# Small Color Differences in the Very Pale and Dark Grayish Regions Measured by Camera

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The camera capability to measure small color differences between sample pairs is evaluated by comparing the camera performance with a reference instrument. To this end, the appropriate working conditions are established, the camera spectral sensitivities and imaging noise are characterized, and the transformation to obtain a device independent representation of color is calculated considering two approaches: one, on the basis of the camera spectral sensitivity (CSS), and two, on the basis of the unified measure of goodness of the camera (UMG) that involves an imaging noise model. The camera performance is assessed from the measurement results of a large number of varied small color differences in the very pale and the dark grayish color regions, the involved uncertainty, the absolute discrepancy, and the relative discrepancy with respect to the reference instrument. In the experimental application, the three CCD camera SONY DX-9100P is assessed and compared with the spectroradiometer Photo Research PR-715 as reference instrument. The results reveal a high quality performance of the camera system, with absolute discrepancies in the estimation of color differences around the camera tolerances (CIELAB  $0.5\Delta E^*_{ab}$  or CIEDE2000  $0.6\Delta E_{00}$ ). The color uniformity in textile dying is evaluated by analyzing some pairs of extreme center fabric samples. Although the camera is more sensitive to the texture effects than the spectroradiometer, both instruments yield consistent and satisfactory Pass/Fail results.

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### Introduction

The characterization of a camera orientated to colorimetric purposes has been described in Refs. 1 through 4. Important applications can be found in color management, for which the acquisition of the color content of either a scene or an image and the transformation to obtain a device independent representation of color are some of the basic stages. Some applications propose to develop databases of calibrated color images. Face colors under varying lighting conditions are the object of the Physics-Based Face Database for color research.<sup>5</sup> Xiao et al. describe an initial methodology to create a database of high dynamic range, color images that represent typical scenes in digital photographs.<sup>6</sup> Such a database<sup>7</sup> should help the development and evaluation of rendering methods and it can also be used to evaluate the constraints imposed by image sensors and lens configurations. Other examples of colorimetric applications of digital cameras can be found in end-to-end color reproduction systems. The possibilities and limitations of commercial input and output devices have been ex-

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amined in order to produce hardcopy results that are spectrally matched to original colors.<sup>8</sup> The approach consists of scene capture using a trichromatic digital camera combined with multiple color filtration,<sup>9</sup> image processing, and four color ink jet printing.<sup>8</sup>

As far as we know, less effort has been devoted to exploit the discrimination capability of color cameras in the measurement of color differences. A possible reason may be the existence of a number of instruments (colorimeters, spectrophotometers, spectroradiometers) capable of measuring color differences with high precision. These instruments, however, measure color in an integration area of the sample with limited flexibility in configuration, dimensions and sample scanning. These conditions cannot be easily modified in general, even when using expensive and sophisticated instruments. Marszalec et al.<sup>10</sup> studied the performance of color cameras for measuring small color differences and related it to metamerism. They concentrated on the fact that, in general, color cameras and human vision have not exactly the same response functions and, consequently, they could find a number of sample pairs that were metameric or very similar for the human observer but were measured by a color camera as separate colors. They evaluated how similar these colors were in the RGB camera color space by using a non established formula.

In this article we consider a 3CCD camera to measure small color differences with applications in industrial inspection. We emphasize that the target measure here is the "size" of color difference, not color accuracy. This goal in itself is valid, especially for applications where color uniformity, not color fidelity, is the concern. We fix the working conditions of the camera system according

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to methods previously described in Ref. 11. In that study, the camera performance was compared with the performance of a reference instrument in a camera independent color space. In addition to the characterization of the spectral sensitivities of the camera and the Vora-Trussell measure of goodness<sup>12</sup> considered previously in Ref. 11, in this work we also consider the characterization of imaging noise related to dark current, shot noise, and the unified measure of goodness (UMG).<sup>13</sup> This more general approach leads us to compute new coefficients for the linear transform applied to the RGB camera values to obtain the XYZ tristimulus values in the device independent color representation. In this work we explore the reliability of the camera system and estimate the precision and accuracy considered before Ref. 11 and the approach involving the UMMG.

In the experiments we pay particular attention to the nearly neutral region of the color space (unsaturated colors). The nearly neutral colors imply a similar stimulation of the three red-, green- and blue-sensitive channels of the camera, and the differences between these colors involve small variations on a nearly constant background signal. Although humans show a subjective preference for colorfully enhanced images, real colors of original scenes are not as saturated as observers prefer.<sup>14,15</sup> There are a large number of examples, particularly in the western culture, for which unsaturated colors compose the main part of real scenes: natural scenes in cold countries, outdoor city scenes, indoor scenes, suits and other clothing, wall paints and decoration, human skin and faces, etc. Saturated colors are rather limited to children in western countries. Due to such cultural reasons, unsaturated colors draw industrial attention, particularly in the textile industry, which has motivated the application presented in this article. Finally, as a practical consideration, two matte Munsell collections: the Book of Color and the Nearly Neutral Collection, were available to the authors. These provided them with large enough color sample sets to carry out this study.

The CIELAB<sup>16,17</sup> and the more recent CIEDE2000<sup>18</sup> formulae are used in this work to compute color differences. More especially, CIEDE2000 includes a term to improve performance of low-chroma colors<sup>19</sup> and therefore we have considered it suitable for our study. We analyze the camera performance for the very pale and the dark grayish color regions. As an example of application, we consider a practical real case of color matching in the textile industry.

# **Method for Camera Evaluation**

The method aims to assess the discrimination capability of a camera to measure small color differences. We are concerned with the accuracy and precision of the camera and compare it with a reference instrument that is assumed to be calibrated, high quality, and to have a linear response. The method has several stages, including the camera calibration.

Firstly, we determine the appropriate working conditions of the acquisition system. A camera based color imaging acquisition system consists of a camera (often 3CCD), a framegrabber, a PC, and a given lighting-viewing configuration. We compare the camera and the reference instrument in the same illumination/observation conditions (Fig. 1): we use an observation booth with a given light source and a given illumination/observation geometry for which the scene is captured away from specular reflections.

In the camera initialization, the gamma function and the automatic gain control are disabled, and the camera



**Figure 1.** Setup scheme. The camera can be replaced by the spectroradiometer (reference instrument) at the same position so that both instruments measure with the same illumination/observation geometry.

raw signal is white balanced to a given illuminant. The framegrabber converts the analog signal of the camera into the R, G, B digital values (for instance, from 0 to 255 in an 8 bit camera). In the analog to digital conversion, the gain and offset values have to be fixed. In Ref. 11, we measured the R, G, and B responses of the camera when it captures a gray scale using all the four possible combinations where the gain and the offset take the extreme values of the range, i.e., either 0 or 255. Since the camera response that profits from maximum dynamic range with minimum alteration in the signal is usually sought, we tentatively selected the combination of (gain, offset) that best approached this property. We considered intervals around these gain and offset tentative values to further analyze the camera response within such intervals and, consequently, to refine the gain and offset selection.

The calibration of a 3CCD camera should involve both the measurement of its 3CCD spectral sensitivities and its noise properties. There are various methods described in the literature to estimate the spectral sensitivity curves of the sensors, e.g., Refs. 2, 3, and 20-22. A conceptually simple method, which we have already followed,<sup>11</sup> is based on stimulating the camera with very narrow band illumination produced by a monochromator.<sup>2</sup> The three RGB spectral sensitivity functions are a set of color scanning filters for which the Vora-Trussell measure of goodness (factor, defined in Ref. 12) can be determined. The v factor is used to characterize input devices, such as cameras or scanners, and indicates the similarity of the set of the device spectral sensitivities to human color matching functions, so that v = 1 means a perfect fit. According to Berns and Reiman,<sup>23</sup> values of the factor above 0.9 are desirable for colorimetric purposes in the first approach.

