Color measurements with colorimetric and multispectral imaging systems

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ABSTRACT

This work is focused on the study and comparison of the performance for color measurements of different systems based on optoelectronic imaging sensors. We used two different configurations of the imaging system, one with three acquisition channels and the other with more spectral bands, in order to measure the color associated to each pixel of the captured scene. We applied different methodologies to obtain the XYZ tristumulus values from the measured digital signals. The different techniques included an absolute spectral and colorimetric characterization of the system and also direct transformations between both sets, which used several mathematical fittings such as the pseudo-inverse technique, a non-linear estimation method and the principal component analysis. The proposed configurations were experimentally tested imaging the patches of the Gretagmacbeth ColorChecker DC and Color Rendition charts placed in a light booth, and measuring the corresponding colors. The results obtained showed that optoelectronic imaging systems can be used in order to perform rather accurate color measurements with high spatial resolution. Specifically, the best results in terms of CIELab color differences were achieved by using a multispectral configuration of the imaging system with seven spectral bands and directly transforming the digital signals into XYZ tristimulus values by means of the pseudo-inverse technique.

Keywords: Spectral imaging, color measurenments, optoelectronic imaging sensors

1. INTRODUCTION

The use of optoelectronic imaging systems in scientific areas such as image processing, artificial vision and in more specific fields such as photometry or radiometry is increasing rapidly owing to their good performance, good accuracy and high spatial resolution. However, many of these applications are still in their experimental stages. In this context, in this work we study the efficiency of several configurations of an optoelectronic imaging system that uses a CCD camera as a sensor[1,2] in order to perform color measurements, as a continuation of work undertaken in previous studies[3-5].

The employed imaging system was composed of a 12-bit depth monochrome camera, an objective lens and a set broadband filters, which permitted us to obtain several digital responses of the imaged objects containing information from different parts of the visible spectrum. We used two different configurations of this system in order to perform the measurements: first, a colorimetric configuration with only three acquisition channels, and second, a multispectral configuration with seven spectral bands. For the colorimetric configuration a tunable filter was placed in front of the camera, allowing the measurement of three digital signals RGB. In the multispectral-based configuration a motorized wheel with seven interference filters was used instead, allowing the measurement of seven camera responses.

From the raw digital signals (RGB) measured with the colorimetric configuration we predicted the X, Y and Z tristimulus values corresponding to each patch of the imaged color charts using two different methodologies. The first one, which has been studied in previous work[6,7], provided the XYZ tristimulus values by means of an absolute spectral and colorimetric characterization of the optoelectronic imaging system. This process permitted us to obtain the spectral sensitivities associated to the whole system and the colorimetric profile between the RGB space of the device and the CIE-1931 XYZ standard space. The second methodology allowed us to directly transform the RGB digital signals into XYZ values performing a mathematical fitting between both sets. The different techniques used in order to perform the

Spectral Imaging: Eighth International Symposium on Multispectral Color Science
edited by Rosen, Imai, Tominaga, Proc. of SPIE-IS&T Electronic Imaging
SPIE Vol. 6062, 60620F, © 2006 SPIE-IS&T · 0277-786X/05/$15

regressions included the Moore-Penrose pseudo-inverse method[8,9] and a non-linear estimation that uses a second order polinomial[10,11].

On the other hand, with the multispectral configuration of the system we also used two different ways for obtaining the colors associated to the imaged scene. In this case, the first methodology employed the same principle as the last one, that is, directly relating the digital responses with the tristimulus values, but now taking into account the seven digital signals associated to the spectral bands of the filter wheel instead of using only the RGB values. Finally, the last proposed methodology did not directly relate the digital signals with the colorimetric ones but initially performed the reconstructions of the spectral radiances associated to each pixel of the image using principal component analysis[12,13], and after that computed the XYZ tristimulus values from the spectral information provided with the tabulated color matching functions of the CIE-1931 standard observer[14].

Before applying the previous methodologies which allowed the use of the CCD camera as an instrument for color measurements, it was necessary to spatially characterize the sensor. The camera response to a uniform radiance field was characterized for each channel of both system configurations. Images of a uniform radiance field were processed in order to achieve the maximum reduction in image noise components such as dark current, shot noise, read noise and quantization noise, and the number of images to be averaged that led to a best reduction in the contribution of these last noise components was determined. The spatial non-uniformity of the sensor's response to a uniform radiance field, due to fixed pattern noise (FPN) which basically originates in detection efficiency differences between pixels and possible spatial variations in the dark current, were corrected by applying an optimized flat-field correction algorithm to the system through the different acquisition channels. As a result, a uniform response over the entire CCD to a uniform radiance field was achieved[15].

