CIE-XYZ fitting by multispectral images and mean square error minimization with a linear interpolation function

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We present a proposal to achieve accurate color reproduction by fitting the CIE-XYZ tristimulus values of a given color stimulus, and using the 16-band multispectral images, as well as the CIE-XYZ tristimulus values of a known color test chart. We propose a simple linear combination of the multispectral images as interpolation function, which is equivalent to fitting the data to a straight line in a 16-dimentional space. By using this interpolation function, we minimize the merit function of the mean error between the measured and estimated CIE-XYZ tristimulus values of the color test chart. We show, by making a visual comparison between the results achieved using this proposal and the results achieved using a spectral reflectance estimation technique, that the proposed interpolation function when using 16-channel multispectral images produces high quality results in terms of color reproduction fidelity.

Keywords: Multispectral images; CIE-XYZ tristimulus values fitting; interpolation function; mean square error minimization; ΔE_{ab} color difference.

Presentamos una propuesta para obtener la reproducción exacta del color ajustando los valores triestímulos CIE_XYZ de un estimulo de color dado, usando imágenes multiespectrales de 16 bandas y los valores triestimulos CIE-XYZ de un patrón estándar de color conocido (*color test chart*). Proponemos una simple combinación lineal de las imágenes multiespectrales como función de interpolación, lo cual es equivalente a ajustar los datos a una línea recta en un espacio de 16 dimensiones. Usando esta función de interpolación, minimizamos la función de merito del error promedio entre los valores triestimulos CIE-XYZ medidos y estimados en el patrón estándar de color. Por medio de una comparación visual entre los resultados obtenidos usando ésta propuesta y los resultados obtenidos usando una técnica de estimación de la reflectancia espectral, mostramos que la función de interpolación propuesta cuando se usan imágenes multiespectrales de 16 canales, produce resultados de alta calidad en términos de fidelidad en la reproducción del color.

Descriptores: Imágenes multiespectrales; ajuste de los valores triestimulos CIE-XYZ; función de interpolación; minimización del error cuadrado promedio; diferencia del color ΔE_{ab}.

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1. Introduction

The interest and the number of research institutions that become involved with the analysis and reproduction of color by using multispectral images have been increasing gradually. The International Commission on Illumination (CIE) has created a technical committee (Division 8, technical committee TC8-07, multispectral imaging) for the discussion, definition, and adoption of a standard multispectral image file format, that allows the management of multispectral images by means of an already available commercial software for reproduction and design of color images. Some of the areas where it is intended to achieve highly real color reproductions are: tele-medicine, electronic commerce, art, and computer graphics among others[1,2].

Since each of the digital devices to capture or display color images has its own RGB native color space, in which the same color stimulus is represented by a different triplet of RGB values, and since all digital devices involved in color management system interchange color information among them by means of RGB images, even color printers make use of RGB images as input data, it becomes necessary in order to achieve high fidelity color reproduction to transform this color information into a color space that can be independent from every digital device involved in the color management system[3].

Furthermore, to achieve a high fidelity color reproduction by means of a digital system to capture and display color images, the digital devices involved in the color management system have to be colorimetrically characterized, in order to obtain their color profiles. These color profiles are thus used to predict the RGB values, that in the dependent color space of the display device will reproduce, with high fidelity, a given color stimulus. The colorimetrical characterization has to be done even if we are working in a multi-channel or multi-dimensional color space, and this characterization will enable us to transform the native device dependent color space into an independent connection color space, which is

called the profile connection space. On the other hand, efficient methods for the digital processing of color images, and the transformation from the native color space of the device into the device independent color space are required[4].

There are two typical approaches to transform from the device native color space to the device independent color space[4] CIE-XYZ, which was defined by the Commission Internationale de l'Eclairage (International Commission for Illumination), and which is widely used as a device independent color space. These approaches are based on spectral and analytical models; in this document we describe an analytical model to carry out this transformation. Others device independent color spaces are the quasi-uniform color spaces CIE-Lab and CIE-Luv [3,5,6].

