Preliminary results of the development of a multispectral imaging system for colour measurements

M. de Lasarte Rigueiro, J. Pujol Ramo, M. Arjona Carbonell, M. Vilaseca Ricart

Centre for Sensors, Instruments and Systems Development (CD6), Department of Optics and Optometry,
Technical University of Catalonia
e-mail: marta.lasarte@oo.upc.edu

ABSTRACT:

Different results are briefly presented in this work. Firstly, the characterization of CCD cameras in the visible range to be used in multispectral imaging systems, which comprises the correction of the noise sources inherent to CCD cameras operation, the spectral characterization of CCD cameras using a method based on direct spectral measurements, and the colorimetric characterization of CCD cameras using methods based on spectral sensitivities and on a training colour chart. Secondly, the development of a multispectral imaging system for colour measurements, and finally, the analysis of the colour measurements performed using imaging systems based on CCD cameras, in order to improve their accuracy.

Key words: CCD cameras, spatial non-uniformity correction, spectral characterization, colorimetric characterization, multispectral imaging system.

REFERENCES AND LINKS

[1] M. de Lasarte, J. Pujol, M. Arjona, M. Vilaseca, Appl. Opt. 46(2), 167-174 (2007).

[2] F. Martínez-Verdú, J. Pujol, P. Capilla, J. Imag. Sci. Technol. 46(1), 15-25 (2002).

[3] F. Martínez-Verdú, J. Pujol, P. Capilla, J. Imag. Sci. Technol. 47(4), 279-374 (2003).

[4] J. Y. Harderberg, F. Schmitt, H. Brettel, J-P. Crettez, H. Maître, "Multispectral image acquisition and simulation of illuminant changes" in *Colour imaging: vision and technology* (John Wiley & Sons, Chichester, England), 145-164 (1999).

[5] G. Hong, M. R. Luo, P. A. Rhodes, Color Res. Appl. 26(1), 76-84 (2001).

[6] F. H. Imai, R. S. Berns, Proc. IS&T/SID, 8th Color Imaging Conference, 234-241 (2000), on line document – pdf file, URL: http://www.art-si.org/PDFs/Acquisition/CIC00_Imai.pdf.

1. Introduction

One of the fundamental objectives of this work was the development of a multispectral imaging system for colour measurements, using imaging systems based on CCD cameras.

CCD cameras are widely used in the scientific image field due to their characteristics, such as high spatial resolution, linearity, fast response, geometric fidelity, etc. They can also be used as instruments for measurement with high spatial resolution carrying out a suitable calibration and correcting the noise sources inherent to their operation.

Specifically, a suitable colorimetric characterization of the imaging system would allow to use it as an instrument for colour measurement.

With respect to their colorimetric applications, most of the commercial CCD colour cameras, having 3 acquisition channels (typically R, G and B), present serious limitations due to the fact that their spectral sensitivities do not satisfy the Luther condition, that is, they are not lineal transformations of the CIE colour matching functions leading to the device metamerism.

The only way to achieve a colour matching for all the observers and different illuminations is by means of a spectral matching, which requires obtaining spectral information. The most direct method to obtain it is increasing the sampling over the 3 traditional acquisitions channels by means of a multispectral imaging system.

The main objectives of this work are, firstly, the characterization of CCD cameras in the visible range to be used in multispectral imaging systems. Secondly, the development of a multispectral imaging system for colour measurement, and finally, the improvement of the accuracy of both colour measurement and spectra reconstruction, using multispectral imaging systems based on CCD cameras.

In section 2, the state of the art of the different topics related to this work are briefly presented. In section 3, the preliminary results and conclusions obtained are summarized, and finally, the future work is presented in section 4.

2. State of the Art

2.a.- Spectral Characterization of CCD Cameras

The objective of the spectral characterization of CCD cameras is to determine the relative spectral sensitivities of the imaging system, which are used in one of the methods for colorimetric characterization analyzed later.

Among of the several methods for spectral characterization existing, the method applied is based on direct spectral measurements [2]. In this method, the Opto-Electronic Spectral Conversion Functions (OESCFs), which relate the normalized digital levels of the spectral response of the camera to the spectral exposure, are firstly determined. From them, the absolute and relative spectral sensitivities are determined for each acquisition channel.