Once the spatial characterization algorithm was applied, the different proposed systems for color prediction were experimentally tested using the Gretagmacbeth ColorChecker chart (CCCR) as the training set and the Gretagmacbeth ColorChecker chart (CCDC) as the test set, and vice-versa. Both charts were placed into a special viewing booth composed of incandescent lamps which provided a uniform illumination over the analyzed patches. The spectral radiances (W/sr*m^2) and the XYZ tristimulus values associated to each sample were measured with a tele-spectracolorimeter and at the same time, the digital signals corresponding to the charts were obtained by using the described configurations of the optoelectronic system. Using the several methodologies proposed, the XYZ tristimulus values associated to the patches were predicted and the CIELab color differences between real and estimated colors were computed.

The results obtained showed that the increase of the number of acquisition channels from three to seven led to a slight improvement on the color measurements and that direct transformations between digital signals and XYZ tristimulus values provided in general better results than the first colorimetric methodology. The worse performance of this process was probably due to the amount of errors that were carried along the calculations involved in the spectral and colorimetric characterizations, because of the number of fittings performed.

The developed system based on a CCD camera, whichever configuration is used, may be integrated as an intelligent sensor in automatic manufacturing cells and allows either color measurements with customizable spatial resolution using only a few registers of the scene. Therefore the system offers a fairly higher spatial resolution when compared with standard systems for color measurements although they are less accurate, which may be a good alternative for some industrial applications.

The present work is structured as follows: in Section 2, the experimental set-up and all the related material used are presented. In Section 3, the proposed configurations of the system and the corresponding methodologies to predict color are described. In Section 4, the most relevant results obtained are summarized. Finally, in Section 5 the conclusions of the study are discussed.

2. MATERIAL

The optoelectronic imaging system used to perform the color measurements consisted of a 12 bit-depth CCD monochrome camera (QImaging QICAM Fast1394 12 bit cooled) attached to an objective lens (Nikon AF Nikkor 28 – 105 mm). Depending on the configuration used, a different set of broadband filters was placed between the camera and the objective lens. For the colorimetric experimental set-up a tunable filter was used in order to obtain the RGB digital signals. In Figure 1 the relative spectral sensitivities associated to the color channels are shown. For the multispectral set-up, a motorized wheel with seven interference filters with spectral transmittances covering the whole visible range were employed (see Figure 2).

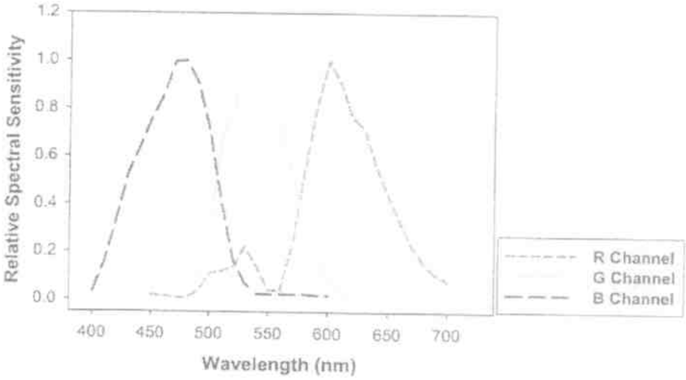


Figure 1. Relative spectral sensitivities of the RGB channels

For the multispectral set-up, a motorized wheel with seven interference filters with spectral transmittance covering the whole visible range was employed. In Figure 2., the corresponding spectral transmittances of the filters are shown.

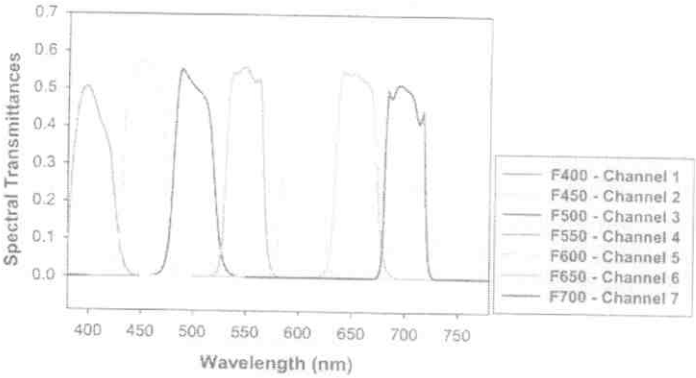


Figure 2. Spectral transmittances of the interference filters.