This document describes a method for fitting the CIE-XYZ tristimulus values of a given color stimulus using both, the n digital images or channels, which are the output of a multispectral digital camera, and the known CIE-XYZ tristimulus values of m color patches of a color test chart. This method finds out that the *nx3* coefficients of a linear combination of the camera output, which is used for the independent fitting of each of the CIE-XYZ tristimulus values of a given color stimulus, is equivalent to fitting the data to a straight line in a 16-dimensional space. The *nx3* computed coefficients are the elements of a color transformation matrix which is used to transform the output of the digital camera into the CIE-XYZ tristimulus values. The method is based on the method proposed by Hardeberg [4] for characterization of a digital scanner, where he minimized the mean square error between the measured and estimated CIE-Lab values of the m color patches of a color test chart, and proposed to fit the CIE-Lab values using polynomial functions of degree n as interpolation function. Furthermore, Hardeberg proposed a non-linear transformation of the RGB values of the scanner to compensate the cubic root involved in the transformation from CIE-XYZ tristimulus values to CIE-Lab color coordinates. In this work, we do not consider such a non-linear transformation and we minimize the mean square errors between the measured and estimated CIE-XYZ tristimulus values of the patches of a color test chart. Then we compute the CIE-Lab values of both, the measured and estimated CIE-XYZ tristimulus values, and finally we compute the ΔE_{ab} color differences for the training and target images. We make a visual comparison between both color reproductions of the target image which are reproduced using this proposal, and a spectral reflectance estimation technique, in this way, we show that the proposed interpolation function produces very high quality results in terms of color reproduction fidelity.

2. Mean square error minimization with a polynomial interpolation function of degree n

If we have a set of data which arises from observations, such as physical measurements or numerical calculations that can

not be modeled by an analytical function, may be sometimes desirable to fit the data to a model that depends on adjustable parameters[7].

To fit a set of m data points (x_i, y_i), one of the possible solutions is to propose a polynomial function as an interpolation function, and to fit the appropriate coefficients. For example, the model could be represented by a polynomial function of degree n

$$y(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n. \tag{1}$$

The task is to find out the values of the coefficients $a_0, a_1, a_2 \cdots a_n$ that minimize the mean square error between all the known theoretical or measured values y_i, and those correspondent values that are calculated by using the polynomial proposed model [7]. Hence, the merit function that measures how well the model agrees with the data is defined by

$$MSE = \frac{1}{m} \sum_{i=0}^{m-1} (y_i - \sum_{j=0}^{n} a_j x_i^j)^2. \tag{2}$$

Small values of the merit function represent close agreements between the data and the model with a particular set of coefficients $a_0, a_1, a_2 \cdots a_n$. Hence, the coefficients of the model have to be adjusted to achieve the minimum of the merit function and in this way, these coefficients will be the best-fitting coefficients. The minimum of the merit function represented by the Eq. (2), occurs when its derivative with respect to all the $n + 1$ coefficients a_k vanish.

$$\frac{\partial MSE}{\partial a_k} = 0,$$

$$\sum_{i=0}^{m-1} x_i^k (y_i - \sum_{j=0}^{n} a_j x_i^j) = 0, \quad k = 0 \cdots n. \tag{3}$$

The Eq. (3) generates a system of $n + 1$ equations to find the solution of the coefficients $a_0, a_1, a_2 \cdots a_n$, then it is introduced the following notation

$$\mathbf{y} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_{m-1} \end{bmatrix}, \tag{4}$$

$$\mathbf{a} = \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix}, \tag{5}$$

$$V = \begin{bmatrix} 1 & x_0 & x_0^2 & \cdots & x_0^n \\ 1 & x_1 & x_1^2 & \cdots & x_1^n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{m-1} & x_{m-1}^2 & \cdots & x_{m-1}^n \end{bmatrix}, \tag{6}$$

with this notation, the Eq. (3), can be expressed as

$$V^t V \mathbf{a} = V^t \mathbf{y}, \tag{7}$$

the solution for the vector **a** which provides the values of the coefficients $a_0, a_1, a_2 \cdots a_n$ that achieve the best-fitting by means of the polynomial approximation model of Eq. (1), is expressed by

$$\mathbf{a} = (VV^t)^{-1}V^t\mathbf{y}. \qquad (8)$$

3. Mean square error minimization with a lineal combination of multispectral camera output as interpolation function

As interpolation function for fitting the CIE-XYZ tristimulus values, we propose a linear combination of the 16-band multispectral camera output, which is equivalent to fit the data to a straight line in a 16-dimentional space. The interpolation functions are defined as

