High Dynamic Range Multispectral System for Wide Color Gamut Measurements

Jaume Pujol, Marta de Lasarte, Meritxell Vilaseca, Montserrat Arjona; Centre for Sensors, Instruments and Systems Development (CD6), Department of Optics and Optometry, Technical University of Catalonia (UPC); Terrassa, Barcelona - SPAIN

Abstract

The aim of the present work is to analyze the performance for color measurements of systems based on optoelectronic imaging sensors, training the imaging system by measuring color patches belonging to widely different color gamuts, and optimizing the capture conditions with a luminance adaptation model so that all the digital signals were located within the linear range of the system response. The application of this luminance adaptation model allows to measure all the colors in a common scene which could contain colors very different in luminance, and as a result, the dynamic range of the system to be increased.

The employed imaging system was composed of a 12 bit-depth CCD monochrome camera attached to an objective lens. Two different configurations were used: a colorimetric one, with three acquisition channels obtained by means of an RGB tunable filter, and a multispectral one, with seven acquisition channels obtained by placing a motorized wheel with seven interference filters.

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. The distribution of the color difference values of the patches for each color chart was also considered by means of histograms of color differences.

The results obtained showed that it is possible to increase the color gamut without a loss of performance. Similar results were obtained using the CCDC chart, the selected Munsell colors, and these both joined as training and test sets, which indicated that either the selected Munsell colors or the CCDC allowed to train the system properly. A slight improvement in the results was observed using the multispectral configuration with respect to the colorimetric one when the same set of colors was used as training and test set.

Introduction

The good performance, good accuracy and high spatial resolution of optoelectronic imaging systems make them useful in scientific areas such as image processing, artificial vision and in more specific fields such as photometry or radiometry. Recently, CCD[1,2] cameras also started to be used in the performance for color measurements, and as a sensor in multispectral imaging systems[3], whose application in many different fields, such as artwork maintenance, color reproduction, e-commerce and tele-medicine, has increased considerably in last years. However, many of these applications are still in their experimental stages.

In a previous work[4], two different configurations of an optoelectronic imaging system that uses a CCD camera as a sensor were considered in order to perform color measurements: a colorimetric configuration, with three acquisition channels, and a multispectral configuration, with seven acquisition channels. The efficiency of these two configurations had been tested applying different mathematical methods in order to predict the XYZ tristimulus values from the digital levels associated to each acquisition channel, and corresponding to the measured color patches, using the Gretagmacbeth ColorChecker DC (CCDC) and Color Rendition (CCCR) charts as training and test sets. In general, for both colorimetric and multispectral configurations, the best results had been obtained when the XYZ values had been predicted using a direct transformation from the digital values, and a slight improvement of the results had been observed when seven channels had been used. As it had been expected, the best results had been obtained using the same chart as training and test set. Taking into account the number of color patches of the training and test sets, the best results had been obtained using the CCDC chart as training and test set, i.e. using the greatest set of color patches between the both considered: the CCDC (180 color patches) and the CCCR (24 color patches).

As a continuation of work undertaken in this previous study, the aim of the present work is to analyze the performance for color measurements of systems based on optoelectronic imaging sensors when a wide color gamut is used. In order to achieve this objective, the imaging system was trained by measuring color patches belonging to widely different color gamuts, and the dynamic range of capture was increased by applying a luminance adaptation model (LAM). The enlargement of the training set of the imaging system was carried out by adding some color patches of the Munsell Book of Color to those belonging to the CCDC and the CCCR charts. If colors very different in luminance are wanted to be measured simultaneously, as it happens in real scenes, it is not possible that the digital levels associated to all the pixels in the image were located within the linear range of the system response. The application of a LAM allows to deal with this situation, since useful digital levels obtained at an exposure time that could be different for each pixel, are transformed into digital levels at a reference exposure time common to all the pixels in the image, so that all the digital levels are located within the linear range of the system response and become comparable, being the dynamic range of the system increased as a result.

Correlation between quality of performance for color measurements and the enlargement of the training gamuts of color has also been analyzed comparing the results obtained using different initial and enlarged training sets, and different tests sets.

This paper is structured as follows: in the following section the material used and the experimental method applied are described. After that, the most relevant results obtained with the two configurations of the proposed system are summarized. Finally, in the last section the most relevant conclusions of the study are discussed.