To overcome the device dependent representation of color based on the R, G, B components provided by the camera, we calculate the coefficients of the linear transformation that defines a mapping between the camera RGB signals and a device independent representation, such as the standard CIE 1931 XYZ. In this study, we consider two ways of calculating the  $(3 \times 3)$  linear matrix. In one of them, the coefficients are calculated following the methods<sup>24,25</sup> which takes into account the three spectral response curves of the camera sensors, the standard observer responses  $x_{10}$ ,  $y_{10}$ ,  $z_{10}$  (CIE 1976), and the spectral distribution of the white light source. This calculation was already used in our former work,<sup>11</sup> but it does not consider the noise properties of the camera.

A more complete calibration increases the camera's measure of goodness by considering noise characteristics. Among the research works on CCD camera calibration that



**Figure 2.** Test of nearly neutral Munsell chips organized in two subsets: (a) very pale sample subset, and (b) dark grayish sample subset. In each one, there are ten groups of samples regularly distributed around the Hue circle. Each group consists of a group center and its closest neighbors (there is a group sketched in detail in both figures).

estimate noise, we mention the work of Healey and Kondepudy for a single CCD camera<sup>26</sup> and the work of Quan et al.<sup>13</sup> that is closer to ours. In the latter, the CCD noise model has two main components: a signal independent noise such as dark noise and a signal dependent noise represented by shot noise. Dark current noise can be measured by taking images with the camera aperture totally closed at ambient temperature. This noise has an average value, which is often subtracted from the output signal, but it also exhibits fluctuations that create fixed pattern noise.<sup>27</sup> Shot noise is associated with the random arrival of photons at the CCD. It is governed by Poisson statistics and, consequently, the shot noise variance is equal to the mean input signal. In our study, we assume the zero mean noise model considered by Quan et al.<sup>13</sup> whose variance  $\sigma_n^2$  is given by

$$\sigma_{\eta}^2 = \sigma_d^2 + k\mu_i , \qquad (1)$$

where  $\sigma_d^2$  denotes the dark noise variance, k is the photon-electron conversion quantum efficiency coefficient of the CCD, and  $\mu_i$  is the input signal intensity, which coincides with the shot noise variance  $\sigma_i^2$ . From Eq. (1), the noise is dominated by dark noise when the input signal level is low. But when the input signal level is high, shot noise, which is proportional to the signal level, dominates. Noise levels can be represented by digital counts relative to the digital count of maximal signal in Eq. (1). The coefficient k associated to shot noise can be obtained by fitting Eq. (1) with a series of signal levels and the corresponding signal variations. Taking into account the metric called Unified Measure of Goodness (UMG), proposed by Quan et al.,<sup>13</sup> we can compute the coefficients of a linear matrix converting camera RGB to CIE XYZ through the minimization of noise propagation. This metric minimizes the average color difference or error for an ensemble of standard reflectance samples in a perceptually uniform color space. For additional properties and details about the computing procedure, the reader is referred to Quan et al.'s paper.13

The CIELAB coordinates  $L^* a^* b^*$  (CIE 1976) can be calculated from CIE XYZ using the standard formulae.<sup>16,17</sup> CIELAB chroma  $C_{ab}^*$  and hue  $h_{ab}$ , that correspond to the polar coordinates of this cylindrical representation system for which the luminance  $L^*$  gives the axis, will also be computed and used.

Concerning the amount of uncertainty associated with the measurement process we consider a specific metric called the mean color difference from the mean (MCDM).<sup>17</sup> For a set of CIELAB measurements, the average ( $\overline{L}^*$ ,  $\overline{a}^{*}, \overline{b}^{*}$ ) is calculated. Then, a color difference equation (in our case, either  $\Delta E^*_{ab}$  CIELAB<sup>16,17</sup> or  $\Delta E_{00}$ CIEDE2000<sup>18</sup>) is calculated between each individual measurement and  $(\overline{L}^*, \overline{a}^*, \overline{b}^*)$ . The average of all the color differences defines the MCDM. The greater the MCDM, the poorer the precision. We calculate the MCDM of the measurements obtained from a set of ten samples taken at the center of a single Munsell patch. In the case of the camera measurements, each individual measurement  $(L_i^*, a_i^*, b_i^*)$  is, in turn, the average CIELAB values of the CIELAB values of each of the  $300 \times 300$  pixels that compose the central field window of the captured image in our case. We repeat the procedure for a number of color patches to observe stability in the final result. Following the notation given in Ref. 17, the value  $v\Delta E_{ab}^*$  is the MCDM in the CIELAB metrics. Similarly, the value  $n\Delta E_{00}$ is the MCDM in the CIEDE2000 metrics. We calculate these values to estimate the precision of both the reference instrument and the camera. According to a common statistical rule, the instrumental color tolerance should be no less than ten times the precision. This rule will give us a magnitude order of our instrumental tolerances.

In the following stage of the method, we assess the capability of the camera to measure small color differences, and compare the measurements obtained by the camera with those obtained by the reference instrument. We focus on the extremes of the unsaturated color region, i.e., the very pale and dark grayish colors. To this end, we build a test consisting of samples from two matte Munsell collections: the Munsell Book of Color and the Nearly Neutral Munsell Collection. Ten selected samples are regularly distributed in the hue circle (Fig. 2). They have low value of Chroma = 2, and two values of Value: V = 8(Fig. 2(a)), and V = 4, (Fig. 2(b)). The two subsets of samples generated in this way are the very pale color subset (with V = 8)<sup>11</sup> and the dark gravish color subset (with V = 4). In the experiment, each one of the selected chips has to be compared with its neighbors according to the sketches of Figs. 2(a) and 2(b).

According to the test of Fig. 2, a large number (140) of color differences between nearest neighbor pairs are separately evaluated by both the camera and the reference instrument. CIELAB  $\Delta E_{ab}^*$  and CIEDE2000  $\Delta E_{00}$  formulae are used to calculate the color differences. The comparison of the results gives the discrepancy between the instruments. The absolute discrepancy  $D_i$  can be es-



**Figure 3.** Spectral power distribution of the fluorescent lamp F40/T12 installed in the booth as D65 daylight simulator.

timated by simply subtracting the color differences measured by the reference instrument and the camera, and taking the absolute value, that is,

$$D_{i} = \left| \Delta E_{i} \left( ref \right) - \Delta E_{i} \left( cam \right) \right|, \tag{2}$$

where subindex  $i = \{ab, 00\}$  indicates either the CIELAB or the CIEDE2000 metric in Eq. (2). The relative discrepancy  $D_i^r$  is the absolute discrepancy divided by the mean value  $\langle \cdot \rangle$  of the color differences measured by the spectroradiometer and the camera,

$$D_{i}^{r} = \frac{D_{i}}{\left\langle \Delta E_{i}(ref), \Delta E_{i}(cam) \right\rangle} = \frac{2\left| \Delta E_{i}(ref) - \Delta E_{i}(cam) \right|}{\Delta E_{i}(ref) + \Delta E_{i}(cam)}.$$
 (3)

These discrepancies are used to test the level of agreement between both the camera and the reference instrument in the estimation of the color differences. Since the reference instrument is of high quality, its tolerance is commonly low ( $\Delta E^*_{ab} \leq 0.5$ ). As a consequence, these discrepancies allow us to evaluate the reliability of the camera's performance. If the absolute discrepancies do not exceed the uncertainty, then the measurements are indistinguishable. This is an ideal case. More realistically, if the camera tolerance is acceptable ( $\Delta E^*_{ab} \simeq 1.0$ ) and the absolute discrepancies fall in general within the camera tolerance, then it can be considered a good achievement for the camera. The relative discrepancies provide information about the accuracy and uniformity of the camera's performance in evaluating hue, chroma or value differences.

#### **Experimental Results**

We have applied the method described above to characterize the discrimination capability of a 3CCD camera. The image acquisition system of our study consists of the following components:

- 3CCD camera SONY DX-9100P, with nominal SNR of 57dB,
- Framegrabber MATROX Meteor II M/C (8 bits) that captures a  $640 \times 780$  pixel size image and digitizes the analog signal provided by the camera into 256 gray levels for each R, G, and B channel. The framegrabber is integrated into a personal computer that is used for subsequent calculations.

• Observation booth VeriVide CAC 120H4 with a D65 daylight simulator given by a fluorescent lamp F40/T12. We measured its spectral power distribution (Fig. 3), and its correlated color temperature was 6,438 K (10° observer).