On the other hand, the ColorChecker charts (CCDC, CCCR) were placed into a special light booth (63cm x 64cm x 52cm) with six incandescent lamps (MAZDA 22c 40W 230V Softone), which provided a uniform illumination field over the charts. A big window on the opposite side of the booth allowed the measurement of the patches with both the CCD camera, that provided the digital signals, and a tele-spectracolorimeter (PhotoResearch PR-650 with MS-75 objective lens) that provided the XYZ tristimulus values and the spectral radiance. With all these measurements the proposed methodologies (colorimetric and multispectral) to predict the color could be applied.

Apart from the described system, two more experimental set-up configurations were used in order to carry out the spectral and the spatial characterization of the system. The experimental set-up for the spectral characterization[6] consisted of a monochromator (CVI Laser Digikröm) with constant spectral resolution attached to a halogen lamp, that provided a uniform field of radiance over a diffuser, whose radiance was varied by using the entrance/exit slits of the monochromator. The digital responses of the camera for each channel and the spectral radiances corresponding to these stimuli were measured over all the visible range, that is, between 380 and 780 mm, allowing the computation of the optoelectronic spectral conversion functions (OECSF), which relate the digital output levels with the exposure over the CCD for each wavelength. With the proper treatment of these curves it was possible to compute the spectral sensitivities of the system (see Figure 1.).

The experimental set-up for the spatial characterization consisted of an integrator cube[15], which had a window built with a translucent diffuser material that acted as a uniform radiance field. It had a spatial variation percentage of 0.50% over the centered region that constituted the camera's viewing field. This spatial variation percentage was determined by measuring the radiance over the camera's viewing field region using the tele-spectracolorimeter (PhotoResearch PR-650 with MS-75 objective lens, 1° aperture).

3. METHOD

As we previously introduced, two different configurations of the system were tested in order to perform the color measurements: a colorimetric configuration with only three channels and a multispectral one with seven channels. In the following sections the methodologies proposed in order to predict color with both configurations are described.

Colorimetric configuration

With this configuration, the system provided three digital signals (RGB) corresponding to the color channels of the tunable filter. From these signals we applied two different methodologies in order to predict the color of each pixel of the captured image. The first one, named COL 1, consisted of performing an absolute spectral and colorimetric characterization of the device. Spectral characterization[6] was experimentally obtained by measuring the optoelectronic conversion spectral functions, that relate the digital responses of the optoelectronic sensor to the spectral exposure levels (OECSF). The OECSFs were fitted mathematically by sigmoid functions of four parameters. After that, the colorimetric characterization[7] was carried out. It consisted of transforming the RGB digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions. Thus, a gray balance was applied over the raw RGB digital data to convert them into RGB relative colorimetric values, and the inverse optoelectronic conversion functions (OECF^{-1}) were obtained. Subsequently, the colorimetric profile M was calculated from the comparison between the estimated and the real color matching functions. The colorimetric profile M allowed the conversion of the camera RGB digital levels into XYZ values. Once the estimated XYZ values were obtained, a color compensation mathematical model was applied, obtaining the correctly scaled tristimulus pseudo-values, the final scaling of the colorimetric profile, and a linear correction term only due to the mismatch of the color matching functions of the camera.

On the other hand, we can also apply a direct transformation, named COL 2, in order to predict the color of the samples rom the measured digital values. This transformation could be achieved by performing a mathematical fitting between he digital values (RGB) and the tristimulus values (XYZ) of the patches belonging to the considered training set and omputing a matrix $\mathbf{D}_{\mathbf{PSE}}$ (3×3), which related both sets of values:

$$\mathbf{O}_{\mathbf{XYZ}} = \mathbf{D}_{\mathbf{PSE}} \cdot \mathbf{O}_{\mathbf{RGB}} \tag{1}$$

where $\mathbf{O}_{\mathbf{XYZ}}$ is a matrix (3×p) that contains the XYZ tristimulus values and $\mathbf{O}_{\mathbf{RGB}}$ is a matrix (3×p) that contains the RGB digital values of the p patches belonging to the training set.

he matrix $\mathbf{D}_{\mathbf{PSE}}$ can be calculated using a linear method, such as the Moore-Penrose pseudo-inverse technique, as ollows:

$$\mathbf{D}_{\mathbf{PSE}} = \mathbf{O}_{\mathbf{XYZ}} \cdot \mathbf{O}'_{\mathbf{RGB}} \cdot (\mathbf{O}_{\mathbf{RGB}} \cdot \mathbf{O}'_{\mathbf{RGB}})^{-1} \tag{2}$$

Once this matrix has been obtained, the tristimulus values of any sample can be predicted by using the following expression, assuming that the training set is a good representation of all the analyzed samples:

$$\mathbf{t}_{\mathbf{XYZ}} = \mathbf{D}_{\mathbf{PSE}} \cdot \mathbf{t}_{\mathbf{RGB}} \tag{3}$$

where $\mathbf{t}_{\mathbf{XYZ}} = [\mathbf{X\,Y\,Z}]'$, $\mathbf{t}_{\mathbf{RGB}} = [\mathbf{R\,G\,B}]'$.

