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Influence of the Number of Samples of the Training Set on Accuracy of Color Measurement and Spectral Reconstruction

Marta de Lasarte, Montserrat Arjona, Meritxell Vilaseca and Jaume Pujol
Centre for Sensors, Instruments, and Systems Development (CD6), Universitat Politècnica de Catalunya (UPC), Rambla Sant Nebridi 10, Terrassa, Barcelona 08222, Spain
E-mail: mvilasec@oo.upc.edu

Abstract. *In this article the authors analyze the influence of the number of samples in a training set on the accuracy of color and spectral measurements made using a colorimetric and multispectral imaging system. The authors develop a method for establishing the minimum and/or sufficient number of color samples in the training set above which the system's performance is independent of the number of samples. The authors also consider the dependence of the system's performance on the training set itself. Two setups of a charge coupled device camera-based imaging system are used for this purpose: a colorimetric configuration with three acquisition channels and a multispectral configuration with seven acquisition channels. On the basis of the criterion established in this article, the results show that the system's performance in terms of the accuracy of color measurement and spectral reconstruction seems to be independent of the training set used when over 110 samples are used for the colorimetric configuration and over 120 samples for the multispectral configuration. This result is true for both the number of samples in the training set and the training set itself. The method that the authors developed can be generalized and implemented in the industry for any application in which an imaging capture device is used for color and spectral measurements. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

In recent years, industry has widely used commercially available standard digital imaging systems for color measurement. The popularity of these systems is mainly due to their low cost and size, which means that they can be embedded in production lines. If an imaging system is to be used as a device for measuring color, its spectral sensitivities should be similar—or linearly related—to the color matching functions of the CIE standard observer. However, this is often not the case with conventional RGB color cameras, which are normally designed to achieve a good color appearance rather than high fidelity color reproduction. The results provided by standard imaging systems are therefore not as good as those obtained with specific colorimetric instruments or cameras with optimized spectral sensitivities.[1] However, they can still be useful for industrial processes that require less color accuracy, such as in the automobile accessories industry and in the production of large format televisions and printers. Moreover, multispectral imaging systems with more than three acquisition channels can be used to overcome some of the limitations of conventional color systems, thus allowing more accurate color measurements or even spectral reconstructions.[2] For this reason, it is of great importance to characterize any imaging system colorimetrically or even spectrally.

The colorimetric characterization of an imaging system is the process of deriving the transformation that defines the correspondence between the camera's digital responses and a color space that is independent of the device, which may be either *XYZ* or CIELAB. This process is essential to achieve high fidelity color measurements. An initial approach for this purpose is to use methods of colorimetric characterization based on spectral sensitivities,[3] which require the previous measurement of the system's spectral sensitivities. The relationship between the camera's spectral sensitivities and the CIE color matching functions must then be found so that it can be used to transform the system's digital responses into *XYZ* values. These methods are usually only applied to colorimetric configurations of imaging systems, i.e., ones with three acquisition channels, due to the growing complexity when the number of acquisition channels is increased. Furthermore, although all the steps in this method are very clear conceptually, their application involves several fittings of experimental data, which leads to a considerable amount of errors that can easily be accumulated in the estimations of the *XYZ* values, particularly if the system's spectral sensitivities are not the most suitable.

However, another approach can be used to transform a conventional imaging system into an instrument for color measurement or spectral reconstruction. It involves methods that establish a direct relationship between the digital levels of the response of the imaging system and the corresponding tristimulus values or, equivalently, the reflectance spectra.[4] These methods are faster and generally require a set of color samples called the training set to train and characterize the imaging system. In addition, they need another set of color samples, called the test set, to test the system's characterization and evaluate the accuracy of the subsequent estimation. The validity of this alternative colorimetric characterization

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is based on the fact that many industrial applications only require color measurements or spectral reconstructions of certain color patterns, which usually have a rather limited color gamut. Therefore, if we use a properly selected training set that includes representative color samples similar to those that will be later measured, this type of colorimetric calibration can provide good enough results.

In such cases, both the training and the test sets can be made up by physical color charts or sets of color samples that are specially selected or manufactured. There are no universal training and test sets to characterize an imaging system, although the GretagMacbeth ColorChecker DC Chart (CCDC),[5–8] and the GretagMacbeth ColorChecker Color Rendition Chart (CCCR),[6,9,10] the IT8 chart,[8,11] the color samples of the Munsell Book of Color,[12,13] and the color samples of the Natural Color System (NCS)[14] are widely used. However, in many cases the training and test sets are selected depending on the application of the imaging system: for example, the color samples may be made from pigments used in painting for restoration and preservation applications[5,6,15,16] or from natural objects.[5,6,12,14,17,18]

There are several methods and criteria for selecting the color samples that constitute the training and test sets of an imaging system. The aim is to generate a set of color samples that are as diverse as possible so that the maximum number of systems can be characterized with the minimum number of color samples.[2,4,14,19,20] The number of samples that are needed in the training set to meet this objective depends on the specific selection method used. However, the dependence of the system's accuracy on the number of samples in the training set, regardless of the selection method, has not been thoroughly considered to date.

If we assume that the diversity of the color samples in the training set is assured for all sizes, we can assume that the greater the number of samples, the more accurate both the color measurement and the spectral reconstruction. However, it can be assumed that the increase in accuracy is not unlimited and that there must be a minimum and/or "sufficient number of samples" above which improvements in accuracy are negligible or nil when the number of samples is increased.

Regarding the influence of the number of color samples in the training set on the accuracy of the estimation made by the imaging system, previous studies have shown that, for a trichromatic camera, the accuracy of the colorimetric estimation (CIE *XYZ* tristimulus values) rose as the number of color samples in the training set increased up to approximately 60 samples. There was no noticeable improvement in training sets with over 60 samples. It appears that a training set with between 40 and 60 color samples is needed to obtain an estimate with reasonable accuracy.[11,21] Hence, it can be established that there is a kind of "limit" in accuracy improvements brought about by increasing the number of color samples in the training set.[11,14,21] The mean error in color measurements made by spectral reconstruction using training sets with a greater number of samples is practically independent of the size of the training set of the imaging system.[14,21]

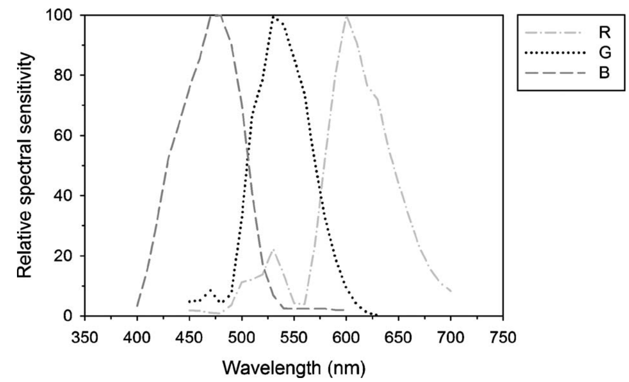


Figure 1. Relative spectral sensitivities of the channels used in the colorimetric configuration of the imaging system (RGB tunable filter and CCD camera).

