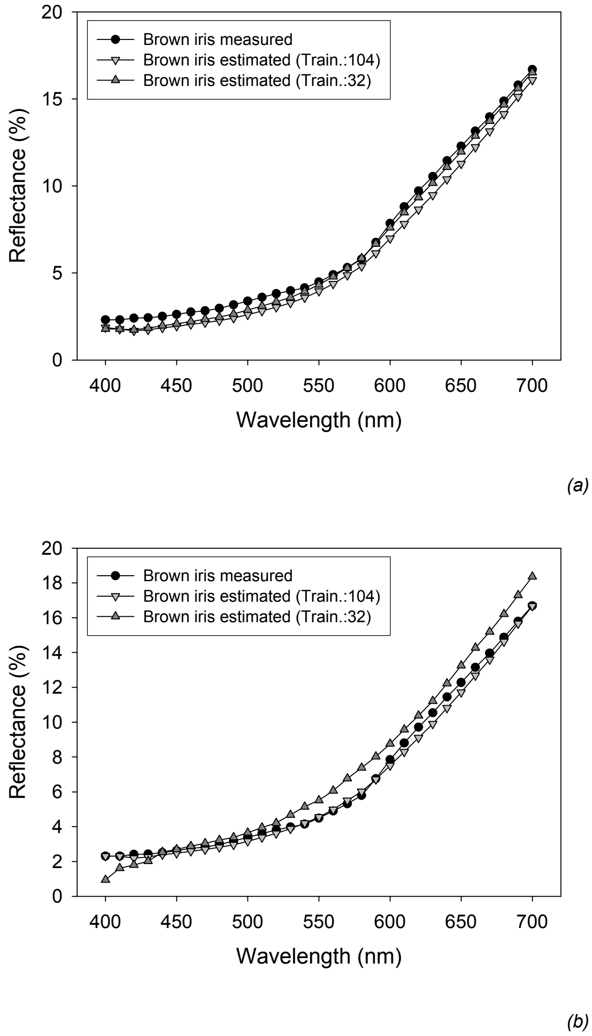

Figure 5. *Examples of measured and estimated iris spectral reflectances using the PSE method, the training sets composed of 104 and 32 samples and the Configuration 1 with 3 channels (a) and 6 channels (b).*

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Author Biography

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