By extension, we can also apply a non-linear transformation in order to predict the tristimulus values from the camera responses. In this case, the matrix $\mathbf{D}_{\mathbf{NLIN}}$ that relates both sets must be computed considering a matrix $\mathbf{O}_{\mathbf{NLIN}}$ instead of using the matrix $\mathbf{O}_{\mathbf{RGB}}$, whose columns are not the RGB digital values but represent a higher order polynomial of the responses. In this work, a complete second order polynomial was used and therefore $\mathbf{O}_{\mathbf{NLIN}}$ was a $(10\times p)$ matrix:

$$\mathbf{O}_{\mathbf{NLIN}} = \begin{bmatrix} 1 & 1 & . & 1 \\ R_1 & R_2 & . & R_P \\ G_1 & G_2 & . & G_P \\ B_1 & B_2 & . & B_P \\ R_1{}^2 & R_2{}^2 & . & R_P{}^2 \\ G_1{}^2 & G_2{}^2 & . & G_P{}^2 \\ B_1{}^2 & B_2{}^2 & . & B_P{}^2 \\ R_1 \cdot G_1 & R_2 \cdot G_2 & . & R_P \cdot G_P \\ R_1 \cdot B_1 & R_2 \cdot B_2 & . & R_P \cdot B_P \\ G_1 \cdot B_1 & G_2 \cdot B_2 & . & G_P \cdot B_P \end{bmatrix} \tag{4}$$

$$\mathbf{D}_{\mathbf{NLIN}} = \mathbf{O}_{\mathbf{XYZ}} \cdot \mathbf{O}'_{\mathbf{NLIN}} \cdot (\mathbf{O}_{\mathbf{NLIN}} \cdot \mathbf{O}'_{\mathbf{NLIN}})^{-1} \tag{5}$$

Therefore, the computation of the XYZ tristimulus values of any analyzed sample could be performed as follows:

$$\mathbf{t}_{\mathbf{XYZ}} = \mathbf{D}_{\mathbf{NLIN}} \cdot \mathbf{t}_{\mathbf{RGB}} \tag{6}$$

Multispectral configuration

In this configuration the motorized filter wheel with the seven interference filters was used and therefore seven digital responses of the camera were provided. From these signals it was possible to predict the XYZ tristimulus values of the analyzed samples using the same procedure as before, that is, computing the matrixes $\mathbf{D}_{\mathbf{PSE}}$ and $\mathbf{D}_{\mathbf{NLIN}}$, which related both sets of values. However, in this case the matrixes $\mathbf{O}_{\mathbf{RGB7}}$ and $\mathbf{O}_{\mathbf{NLIN7}}$ must include the seven signals, that is, their size is $(7\times p)$ and $(36\times p)$, respectively. This process was called MULTI 1.

Finally, the other methodology applied in order to obtain the color of the analyzed samples from the seven measured digital signals, did not directly relate the digital signals with the tristimulus values but initially performed the reconstructions of the spectral emissions corresponding to the digital signals, specifically spectral radiances (W/sr*m^2). This method, called MULTI 2, used the principal component analysis (PCA) in order to reconstruct the spectra. This technique is completely equivalent to the pseudo-inverse technique (PSE) but in this case a previous principal component analysis is performed on the spectral radiances corresponding to the patches of the training set. The spectral reconstructions are carried out only taking into account the same number of principal components as spectral bands, that is, seven. By performing this analysis any spectral radiance could be calculated by a combination of the principal components:

$$\mathbf{t}_{\mathbf{rad}} = \phi \cdot \alpha \tag{7}$$

where ϕ is matrix (41×7) containing the seven principal components (eigenvectors) and α is a column vector (7×1) with the corresponding scalar coefficients.