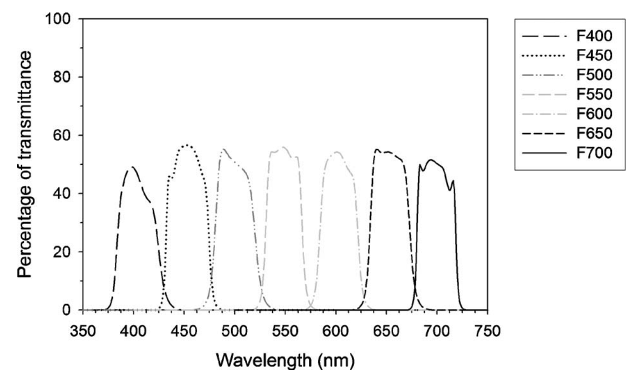


Figure 2. Transmittance spectra of the interference filters used in the multispectral configuration of the imaging system. Interference filters are named by their central wavelength.

In this article, we analyze the influence of the number of samples in the training set on the system's accuracy in color measurement and spectral reconstruction. We consider the dependence of the system's performance on the size of the training set and on the training set itself. Hence, we develop a method for establishing the minimum and/or sufficient number of color samples in the training set above which the system's performance is independent of the number of samples. Two configurations of a charge coupled device (CCD) camera-based imaging system are used for this purpose: a colorimetric configuration with three acquisition channels and a multispectral configuration with seven acquisition channels.[22] This article is considered to be the first step in the process of analyzing a system's accuracy in color measurement and spectral reconstruction since it allows us to define the training set used in any colorimetric or multispectral imaging system, taking into account the accuracy needed for the specific application.

The paper is structured as follows. The next section describes the experimental setup and the configurations of the imaging system, the methods used to perform the color

Table I. Correspondence between the values of the *inca* and *incb* variables used in the selection criterion and the number of color samples selected from the CCDC chart.

inca = *incb*	No. of color samples	*inca* = *incb*	No. of color samples
17.00	10	2.15	100
9.20	20	1.69	110
6.98	30	1.45	120
5.35	40	1.22	130
4.50	50	0.80	140
4.00	60	0.58	150
3.12	70	0.20	160
2.68	80	0.05	166
2.36	90		

measurement and spectral reconstruction, and the selection criterion applied to obtain a training set that has the greatest possible variety of samples in terms of color ranges. The results section presents a summary of the results obtained for the colorimetric and multispectral configurations of the CCD camera-based imaging system. Finally, the most relevant conclusions are discussed in the last section.

MATERIAL AND METHOD

Experimental Setup and Configurations

We used an imaging system based on a QImaging QICAM Fast 1394 monochrome 12-bit cooled CCD camera and a Nikon AF Nikkor 28–105 mm objective lens. Two configurations of this imaging system are considered: a colorimetric configuration with three acquisition channels and a multispectral configuration with seven acquisition channels.[22]

The colorimetric configuration is obtained by inserting between the CCD camera and the objective lens a QImaging RGB-HM-NS tunable filter, which is controlled through the camera via software (Figure 1).

The multispectral configuration is obtained by inserting between the CCD camera and the objective lens a motorized filter wheel with seven CVI laser interference filters covering the whole visible range of the spectrum and controlled via software. The interference filters used have peak positions or central wavelengths (CWLs) at 400, 450, 500, 550, 600, 650, and 700 nm. All of them have full widths at half maximums (FWHMs) of 40 nm, and their peak transmittances are 35%, 45%, and 50%, depending on the CWL (Figure 2).

The training sets considered in this study are made up of a previous selection of color samples from the widely used GretagMacbeth ColorChecker DC Chart (CCDC, 166 useful color samples). The GretagMacbeth ColorChecker Color Rendition Chart (CCCR, 24 color samples) is used as the test set. These color charts are placed in a special light booth. Incandescent lamps provide a uniform illumination field over the charts when they are placed at the bottom of the booth. The color samples are imaged using the two configurations of the imaging system, and their reflectance spectra are also measured using a tele-spectracolorimeter PhotoResearch PR650 with an MS-75 objective lens.

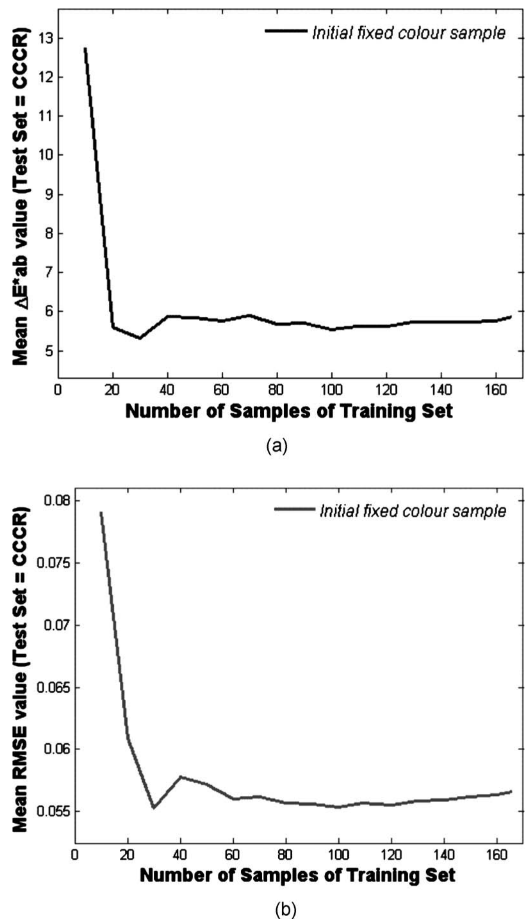


Figure 3. Colorimetric configuration: (a) mean CIELAB color difference and (b) mean RMSE values plotted vs the number of color samples in the training set (initial fixed color sample).

Methods and Selection Criterion

The following methods are used for the color measurement and spectral reconstruction from the system's digital responses: the pseudoinverse (PSE) method[2,6,23–25] for the colorimetric configuration; and the principal component analysis (PCA) method[1,2,6,25,26] for the multispectral configuration.

In the PSE method, a transformation matrix directly relates the reflectance spectra of the color samples to the corresponding digital responses of the imaging system. Using a training set of N color samples with known reflectance spectra, the transformation matrix (D_{PSE}) is determined by applying the Moore-Penrose pseudoinverse matrix as follows:

$$R_{(41\times N)} = D_{PSE(41\times k)} \cdot P(k)_{(k\times N)}, \tag{1}$$

$$D_{PSE} = R \cdot P(k)^t \cdot [P(k) \cdot P(k)^t]^{-1}, \tag{2}$$

where R is the $41\times N$ matrix of reflectance spectra for the N color samples in the training set in which the reflectance spectrum is sampled from 380 to 780 nm in intervals of 10 nm, and $P(k)$ is the $k\times N$ matrix of the digital responses of the k acquisition channels of the imaging system for the N color samples in the training set.