$$X(v) = \alpha_1 v_1 + \alpha_2 v_2 + \cdots + \alpha_{16} v_{16},$$
$$Y(v) = \beta_1 v_1 + \beta_2 v_2 + \cdots + \beta_{16} v_{16},$$
$$Z(v) = \gamma_1 v_1 + \gamma_2 v_2 + \cdots + \gamma_{16} v_{16}, \qquad (9)$$

where $v_1, v_2, \ldots v_{16}$ are the output digital counts of the 16-band multispectral camera, and $\alpha_1, \alpha_2, \ldots \alpha_{16}$, $\beta_1, \beta_2, \ldots \beta_{16}$, and $\gamma_1, \gamma_2, \ldots \gamma_{16}$ are the coefficients that have to be adjusted independently in order to obtain the minimum of the merit functions expressed by:

$$MSE_X = \frac{1}{m} \sum_{i=0}^{m-1} (X_i - \sum_{j=1}^{16} \alpha_j v_{i,j})^2,$$
$$MSE_Y = \frac{1}{m} \sum_{i=0}^{m-1} (Y_i - \sum_{j=1}^{16} \beta_j v_{i,j})^2,$$
$$MSE_Z = \frac{1}{m} \sum_{i=0}^{m-1} (Z_i - \sum_{j=1}^{16} \gamma_j v_{i,j})^2. \qquad (10)$$

The notation $v_{i,j}$ represents the value of the *j-th* $(j = 1 \cdots 16)$ digital count or channels of the 16-band multispectral camera for the *i-th* (in this work we used the Macbeth color test chart, hence $i = 1 \cdots 24$) color patch of the color test chart that is used as a training image to adjust the values of the coefficients $\alpha_1, \alpha_2, \ldots \alpha_{16}$, $\beta_1, \beta_2, \ldots \beta_{16}$, and $\gamma_1, \gamma_2, \ldots \gamma_{16}$.

Minimizing the merit functions of the Eq. (10), with respect to the *k-th* correspondent unknown coefficient

$$\frac{\partial MSE_X}{\partial \alpha_k} = 0,$$
$$\frac{\partial MSE_Y}{\partial \beta_k} = 0,$$
$$\frac{\partial MSE_Z}{\partial \gamma_k} = 0, \qquad (11)$$

we obtain the following set of equations

$$\sum_{i=0}^{m-1} v_{i,k} X_i - \sum_{j=1}^{16} \alpha_j v_{i,j} = 0,$$
$$\sum_{i=0}^{m-1} v_{i,k} Y_i - \sum_{j=1}^{16} \beta_j v_{i,j} = 0, \quad k = 1 \cdots 16$$
$$\sum_{i=0}^{m-1} v_{i,k} Z_i - \sum_{j=1}^{16} \gamma_j v_{i,j} = 0, \qquad (12)$$

each one of the last equations generates a system of 16 equations that will be used to find out the adjusted values of $\alpha_1, \alpha_2, \ldots \alpha_{16}$, $\beta_1, \beta_2, \ldots \beta_{16}$, and $\gamma_1, \gamma_2, \ldots \gamma_{16}$ independently, if we define the following matrices

$$P = \begin{bmatrix} X_0 & Y_0 & Z_0 \\ X_1 & Y_1 & Z_1 \\ \vdots & \vdots & \vdots \\ X_{m-1} & Y_{m-1} & Z_{m-1} \end{bmatrix}, \qquad (13)$$

$$A = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \vdots & \vdots & \vdots \\ \alpha_n & \beta_n & \gamma_n \end{bmatrix}, \qquad (14)$$

$$V = \begin{bmatrix} v_{0,1} & v_{0,2} & v_{0,3} & \cdots & v_{0,16} \\ v_{1,1} & v_{1,2} & v_{1,3} & \cdots & v_{1,16} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ v_{m-1,1} & v_{m-1,2} & v_{m-1,3} & \cdots & v_{m-1,16} \end{bmatrix}, \qquad (15)$$

where P is the matrix of the CIE-XYZ tristimulus values of the m known color patches, A is a matrix which columns are the correspondent adjusted coefficients of the interpolation functions proposed in the Eq. (9), and V is the matrix of the 16 digital counts for the m known color patches. Using this matrix notation the Eqs. (12) can be expressed as

$$V^t V A = V^t P, \qquad (16)$$

and the solution of the matrix system or the adjusted values of the coefficients for the best-fitting of the CIE-XYZ tristimulus values can be obtained by inverting the matrix $V^t V$

$$A = (V^t V)^{-1} V^t P, \qquad (17)$$

Once we have calculated the adjusted coefficients, we proceed to the fitting of the CIE-XYZ tristimulus values for every pixel in the target image by using the Eqs. (9) and the output of the multispectral camera which is 16-digital counts for every pixel, and also using the transpose of the transformation matrix A given by the last equation