Finally, a relative group scaling and an equienergetic white balance of the relative spectral sensitivities allow to obtain the colour matching functions of the imaging system [3].

2.b.- Colorimetric Characterization of CCD Cameras

The methods for colorimetric characterization of CCD cameras can be classified in two categories: those that use the spectral sensitivities of the imaging system, and those that use a training colour chart. From these last ones, two kinds of methods can be considered: the direct transformation methods, and the spectra reconstruction methods.

The colorimetric characterization method that uses the spectral sensitivities was developed by our colour group [3] and it is based on the determination of the basic colorimetric profile M of the imaging system, from its colour matching functions T_{RGB} and the CIE colour matching functions T_{XYZ} (eq. 1).

$$M = T_{XYZ}^{t} \cdot T_{RGB} \cdot \left(T_{RGB}^{t} \cdot T_{RGB} \right)^{-1} \qquad (1)$$

The XYZ tristimulus values are predicted using this basic colorimetric profile. The comparison between the predicted (t'_{XYZ}) and the measured (t_{XYZ}) XYZ values allows the later application of a linear colour correction model (eq. 2), and finally, obtaining the scaled basic colorimetric profile of the system ($B_C \cdot M$).

$$t_{XYZ} = A_C + B_C \cdot t'_{XYZ} \qquad (2)$$

Due to the high complexity of this method, it is only applied to colorimetric configurations, that is, having 3 acquisition channels.

Among of the methods that use a training colour chart, direct transformation methods allow to obtain the XYZ tristumulus values corresponding to the colour patches of a training chart (O_{XYZ}), directly from the digital levels of the response of an imaging system ($O_{K_1K_2K_3...K_n}$, n channels), by a mathematical regression performed between both groups, calculating the D transformation matrix that relates them (eq. 3).

$$O_{XYZ} = D \cdot O_{K_1K_2K_3...K_n} \qquad (3)$$

The first direct transformation method used is the Moore-Penrose pseudo-inverse technique [4]. It is a lineal estimation method based on a least squared regression from which the D_{PSE} matrix is obtained. This matrix permits us to predict the XYZ values of any colour sample (t_{XYZ}^{t}) directly from its corresponding digital levels ($t_{K_1K_2K_3...K_n}^{t}$, n channels) (eqs. 4).

$$D_{PSE} = O_{XYZ} \cdot O_{K_1K_2...K_n}^{t} \cdot \left(O_{K_1K_2...K_n} \cdot O_{K_1K_2...K_n}^{t} \right)^{-1}$$

$$t_{XYZ}^{t} = D_{PSE} \cdot t_{K_1K_2...K_n}^{t} \qquad (4)$$

The second direct transformation method used is the Second Order Non-Linear method [5]. In this case, the tristimulus values of each colour sample (t_{XYZ}^{t}) are directly related to a full second order polynomial of the corresponding digital levels ($t_{Pol_i(K_1K_2...K_n)}{}^t$, n channels), obtaining the D_{NLIN} transformation matrix (eqs. 5).

$$D_{NLIN} = O_{XYZ} \cdot O_{Pol_i(K_1K_2...K_n)}{}^t \cdot \left(O_{Pol_i(K_1K_2...K_n)} \cdot O_{Pol_i(K_1K_2...K_n)}{}^t\right)^{-1}$$

$$t_{XYZ}{}^t = D_{NLIN} \cdot t_{Pol_i(K_1K_2...K_n)}{}^t \qquad (5)$$

The spectra reconstruction method performs a previous reconstruction of spectral radiances of each colour sample, from which the corresponding XYZ values are determined. The necessity of spectral information in reconstruction makes these methods to be applied usually to multispectral configurations.

Among of the existing spectra reconstruction methods, the Principal Component Analysis (PCA) is used [6]. In the PCA method, the principal components (ϕ matrix), which correspond to the maximum variance direction, of the variance-covariance matrix of the original matrix of spectral radiances of the training set, and the matrix of scalar coefficients (O_α) corresponding to the training set are determined.

In the spectra reconstruction from measurements performed with a multispectral imaging system the number of principal components considered corresponds to the number of acquisition channels.