The color camera was configured with the automatic gain control disabled (0 dB level) and the gamma function equal to 1.0 because otherwise it could distort colors. For the white calibration or white balance, we imaged a standard reflectance plate (Photoresearch RS-3) under the illumination given by the D65 daylight simulator of the booth. The entire field of view was then a white area of the standard plate imaged by the camera and, in this situation, the camera made automatic adjustments of the channel responses to achieve the white balance. The reflectance spectral distribution of the plate was nearly constant and equal to 1 (its calibration did not exceed ±0.6% versus the values of a reference calibrating source, within 380-780 nm). We occluded totally the camera lens aperture for the black reference. The camera aperture remained fixed at f/4during the rest of the experiment.

The camera is compared with a calibrated spectroradiometer as reference instrument. We used the spectroradiometer Photo Research PR-715. It measured the central area of a Munsell chip with 1° aperture or field coverage.

The camera and the reference instrument worked with the same illumination/observation geometry 20% (replacing the camera by the spectroradiometer in the setup of Fig. 1). Since the samples we consider are matte in general, the choice of the illumination geometry is not critical. We observed that a standard 45° illumination gave rise to some image artifacts or noise caused by a shading effect on the rough matte surface. Instead, we decided to use an approximate 20° illumination for all the measurements. Regarding the observation, the camera was placed in front of the sample, in the direction perpendicular to the sample surface. A frontal viewing is preferable to a slant viewing because it reduces focus errors and geometrical distortions produced by perspective that could be important for future applications to spatially variant images. We verified that the illumination was almost uniform throughout the sample placed inside the booth. The camera lens was adjusted so that the field of view was entirely filled by a single Munsell chip (approximately 3.5 cm<sup>2</sup>). We always analyzed, however, a central window of  $300 \times 300$  pixel size.

The gain and offset values were not selected for each R, G, B channel independently, but on the contrary, the gain and offset pair was the same for all the three channels. For an initial selection of the gain and offset values, a gray scale was captured by the camera setting the four combinations of extreme values, i.e., (gain, offset) =  $\{(0,0), (0,255), (255,0), (255,255)\}$ .<sup>11</sup> The camera response that allowed maximum dynamic range with the minimum alteration in the signal was sought. The combination (gain, offset) = (255,0) gave the best camera response out of the four measured. After this coarse selection, we considered intervals around the gain and offset values to further analyze the camera response within such intervals and, consequently, to make a fine selection of the gain and offset. The intervals of greatest interest were eventually limited to gain = [255...128] and offset = [0...64] in our former work. We considered six gain and offset pairs belonging to these intervals and measured the R, G, B responsitivity functions of the camera for each pair. The R, G, B



Figure 4. Spectral responsivities of the SONY DX-9100P camera for the (gain, offset) values: (a) (128, 32), and (b) (255, 32).

responsitivity functions were measured by applying the classical technique based on stimulating the camera sensors with a very narrow band illumination generated by a light source and a monochromator. We calculated the factor v associated to each set of RGB spectral responsivity curves<sup>12</sup> and values > 0.9 were only reached for the pairs (gain,offset) = {(128,32),(255,32)} that yield very close v values. These spectral responsitivities are represented in Fig. 4. We prefer the RGB responsitivity functions obtained setting (gain,offset) = (255,32), with v = 0.9162, because the shape of the R sensitivity function is slightly smoother than the corresponding to (gain, offset) = (128, 32).

Regarding the influence of imaging noise in our measurements, we examined dark noise and shot noise among the different noise sources. Dark noise is a signal independent noise, and it can be estimated from the signal fluctuations in the absence of light exposure. In our case, when the offset value was set equal to zero, the dark noise in the three R, G, B components was characterized by non zero mean values (14 for the B channel and 15 for the G and R channels) and a similar variance  $\sigma_d^2$  (Fig. 5). By setting the offset value equal to 32, however, we compensated for the uniform constant of the dark noise and obtained a nearly zero mean distribution. This result for the dark level result reveals a physically meaningful characteristic of the camera and clarifies our final selection of the offset = 32. Shot noise is a signal dependent noise, and it can be estimated from the signal variations corresponding to a series of different signal levels. The coefficient k associated to shot noise can be obtained by fitting Eq. (1), where noise levels can be represented by digital counts normalized to the digital count of maximal signal. To estimate the parameters of noise model for the camera capturing with (gain, offset) = (255, 32), we captured multiple images of the white standard plate, uniformly illuminated, with different apertures of the camera lens (including total occlusion). The apertures producing saturation were excluded. In this simple way, we had a variation in the signal level without affecting other acquisition condi-



**Figure 5.** Effects of the offset setting on the dark noise level measured in the R, G, B components of an image captured in absence of light exposure: offset = 0 (dashed lines), offset = 32 (solid lines).



**Figure 6.** Imaging noise model of the 3CCD camera with contributions of the dark and shot noise. Experimental points and linear fits are given for the R, G, B channels.

tions. The variances of the RGB components of the captured images were calculated. Figure 6 shows the experimental points and the results of fitting Eq. (1) in the R, G, B channels of the camera. The three channels obtained very close linear fits. The coefficients *k* associated to shot noise were  $(k_R, k_G, k_B) = 3.011, 3.048, 3.073) \times 10^{-4}$ . Since they are very close in the three channels, we used the average value  $k = 3.044 \times 10^{-4}$ . The dark noise variances were  $(\sigma_{dR}^2, \sigma_{dG}^2, \sigma_{dB}^2) = (3.8, 5.8, 3.7) \times 10^{-6}$  and the correlation coefficients of the fits  $(r_R, r_G, r_B) = (0.995, 0.997, 0.997)$  were acceptable.

Following the procedure outlined in Refs. 24 and 25, we calculated the coefficients of the linear transform to pass from the RGB device dependent values to the XYZ tristimulus values. Taking into account the camera spectral sensitivities (CSS) for the pair (gain, offset) = (255, 32), the spectral power distribution of the D65 simulator, and the standard observer responses, we computed the coefficients of the linear transform and obtained

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{vmatrix} 1.947 & 0.237 & 0.373 \\ 1.155 & 1.000 & 0.103 \\ 0.062 & 0.112 & 2.179 \end{vmatrix}_{CSS} \begin{pmatrix} R \\ G \\ B \end{pmatrix}.$$
(4)

From the XYZ values, the CIELAB coordinates  $L^* a^*$  $b^*$  are calculated using the CIE 1976 formula.<sup>16,17</sup> As white reference for this calculation we used the  $X_n$ ,  $Y_n$ and  $Z_n$  obtained for the standard reflectance plate Photoresearch RS-3.

We measured the CIELAB coordinates of a gray scale using the camera with (gain, offset) = (255, 32). We compared the camera response with the measurements obtained by a spectroradiometer (see Figs. 5 through 7 in Ref. 11) and they nearly coincided in the measurement of  $L^*$  over the whole range of grayscale. They were also close in the measurement of low chromaticities  $C^*_{ab}$  for bright neutral chips, but the camera measured higher chromaticity values for dark gray chips that might be due to higher dark current effects. In comparison with other gain and offset pairs, the response of the camera with (gain, offset) = (255, 32) provided the CIELAB measurements closest to those obtained by the spectroradiometer.

The uncertainties associated with the measurement process, expressed as MCDM and calculated following the procedure outlined above, are  $0.025 \Delta E^*_{ab}$  in CIELAB (0.020  $\Delta E_{00}$  in CIEDE2000) for the spectroradiometer, and 0.05  $\Delta E^*_{ab}$  in CIELAB (0.020  $\Delta E_{00}$  in CIEDE2000) for the camera working with (gain,offset) = (255,32). Accordingly, the instrumental color tolerances are 0.25  $\Delta E^*_{ab}$  (0.20  $\Delta E_{00}$ ) for the spectroradiometer and 0.5.  $\Delta E^*_{ab}$  (0.6  $\Delta E_{00}$ ) for the camera.