These coefficients were obtained for each sample with the following expression:

$$\alpha = \mathbf{D}_{\mathbf{PCA}} \cdot \mathbf{t}_{\mathbf{RGB7}} \tag{8}$$

where $\mathbf{D}_{\mathbf{PCA}}$ is a (7×7) matrix computed as follows:

$$\mathbf{D}_{\mathbf{PCA}} = \mathbf{O}_{\alpha} \cdot \mathbf{O}'_{\mathbf{RGB7}} \cdot (\mathbf{O}_{\mathbf{RGB7}} \cdot \mathbf{O}'_{\mathbf{RGB7}})^{-1} \tag{9}$$

being $\mathbf{O}_{\alpha}$ a matrix ($7 \times p$) whose columns are the scalar coefficients corresponding to the patches of the training set.

After applying this PCA technique, the XYZ tristimulus values for each sample could be computed from the spectral information provided by the system (spectral radiances) using the tabulated color matching functions of the CIE-1931 standard observer.

4. RESULTS

The Gretagmacbeth ColorChecker DC (CCDC) and Color Rendition (CCCR) charts were used to test the performance for color measurements of the two configurations considered. The methodologies proposed in the last section were used in order to predict the XYZ tristimulus values of their color patches and both charts were used as training or test charts, respectively. The efficiency of each configuration was analyzed in terms of the mean, maximum and minimum CIELab color differences between the predicted XYZ and the measured XYZ values for all the color patches belonging to each color chart.

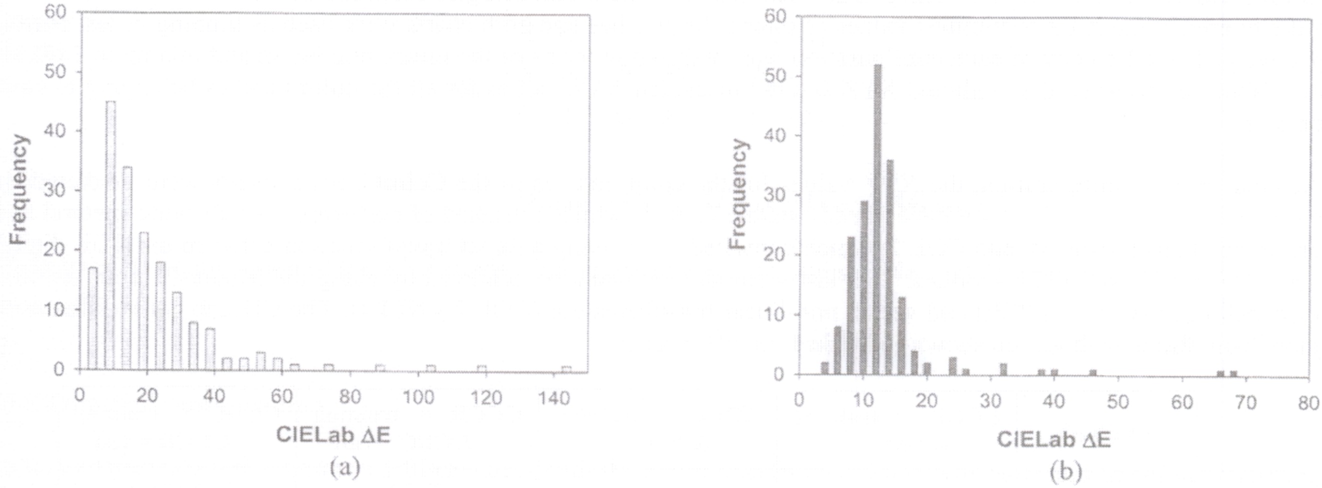
In the colorimetric configuration, the XYZ values for the color patches of the ColorChecker charts were predicted by using the following methods as we have already stated: COL 1, which consisted of performing an absolute spectral and colorimetric characterization, and COL 2, which consisted of applying a direct transformation between the RGB digital values and the XYZ tristimulus values. This last methodology could be achieved by using the Moore-Penrose pseudo-inverse technique (COL 2 - PSE) and with a non-linear transformation (COL 2 - NLIN). The CIELab color differences obtained with these methods are shown in Table 1.

	CIELab ΔE	**CCCR = training & test**	**CCDC = training & test**	**CCCR = training CCDC = test**	**CCDC = training CCCR = test**
COL 1	**mean ΔE**	14.66	19.83	23.22	20.04
	minimum ΔE	2.36	0.94	6.75	3.86
	maximum ΔE	42.92	143.65	130.62	51.84
COL 2 – PSE	**mean ΔE**	5.18	7.17	12.33	12.55
	minimum ΔE	0.818	0.53	3.54	8.76
	maximum ΔE	12.66	56.72	66.74	16.21
COL 2 – NLIN	**mean ΔE**	3.09	6.39	13.82	12.34
	minimum ΔE	0.49	0.52	3.79	6.72
	maximum ΔE	8.87	51.28	70.44	22.41

Table 1. Mean, maximum, and minimum CIELab color differences (ΔE) for the color patches of the ColorChecker DC and Color Rendition charts obtained with the colorimetric configuration.