In this case, digital levels corresponding to each colour sample ($t_{K_1K_2...K_n}$) are directly related to scalar coefficients in the principal components base (α), by means of the D_{PCA} matrix. The linear combination of the principal components (ϕ matrix) with the scalar coefficients allow to predict the spectral radiance (t_{rad}) of each colour sample, from which the XYZ values are calculated (eqs. 6).

$$D_{PCA} = O_\alpha \cdot O_{K_1K_2...K_n}{}^t \cdot \left(O_{K_1K_2...K_n} \cdot O_{K_1K_2...K_n}{}^t\right)^{-1}$$

$$\alpha = D_{PCA} \cdot t_{K_1K_2...K_n} \qquad (6)$$

$$t_{rad} = \phi \cdot \alpha$$

2.c.- Multispectral Image Acquisition Systems

The main objective of the multispectral image acquisition systems is to obtain spectral information of the measured samples. The most common configuration of a multisectral imaging system is composed by a CCD monochromatic camera + N interference or tunable filters. Other configurations used are composed by a CCD colour camera + absorption filters, or a CCD colour camera + different illumination sources.

The N (N > 3) filters used are highly selective and have spectral transmittances covering the whole visible range. Each filter acts as an acquisition channel.

The fundamental advantage of the multispectral image acquisition systems, in front of the traditional colorimetric ones, is to allow an accurate prediction of the spectral reflectance at each pixel by means of a previous spectral analysis, so the accuracy of the colorimetric characterization is improved and, consequently, an accurate prediction of the XYZ values associated to each pixel, avoiding metamerism, can be carried out.

3. Preliminary Results & Conclusions

2.a.- Optimization of a linear algorithm for the spatial non-uniformity correction

A linear correction algorithm based on the calculation of the correction gain (G) and offset (O) matrixes (eqs. 7), from a dark image and a uniform illumination field image called correction base image, was optimized using a CCD colour camera QImaging QICAM 10 bits.

$$DL_c = O(i,j) + G(i,j) \cdot DL(i,j)$$

$$G(i,j) = \frac{DL_B - DL_0}{DL_B(i,j) - DL_0(i,j)} \qquad (7)$$

$$O(i,j) = DL_0 - G(i,j) \cdot DL_0(i,j)$$

The correction quality was evaluated using the Spatial Non-Uniformity Percentage (SNUP), which is calculated from the mean digital level of the image and its associated standard deviation (eq. 8).

$$SNUP = 100 \cdot \frac{\sigma(Mean)}{Mean} \qquad (8)$$

The gain and offset electronic parameters, which allow working in zero and non-zero dark image conditions, and the number of averaged images necessary to correct the temporal noise sources as much as possible, were determined for the used camera.

The optimization of the algorithm was carried out from its variables, obtaining the best correction when working in non-zero dark image conditions, using the central image in the linear response range of the system as correction base image, and using the mean digital level of the image as reference digital level.

2.b.- Development of a multispectral imaging system for colour measurements

The multispectral imaging system developed is composed by a CCD 12 bits monochromatic cooled camera, an objective lens, and a set of 7 Interference filters fitted in a motorized filter wheel, which have spectral transmittances covering the whole visible range and a Full Width at Half Maximum (FWHM) of 40nm (fig. 1).

Fig. 1. Multispectral imaging system developed.

2.c.- Correction of the response of a 12 bits cooled monochromatic CCD camera

Two configurations based on a 12 bits cooled monochromatic CCD camera QImaging QICAM Fast 1394 were used: a colorimetric configuration, with 3 acquisition channels obtained using an RGB tunable filter (fig. 2), and a multispectral configuration, with 7 acquisition channels obtained using 7 interference filters fitted in a motorized filter wheel (fig. 1).

Fig. 2. Colorimetric configuration of the imaging system based on a 12 bits cooled monochromatic CCD camera.

The values of the gain and offset parameters necessary to work in non-zero dark image conditions and the number of averaged images were determined.

The application of the optimized linear correction algorithm allows to reduce the mean spatial non-uniformity percentages over the linear response range of the system between a 14.29% (B channel) and a 34.78% (R channel) for the colorimetric configuration, and between a 24.09% (F650) and a 29.59% (F550) for the multispectral configuration.