Table II. Colorimetric configuration: mean, minimum, maximum, and standard deviation of the CIELAB color difference and the RMSE values obtained using different sized training sets (initial fixed color sample) from the CCDC chart. The CCCR chart was used as the test set.

No. of color samples	Mean ΔE^*_{ab}	min ΔE^*_{ab}	max ΔE^*_{ab}	Std. dev ΔE^*_{ab}	Mean RMSE	Min RMSE	Max RMSE	Std. dev RMSE
10	12.751	2.179	90.215	19.211	7.905×10^{-2}	2.918×10^{-2}	1.989×10^{-1}	4.352×10^{-2}
20	5.606	0.295	12.216	3.278	6.086×10^{-2}	2.647×10^{-2}	1.671×10^{-1}	3.201×10^{-2}
30	5.317	1.777	13.503	3.356	5.524×10^{-2}	3.307×10^{-2}	1.688×10^{-1}	2.802×10^{-2}
40	5.885	2.577	14.097	3.358	5.779×10^{-2}	3.405×10^{-2}	1.746×10^{-1}	3.053×10^{-2}
50	5.852	1.941	14.118	3.511	5.717×10^{-2}	2.923×10^{-2}	1.742×10^{-1}	3.055×10^{-2}
60	5.763	2.198	14.110	3.460	5.607×10^{-2}	2.762×10^{-2}	1.735×10^{-1}	3.030×10^{-2}
70	5.903	2.256	14.148	3.426	5.616×10^{-2}	3.075×10^{-2}	1.732×10^{-1}	2.989×10^{-2}
80	5.681	2.323	13.967	3.431	5.569×10^{-2}	2.983×10^{-2}	1.720×10^{-1}	2.950×10^{-2}
90	5.710	2.291	13.891	3.411	5.561×10^{-2}	3.035×10^{-2}	1.711×10^{-1}	2.898×10^{-2}
100	5.537	2.089	13.719	3.393	5.534×10^{-2}	3.082×10^{-2}	1.717×10^{-1}	2.929×10^{-2}
110	5.628	2.225	13.794	3.333	5.569×10^{-2}	3.213×10^{-2}	1.706×10^{-1}	2.872×10^{-2}
120	5.625	2.265	13.837	3.368	5.556×10^{-2}	2.987×10^{-2}	1.715×10^{-1}	2.933×10^{-2}
130	5.735	2.312	13.977	3.415	5.586×10^{-2}	2.967×10^{-2}	1.716×10^{-1}	2.945×10^{-2}
140	5.726	2.255	13.858	3.409	5.597×10^{-2}	3.046×10^{-2}	1.710×10^{-1}	2.911×10^{-2}
150	5.749	2.218	13.879	3.404	5.622×10^{-2}	3.152×10^{-2}	1.716×10^{-1}	2.928×10^{-2}
160	5.777	2.219	13.905	3.410	5.633×10^{-2}	3.118×10^{-2}	1.723×10^{-1}	2.963×10^{-2}
166	5.886	2.241	13.962	3.414	5.658×10^{-2}	3.215×10^{-2}	1.728×10^{-1}	2.972×10^{-2}

This transformation matrix allows the reflectance spectrum of any color sample to be estimated from its digital responses provided that the training set is a good representation of all the color samples that will be measured with the imaging system.

In the PCA method, a previous principal component analysis is applied to the matrix of reflectance spectra for the color samples in the training set to obtain the eigenvector basis and the coefficients of the reflectance spectra on this basis:

$$R_{(41\times N)} = V_{(41\times p)} \cdot C_{(p\times N)}, \tag{3}$$

where V is the $41\times p$ matrix for the p first eigenvectors, and C is the $p\times N$ matrix of scalar coefficients of the reflectance spectra for the N color samples in the training set on the eigenvector basis V.

The scalar coefficients of the reflectance spectra of the N color samples in the training set are related to the digital responses of the imaging system by means of a transformation matrix (D_{PCA}) that is determined by applying the Moore-Penrose pseudoinverse matrix:

$$C_{(p\times N)} = D_{PCA(p\times k)} \cdot P(k)_{(k\times N)}, \tag{4}$$

$$D_{PCA} = C \cdot P(k)^t \cdot [P(k) \cdot P(k)^t]^{-1}. \tag{5}$$

This transformation matrix allows the coefficients of any color sample to be calculated on the eigenvector basis from the digital responses of the imaging system. The linear combination of the eigenvectors with the calculated coefficients provides an estimation of the reflectance spectrum of the color sample. From the spectral reflectances estimated using the PSE and PCA methods, the CIELAB coordinates of each color sample can be easily computed.

The selection criterion applied in this article to obtain a training set with the greatest variety of samples possible, in terms of color ranges, for each number of samples considered is based on differences in the a^* (Δa^*) and b^* (Δb^*) CIELAB coordinates between each pair of color samples in the final selected set. Each pair of selected samples must fulfill:

$$\Delta a^* \geq inca \quad \text{and} \quad \Delta b^* \geq incb \tag{6}$$

where the values for the $inca$ and $incb$ variables are chosen so that $inca = incb$ for simplicity, and allow us to establish the number of color samples to be selected.

The two configurations of the imaging system are trained using training sets of sizes between 10 and 166 color samples in steps of ten samples (Table I), and their performance is tested using the 24 color samples from the CCCR chart. The accuracy of the color measurement is evaluated in terms of the mean, minimum, maximum, and standard deviation of the CIELAB color difference between the estimated and the measured tristimulus values of the CCCR color samples. The accuracy of the spectral reconstruction is evaluated in terms of the mean, minimum, maximum, and standard deviation of the root mean square error (RMSE)

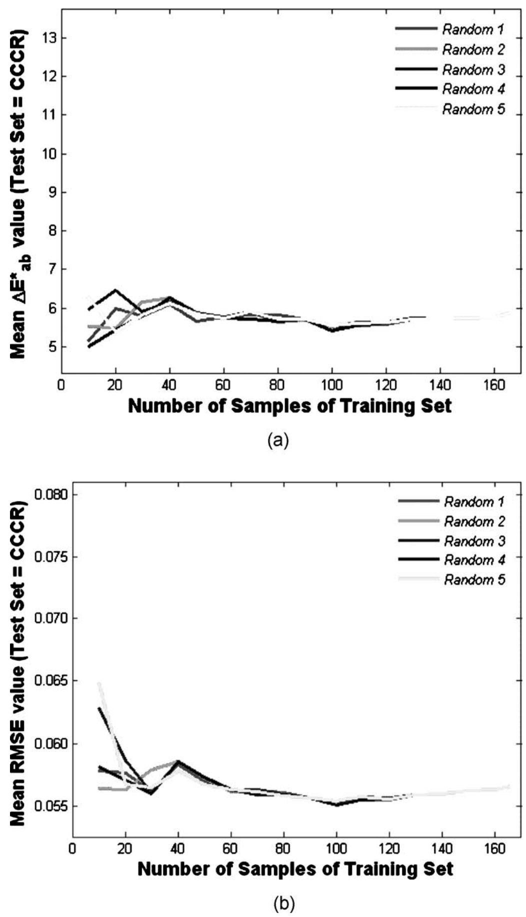


Figure 4. Colorimetric configuration: (a) mean CIELAB color difference and (b) mean RMSE values plotted versus the number of color samples in the training set for the five initial randomly selected color samples and the resulting training sets.