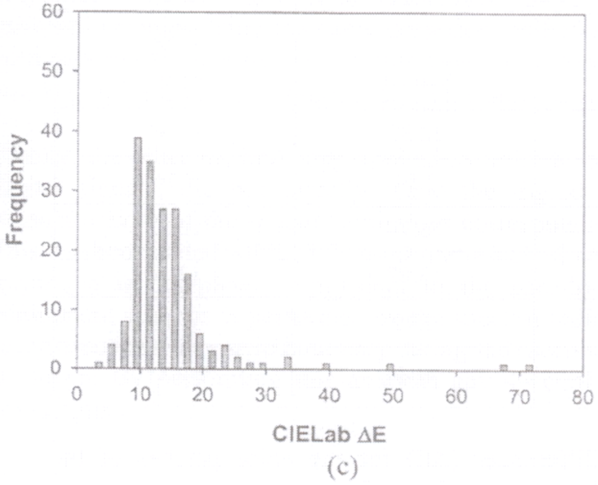
As it can be seen, the best results were obtained when the XYZ values were predicted by using the COL 2 methodology, that is, with a direct transformation from the RGB digital values. In general, the mean color differences achieved by the COL 2 - PSE and the COL 2 - NLIN mathematical methods were quite similar. Furthermore, as it was expected, the results obtained for the patches included in the training set chart were better than for those not belonging to it. When the CCCR was used as training and test set at the same time the results were rather accurate because it only has 24 different patches, meanwhile for the CCDC, since it has much more patches (180), deviations in the maximum color differences were obtained. Using different charts as training and test sets, similar values of the mean color differences were obtained for the different combinations considered. However, minimum ΔE values were smaller when the CCCR chart was used as training and the CCDC as test, while maximum ΔE values were smaller when the CCDC was used as training and the CCCR as test. In general, a better performance was achieved when a smaller number of patches was considered as the test set.

Since the mean, maximum, and minimum CIELab color differences did not provide much information on the distribution of the color differences obtained, in order to complete the evaluation of the results we also present the histograms including the color differences for all the analyzed patches (Figure 3). As it can be seen, the greatest ΔE values corresponded to specific color patches whose measured digital values did not allow the correct prediction of their XYZ values. This can be probably due to the fact that, although not being saturated or at noise level, these digital values were not placed within the linear response zone of the imaging system. Therefore, the minimum and the mean values are considered the most significant parameters in order to be used for color measurement evaluation.



(a)

(b)



(c)