2.d.- Spectral Characterization of CCD cameras in the visible range

The relative spectral sensitivities of a 10 bits CCD colour camera and of the colorimetric configuration of a 12 bits cooled monochromatic CCD camera were obtained (fig. 3.).

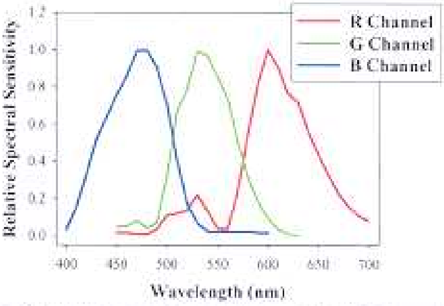


Fig. 3. Relative spectral sensitivities of a 12 bits cooled monochromatic CCD camera.

2.e.- Colorimetric characterization of a CCD camera

The colorimetric characterization of a CCD camera consists of obtaining the transformation that defines the connection between the digital responses of the camera, and a colour space independent of the device as, for example, the CIE – XYZ.

The colorimetric characterization of both configurations of the imaging system based on the 12 bits cooled monochromatic CCD camera was carried out.

The colorimetric configuration was characterized using the method based on spectral sensitivities and the direct transformation methods among of methods based on a training colour chart.

The multispectral configuration was characterized using the methods based on a training colour chart, both direct transformation methods and spectra reconstruction methods.

The colorimetric characterization was carried out using the GretagMacbeth ColorChecker Color Rendition and Color DC charts as training and test sets, considering all possible combinations, placed in a light booth that provided a uniform illumination over them.

The colour measurement accuracy obtained using each method was evaluated in terms of the mean, minimum and maximum CIELab colour difference, between the XYZ values measured and predicted, and the histograms of the colour differences associated to the colour samples of the test set.

For the colorimetric characterization, very high colour differences for a great number of samples were obtained using the method based o spectral Sensitivities, probably due to the accumulation of errors in the regressions and simulations that are carried out in this method.

The best results for this configuration were obtained using the methods of direct transformation based on a training colour chart, and similar results were obtained for both of these methods.

For the multispectral configuration, slightly lower colour differences were obtained using the direct transformation methods than for the colorimetric configuration, and the globally best results were obtained using the Pseudo-Inverse Technique. Results obtained using the Principal Component Analysis were slightly worse than those obtained with the Pseudo-Inverse Technique.

For the analyzed samples, the best results in colour measurements were obtained using the multispectral configuration and the Moore-Penrose Pseudo-Inverse direct transformation method.

2.f.- Analysis of colour measurements performance

Firstly, a Luminance Adaptation Model was proposed, and its application studied.

The CCDC was used for system calibration, which consists on obtaining, for each acquisition channel, the LAM coefficients associated to each exposure time.

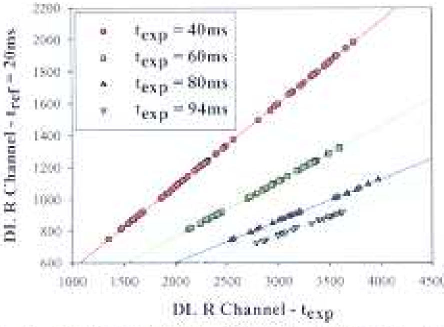


Fig. 4. Linear regression fitting to obtain the LAM coefficients associated to each exposure time for the R channel.

For each acquisition channel a reference exposure time was defined so that digital levels associated to all colour patches of the CCDC were placed in the linear response range of the system. The LAM coefficients were obtained as a result of the linear regression fitting between digital levels at a certain exposure time plotted versus digital levels of the same colour patches at the reference exposure time (fig. 4).

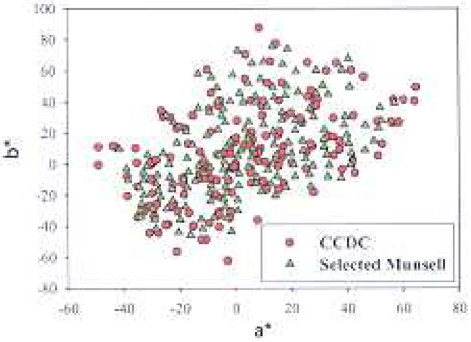
The validity of the LAM proposed was proved by the highly similar results on colour measurements obtained with and without LAM application, for both system configurations.