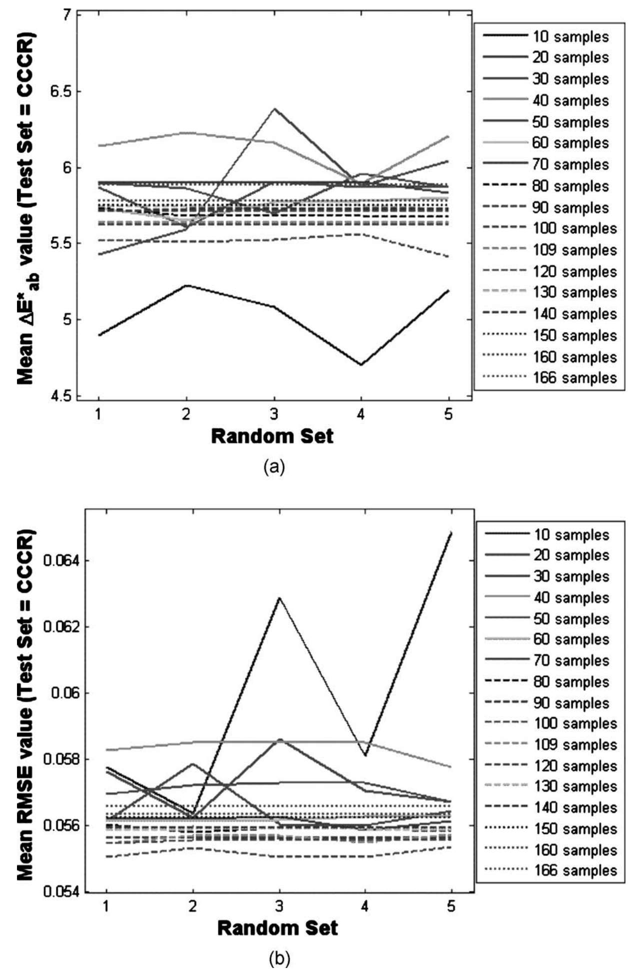


Figure 5. Colorimetric configuration: (a) mean CIELAB color difference values and (b) mean RMSE values obtained using the five training sets generated from an initial randomly selected CCDC color sample, for all sizes of the training set considered. CCCR color samples were used as the test set.

between the reconstructed and the measured reflectance spectra of the CCCR color samples.

We carry out two analyses of the training set selection process. In the first analysis, the first useful non-neutral color sample from the CCDC chart (color sample B2) is used as the initial fixed color sample. Starting from this sample, training sets of different sizes are selected from the CCDC color samples by applying the selection criterion row by row. That is, the first pair of color samples to be compared is B2 and C2. If they fulfill $\Delta a^* \geq inca$ and $\Delta b^* \geq incb$, C2 is incorporated into the training set and compared with the next available patch, in this case, D2. If the color samples do not meet the imposed condition, sample C2 is rejected and B2 is again compared with the next available patch (D2). This process continues until the necessary number of color samples is reached for each size of the training set. Therefore, the selection of the patches depends strongly on the initial fixed color sample. With this first analysis, the results will show that the performance of the imaging system depends on the size of the training set but not on the training set itself, since the training sets that are selected will be specific to the initial fixed color sample and mainly of lower sizes. To overcome this limitation and analyze the dependence of the system's performance on different sized training sets, a second analysis is performed. In this second analysis, an initial color sample is selected randomly from the CCDC chart (initial randomly selected color sample). Then, the rest of the color samples are selected by applying the former selection criterion to this starting point for all sizes considered. The process is repeated five times to provide five random training sets for each size, which consist of very different subsets of the CCDC color samples. The comparison of results obtained using these training sets enables us to analyze the influence of the training set on the system's performance depending on its size.

RESULTS

Next, we present the results of the two analyses performed for the colorimetric and the multispectral configurations of the CCD camera-based imaging system.

Colorimetric Configuration

Analysis I: Initial Fixed Color Sample

As expressed earlier, the first useful CCDC color sample (the B2 color sample) is used in this analysis as the initial fixed color sample. Starting from this point, the rest of the color

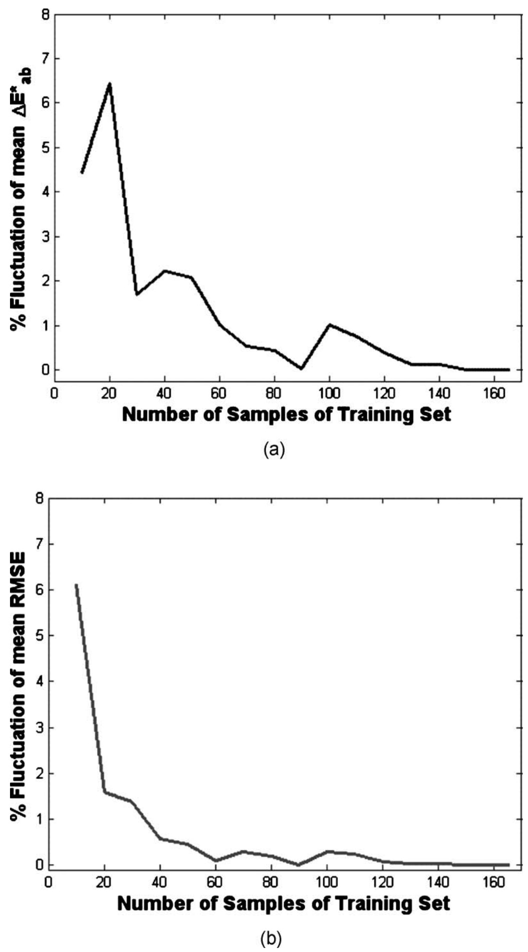


Figure 6. Colorimetric configuration: percentage of fluctuation of (a) the mean CIELAB color difference values, and (b) the mean RMSE values between results obtained using the five random training sets, depending on the number of samples in the training set. The CCCR chart was used as the test set.

samples in the training sets, for all sizes considered, are selected row by row from the color samples of the CCDC chart by applying the selection criterion.

The results obtained in this analysis indicate the tendency of the system's performance depending on the number of samples in the training set, assuming that the behavior of the system's performance is similar when we consider training sets of different sizes selected from a different initial color sample. The validity of this assumption and the influence of the training set on the system's performance are studied in analysis II.