Material and Method

The imaging system used in this work was composed 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), and two sets of filters: an RGB tunable filter (Figure 1.) and a set of seven broadband interference filters, with a full-width half maximum (FWHM) of approximately 40 nm covering the whole visible range of the electromagnetic spectrum (Figure 2.). Two different configurations of the imaging system, which were obtained by placing these two sets of filters between the camera and the objective lens, were used in order to perform color measurements: a colorimetric configuration, with three acquisition channels obtained by using the RGB tunable filter; and a multispectral configuration, with seven acquisition channels obtained by using a motorized wheel with the seven broadband interference filters.

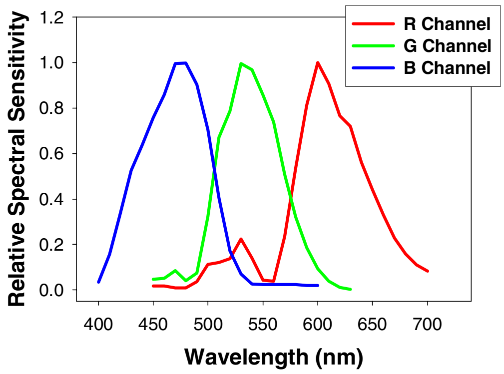


Figure 1. Relative spectral sensitivities of the RGB channels obtained from the spectral characterization of the colorimetric configuration of the imaging system.

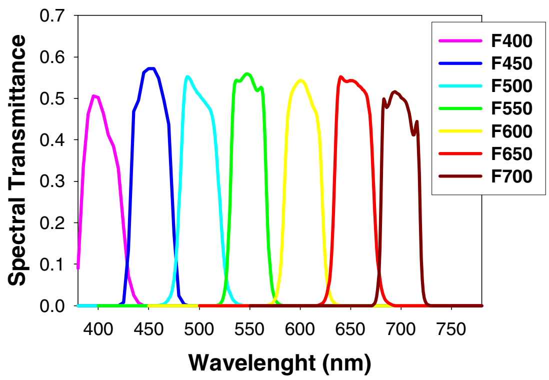


Figure 2. Spectral transmittances of the interference filters.

For both the colorimetric and the multispectral configurations, the XYZ tristimulus values were predicted using a direct transformation from the RGB digital values. This transformation was achieved by performing a mathematical fitting between the digital values (RGB) and the tristimulus values (XYZ) of the patches belonging to the considered training set, and computing a matrix that related both sets of values. This transformation matrix was calculated using the Moore-Penrose pseudo-inverse technique (PSE) [5,6].

Before applying this methodology, 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. The spatial non-uniformity of the sensor's response to a uniform radiance field was corrected by applying an optimized flat-field correction algorithm to the system through the different acquisition channels[7]. As a result, a uniform response over the entire CCD to a uniform radiance field was achieved.

In order to increase the color gamut of the training set, a number of color patches belonging to Munsell Book of Color were selected in order to complement the CCDC's color patches. The selection criteria of the Munsell colors was established in terms of differences of a* (Δa*) and b* (Δb*) CIELab coordinates between on one hand, each Munsell selected color and all the CCDC's color patches, and on the other hand, each pair of selected Munsell colors. Several pairs of values of Δa* and Δb* were tested for the both a* and b* differences mentioned above (Munsell – CCDC and Munsell – Munsell) in order to obtain the best selection of Munsell colors. Obtaining a number of selected Munsell colors similar to the number of the CCDC's color patches allowed to choose the final Δa* and Δb* values for each one of the both differences considered. A number of colors belonging to Munsell Book of Color were selected satisfying that: 1 ≤Δa* ≤5 and 1 ≤Δb* ≤5 between each Munsell selected color and all the CCDC's color patches the inequalities; and Δa* ≥4 and Δb* ≥4 between each pair of selected Munsell colors (Figure 3.).

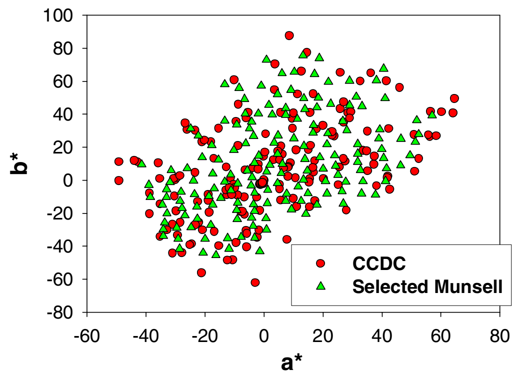


*Figure 3. a*b* diagram corresponding to the CCDC's color patches and the selected Munsell colors.*

The color patches were imaged and measured, 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 them. 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.