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = A^t \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_{16} \end{pmatrix}. \qquad (18)$$

4.   Experiment

For this experiment we used a 16-channel multispectral camera (delta-MSC) developed by Natural Vision Research Center of Telecommunication Advancement Organization of Japan (TAO)[8]. This camera basically consist of a CCD sensor with a rotating wheel which has attached sixteen optical narrow-band color filters, the sensitivities of the camera with the attached filters are shown in Fig. 1.

Two images were captured using this multispectral camera, one for training and the other one for testing the proposed model. The training image corresponded to the Macbeth's color test chart with 18 color patches and 6 achromatic color patches, see Fig. 2. The Macbeth color test chart was captured using three different types of illumination, we used tungsten (A) illumination and white light that simulates daylight (D65), both from a booth-light Gretag-Macbeth Spectralight III, and the third one was also white light produced by a couple of Xenon lamps. Figure 3 shows the spectral distribution of the three illuminants used for this experiment.
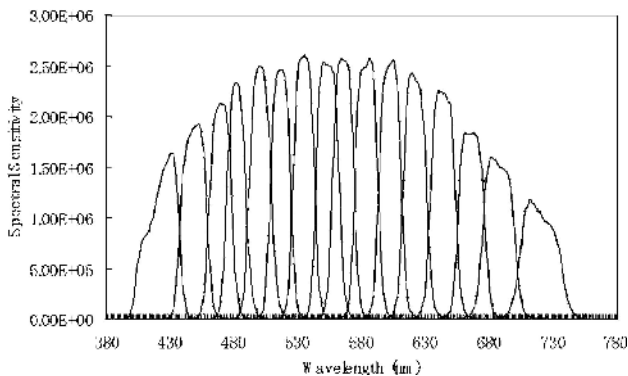

FIGURE 1. The sixteen spectral sensitivities of the multispectral camera and attached narrow-band color filters described in the text.

FIGURE 2. Image of the Macbeth color test chart used for this experiment.
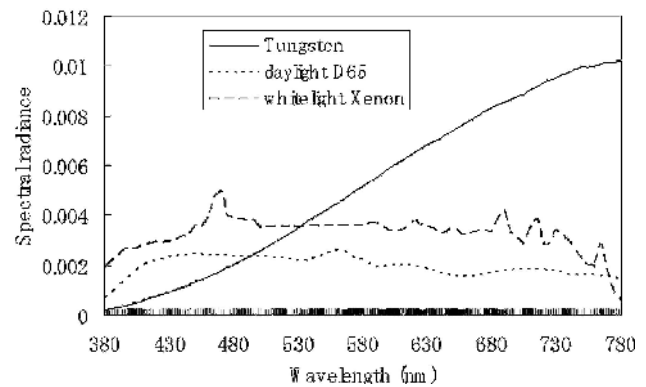

FIGURE 3. Spectral distribution of the A, D65 and Xenon illuminants used for this experiment.

The target image is a scene that contains three color scarves. This image was captured under the simulated daylight (D65) illumination of the Gretag-Macbeth Spectraligth III, in order to make a visual comparison between the image reproduced using spectrum estimation techniques like the Wiener estimation method, and the image that results from the method described in this work.

For computing the color transformation matrix A described in Sec. 3, it was use the CIE-XYZ tristimulus values of the test chart of 24 Macbeth's color and achromatic patches, measured by the spectrophotometer Topcon SR-2, and the sixteen averaged digital counts of the training multispectral image of the Macbeth color chart's patches, too.

The CIE-XYZ tristimulus values of the Macbeth color test chart were measured under each one of the three illuminants, tungsten (A), simulated daylight (D65), and Xenon white light. The digital counts of the training image were averaged from the 16-channels multispectral image captured by a delta-MSC camera using a 40×40 pixels area for every color and achromatic patch.