So far, the calculations to measure the CIELAB coordinates from the camera RGB values and the measure of goodness of the system do not consider the imaging noise characterization of the camera. In this article, taking into account the Unified Measure of Goodness (UMG) proposed by Quan et al.,<sup>13</sup> we have alternatively computed the coefficients of the linear matrix converting camera RGB to CIE XYZ. This linear transform is obtained through the minimization of noise propagation. The noise model assumed in Ref. 13 is zero mean and the noise variance has the main contributions of dark and shot noises. The UMG metrics minimizes the average color difference or error for an ensemble of standard reflectance samples in a perceptually uniform color space. As representative ensemble of standard object

TABLE I. Hardeberg's Optimal Set of Munsell Patches (see Ref. 28)

Hardeberg's optimal set of 20 Munsell patches <sup>28</sup>											
7.5RP9/2	10R7/12	10B6/10	7.5PB5/12								
5R4/14	7.5RP6/10	10Y8/4	10Y8.5/6								
7.5Y8/12	2.5B5/8	7.5YR8/8	10PB4/10								
2.5G7/10	10P3/8	10RP8/6	10YR3/1								
5P2.5/6	7.5R7/4	10R3/2	7.5YR6/4								

reflectance spectra we took Hardeberg's<sup>28</sup> optimal set consisting of 20 Munsell patches distributed approximately uniformly in the  $(a^*, b^*)$  plane (Table I). In addition to the measured spectral reflectance of each sample of the set, we took into account the following data to calculate the coefficients of the linear matrix: the spectral sensitivity curves of the camera, the imaging noise characterization (dark current variances and k coefficient associated to shot noise), the spectral power distribution of the recording and viewing illuminant given by the D65 simulator (Fig. 3), the CIE color matching functions. We completed the UMG computing procedure (see Ref. 13 for details), which requires much more computation than the Vora–Trussell's v factor, and obtained the following results:

The linear transform is

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 1.761 & 0.319 & 0.206 \\ 0.867 & 1.139 & 0.003 \\ -0.075 & 0.009 & 1.886 \end{bmatrix}_{IJMG} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}.$$
(5)

The minimal color error for the ensemble in CIELAB units is  $\varepsilon_{\min} = 1.423$ , and the UMG value is  $\theta = 0.899$ .

Note that the UMG value ( $\theta = 0.899$ ) is lower than the v factor (x = 0.9162). Since noise effects are also considered in UMG, it gives a more complete measure of goodness of the camera and, consequently, its value is lower than the v factor, which exclusively characterizes the deviation from the human color subspace (given by the CIE color matching functions). Using the linear transform of Eq. (5), we can calculate the XYZ, and hence, the CIELAB coordinates from some given RGB values provided by the camera.

Although we are more interested in color differences between sample pairs rather than in the absolute measurement of color, we briefly report on what the color fidelity of the camera estimates are. Figure 7 shows the  $a^{*}b^{*}$  plane with the points corresponding to the CIELAB cromaticities of the Munsell group center patches of the very pale and dark grayish sets measured by the spectroradiometer, and by the 3CCD camera with the linear transforms given by either Eq. (4) or Eq. (5). The mean color differences between the camera estimated CIELAB values and the spectroradiometer CIELAB measured values were calculated for the entire 90 samples of the very pale test plus the 70 samples of the dark grayish test, and they are contained in Table II. The results are quite close for the two sets and also for the two linear transforms. They reveal that the color fidelity of the camera estimates is limited by an average error of 7 CIELAB units. Although the UMG based linear transform leads to a mean color difference (or error) slightly higher than the CSS based linear transform (about 1 CIELAB or CIEDE2000 unit higher), the dispersion is lower. This means that the CSS based lin-



**Figure 7.** Chromaticity plane showing the CIELAB  $a^*b^*$  values of the Munsell group center patches measured by the spectroradiometer, and by the 3CCD camera with the linear transforms given by either Eq. (4) (CSS) or Eq. (5) (UMG). (a) Very pale set, (b) dark grayish set.

TABLE II. Statistics of the Color Differences Calculated between the Camera Estimated CIELAB Values and the Spectroradiometer Measured CIELAB Values for Each Patch of Both the Very Pale and the Dark Grayish Set. The Camera CIELAB Values were Computed using Two Different Linear Transforms: The Matrix with Subindex CSS (Eq. (4)), and the Matrix with Subindex UMG (Eq. (5)).

	Color differences tha camera estimated and the spectroradiometers mesured CIELAB values											
	Very F	Pale	Dark G	rayish	Me	an						
CIELAB	CSS	UMG	CSS	UMG	CSS	UMG						
Mean $\left(\overline{\Delta E_{ab}}\right)$	6.29	7.40	5.96	6.78	6.13	7.09						
std. dev ( $\sigma$ )	2.33	1.43	1.70	0.99	2.02	1.21						
$Max\left(\left\{\Delta E_{ab}^{*}\right\}_{max}\right)$	10.48	9.99	9.87	9.35								
$MIn \left( \left\{ \Delta E_{ab}^{\star} \right\}_{min} \right)$	1.19	3.70	3.38	5.06								
CIEDE2000												
$Mean\left(\overline{\Delta \mathcal{F}_{00}}\right)$	7.25	8.50	6.68	7.61	6.97	8.06						
std. dev ( $\sigma$ )	2.85	1.75	2.40	1.63	2.63	1.69						
$\operatorname{Max}\left(\left\{\Delta \mathcal{E}_{00}\right\}_{\max}\right)$	11.60	11.46	11.95	13.30								
$\operatorname{Min}\left(\left\{\Delta \mathcal{E}_{00}\right\}_{\min}\right)$	0.90	3.84	3.14	4.60								

ear transform leads to slightly more accurate results whereas the UMG based linear transform leads to slightly more precise results.

Using the test of very pale and dark grayish color patches of Fig. 2, we measured the color differences between each group center and its neighbors by both the reference instrument and the camera. The linear transforms from RGB to XYZ values, given by Eqs. (4) and (5), were separately taken into account to calculate the camera based color differences. Figure 8 shows the CIEDE2000 color differences  $\Delta E_{00}$  between the very pale Munsell patches. Each diagram corresponds to a given Munsell variation from the group center, e.g., +0.5 Value, -2.5 Hue, +1.0 Chroma, etc. From the results, it can be said that the camera (for both linear transforms) and the reference instrument show a high degree of agreement in the estimation of the color differences between very pale patches. Looking at the diagrams in detail, we can see that the highest coincidence is obtained in the estimation of the color differences corresponding to  $\pm 0.5$  variations in the Munsell Value. Figure 9 shows the CIEDE2000 color differences  $\Delta E_{00}$  between the dark grayish Munsell patches. Again, the diagrams show a good agreement between color differences measured by the spectroradiometer and the camera (for both linear transforms).

We have calculated the absolute discrepancies  $D_i$  (Eq. (2)) between the measurements obtained by both instruments for the very pale test (Table III) and the dark grayish test (Table IV). The mean values of the absolute discrepancies corresponding to each color variation are calculated in Tables III and IV. These mean values of the absolute discrepancy exceed the camera uncertainty in general. However, in the case of the very pale

CIEDE2000 – Very Pale



**Figure 8.** CIEDE2000 color differences  $\Delta E_{00}$  between each group center and its neighbors in the very pale set of Munsell patches (Fig. 2(a)).  $\Delta E_{00}$  are calculated from the measurements obtained by the spectroradiomenter and by the camera using either the CSS or the UMG linear transforms. The Munsell color variations concerned are: ±1.0 and ±0.5 Chroma, ±0.5 Value, and ±2.5 Hue.

subset, most of them fall in the camera tolerance (either 0.5  $\Delta E^*_{ab}$  or 0.6  $\Delta E_{00}$ ). This fact, along with the magnitude of the camera tolerance, can be considered a good achievement for the camera's performance. In the case of the dark grayish subset, whose color variations in Value and Chroma are also bigger, the absolute discrepancies are somewhat higher, and correspond to a much lower stimulation of the instrument sensors and a greater influence of dark current. If we consider the minimal color error calculated with the UMG approach for Hardeberg's ensemble ( $\varepsilon_{\min} = 1.423$  CIELAB units) as another reference for comparison, nearly all the absolute discrepancies calculated with the UMG matrix are lower than it.