There is a limit to the improvement in the accuracy of color measurement and spectral reconstruction when the number of color samples in the training set is increased (Figure 3, Table II). Improvement appears to be negligible when there are more than about 60 color samples in the training set. This is consistent with previous studies.[11,14,21]

These results prove that there are a relatively low minimum and/or sufficient number of color samples for the training set of the imaging system. After this point, increases in the number of samples in the training set do not lead to noticeable improvements in the system's performance.

Table III. Colorimetric configuration: mean, minimum, maximum, and standard deviation of the CIELAB color difference and the RMSE values obtained using the five random training sets from the CCDC chart, with 110 samples. The CCCR chart was used as the test set. The corresponding percentages of fluctuation are also given.

	Mean ΔE^*_{ab}	min ΔE^*_{ab}	max ΔE^*_{ab}	Std. dev ΔE^*_{ab}
Random 1	5.535	2.201	13.737	3.322
Random 2	5.628	2.210	13.794	3.333
Random 3	5.616	2.169	13.765	3.325
Random 4	5.552	2.165	13.747	3.325
Random 5	5.613	2.168	13.752	3.332
Mean	5.589	2.183	13.759	3.327
Std. dev	0.043	0.021	0.022	0.005
%fluctuation	0.761	0.971	0.159	0.145
	Mean RMSE	Min RMSE	Max RMSE	Std.dev RMSE
Random 1	5.545×10^{-2}	3.240×10^{-2}	1.705×10^{-1}	2.885×10^{-2}
Random 2	5.569×10^{-2}	3.273×10^{-2}	1.706×10^{-1}	2.872×10^{-2}
Random 3	5.571×10^{-2}	3.284×10^{-2}	1.706×10^{-1}	2.870×10^{-2}
Random 4	5.550×10^{-2}	3.234×10^{-2}	1.705×10^{-1}	2.882×10^{-2}
Random 5	5.574×10^{-2}	3.313×10^{-2}	1.707×10^{-1}	2.871×10^{-2}
Mean	5.562×10^{-2}	3.269×10^{-2}	1.706×10^{-1}	2.876×10^{-2}
Std. dev	1.329×10^{-4}	3.257×10^{-4}	8.367×10^{-5}	6.964×10^{-5}
%fluctuation	0.239	0.996	0.049	0.242

Analysis II: Initial Randomly Selected Color Sample

In this second analysis, the initial color sample is randomly selected from the CCDC chart. Starting from this point, the rest of the color samples in the training sets are selected row by row from the CCDC color samples by applying the selection criterion for all sizes considered. Five initial color samples are selected randomly and used to generate the subsequent random training sets for the different sizes considered.

Slightly different accuracies in the system's performance are obtained using the five different random training sets for fewer than about 80 color samples (Figure 4). The system's performance fluctuates when the five different random training sets of the same size are used. This is due to the system's dependence on the training set, which tends to converge for the equally sized five different random training sets when the number of color samples is above 80.

The dependence of the system's performance (accuracy of color measurement and spectral reconstruction) on the training set is clearly seen through a direct comparison of the results obtained using the five different random training sets for the different sizes considered (Figure 5). As can be observed, the smaller the number of samples in the training set, the greater the fluctuations between the CIELAB color difference and the RMSE values obtained using the five random training sets.

It is difficult to determine the exact number of samples in the training set above which the system's performance is

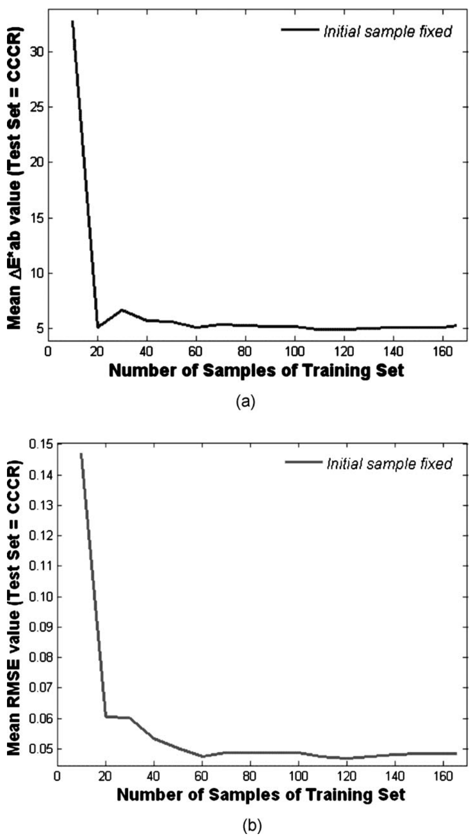


Figure 7. Multispectral configuration: (a) mean CIELAB color difference and (b) mean RMSE values plotted versus the number of color samples in the training set (initial fixed color sample).

independent of the set and of the number of color samples. Consequently, taking into account several parameters calculated from the individual results for each of the five random training sets—specifically the mean, minimum, maximum, and standard deviation of the CIELAB color differences and the RMSE values. Percentages of fluctuation defined as follows have been computed for each size:

$$\%\text{Fluctuation} = 100\frac{\text{std. dev(mean)}}{\text{mean}}. \tag{7}$$

For instance, if the mean CIELAB color difference is analyzed, std. dev is the standard deviation of the mean color difference (mean) of the five random training sets. If the minimum color difference is considered, std. dev. is the standard deviation of the mean minimum color difference (mean) of the five random training sets. The same analysis has been carried out for the maximum color difference and the standard deviation, thus providing four percentages which account for the fluctuation of the system depending on the size of the training set used. The same analysis has been carried out for RMSE values, providing four additional percentages of fluctuation. Therefore, eight percentages of fluctuation are obtained for each size of the training set.

These percentages are used to establish the minimum and/or sufficient number of color samples necessary to properly train any imaging system. Specifically, the criterion used in this paper has been chosen as the minimum number of color samples that provides all eight percentages of fluc-

Table IV. Multispectral configuration: mean, minimum, maximum and standard deviation of the CIELAB color difference and the RMSE values obtained using different sized training sets (initial fixed color sample) from the CCDC chart. The CCCR chart was used as the test set.