This LAM allows the dynamic range of the imaging system to be increased.

Secondly, the effect of increasing the size of the training set on colour measurements was studied. The basic training set constituted by the CCDC was increased adding a set of selected Munsell colour chips. The selection criteria was established in terms of differences of a* and b* CIELab coordinates between, on one hand, each Munsell selected colour and all the colour patches of the CCDC and, on the other hand, each pair of selected Munsell colours between themselves.

The final values of Δa* and Δb* were fixed to obtain a number of selected Munsell similar to the number of useful colour patches in CCDC. 161 Munsell colour chips were finally selected (fig. 5).

Fig. 5. a*b* diagram of the CCDC colur patches and the selected Munsell colour chips.



Similar results were obtained increasing the size of the training set without a loss of performance in colour measurements.

Finally, a study on the size of the training set was performed using the CCDC as training set, and selecting sets of its colour patches applying a selection criteria based, as before, on differences of a* and b* CIELab coordinates between, in this case, the selected colour patches of the CCDC.

The selected colour patches of the CCDC and the CCCR colour chart were used as test sets.

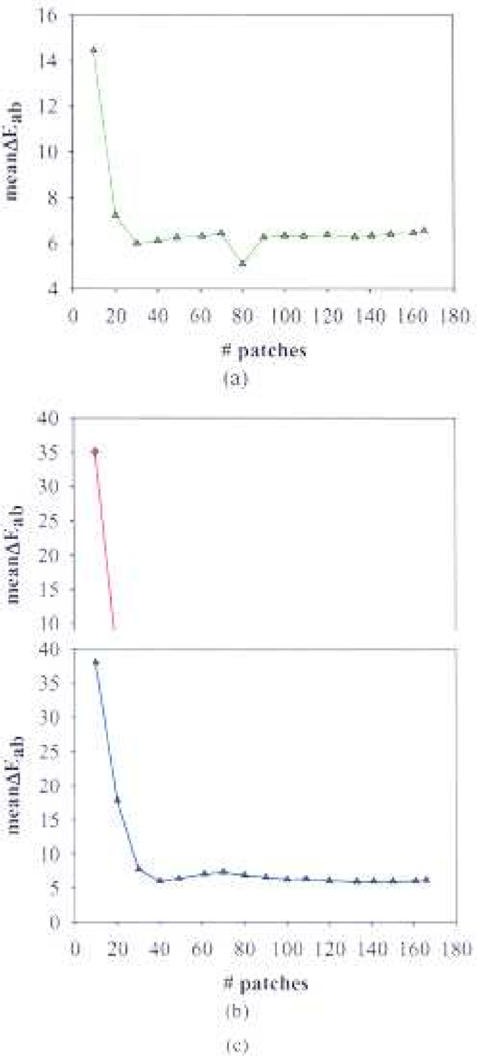


Fig. 6. Mean ΔE_{ab} of the colour patches of the CCCR plotted versus the number of the selected colour patches of the CCDC (training set) for (a) the colorimetric configuration using the Pseudo-Inverse direct transformation method, (b) the multispectral configuration using the Pseudo-Inverse direct transformation method, and (c) the multispectral configuration using the PCA.

For both configurations and for all direct transformation methods it can be seen that the improvement in colour differences with respect to the increase in size of the training set is limited (figs. 6).

4. Future Work

Future work is oriented to, firstly, continue the analysis of colour measurement performance per colour ranges for both the colorimetric and the multispectral configurations of the imaging system. Secondly, to determine if an increase in the number of acquisition channels may improve the performance for color measurements of the imaging system, and finally, the development and application of a new instrumentation to measure the colour of ocular structures, based on multispectral imaging systems.

5. Acknowledgements

This research was supported by the Spanish Ministry for Education and Science (Ministerio de Educación y Ciencia, MEC) by means of the grant number DPI2005-08999-C02-01. M. de Lasarte would like to thank the MEC for the Ph.D. grant she has received.