We have calculated the relative discrepancies  $D_i^r$  (Eq. (3)) to further analyze the uniformity of the camera performance. Tables V and VI contain the results for the very pale and the dark grayish tests, respectively. In Tables V and VI, we have calculated the mean value of the (CSS or UMG) relative discrepancies aligned on the same row, i.e., corresponding to a given group center, and also the mean value of the relative discrepancies aligned on the same column, i.e., corresponding to a given color variation. These mean values, calculated using CIELAB and CIEDE2000 metrics, are graphed in Figs. 10 and 11. From Fig. 10, the relative discrepancies are low and quite uniform around the circle of hue in both the very pale and the dark grayish regions. This

fact also reveals a good property of the camera performance. In Fig. 10, the values calculated using CIEDE2000 and graphed in Fig. 10(a) lead to similar comments to those calculated using CIELAB and graphed in Fig. 10(b). Also the values calculated using either the CSS or the UMG linear transform lead to close graphs in Fig. 10. In Fig. 11, we observe again that the relative discrepancies are low in the evaluation of the color variations of the Munsell components. It can be appreciated that relative discrepancies are slightly higher in the evaluation of Munsell Hue variations than for Munsell Value variations. This is common for both color regions considered, the very pale (Figs. 11(a) and 11(b)) and the dark grayish (Figs. 11(c) and 11(d)). Slight differences in the estimation of small chroma variations (less than ±1.0 Munsell Chroma) can be appreciated depending on the use of CIEDE2000 or CIELAB. In such a case, CIEDE2000 formula tends to be more sensitive and makes the relative discrepancy between the camera and the reference instrument measurements higher than CIELAB formula.

The results shown in Figs. 8 through 11 and Table III through Table VI, computed from the camera estimated XYZ values using either the linear transform of Eq. (4) (matrix with subindex CSS) or Eq. (5) (matrix with subindex UMG), are very close each other, and do not allow us to extract any conclusion about the advantages of using one of them in particular. This fact means that

# CIEDE2000 – Dark Grayish



**Figure 9.** CIEDE2000 color differences  $\Delta E_{00}$  between each group center and its neighbors in the dark grayish set of Munsell patches (Fig. 2(b)).  $\Delta E_{00}$  are calculated from the measurements obtained by the spectroradiomenter and by the camera using either the CSS or the UMG linear transforms. The Munsell color variations concerned are: -1.0 and +2.0 Chroma, ±1.0 Value, and ±2.5 Hue.



**Figure 10.** Mean relative discrepancies between the camera and the spectroradiometer around the circle of Hue using: (a) CIEDE2000 metric, and (b) CIELAB metric. The data represented are contained in Tables V and VI. The graphs labeled with V = 8 corresponds to the very pale test, whereas V = 4 corresponds to the dark grayish test. CSS and UMG have the same meaning as in previous figures.

Small Color Differences in the Very Pale and Dark Grayish Regions Measured by Camera Vol. 49, No. 6, November/December 2005 613



**Figure 11.** Mean relative discrepancies between the camera and the spectroradiometer versus the Munsell color variations of Hue, Chroma and Value: (a)-(b) for the very pale test, and (c)-(d) for the dark grayish test. The data represented are contained in Tables V and VI.

the effects of the sources of imaging noise considered in our experiment do not significantly alter the color difference measurements.

# Application: Evaluation of Color Uniformity in Textile Dying

From the results obtained above, we consider that the camera system has promising characteristics for objective and automatic inspection of color matching. For this reason, we have applied this system to the evaluation of color uniformity in textile dying. A common task in inspection of textile color is the comparison between the center and both the left and right extremes of the usable width of a fabric piece (usually 150 cm). This is known as extreme-center color matching. The assessment may be repeated several times along the fabric length to evaluate the color uniformity of a piece. An extreme-center sample pair consists of an extreme sample, from either the left or the right side of the fabric piece, sewn side by side, to a sample taken from the central part of the fabric piece. Commonly, the color difference between them is visually estimated by an expert. If the color difference of the extreme-center samples is visually perceived, then the fabric is rejected. Two extreme-center sample pairs, i.e., the left center sample pair and the right center sample pair, are always assessed together at a given length of the fabric

piece. This inspection of the fabric quality is difficult to carry out and requires trained vision in color evaluation. Frequently, the standard of quality in the textile industry is very high, but it is difficult to apply because, in addition, the samples to compare are often of unsaturated dark colors, e.g., fabrics for men's suits, and may show very subtle color differences, and may involve texture effects, etc.

In this application, assessing textile samples is more complex than Munsell chips because the structure of the woven fabric adds texture to the colored sample. We have applied our camera vision system to assess eight extreme-center sample pairs of cloths of navy, blue, black and green colors in the dark grayish region. They are also assessed using the spectroradiometer as a reference instrument.

Because the fabric samples are textured, we have first analyzed their variability expressed as MCDM in CIEDE2000. We have calculated the MCDM from the measurements obtained by the spectroradiometer and the camera at ten different positions of each side, named A and B, of every extreme-center sample pair. In the case of the camera measurements, as was already stated above, each individual measurement  $(L_i^*, a_i^*, b_i^*)$  at a given position is, in turn, the average CIELAB values of the CIELAB values of each of the 300 × 300 pixels that compose the central field window of the captured

TABLE III. Absolute Discrepancy between the Measurements of the Color Difference Obtained by the Camera and by the Spectroradiometer for the Very Pale Subset Test.

								D <sub>00</sub> CIE	DE2000									
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	Chroma	-0.5 C	hroma	+0.5 0	hroma	+1.0 C	hroma	-0.5 V	/alue	+0.5	Value	Mea	an
	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 8/2	0.331	0.320	0.111	0.355	0.663	0.160	0.234	0.023	0.439	0.174	0.918	0.475	0.218	0.312	0.038	0.005	0.369	0.228
5RP 8/2	0.171	0.173	0.464	0.335	1.326	1.036	0.574	0.462	1.060	0.858	1.825	1.481	0.095	0.041	0.596	0.626	0.764	0.627
5P 8/2	0.586	0.537	0.402	0.086	0.869	0.848	0.401	0.391	0.606	0.576	0.915	0.850	0.272	0.225	0.015	0.059	0.508	0.447
5PB 8/2	1.060	0.987	0.722	0.295	0.221	0.705	0.025	0.266	0.024	0.270	0.037	0.538	0.051	0.025	0.410	0.458	0.319	0.443
5B 8/2	0.984	0.801	0.524	0.252	0.681	2.152	0.654	1.430	0.320	0.969	0.321	1.372	0.052	0.064	0.355	0.405	0.486	0.931
5BG 8/2	0.209	0.158	0.424	0.622	0.785	2.440	0.486	1.237	0.491	1.040	0.504	1.440	0.577	0.570	0.046	0.021	0.440	0.941
5G 8/2	0.968	1.609	0.668	0.747	1.558	3.127	0.909	1.581	0.521	0.953	0.771	1.496	1.465	1.397	2.458	2.437	1.165	1.668
5GY 8/2	0.268	0.638	1.052	0.438	1.903	2.450	1.484	1.909	0.604	0.786	0.512	0.743	0.027	0.030	0.442	0.504	0.786	0.937
5Y 8/2	0.461	0.178	0.107	0.045	1.125	1.314	0.643	0.750	0.493	0.608	0.841	1.071	0.296	0.288	0.148	0.174	0.514	0.553
5YR 8/2	0.039	0.069	0.693	0.687	0.227	0.110	0.068	0.070	0.053	0.146	0.175	0.026	0.268	0.250	0.896	0.928	0.302	0.286
Mean	0.508	0.547	0.517	0.386	0.936	1.434	0.548	0.812	0.461	0.638	0.682	0.949	0.332	0.320	0.540	0.562		
								D <sub>ab</sub> C	IELAB									
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	Chroma	-0.5 C	hroma	+0.5 0	hroma	+1.0 C	hroma	-0.5 V	/alue	+0.5	Value	Me	an
	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 8/2	0.363	0.415	0.112	0.336	0.295	0.021	0.093	0.076	0.161	0.055	0.399	0.026	0.255	0.332	0.131	0.109	0.226	0.171
5RP 8/2	0.214	0.160	0.179	0.096	0.777	0.567	0.365	0.276	0.734	0.549	1.354	1.009	0.083	0.048	0.921	0.930	0.578	0.454
5P 8/2	0.664	0.620	0.434	0.132	0.613	0.557	0.285	0.259	0.480	0.431	0.801	0.702	0.394	0.357	0.035	0.001	0.463	0.382
5PB 8/2	0.990	0.949	0.677	0.377	0.229	0.570	0.078	0.079	0.141	0.011	0.350	0.077	0.212	0.200	0.638	0.681	0.414	0.368
5B 8/2	0.816	0.706	0.541	0.346	0.380	1.185	0.307	0.731	0.038	0.488	0.141	0.656	0.125	0.125	0.364	0.411	0.339	0.581
5BG 8/2	0.276	0.235	0.209	0.423	0.333	1.389	0.205	0.712	0.264	0.672	0.000	0.835	0.591	0.575	0.329	0.261	0.276	0.638
5G 8/2	0.479	0.860	0.687	0.764	0.857	1.829	0.495	0.882	0.233	0.585	0.276	0.973	2.427	2.362	3.548	3.517	1.125	1.471
5GY 8/2	0.010	0.249	1.051	0.749	1.238	1.696	0.879	1.183	0.434	0.563	0.374	0.530	0.191	0.197	0.462	0.518	0.580	0.711
5Y 8/2	0.527	0.208	0.325	0.251	0.910	1.179	0.525	0.644	0.378	0.486	0.656	0.862	0.559	0.565	0.114	0.133	0.499	0.541
5YR 8/2	0.143	0.021	0.631	0.604	0.318	0.573	0.163	0.273	0.133	0.222	0.007	0.202	0.485	0.486	1.386	1.400	0.408	0.473
Mean	0.448	0.442	0.485	0.408	0.595	0.957	0.339	0.512	0.300	0.406	0.436	0.587	0.532	0.525	0.793	0.796		