On the other hand, the dynamic range of the system was increased by applying a luminance adaptation model (LAM), which consists of transforming the useful digital levels measured at a certain exposure time into digital levels at a reference exposure time. The application of the LAM allows to measure all the colors in a common scene which could contain colors very different in luminance.

The CCDC chart was used in order to perform the LAM. For each CCDC's color patch, and for each acquisition channel, several images were captured using different exposure times. For each acquisition channel, the exposure time for which the digital levels (DL) associated to all the CCDC's color patches were useful was chosen as the reference exposure time associated to this acquisition channel. Taking into account all the images captured, the digital levels of the useful color patches at all the exposure times considered were plotted versus the digital levels of the same color patches at the reference exposure time, and fitted by a linear regression for each acquisition channel. By this way, each exposure time has an associate set of regression coefficients that are used to apply the LAM to digital levels measured at this exposure time. The exposure times considered corresponded to all exposure times used in the captured images of the CCCR chart and the selected colors of the Munsell Book of Color. The luminance adaptation model was applied to the useful digital levels measured at each exposure time in order that these digital levels became comparable with the ones associated to color patches imaged usefully at different exposure time conditions and, as a consequence, at different exposure levels, for each acquisition channels (Figure 4.).

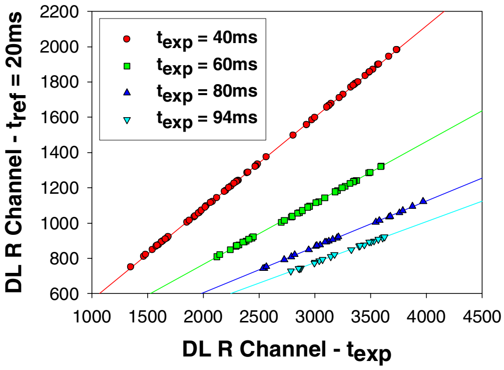


***Figure 4.** Useful digital levels (DL) of the CCDC chart obtained using a reference exposure time (20ms) versus useful digital levels obtained using different exposure times for the R channel of the colorimetric configuration. Each point in the plot represents a color patch of the CCDC chart.*

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 using a telespectroradiometer. The distribution of the color difference values of the patches for each color chart was also considered by means of histograms of relative frequencies of color differences.

Results

The performance of the LAM was tested using the color patches of the CCDC and the CCCR charts, since it was possible to obtain useful digital levels for all the color patches of each chart by using a unique exposure time per chart. The set of regression coefficients associated to each exposure time for each acquisition channel, which are used to apply the LAM to digital levels measured at this exposure time, were obtained performing high quality linear regression fittings (r2 > 0.998) on the useful digital levels (DL) associated to the CCDC's color patches at each exposure time.

The quality of the color measurements obtained without applying the LAM (NO – LAM), i.e. using a unique exposure times for all the color patches of the color charts and for each acquisition channel, and those obtained applying the LAM, i.e. using several exposure times for each color patch and for each acquisition channels, was compared for each technique applied to predict the XYZ values for the two configurations of the system used (Table 1).

The high similarity between the results obtained with and without applying the LAM, for all the combinations of the CCDC and the CCCR charts as training and test sets considered, and for each one of the techniques used for both the colorimetric and the multispectral configurations, allowed to test the validity of the LAM proposed when it was applied to the color measurements performed.

Table 1. Comparison between the color measurements provided by the colorimetric and the multispectral configurations using the PSE technique (COL – PSE and MULTI – PSE, respectively), applying LAM and without applying (NO – LAM), for the different combinations of the CCDC and CCCR charts as training and test sets considered.