5.   Results

Both sets of CIE-XYZ tristimulus values of the Macbeth color test chart, the measured and estimated ones were transformed to the CIE-Lab color space, after this color transformation, the ΔE_{ab} color differences under the three different illuminants, tungsten (A), simulated daylight (D65), and Xenon white light were computed. Table I shows the results of the computed ΔE_{ab} color differences between the CIE-Lab color coordinates of the measured and estimated color stimulus, and the 24 color patches of the training image ones (Macbeth color test chart). The ΔE_{ab} color differences were computed using the CIE *1976 color-difference formula*, which is the Euclidean distance between the measured and estimated CIE-Lab values, its formula was defined by the CIE as follows[5,6]

$$\Delta E_{ab} = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}. \quad (19)$$

In the Table I, it can be observed that the best results in terms of color differences are obtained when an illuminant

TABLE I. ΔE_{ab} Color differences between the measured and the estimated color stimulus of the 24 color patches of the Macbeth color test chart under three different illuminants A, D65 and Xenon.

Macbeth's color test chart patch	Illuminant		
	A	D65	Xenon
1	2.32492	1.756	0.536856
2	0.348799	0.390138	0.103411
3	0.298123	0.454805	0.0419923
4	0.631751	0.853397	0.0273243
5	0.113124	0.0310552	0.0497523
6	0.75227	0.33888	0.112938
7	0.245769	0.0832187	0.162213
8	0.616837	0.110497	0.139658
9	0.25563	0.107783	0.0553544
10	0.898643	0.441741	0.233001
11	0.348274	0.543786	0.170674
12	0.462515	0.315635	0.113625
13	1.04964	0.240441	0.0754385
14	0.302752	0.587561	0.0857564
15	0.0197809	0.143136	0.0601342
16	0.334876	0.509151	0.063322
17	0.236338	0.120037	0.0480535
18	1.95275	0.535001	0.114231
19	0.374383	0.0659562	0.0370512
20	0.288211	0.145799	0.135075
21	1.0378	0.267827	0.190892
22	1.86166	0.230545	0.303776
23	1.16846	0.299347	0.20237
24	0.970452	1.14408	0.310191

with an spectral distribution like the produced by Xenon lamps is used, the whereas accurate the least results are obtained when tungsten lamps, which produce the spectral distribution of the A illuminant, are used. Even in the case of tungsten (A) illumination, the achieved results to prediction the CIE-XYZ tristimulus values, present a very high degree of accuracy as we will analyze in the next paragraph.

Table II shows the results of the average, maximal, and minimal color differences of the data presented in the Table I. Even though the least accurate results for the average color difference are obtained for tungsten (A) illumination, according to the rule of thumb described by Hardeberg[4]; a practical interpretation for ΔE_{ab} color differences states that: when two colors are shown side by side, average color differences that are less than 3.0 are classified as hardly perceptible, between 3.0 and 6.0 are perceptible, and acceptable, and more than 6.0 are not acceptable. The average color dif-

TABLE II. Average, maximal and minimal ΔE_{ab} color difference between the measured and the estimated CIE-XYZ color stimulus of the 24 color patches of the Macbeth color test chart under three different illuminants A, D65 and Xenon.

	Average	Maximal	Minimal
A	0.703906	2.32492	0.0197809
D65	0.404826	1.756	0.0310552
Xenon	0.140545	0.536856	0.0273243

ferences obtained under each one of the three different kinds of illuminants used, in this work, are hardly perceptible since they all are less than 1.

A set of 9 color regions, in the target image of the color scarves, was chosen, The CIE-XYZ tristimulus values of these color regions were measured using a spectrophotometer TOPCON SR-2 under the simulated daylight (D65) illumination. The target image was also captured by using a delta-MSC, multispectral camera under the same illumination conditions of simulated daylight (D65). The measured CIE-XYZ tristimulus values of the 9 selected color regions and the corresponding estimated CIE-XYZ tristimulus values, which were computed for the same color regions using the Eq. (18) with the matrix A obtained from the Eq. (17), and the process described in Sec. 3 of this study, were transformed to CIE_Lab color coordinates. Table III shows the results of the ΔE_{ab} color differences between the measured and estimated color stimulus of the 9 samples. From this table, it can be deduced the average maximal and minimal color differences for the target image, which values are: 1.325123875, 2.98614, and 0.459274, respectively. Once again making refering to the Hardeberg color differences classification, these results are classified as hardly perceptible color differences. It is very important to point out here that it is involuntarily to introduce some error in the computation of the ΔE_{ab} color differences in the target image, since it is almost impossible to match accurately the area of the measured color regions in the original image with the selected areas of the 16-band multispectral digital image in order to match the correspondent color regions in the original image.