No. of color samples	Mean ΔE^*_{ab}	min ΔE^*_{ab}	max ΔE^*_{ab}	Std. dev ΔE^*_{ab}	Mean RMSE	Min RMSE	Max RMSE	Std. dev RMSE
10	32.756	2.704	124.469	34.993	1.469×10^{-1}	1.541×10^{-2}	5.474×10^{-1}	1.379×10^{-1}
20	5.072	1.524	14.669	3.099	6.050×10^{-2}	2.166×10^{-2}	1.616×10^{-1}	3.235×10^{-2}
30	6.712	1.044	31.116	8.048	6.020×10^{-2}	2.396×10^{-2}	1.546×10^{-1}	3.642×10^{-2}
40	5.722	1.662	21.737	4.346	5.335×10^{-2}	2.683×10^{-2}	8.531×10^{-2}	1.708×10^{-2}
50	5.627	1.679	24.508	4.880	5.033×10^{-2}	2.572×10^{-2}	9.066×10^{-2}	1.654×10^{-2}
60	5.135	1.564	21.397	4.177	4.755×10^{-2}	2.269×10^{-2}	7.803×10^{-2}	1.485×10^{-2}
70	5.346	1.682	23.328	4.624	4.870×10^{-2}	2.063×10^{-2}	8.471×10^{-2}	1.642×10^{-2}
80	5.308	1.633	23.437	4.645	4.865×10^{-2}	1.996×10^{-2}	8.691×10^{-2}	1.676×10^{-2}
90	5.218	1.587	22.196	4.353	4.890×10^{-2}	2.099×10^{-2}	8.267×10^{-2}	1.569×10^{-2}
100	5.170	1.620	20.424	3.963	4.870×10^{-2}	2.271×10^{-2}	7.601×10^{-2}	1.475×10^{-2}
110	4.951	1.320	19.858	3.894	4.742×10^{-2}	2.400×10^{-2}	7.233×10^{-2}	1.389×10^{-2}
120	4.924	1.119	19.511	3.802	4.694×10^{-2}	2.371×10^{-2}	7.195×10^{-2}	1.400×10^{-2}
130	5.002	1.131	19.894	3.868	4.749×10^{-2}	2.378×10^{-2}	7.307×10^{-2}	1.382×10^{-2}
140	5.063	1.235	19.868	3.848	4.818×10^{-2}	2.464×10^{-2}	7.431×10^{-2}	1.389×10^{-2}
150	5.107	1.143	20.003	3.871	4.850×10^{-2}	2.429×10^{-2}	7.595×10^{-2}	1.411×10^{-2}
160	5.141	1.379	20.339	3.918	4.851×10^{-2}	2.380×10^{-2}	7.729×10^{-2}	1.443×10^{-2}
166	5.285	1.794	21.005	3.971	4.835×10^{-2}	2.380×10^{-2}	7.873×10^{-2}	1.457×10^{-2}

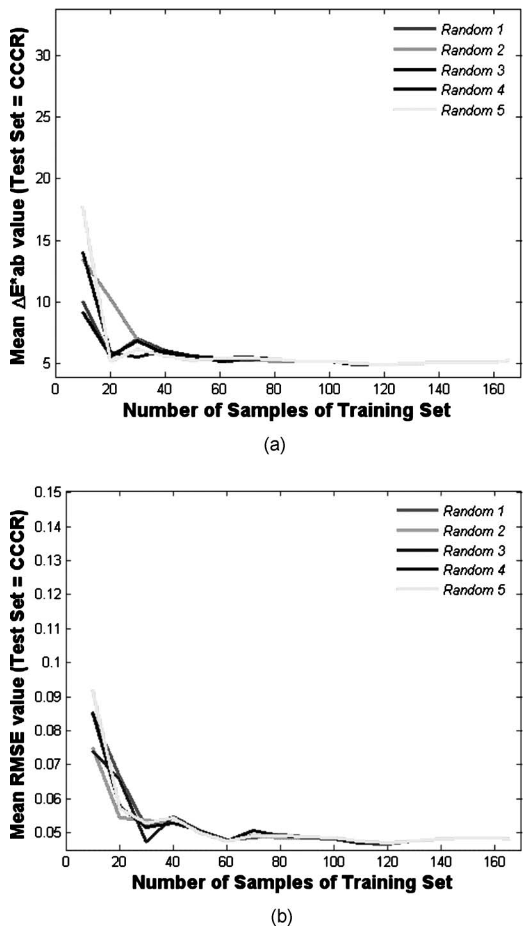


Figure 8. Multispectral configuration: mean (a) CIELAB color difference and (b) RMSE values plotted versus the number of color samples in the training set for the five initial randomly selected color samples and the resulting training sets.

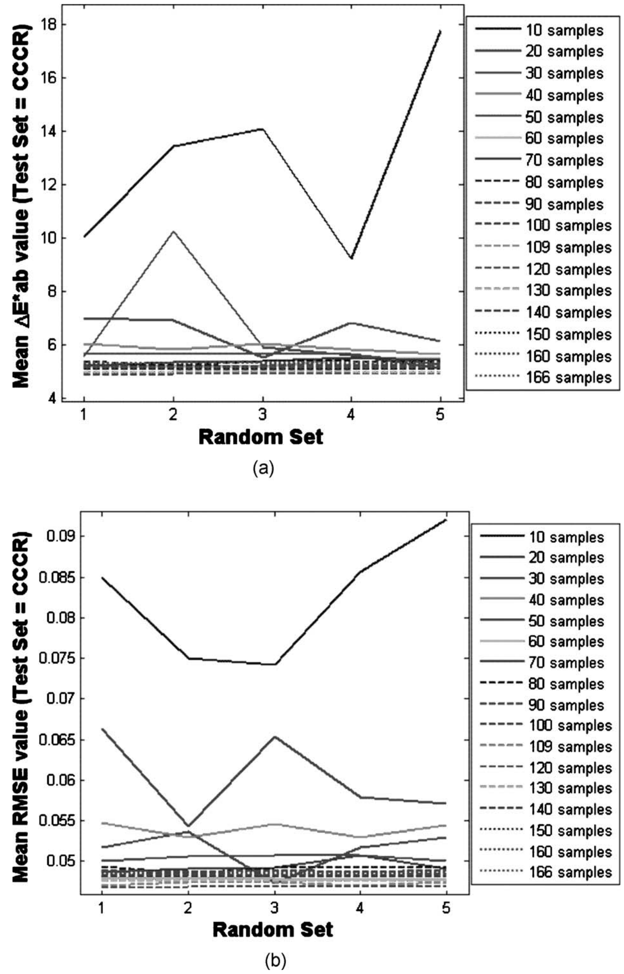


Figure 9. Multispectral configuration: (a) mean CIELAB color difference values and (b) mean RMSE values obtained using the five training sets selected from an initial randomly selected CCDC color sample, for all sizes of the training set considered. The CCCR color samples were used as the test set.

tuation below 1%. However, this criterion can be suitably modified depending on the color and spectral accuracy needed when the imaging system is used for any specific industrial application.

Figure 6 shows the percentages corresponding to the mean CIELAB color difference and the mean RMSE value as a function of the size of the training set for the colorimetric configuration. Taking into account the former criterion, the number of color samples for which the percentage of fluctuation is negligible (i.e., below 1%) can be established as 110 color samples for this configuration. The eight percentages of fluctuation for this size of the training set are given in Table III as well as the mean, minimum, maximum, and standard deviation of the CIELAB color differences and the RMSE values.

Taking all these results into account, we can conclude that the system's performance for the colorimetric configuration seems to be independent of the training set used, in terms of both the number of samples in the training set and the training set itself, when the number of samples is above 110. These results hold in terms of accuracy of both color measurement and spectral reconstruction.