COL – PSE	NO – LAM	Training	CCDC	CCDC	CCCR	CCCR
		Test	CCDC	CCCR	CCCR	CCDC
		meanΔE	4.2	6.3	5.2	5.4
		minΔE	0.6	0.8	0.8	0.6
		maxΔE	11.8	12.8	12.5	16.6
	LAM	Training	CCDC	CCDC	CCCR	CCCR
		Test	CCDC	CCCR	CCCR	CCDC
		meanΔE	4.2	5.9	5.1	4.9
		minΔE	0.6	0.4	0.9	0.8
		maxΔE	11.8	13.5	12.3	13.6
MULTI – PSE	NO – LAM	Training	CCDC	CCDC	CCCR	CCCR
		Test	CCDC	CCCR	CCCR	CCDC
		meanΔE	3.0	4.7	3.9	4.8
		minΔE	0.5	1.9	0.5	0.9
		maxΔE	9.7	16.6	14.9	11.1
	LAM	Training	CCDC	CCDC	CCCR	CCCR
		Test	CCDC	CCCR	CCCR	CCDC
		meanΔE	3.1	5.1	3.5	4.3
		minΔE	0.2	1.7	0.2	0.8
		maxΔE	10.7	22.0	11.8	9.7

On the other hand, as it has been previously said, the selected color patches belonging to Munsell Book of Color complemented, in terms of CIELab coordinates, the CCDC's color patches, which were considered the initial training set of the system The great variety of these selected Munsell colors did not allow to obtain useful digital signals for all the color patches using a unique exposure time per acquisition channel becoming necessary to apply the LAM proposed. In order to check the performance of the two configurations used when a wide color gamut composed by the selected Munsell colors and the CCDC's color patches was used, the quality of the color measurements provided by each configuration was analyzed considering several combinations of training and test sets (Table 2.).

Table 2. Mean, maximum and minimum CIELab color differences between the predicted XYZ tristimulus values and the measured XYZ, for the color measurements provided by the colorimetric and the multispectral configurations using the PSE technique (COL – PSE and MULTI – PSE, respectively), for the different combinations of the CCDC and the CCCR charts, and the selected Munsell colors (Sel. Mun.) as training and test sets considered.

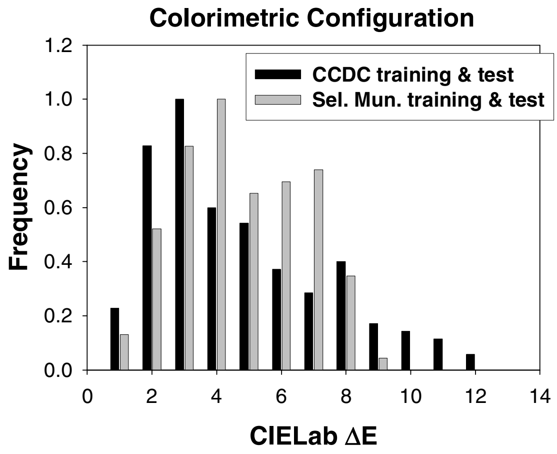
	Training	**Sel. Mun.**	**Sel. Mun.**	**CCDC & Sel. Mun.**	**CCDC & Sel. Mun.**
COL – PSE	**Test**	**Sel. Mun.**	**CCCR**	**CCDC & Sel. Mun.**	**CCCR**
	mean∆E	4.2	5.1	4.3	5.3
	min∆E	0.7	0.6	0.2	0.8
	max∆E	8.0	11.8	12.1	12.4

	Training	**Sel. Mun.**	**Sel. Mun.**	**CCDC & Sel. Mun.**	**CCDC & Sel. Mun.**
MULTI – PSE	**Test**	**Sel. Mun.**	**CCCR**	**CCDC & Sel. Mun.**	**CCCR**
	mean∆E	3.1	5.3	3.3	5.2
	min∆E	0.2	1.2	0.3	1.2
	max∆E	8.1	16.4	11.4	20.3

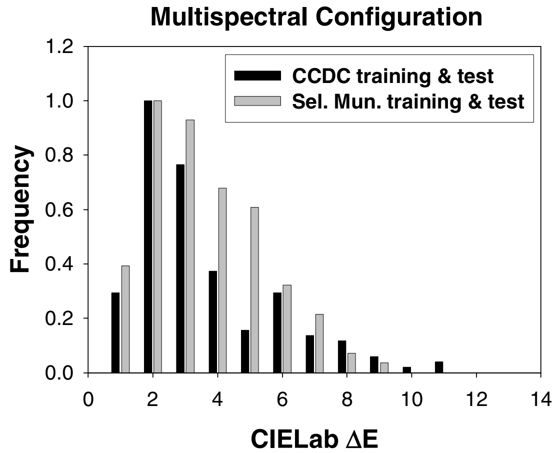
As it can be seen comparing the LAM values in Table 1. obtained using the CCDC chart as training and test, and values in Table 2. obtained using the selected Munsell (Sel. Mun.) instead, for both the colorimetric and multispectral configurations very similar results were obtained. However, taking into account the corresponding distributions of color differences, it could be seen that, on one hand, smaller color differences for a larger number of color patches were obtained using the CCDC chart than using the selected Munsell colors; but, on the other, greater color differences were obtained using the CCDC chart than using the selected Munsell colors (Figure 5.). These results allowed us to consider the selected Munsell colors as a set of colors comparable to the CCDC chart one, in order to be used as a training set of the imaging system.