TABLE IV. Absolute Discrepancy between the Measurements of the Color Difference Obtained by the Camera and by the Spectroradiometer for the Dark Grayish Subset Test

$D_{_{00}}$ CIEDE2000														
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	+2.0 C	hroma	-1.0 V	'alue	+1.0 V	alue	M	ean
	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 4/2	1.539	1.468	0.633	0.607	0.984	0.412	1.112	0.683	1.435	1.567	0.041	0.021	0.957	0.793
5RP 4/2	0.027	0.000	0.442	0.466	1.283	0.831	2.367	1.931	2.254	2.233	0.028	0.001	1.067	0.910
5P 4/2	0.409	0.235	0.229	0.447	0.833	0.732	0.864	0.640	2.776	2.753	0.155	0.156	0.878	0.827
5PB 4/2	0.404	0.038	0.318	0.120	0.852	1.272	1.545	2.568	1.895	1.487	1.425	1.443	1.073	1.155
5B 4/2	0.180	0.218	0.243	0.488	1.226	2.678	0.149	1.394	2.136	1.584	0.229	0.331	0.694	1.115
5BG 4/2	0.036	0.027	1.344	1.822	1.057	2.359	0.305	0.931	1.092	0.221	0.119	0.048	0.659	0.901
5G 4/2	0.572	0.675	0.275	0.292	1.167	0.354	1.463	2.682	1.855	1.177	0.129	0.062	0.910	0.874
5GY 4/2	0.522	0.408	0.254	0.233	0.059	0.277	0.949	1.457	0.760	0.684	0.803	0.913	0.558	0.662
5Y 4/2	1.032	0.863	0.650	0.329	0.393	0.684	1.460	2.257	1.105	1.099	0.889	0.783	0.922	1.003
5YR 4/2	0.427	0.510	0.310	0.213	0.383	0.069	0.555	0.006	0.276	0.247	0.747	0.725	0.449	0.295
Mean	0.515	0.444	0.470	0.502	0.824	0.967	1.077	1.455	1.558	1.305	0.457	0.448		
							D <sub>ab</sub> CIEL	AB						
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	+2.0 C	hroma	-1.0 V	'alue	+1.0 V	alue	M	ean
-	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 4/2	1.677	1.584	0.660	0.630	0.164	0.168	0.698	0.076	1.315	1.339	0.431	0.550	0.824	0.725
5RP 4/2	0.014	0.048	0.556	0.612	0.747	0.301	2.294	1.639	2.409	2.283	0.446	0.611	1.077	0.916
5P 4/2	0.037	0.190	0.431	0.659	0.131	0.076	0.667	0.356	2.983	2.879	0.801	0.925	0.842	0.848
5PB 4/2	0.021	0.263	0.343	0.557	1.019	1.332	1.233	1.650	2.296	1.998	2.078	2.147	1.165	1.324
5B 4/2	0.478	0.534	0.072	0.091	1.081	1.770	0.044	1.049	2.547	2.233	1.010	1.099	0.872	1.129
5BG 4/2	0.084	0.023	1.022	1.323	0.897	1.627	0.890	0.432	1.622	1.111	0.724	0.754	0.873	0.878
5G 4/2	0.542	0.660	0.241	0.263	0.942	0.395	0.559	1.899	2.207	1.811	0.515	0.645	0.834	0.945
5GY 4/2	0.585	0.492	0.166	0.111	0.021	0.200	0.835	1.291	0.293	0.217	1.376	1.463	0.546	0.629
5Y 4/2	0.594	0.441	0.410	0.109	0.346	0.598	1.957	2.942	2.022	2.075	0.474	0.325	0.967	1.081
5YR 4/2	0.485	0.605	0.119	0.014	0.122	0.449	0.310	0.395	0.688	0.725	0.288	0.134	0.335	0.387
Mean	0.452	0.484	0.402	0.437	0.547	0.692	0.949	1.173	1.838	1.667	0.814	0.865		

TABLE V. Relative Discrepancy between the Measurements of the Color Difference Obtained by the Camera and by the Spectroradiometer for the Very Pale Subset Test