TABLE III. ΔE_{ab} Color differences between the measured and the estimated color stimulus of the target image under D65 Illuminant.

Color region in the target image	ΔE_{ab} color difference
1	0.459274
2	1.29191
3	0.463065
4	0.484865
5	2.98614
6	1.01508
7	0.946577
8	2.95408

FIGURE 4. Visual color comparison between the digital reproductions of the training and target images, in the left side are shown the images reproduced by using a spectrum based estimation method, in the right side are shown the corresponding images reproduced in this study.

In order to make a visual evaluation of the effectiveness of this proposal to fit the CIE-XYZ tristimulus values, the target image reproduced by this method is visually compared with the target image reproduce by using a method based on the spectral reflectance estimation [9,10]. Spectral based estimation methods produce very high quality results in terms of accurate color reproduction when the number of bands used for the process of digital capture is increased [8,11]. The estimation of the spectral reflectance is almost perfect in the case of using sixteen narrow band color filters along with the visible spectrum, like those ones in the Fig. 1. The training and target images reproduced by both of these methods are shown in Fig. 4. On the left side of the figure are the training and target images reproduced by using a spectrum estimation technique, and on the right side of the figure the corresponding training and target images reproduced by using the proposal in this study. There are many factors that influence the visual comparison of these results: the type of monitor used to display these images, the illumination under which these images were observed, and the slight individual deviations of observers from the color matching functions of the 1931 standard observers defined by the CIE (International Commission for Illumination). These functions were based on experimental data and allowed us to calculate the amount of the three stimulus required by the standard observer to match a given color, as need as the observation angle among others[5,6]. As a particular evaluation, we can say that color differences between both digital reproductions of the target image are hardly perceptible, and that the model, for fitting the CIE-XYZ tristimulus values described in this work produces satisfactory results in terms of digital color reproduction.

6. Conclusion

We conclude that this proposal provides very satisfactory and high quality results in terms of color reproduction fidelity, from the visual comparison between the image reproduced by using this color reproduction proposal and the image reproduced by using the spectral reflectance estimation technique additionally, we can also conclude that when the number of bands or channels to fit the CIE-XYZ tristimulus values are increased, the number of color patches in the training image are reduced as low as only 18 color patches, and 6 achromatic patches of the Macbeth color test chart, both of achieve a high quality color reproduction. It is important to point out that if the number of channels are gradually reduced from sixteen to only three channels, then it will also be necessary to increase gradually the number of color patches in the training image in order to compensate the metameric colors, and achieve high quality results by considering a wider gamut of training colors. In other words to reduce the metamerism, it is necessary to increase the number of channels to sample a color signal. Hardeberg appoints to usage as many as 288 color patches for the scanner characterization (three channels), and eventually reduces this number up to 54 color patches loosing certain fitting data accuracy. One advantage of this color reproduction method over the spectrum based estimation methods, is that its algorithm is very easy to implement, and it is considerably faster in terms of data processing, which reduces the computation cost. Furthermore, for the proposed method, we not have made use of the spectral response of the CCD, or the spectral transmittance curves of the 16-interference filters attached to it; hence, it has not been necessary to do any spectral characterization of the multispectral camera, which may require some expensive equipment, experience, and time. If it is necessary to recalibrate the capture system every certain period of time, it will be just enough to recapture the training image of the color test chart, and to measure its tristimulus values under the required illumination conditions. A drawback of this proposal is that in order to adjust the coefficients of the matrix A in the Eq.(17), it is necessary to measure the CIE-XYZ tristimulus values of the training image under the same illumination conditions as the target image, in other words, we can not make a digital processing to the images to change illumination conditions as in the case of spectral based methods; nevertheless, for a given application, it is always possible to capture a training image (color test chart) under the same illumination conditions as a target image.

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