On the other hand, when the training set was increased from the CCDC chart to it enlarged with the selected Munsell, and the same set was used as training and test set, similar results were obtained (Table 1.(LAM – CCDC) and Table 2. (CCDC & Sel. Mun.)) for both the colorimetric and the multispectral configurations.

Taking into account the corresponding distributions of color differences, it could be seen that the enlargement of the training set implied an increase of the number of color patches with medium color differences, a decrease of the number of color patches with the greatest color differences, and a slight increase of the maximum color difference (Figure 6.). In spite of all of these changes introduced in the distribution of color differences, as it has been said above the mean color difference obtained when the training set is enlarged remained very similar to the one obtained using the CCDC.



(a)

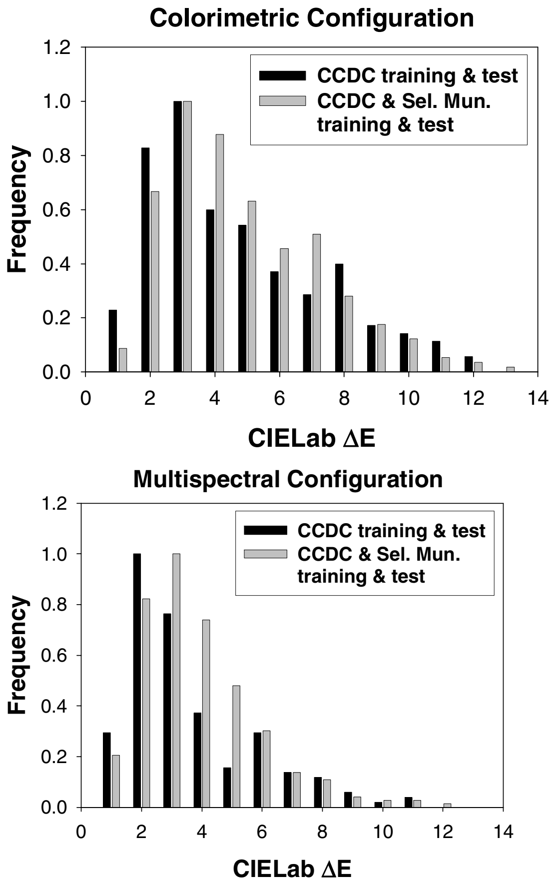


(b)

Figure 5. *Histograms of relative frequencies of color differences corresponding to the distribution of the values obtained using the CCDC chart (black), and the selected Munsell (Sel. Mun.) (grey) as training and test sets, for the colorimetric (a) and the multispectral (b) configurations.*

Therefore, it was possible to increase the color gamut to be measured by the system without a loss of performance for color measurements. These results also indicated that, in spite of the fact that increasing the color gamut of the training set from the CCCR to the CCDC charts implied an improvement in the performance of the color measurements (Table 1.), this improvement seemed to have a limit in the number of colors of the training set, and the color gamut variety in the CCDC chart was wide enough to constitute a good training set of the imaging system.

The results obtained using different training and test sets were slightly worse than those obtained using the same training and test set. On the other hand, similar results were obtained using the CCDC, the selected Munsell, and the CCDC enlarged with the selected Munsell as training set, and the CCCR as test set (LAM values in Table 1.(LAM – CCDC – CCCR) and Table2.(Sel. Muns-CCCR and CCDC& Sel.Mun.-CCCR)), i.e. using different training and test sets, which confirmed that the CCDC chart and the selected Munsell were comparable in order to be used as training set of the system, so it was the CCDC enlarged with the selected Munsell colors.