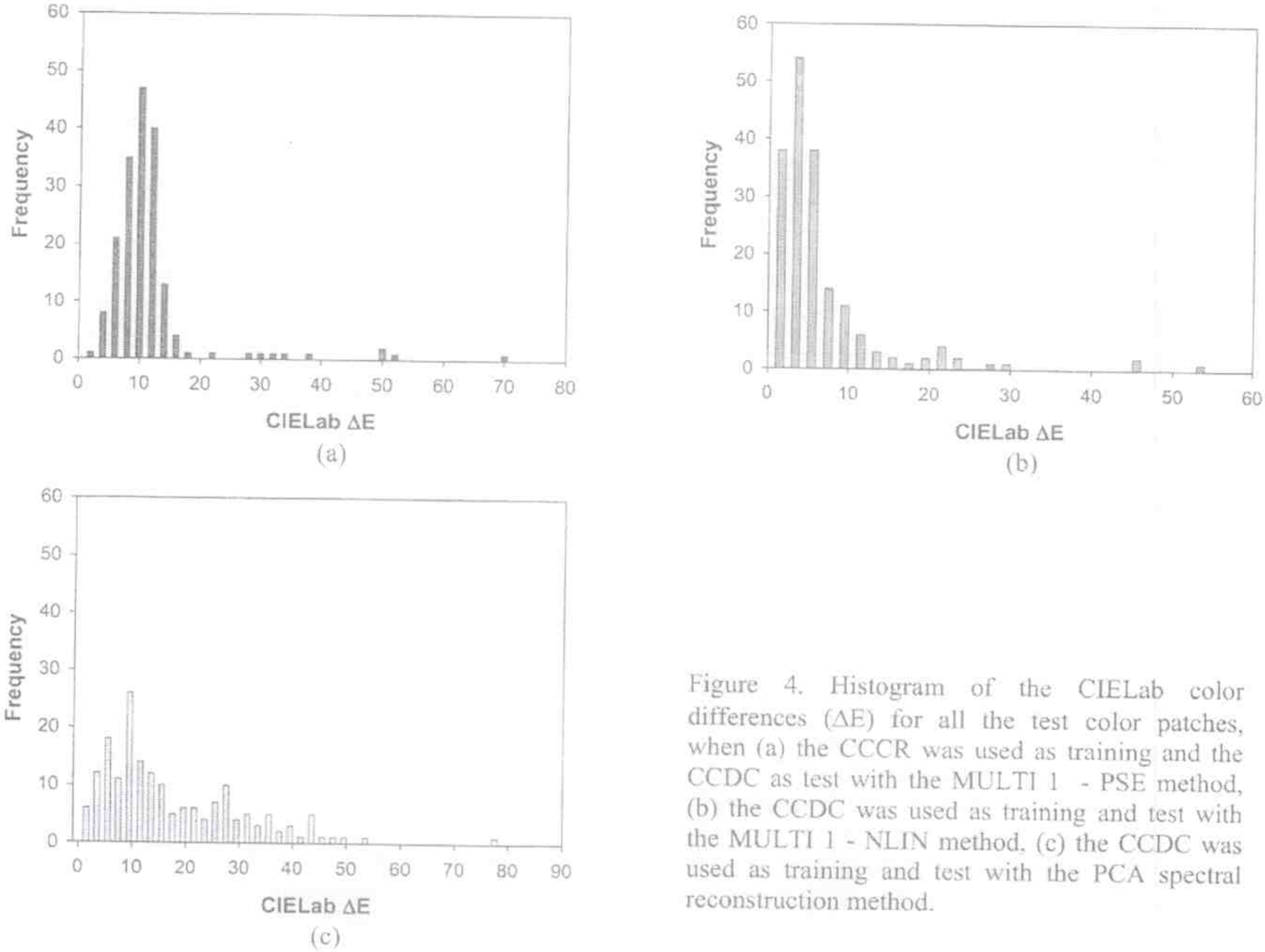
Figure 3. Histogram of CIELab color differences (ΔE) for all the test color patches, when (a) the CCDC was used as training and test with the COL 1 method, (b) the CCCR was used as training and the CCDC as test with the COL 2 – PSE method, (c) the CCCR was used as training and the CCDC as test with the COL 2 – NLIN method.

In the multispectral configuration, the XYZ values for the color patches of the ColorChecker charts were predicted also using two methods. The first, named MULTI 1, consisted of applying a direct transformation between the digital values of the seven channels and the XYZ tristimulus values. MULTI 1 – PSE used the pseudo-inverse technique and MULTI 1 - NLIN the non-linear estimation. The second method consisted of reconstructing the spectral radiances by means of principal component analysis (MULTI 2 - PCA). The mean, maximum and minimum CIELab color differences between the XYZ predicted and measured values can be seen in Table 2.

	CIELab ΔE	**CCCR = training & test**	**CCDC = training & test**	**CCCR = training CCDC = test**	**CCDC = training CCCR = test**
MULTI 1 - PSE	**mean ΔE**	4.83	6.13	10.41	11.02
	minimum ΔE	0.78	0.82	1.48	5.99
	maximum ΔE	11.34	57.07	68.52	31.17
MULTI 1 – NLIN	**mean ΔE**	0.00	6.18	59.02	22.34
	minimum ΔE	0.00	0.64	3.62	5.57
	maximum ΔE	0.005	52.42	284.72	106.55
MULTI 2 – PCA	**mean ΔE**	15.18	16.86	20.30	20.47
	minimum ΔE	0.99	0.57	2.58	3.99
	maximum ΔE	42.08	77.64	68.04	62.19

Table 2. Mean, maximum, and minimum CIELab color differences (ΔE) for the color patches of the ColorChecker DC and Color Rendition charts obtained with the multispectral configuration.