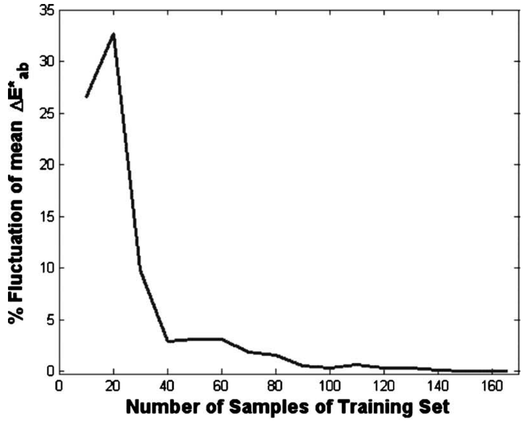
Multispectral Configuration

Analysis I: Initial Fixed Color Sample

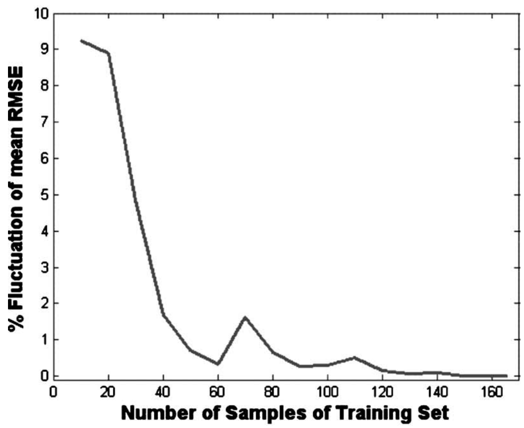
Similarly to the colorimetric configuration, in the multispectral configuration there is a limit to the improvements in the accuracy of color measurement and spectral reconstruction that can be brought about by increasing the number of color samples in the training set. Improvements seem to be negligible when the training set is more than about 60 color samples (Figure 7 and Table IV). This appears to be in agreement with the findings of previous studies.[11,14,21] The results obtained in terms of CIELAB color differences and RMSE values are slightly better in this case than those obtained with the colorimetric configuration. This can be explained by the larger experimental errors involved in the acquisition sequence of the multispectral configuration, in which the filters are mounted in a motorized filter wheel. The RGB tunable filter used in the colorimetric configuration allows faster and easier measurement performance.

Analysis II: Initial Randomly Selected Color Sample

With respect to different random training sets of the same size, the system's performance for the multispectral configu-



(a)



(b)

Figure 10. Multispectral configuration: percentage of fluctuation of the (a) mean CIELAB color difference values, and (b) mean RMSE values among the results obtained using the five random training sets, according to the number of samples in the training set. The CCCR chart was used as the test set.

ration fluctuates depending on the random training set used when the sample sizes are low (Figure 8). However, the performance seems to be similar for the five random training sets that have 80 or more samples.

The dependence of the system's performance (accuracy of color measurement and spectral reconstruction) on the training set is clearly seen through a direct comparison of the results obtained using the five random training sets for the different sizes considered (Figure 9).

Again, we observe that the smaller the number of samples in the training set, the greater the fluctuations between the results obtained using the five random training sets. With respect to the percentages of the CIELAB color differences and RMSE values, the fluctuations in the mean, minimum, maximum, and standard deviation are negligible (below 1%) when the number of samples in the training set is greater than about 120 (Figure 10).

When these results are taken into account, an agreement can be reached in terms of the accuracy of color measurement and spectral reconstruction. With the criterion established, we conclude that the system's performance is independent of the training set used in terms of both the number of samples in the training set and the training set

Table V. Multispectral configuration: mean, minimum, maximum and standard deviation of the CIELAB color difference and the RMSE values obtained using the five random training sets from the CCDC chart, with 120 color samples. The CCCR chart was used as the test set. The corresponding percentages of fluctuation are also given.

	Mean ΔE^*_{ab}	min ΔE^*_{ab}	max ΔE^*_{ab}	Std. dev ΔE^*_{ab}
Random 1	4.888	1.118	19.108	3.717
Random 2	4.929	1.134	19.576	3.815
Random 3	4.922	1.145	19.440	3.785
Random 4	4.925	1.129	19.496	3.794
Random 5	4.925	1.129	19.496	3.794
Mean	4.918	1.131	19.423	3.781
Std. dev	0.017	9.772	0.183	0.037
%fluctuation	0.342	0.864	0.941	0.990
	Mean RMSE	**Min RMSE**	**Max RMSE**	**Std. dev RMSE**
Random 1	4.679×10^{-2}	2.383×10^{-2}	7.254×10^{-2}	1.401×10^{-2}
Random 2	4.692×10^{-2}	2.363×10^{-2}	7.215×10^{-2}	1.407×10^{-2}
Random 3	4.693×10^{-2}	2.375×10^{-2}	7.213×10^{-2}	1.400×10^{-2}
Random 4	4.695×10^{-2}	2.378×10^{-2}	7.224×10^{-2}	1.402×10^{-2}
Random 5	4.695×10^{-2}	2.378×10^{-2}	7.224×10^{-2}	1.402×10^{-2}
Mean	4.691×10^{-2}	2.375×10^{-2}	7.226×10^{-2}	1.402×10^{-2}
Std. dev.	6.723×10^{-5}	7.503×10^{-5}	1.645×10^{-4}	2.702×10^{-5}
%fluctuation	0.143	0.316	0.228	0.193

itself, when the number of samples is more than about 120. The eight percentages of fluctuation for this size of training set are given in Table V as well as the mean, minimum, maximum and standard deviation of the CIELAB color differences and the RMSE values.

CONCLUSIONS

In this article, we have analyzed the influence of the number of samples in the training set on the accuracy of the color measurement and spectral reconstruction. We have considered the imaging system's performance depending on the size of the training set and on the specific training set for each size. A method based on the calculation of percentages of fluctuation according to the training set has been developed to establish the minimum and/or sufficient number of color samples in the training set above which the system's performance is independent of the number of samples. This increases the robustness of the colorimetric and spectral characterizations that are often used in the industry, which are based on establishing a direct relationship between the digital levels of the response of the imaging system and the corresponding tristimulus values or, equivalently, the reflectance spectra.

Two configurations of a CCD camera-based imaging system have been used for this purpose: a colorimetric configuration with three acquisition channels and a multispectral configuration with seven acquisition channels. The results suggest that the system's performance seems to be independent of the training set, in terms of both the number of samples in the training set and the training set itself, when there are over 110 samples for the colorimetric configuration and over 120 samples for the multispectral configuration. This result is true when percentages of fluctuation below 1% are considered. The results hold in terms of accuracy of color measurement and spectral reconstruction and can be considered as the minimum and/or sufficient number of color samples in the training set for the two configurations of the imaging system. However, depending on the level of accuracy of color and spectral assessments that is required of the imaging system, the chosen criterion can be suitably modified to obtain the size of the training set that is needed for a specific industrial application. Furthermore, the methodology can also be used for suitable color samples other than those included in this article, depending on the industrial process under consideration.