								D ' <sub>00</sub> Cl	EDE20	00								
Group	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	-0.5 Cł	nroma	+0.5 C	hroma	+1.0 Chr	oma	-0.5 V	alue	+0.5 \	/alue	Mear	ı
Center	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS l	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 8/2	0.232	0.225	0.059	0.177	0.208	0.046	0.143	0.013	0.203	0.076	0.222 (	0.109	0.064	0.090	0.013	0.002	0.143	0.092
5RP 8/2	0.100	0.102	0.363	0.250	0.553	0.407	0.593	0.452	0.569	0.437	0.551 (	0.425	0.030	0.013	0.207	0.216	0.371	0.288
5P 8/2	0.437	0.394	0.221	0.044	0.426	0.414	0.431	0.419	0.408	0.384	0.341 (	0.314	0.085	0.069	0.005	0.019	0.294	0.257
5PB 8/2	0.992	0.894	0.271	0.103	0.076	0.224	0.018	0.171	0.014	0.142	0.011 (	0.146	0.016	0.008	0.145	0.160	0.193	0.231
5B 8/2	0.771	0.586	0.372	0.163	0.145	0.395	0.276	0.518	0.121	0.326	0.068 0	0.262	0.016	0.020	0.120	0.136	0.236	0.301
5BG 8/2	0.212	0.156	0.215	0.300	0.139	0.376	0.180	0.401	0.215	0.407	0.119 (	0.306	0.184	0.182	0.015	0.007	0.160	0.267
5G 8/2	0.394	0.580	0.386	0.422	0.255	0.453	0.304	0.476	0.253	0.419	0.200 0	0.355	0.590	0.554	0.719	0.715	0.388	0.497
5GY 8/2	0.129	0.282	0.341	0.129	0.325	0.400	0.493	0.593	0.287	0.358	0.154 (	0.216	0.009	0.010	0.149	0.168	0.236	0.269
5Y 8/2	0.211	0.077	0.075	0.030	0.215	0.247	0.267	0.304	0.233	0.280	0.209 0	0.259	0.096	0.093	0.051	0.059	0.170	0.169
5YR 8/2	0.023	0.041	0.425	0.420	0.055	0.025	0.031	0.031	0.027	0.072	0.048 (	0.007	0.098	0.091	0.282	0.291	0.124	0.122
Mean	0.350	0.333	0.273	0.204	0.240	0.299	0.274	0.338	0.233	0.290	0.192 (	0.240	0.119	0.113	0.171	0.177		
								D rab	CIELAB									
Group	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	-0.5 Cł	nroma	+0.5 C	hroma	+1.0 Chr	oma	-0.5 V	alue	+0.5 \	/alue	Mear	<u>ו</u>
Center	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS l	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 8/2	0.233	0.262	0.051	0.146	0.122	0.008	0.072	0.055	0.086	0.028	0.106 (	0.007	0.052	0.067	0.030	0.025	0.094	0.075
5RP 8/2	0.110	0.081	0.162	0.083	0.439	0.302	0.500	0.356	0.494	0.347	0.496 0	0.348	0.018	0.010	0.212	0.214	0.304	0.218
5P 8/2	0.417	0.385	0.255	0.071	0.317	0.284	0.320	0.287	0.334	0.295	0.300 0	0.258	0.085	0.077	0.007	0.000	0.255	0.207
5PB 8/2	0.983	0.924	0.308	0.160	0.087	0.203	0.058	0.056	0.085	0.006	0.106 (	0.022	0.046	0.044	0.154	0.163	0.228	0.197
5B 8/2	0.835	0.684	0.500	0.293	0.111	0.311	0.176	0.373	0.018	0.206	0.035 0	0.149	0.027	0.028	0.083	0.093	0.223	0.267
5BG 8/2	0.271	0.226	0.114	0.219	0.085	0.314	0.104	0.321	0.145	0.332	0.000 0	0.215	0.132	0.128	0.073	0.057	0.116	0.227
5G 8/2	0.206	0.341	0.359	0.392	0.199	0.381	0.224	0.368	0.141	0.319	0.086 0	0.272	0.687	0.663	0.690	0.686	0.324	0.428
5GY 8/2	0.005	0.120	0.422	0.284	0.255	0.333	0.345	0.438	0.209	0.262	0.110 (	0.152	0.042	0.044	0.105	0.117	0.187	0.219
5Y 8/2	0.321	0.115	0.230	0.173	0.195	0.245	0.233	0.278	0.177	0.222	0.155 (	0.199	0.124	0.126	0.026	0.030	0.183	0.174
5YR 8/2	0.090	0.012	0.364	0.346	0.090	0.157	0.083	0.135	0.068	0.110	0.002 (	0.053	0.121	0.121	0.291	0.293	0.139	0.153
Mean	0.347	0.315	0.277	0.217	0.190	0.254	0.212	0.267	0.176	0.213	0.139 (	0.167	0.134	0.131	0.167	0.168		

TABLE VI. Relative Discrepancy between the Measurements of the Color Difference Obtained by the Camera and by the Spectroradiometer for the Dark Grayish Subset Test

D <sup>r</sup> <sub>00</sub> CIEDE2000														
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	+2.0 C	hroma	-1.0 V	/alue	+1.0 V	alue	Me	ean
	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 4/2	0.637	0.598	0.925	0.870	0.184	0.073	0.188	0.112	0.141	0.155	0.004	0.002	0.347	0.302
5RP 4/2	0.014	0.000	0.305	0.319	0.391	0.237	0.423	0.332	0.263	0.260	0.003	0.000	0.233	0.191
5P 4/2	0.298	0.161	0.096	0.180	0.206	0.179	0.184	0.133	0.284	0.282	0.014	0.014	0.180	0.158
5PB 4/2	0.202	0.017	0.114	0.040	0.210	0.298	0.235	0.362	0.184	0.142	0.127	0.128	0.178	0.164
5B 4/2	0.092	0.110	0.213	0.387	0.225	0.433	0.020	0.175	0.239	0.172	0.021	0.030	0.135	0.218
5BG 4/2	0.021	0.015	0.520	0.645	0.212	0.419	0.043	0.120	0.117	0.023	0.011	0.004	0.154	0.204
5G 4/2	0.250	0.289	0.240	0.253	0.279	0.077	0.176	0.300	0.205	0.125	0.012	0.006	0.194	0.175
5GY 4/2	0.267	0.203	0.101	0.084	0.017	0.078	0.124	0.184	0.084	0.075	0.072	0.082	0.111	0.118
5Y 4/2	0.534	0.428	0.300	0.141	0.082	0.138	0.189	0.277	0.119	0.119	0.080	0.070	0.217	0.196
5YR 4/2	0.173	0.204	0.219	0.145	0.071	0.012	0.088	0.001	0.031	0.028	0.063	0.061	0.108	0.075
Mean	0.249	0.203	0.303	0.306	0.188	0.194	0.167	0.200	0.167	0.138	0.041	0.040		
	D <sup>r</sup> <sub>ac</sub> CIELAB													

							ab -							
Group Center	-2.5	Hue	+2.5	Hue	-1.0 C	hroma	+2.0 C	hroma	-1.0 V	alue	+1.0 V	alue	Me	ean
	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG	CSS	UMG
5R 4/2	0.674	0.625	0.920	0.861	0.040	0.039	0.116	0.012	0.109	0.111	0.042	0.053	0.317	0.284
5RP 4/2	0.007	0.022	0.355	0.383	0.299	0.111	0.444	0.299	0.236	0.222	0.041	0.056	0.230	0.182
5P 4/2	0.033	0.157	0.180	0.263	0.035	0.020	0.138	0.071	0.255	0.245	0.071	0.082	0.119	0.140
5PB 4/2	0.014	0.156	0.161	0.249	0.268	0.337	0.176	0.229	0.192	0.165	0.180	0.185	0.165	0.220
5B 4/2	0.244	0.268	0.075	0.088	0.253	0.384	0.006	0.135	0.245	0.211	0.090	0.097	0.152	0.197
5BG 4/2	0.047	0.013	0.479	0.579	0.251	0.413	0.137	0.061	0.152	0.102	0.063	0.065	0.188	0.205
5G 4/2	0.238	0.282	0.201	0.217	0.313	0.120	0.072	0.226	0.214	0.172	0.048	0.060	0.181	0.180
5GY 4/2	0.288	0.237	0.082	0.052	0.007	0.064	0.095	0.143	0.027	0.020	0.121	0.128	0.103	0.107
5Y 4/2	0.410	0.289	0.279	0.067	0.080	0.135	0.212	0.303	0.183	0.187	0.042	0.029	0.201	0.168
5YR 4/2	0.203	0.247	0.095	0.010	0.027	0.097	0.044	0.054	0.065	0.068	0.024	0.011	0.076	0.081
Mean	0.216	0.230	0.283	0.277	0.157	0.172	0.144	0.153	0.168	0.150	0.072	0.076		

TABLE VII. Assessment of Extreme-Center Sample Pair of Fabrics. In the Measurements Made by the Camera, the UMG Based Linear Transform from RGB to CIE XYZ Values was Used

Extreme-Ce	enter Sample	M	Color Va CDM CIEDE	ariability E2000 ( <i>n</i> ∆E	= <sub>00</sub> )	С	olor differer	Result		
Pair (I	_*a*b*)	Side A		Side B						
		SpecR.	Camera	SpecR.	Camera	SpecR.	Abs. Disc	Camera	SpecR.	Camera
Navy 1	(17,5:0,7:-4,8)	0,49	2,18	0,72	2,44	0,83	1,91	2,74	Pass	Pass
Navy 2	(17,6:0,6:-5,2)	0,27	1,20	0,35	1,18	0,75	2,19	2,94	Fail	Fail
Blue 1	(18,3:0,6:-5,4)	0,52	3,74	0,75	3,22	0,74	3,94	4,68	Pass	Pass
Blue 2	(18,2:0,6:-5,1)	0,24	2,44	0,33	2,72	0,37	2,77	3,14	Pass	Pass
Black 1	(16,3 : 1,0 : -2,6)	0,43	2,75	0,62	3,13	0,66	2,55	3,21	Pass	Pass
Black 2	(16,1:0,9:-2,4)	0,24	1,67	0,35	1,67	0,93	1,86	2,79	Fail	Pass
Green 1	(33,4:-0,4:8,9)	0,34	0,59	0,41	0,83	0,71	0,38	1,09	Pass	Pass
Green 2	(32,4:-0,4:8,9)	0,59	1,44	0,73	1,82	0,77	0,94	1,71	Pass	Pass