In this case, the best results were obtained when the MULTI 1 – PSE method was used. The MULTI 1 – NLIN method provided rather good results when the same chart was used as training and test set, specifically with the CCCR. In this last case, only the color of 24 patches might be predicted and therefore the fitting performed with the non-linear estimation was very accurate. However the non-linear estimation provided poor results when the test patches were not included in the training set. This behavior was probably due to the fact that this method takes into account a second order polynomial, and that errors can be considerably amplified. Because in this case we used seven acquisition channels to perform the prediction of the tristimulus values instead of three, more errors were included in the calculations. Therefore, the samples that are not well represented by the training set can have a bad estimation of their XYZ values. This also explains the extremely great maximum color differences obtained in comparison with the mean and minimum values. These values corresponded to specific and isolated color patches as it can be seen in the histograms of color differences (Figure 4.). Furthermore, the fact that some of the measured digital levels, although not being saturated or at noise level, were not placed within the linear range of the imaging system, as in the colorimetric configuration, the XYZ values of some samples could not be correctly predicted. On the other hand, the MULTI 2 – PCA method gave worse results than the MULTI 1 – PSE. These results can probably indicate that seven principal components were not enough to properly describe the spectral radiances associated to all the color patches.



(a)

(b)

(c)

Figure 4. Histogram of the CIELab color differences (ΔE) for all the test color patches, when (a) the CCCR was used as training and the CCDC as test with the MULTI 1 - PSE method, (b) the CCDC was used as training and test with the MULTI 1 - NLIN method, (c) the CCDC was used as training and test with the PCA spectral reconstruction method.

Finally, comparing the results obtained using the colorimetric and multispectral configurations, it can be stated that a slight improvement of the color measurements was observed when seven channels were used. This was not accomplished by the MULTI 1 - NLIN method and when different charts were considered as training and test sets. Therefore, it can be concluded that in the analyzed cases the best methodology in order to perform color measurements is the MULTI 1 – PSE.

5. CONCLUSIONS

Two different configurations of an optoelectronic imaging system based on a CCD monochrome 12-bit camera were used in order to perform color measurements: a colorimetric configuration, with three acquisition channels, and a multispectral configuration, with seven acquisition channels. The Gretagmacbeth ColorChecker DC (CCDC) and Color Rendition (CCCR) charts were used to test the efficiency of these two configurations in order to measure the colors associated to their patches. Different mathematical methodologies were used to predict the tristimulus values and both charts were used as training and test sets, respectively. The quality of the color measurements provided by each configuration was analyzed in terms of the mean, maximum and minimum CIELab color differences between the predicted XYZ tristimulus values and the measured XYZ ones, with every proposed method. The distribution of the color difference values of the patches for each color chart were also considered by means of histograms of color differences.

For the colorimetric configuration, the best results were obtained when the XYZ values were predicted using a direct transformation from the RGB digital values (method COL 2). Using both COL 2 - PSE and COL 2 - NLIN methods, the mean color differences obtained were rather similar.

For the multispectral configuration, the best results were obtained when the MULTI 1 – PSE method was used. The MULTI 1 – NLIN method provided rather good results when the same chart was used as training and test set but poor results were achieved when the test patches were not included in the training set. This was probably due to the amplification of errors carried out with this estimation method. On the other hand, the MULTI 2 - PCA method provided worse results probably because seven principal components were not enough to describe the whole set of spectral radiances associated to the analyzed colors.

The maximum color differences provided by all the tested methodologies corresponded to a small number of patches, so the mean color difference becomes the most representative value in color performance evaluation. The great differences of color could be explained by the fact that the digital values associated to some color patches were not placed within the linear response zone of the camera, providing digital values useless to predict the corresponding XYZ values.

In general, for both colorimetric and multispectral configurations, a better performance was achieved when a smaller number of patches was considered as the test set, as it was expected. The best color differences were achieved by the PSE method and a slight improvement of the results was observed when seven channels were used. Therefore, it can be concluded that in the analyzed cases the best configuration and methodology in order to perform color measurements is the multispectral with the pseudo-inverse technique, that is, the MULTI 1 – PSE method.

Future work is oriented, on one hand, to determine if an increase in the number of acquisition channels and in the number of training color patches may improve the performance for color measurements of the imaging system, and, on the other hand, to achieve useful digital value measurements for all acquisition channels and color patches within the linear range of the camera and therefore to better predict the corresponding XYZ values. So far, digital value measurements were performed using fixed capture conditions for each acquisition channel and, although these conditions were set to avoid any pixel being saturated or at dark noise level, it was not possible to assure that all the digital responses were placed within the linear response range. In order to overcome this limitation an algorithm of luminance adaptation is proposed to be applied.

ACKNOWLEDGEMENTS

This research was supported by the Spanish Ministry for Science and Technology (Ministerio de Ciencia y Tecnología) by means of the grant number DPI2002-00118. M. de Lasarte would like to thank the Ministerio de Educación, Ciencia y Deportes of Spain for the Ph.D. grant she has received.

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