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REFERENCES

[1] F. H. Imai and R. S. Berns, "Comparative analysis of spectral reflectance reconstruction in various spaces using a trichromatic camera system", J. Imaging Sci. Technol. **44**, 280 (2000).

[2] J. Y. Harderberg, "Acquisition and reproduction of color images: colorimetric and multispectral approaches", Ph.D. thesis, École Nationale Supérieur des Télécommunications, 1999.

[3] F. Martínez-Verdú, J. Pujol, and P. Capilla, "Calculation of the color matching functions of digital cameras from their complete spectral sensitivities", J. Imaging Sci. Technol. **46**, 15–25 (2002).

[4] J. Y. Harderberg, H. Brettel, and F. Schmitt, "Spectral characterisation of electronic cameras", Proc. SPIE **3409**, 100 (1998).

[5] F. H. Imai, S. Quan, M. R. Rosen, and R. S. Berns, "Digital camera filter design for colorimetric and spectral accuracy", *Proceeding of the Third International Conference on Multispectral Color Science*, edited by M. Hauta-Kasari, J. Hiltunen, and J. Vanhanen (University of Joensuu, Joensuu, Finland, 2001) pp. 13–16.

[6] F. H. Imai, L. A. Taplin, and E. A. Day, "Comparison of the accuracy of various transformations from multiband images to reflectance spectra", Munsell Color Science Laboratory Technical Report (RIT, Rochester, NY, 2002), https://ritdml.rit.edu/dspace/bitstream/1850/4356/1/LTaplinTechReport2002.pdf

[7] V. Cheung, S. Westland, C. Li, J. Harderberg, and D. Connah, "Characterization of trichromatic color cameras by using a new multispectral imaging technique", J. Opt. Soc. Am. A Opt. Image Sci. Vis **22**, 1231 (2005).

[8] E. P. M. Smoyer, L. A. Taplin, and R. S. Berns, "Experimental evaluation of museum case study digital camera systems", Munsell Color Science Laboratory Technical Report (RIT, Rochester, NY, 2005), http://www.art-si.org/PDFs/Metric/Archive05_smoyer.pdf

[9] P. D. Burns and R. S. Berns, "Analysis multispectral image capture", *Proc. IS&T/SID Fourth Color Imaging Conference* (IS&T, Springfield, VA, 1996) pp. 19–22.

[10] F. H. Imai, "Preliminary experiment for spectral reflectance estimation of human iris using a digital camera", Munsell Color Science Laboratory Technical Report (RIT, Rochester, NY, 2002), http://www.cis.rit.edu/mcsl/research/PDFs/IrisImaging.pdf

[11] G. Hong, M. R. Luo, and P. A. Rhodes, "A study of digital camera colorimetric characterization based on polynomial modelling", Color Res. Appl. **26**, 76 (2001).

[12] W. Wu, J. P. Allebach, and M. Analoui, "Imaging colorimetry using a digital camera", J. Imaging Sci. Technol. **44**, 267 (2000).

[13] M. de Lasarte, J. Pujol, M. Arjona, and M. Vilaseca, "Influence of color ranges on color measurements performed with a colorimetric and a multispectral imaging system", *Proc. IS&T Fourth European Conference on Color in Graphics, Imaging, and Vision* (IS&T, Springfield, VA, 2008) pp. 444–449.

[14] T. L. V. Cheung and S. Westland, "Color selections for characterization charts", *Proc. IS&T Second European Conference on Color in Graphics, Imaging and Vision* (IS&T, Springfield, VA, 2004) pp. 116–119.

[15] F. H. Imai, M. R. Rosen, and R. S. Berns, "Comparison of spectrally narrow-band capture versus wide-band with a priori sample analysis for spectral reflectance estimation", *Proc. IS&T/SID Eight Color Imaging Conference* (IS&T, Springfield, VA, 2000) pp. 234–241.

[16] F. H. Imai, L. A. Taplin, and E. A. Day, "Comparative study of spectral reflectance estimation based on broad-band imaging systems", Munsell Color Science Laboratory Technical Report (RIT, Rochester, NY, 2003), http://www.art-si.org/PDFs/Acquisition/ReportBrdBnd_April_2003.pdf

[17] M. Vilaseca, J. Pujol, M. Arjona, and M. de Lasarte, "Multispectral system for the reflectance reconstruction in the near-infrared region", Appl. Opt. **45**, 4241 (2006).

[18] J. Pladellorens, A. Pintó, J. Segura, C. Cadevall, J. Antó, J. Pujol, M. Vilaseca, and J. Coll, "A device for the color measurement and detection of spots on the skin", Skin Res. Technol. **14**, 65 (2008).

[19] P. Pellegri, G. Novati, and R. Schettini, "Training Set Selection for Multispectral Imaging Systems Characterization", J. Imaging Sci. Technol. **48**, 203 (2004).

[20] M. A. López-Álvarez, J. Hernández-Andrés, and J. Romero, "Developing an optimum computer-designed multispectral system comprising a monochrome CCD camera and a liquid-crystal tunable filter", Appl. Opt. **47**, 4381 (2008).

[21] M. de Lasarte, J. Pujol, M. Arjona, and M. Vilaseca, "Influence of the size of the training set on color measurements performed using a multispectral imaging system", *Proc. IS&T Fourth European Conference on Color in Graphics, Imaging and Vision* (IS&T, Springfield, VA, 2008) pp. 437–440.

[22] M. Vilaseca, R. Mercadal, J. Pujol, M. Arjona, M. de Lasarte, R. Huertas, M. Melgosa, and F. H. Imai, "Characterization of the human iris spectral reflectance with a multispectral imaging system", Appl. Opt. **47**, 5622 (2008).

[23] A. Ribés, F. Schmitt, and H. Brettel, "Reconstructing spectral reflectances of oil pigments with neural networks", *Proc. Third International Conference on Multispectral Color Science*, edited by M. Hauta-Kasari, J. Hiltunen, and J. Vanhanen (University of Joensuu, Joensuu, Finland, 2001) pp. 9–12.

[24] Y. Zhao, L. A. Taplin, M. Nezamabadi, and R. S. Berns, "Methods of spectral reflectance reconstruction for a Sinarback 54 digital camera", Munsell Color Science Laboratory Technical Report (RIT, Rochester, NY, 2004), http://www.art-si.org/PDFs/Acquisition/Sinar_Spectral_Est_2004.pdf

[25] M. de Lasarte, M. Vilaseca, J. Pujol, and M. Arjona, "Color measurements with colorimetric and multispectral imaging systems", Proc. SPIE **6062**, 0F1 (2006).

[26] J. Y. Hardeberg, F. Schmitt, and H. Brettel, "Multispectral color image capture using a liquid crystal tunable filter", Opt. Eng. **41**, 2532 (2002).