**Figure 12.** Assessment of the extreme-center sample pairs by: (a) camera, (b) spectroradiometer. The variability (side A, side B) and CIEDE2000 color difference () data are taken from Table VII.

image. Although we have computed the camera XYZ values using both the CSS and UMG based linear transforms of Eqs. (4) and (5), we only present the results obtained using the UMG linear transform in this section. Since each sample pair is made of a single fabric, we expect to obtain similar variabilities for both sides. The results are contained in Table VII and in Fig. 12. Note that each extreme-center sample pair is labeled by a generic color followed by a number and their mean  $L^* a^* b^*$  CIELAB coordinates measured by the spectroradiometer. As expected, the color variabilities of both sides of given pair, represented by small triangles in Fig. 12, are quite similar in all cases. The influence of texture can be clearly appreciated in the magnitudes of the MCDM values, especially those high values measured by the camera.

We measure the color difference between the sides A and B of each pair following this procedure: we calculate the color differences between a sample point of one side and each one of the ten sample points of the other side; then, we repeat the same calculation for the rest of nine sample points of the first side to complete a set of 100 individual measurements of the color differences between sides A and B of the given pair. We take then the mean value and compare it with the variabilities (expressed as MCDM) of both sides of the pair. If the mean color difference between both sides is clearly higher, depending of the quality standard, than the variabilities, then it can be said that the extreme-center samples of the pair are different, and the result is "fail". Otherwise, they are accepted as similarly dyed, and the color matching "passes" the test. The mean color differences, the absolute discrepancy between the camera and the reference instrument, and the pass-fail results obtained in our experiment are contained on the righthand of Table VII. The mean color differences measured by the spectroradiometer and the camera are also represented in Fig. 12 by small circles. As a quality standard, we have considered that a given extreme-center sample pair obtains a "fail" result when the mean color difference between its sides is higher than twice the highest variability of the sides. The instrument precision and the standard of quality have a decisive influence in the final result. Thus, for instance, if the common human visual discrimination of color was applied as quality standard, a suprathreshold of visual discrimination (0.887 CIELAB units<sup>29</sup>) could be used alternatively. We observe that the values obtained by the camera are generally higher than those obtained by the spectroradiometer, which might be due to a higher sensitivity of the camera to texture than the reference instrument. In other words, the spectroradiometer performs a certain integration within the sample area assessed, whereas the camera is more influenced by the variations of the fabric structure imaged pixel by pixel. However, both instruments lead ultimately to similar results. There is only one case (Black 2) out of the eight cases analyzed for which the final decision depends on the instrument: it fails for the reference instrument, but passes for the camera. In fact, this case is near the limit of the applied standard of quality (the mean color difference measured by the camera is 1.7 times the variability of the sides) and we should also bear in mind the difficulty of the color involved (black).

TABLE VIII. Absolute Discrepancies in the Color Differences of the Extreme-Center Sample Pairs Measured by the Spectroradiometer and the Camera in Three Cases: Without Filtering the Camera Images (the Data Coincide with those Presented in Table VII), with a Smoothing Filter, with a ( $\pm 20\%$ ) Filter.

		Color Difference								
Extreme	-Center Sample	Al	Absolute discrepancy							
Pair	(L*a*b*)	Without filtering	Without filtering Smoothing filter (							
Navy 1	(17,5:0,7:-4,8)	1,91	1,83	1,70						
Navy 2	(17,6:0,6:-5,2)	2,19	2,28	1,98						
Blue 1	(18,3:0,6:-5,4)	3,94	3,91	3,97						
Blue 2	(18,2:0,6:-5,1)	2,77	2,64	2,43						
Black 1	(16,3 : 1,0 : -2,6)	2,55	2,52	2,39						
Black 2	(16,1:0,9:-2,4)	1,86	1,83	1,66						
Green 1	(33,4:-0,4:8,9)	0,38	0,33	0,25						
Green 2	(32,4:-0,4:8,9)	0,94	0,91	0,93						

For a better understanding of both instrument performances, we have filtered the measurements obtained by the camera in order to introduce some integration in the sample area imaged. Two sorts of filters have been applied. One of them is a smoothing filter. In each sample, we have lightly smoothed the image using a Gaussian mask of  $5 \times 5$  pixels before taking the mean values of  $L^*a^*b^*$ . This filter averages the effects of texture within a sample area that approximately corresponds to thread size, more specifically, 5 pixels corresponds to the mean thread width in both the warp and weft directions of the fabric samples under study (in comparison, the integration area of the spectroradiometer is 100 times wider). Alternatively, we have built the  $L^*$  histogram of the sample image and then, we have neglected all the values within either the lowest 20% (shadow) or the highest 20% (bright) of the histogram. This other filter resembles a median filter. From the filtered images, we have recalculated all the variabilities and the color differences obtained by the camera system. For each sort of filter, we have built a table analogous to Table VII. In both cases of filtering, the results obtained by the camera were slightly closer to those obtained by the spectroradiometer than before (Table VII). The final Pass/Fail results did not alter in any case. Table VIII contains the absolute discrepancies between the measurements obtained by the spectroradiometer and the camera in all the three cases analyzed: without filtering (same as in Table VII), smoothing filter, and (±20%) filter. It can be seen that, in general, the absolute discrepancies reduce when some integrating filter is applied to the sample images captured by the camera.

# Conclusions

The method presented here analyzes the camera's capability to measure small color differences between sample pairs with reliability. In the first part, the appropriate working conditions are established, the camera spectral sensitivities and imaging noise are characterized, and the transformation to obtain a device independent representation of color is calculated considering two different approaches: one, on the basis of the camera spectral sensitivity (CSS), and two, on the basis of the unified measure of goodness of the camera (UMG) that involves an imaging noise model. In the second part, a large number of varied small color differences in the very pale and the dark grayish color regions are measured by both the camera and the reference instrument. The assessment of the camera performance is based on the analysis of the results, the involved uncertainty, the absolute discrepancy and the relative discrepancy between the camera and the reference instrument.

The method was applied to a camera vision system (3CCD camera SONY DX-9100P) placed in an observation booth with controlled illumination of a D65 real simulator. We used a spectroradiometer (PhotoResearch PR-715) as the reference instrument. Good agreement was obtained between the color differences measured by the spectroradiometer and the camera. Although the mean values of the absolute discrepancy exceed the camera uncertainty, most of them fall within the camera tolerance in the case of very pale colors (CIELAB 0.5  $\Delta E^*_{ab}$  or CIEDE2000 0.6  $\Delta E_{00}$ ). This fact, along with the magnitude of the camera tolerance, is considered a good achievement for the camera's performance. In the dark grayish region, probably caused by a greater influence of dark current, the absolute discrepancies are somewhat higher. Nevertheless, nearly all of them are still lower than the minimal color error calculated with the UMG approach ( $\varepsilon_{min}$  = 1.423 CIELAB units). The relative discrepancies are low and nearly uniform around the circle of hue in both the very pale and the dark grayish regions. This fact is also a good property of the camera performance. The use of the two CIELAB and CIEDE2000 metrics in parallel led to similar results. The two approaches (CSS and UMG) used in the linear transformation of the RGB values to the camera estimate XYZ values led also to similar results in the measurement of the color differences between sample pairs.

The camera system has been applied to the evaluation of color uniformity in textile dyeing. Eight pairs of extreme-center fabric samples have been analyzed by both the camera and the reference instrument. In this case, the effects of the texture are noticed. Although the camera is more sensitive to texture than the spectroradiometer, both instruments yielded consistent and satisfactory Pass/Fail results. Since the samples assessed were real cases of high difficulty (most of them were very dark colors), the results showed the high quality of the camera performance and, thereby, the potential of this sort of machine vision system for colorimetric tasks that usually have been exclusively the domain of trained observers.

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