(a)

(b)

Figure 6. *Histograms of relative frequencies of color differences corresponding to the distribution of the values obtained using the CCDC chart (black), and the CCDC enlarged with the selected Munsell (CCDC & Sel. Mun.) (grey) as training and test sets, for the colorimetric (a) and the multispectral (b) configurations.*

Finally, comparing the results obtained for the colorimetric and for the multispectral configurations, when the same color set was used as training and test set, a slight improvement in the results was observed using the multispectral configuration with respect to the colorimetric one, i.e. increasing the number of acquisition channels from three to seven. When different color sets were used as training and test, similar results were obtained for both configurations, probably due to the fact that the possible improvement introduced by the increase of the number of acquisition channels and, consequently, of information, was compensated by errors introduced in using different training and test sets.

Conclusions

In the present work, we analyze the performance for color measurements of systems based on optoelectronic imaging sensors when a wide color gamut is used. On one hand, a luminance adaptation model (LAM), which allowed all the digital signals to be located within the linear range of the system response, and the dynamic range of the system to be increased as a result, was proposed, tested and applied. On the other hand, the training set of the imaging system, initially composed by the CCDC chart, was increased by means of a number of selected colors of the Munsell Book of Color, which complemented the CCDC's color patches and increased the color gamut of the training set of the system. Two different configurations were used: a colorimetric configuration, with three acquisition channels, and a multispectral configuration with seven acquisition channels.

The LAM proposed consists on the transformation of the useful digital levels measured at a certain exposure time into digital levels at a reference exposure time. In order to perform this transformation, the digital levels obtained using different exposure times were plotted versus the digital values corresponding to a reference exposure time and fitted by a linear regression, for each acquisition channel. We used the CCDC chart to perform these fittings. By this way, a set of regression coefficients that are used to apply the LAM to digital levels measured at this exposure time, was associated to each exposure time. The validity of the LAM proposed was proved obtaining the highly similar results with and without its application, for all the combinations of the CCDC and the CCCR charts as training and test sets considered, and for both the colorimetric and the multispectral configurations.

The performance of these two configurations was analyzed by using a wide color gamut composed by the selected Munsell colors and the CCDC's color patches. The results obtained using either the CCDC chart or the selected Munsell colors as training and test sets, were globally very similar. Consequently, it was possible to consider the selected Munsell colors as a set of colors comparable to the CCDC chart one, in order to be used as a training set of the imaging system.

Similar results were obtained increasing the training set from the CCDC chart to it enlarged with the selected Munsell colors, and using the same set of colors as training and test set, which allowed to conclude that it was possible to increase the color gamut to be measured by the system without a loss of performance. The improvement in performance for color measurements obtained increasing the number of colors of the training set when the CCDC chart was used instead of the CCCR one, seemed to have a limit in the number of colors. Moreover, the variety in color gamut of the CCDC chart was proved to be wide enough to constitute a good training set of the imaging system.

The results obtained using different training and test sets were slightly worse than those obtained using the same training and test set. On the other hand, similar results were obtained using the CCDC, the selected Munsell, and the CCDC enlarged with the selected Munsell as training set, and the CCCR as test set, which confirmed that the CCDC chart and the selected Munsell were comparable in order to be used as training set of the system, so it was the CCDC enlarged with the selected Munsell colors.

Finally, a slight improvement in the results was observed using the multispectral configuration with respect to the colorimetric one when the same set of colors was used as training and test set, and similar results were obtained for both configurations when different color sets were used as training and test, probably due to the compensation of the possible improvement introduced by the increase of the number of acquisition channels by errors introduced in using different training and test sets.

Future work is oriented, on one hand, to determine if an increase in the number of acquisition channels may improve the performance for color measurements of the imaging system; and, on the other hand, to study the evolution of the improvement in performance for color measurements with the number of colors in the training set of the system, and to test if performing color measurements separately for different color gamuts, increasing progressively the number of training color patches per color gamut, may improve the performance for color measurements of the imaging system for both configurations used.

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Author Biography

J. Pujol received his BS in Physics from the Autonomous University of Barcelona (Spain) in 1981 and a Ph.D. in Physics from the same University in 1990. Since 1984 he teaches Vision Sciences and Colour at School of Optics & Optometry in the Technical University of Catalonia. His work is primarily focused on Color Imaging (device calibration and characterization, color management), Industrial Colorimetry and Physiological Optics (eye optics quality). He is president of the Color Committee of SEDO from 2003, and a member of IS&T, JOSA, ARVO, EOS and SEDO (Spanish Optics Society). He has been the head of Optics and Optometry Department of the Technical University of Catalonia from 1994 since 2000, and nowadays is the head of the Center for Sensors, Instruments and Systems Development (CD6) of the Technical University of Catalonia since 1997.

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