High Color-Fidelity Imaging System Using B/W Digital Camera and Rotary Color Filters

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Abstract

We have developed a camera system that can acquire a high-resolution colorimetric image to reproduce an actual scene accurately. This system, which is based on color sequential technology, consists of a monochromatic digital camera and three color filters. Furthermore, to improve measurement accuracy, the image data are corrected using a set of calibration data, calculated from color chart optical data and diffuse-white plate data measured with a spectro-radiometer. The accuracy of the calibrated image data was tested under different illuminants. The result was satisfactory as a high color-fidelity imaging system.

Introduction

To acquire the spectral information of an illuminant or an object, a spectro-radiometer or spectral colorimeter is usually used. In recent years, studies on the acquisition of scene spectral information by means of multi-band image-capturing technique [1] have advanced. High-resolution and high-accuracy colorimetric images obtained by such approach are expected to be useful in various fields such as printing, electronic commerce, etc.

In order to reproduce colorimetric images, a monochromatic digital camera and three rotary thin-film interference color filters were used. To further improve colorimetric accuracy, a calibration method using the spectral as well as image data of a color chart such as Macbeth ColorChecker, NCS, and that of a diffuse-white plate.

In the present paper, a system capable of recording high-resolution, high-accuracy colorimetric images (referred to as NEDO-DSC, hereinafter) is described together with some evaluation results thereof.

System

System constitution

NEDO-DSC comprises a monochromatic digital camera (modified FinePix S2 Pro), a lens (Nikon AF Zoom, Nikkor ED 28-200mm, F3.5-5.6G), three thin-film interference color filters, a rotation-regulating controller (fabricated in-house) and a PC (Figure 1). The image-shooting operation and camera settings (shutter speed and aperture) are controlled by the PC.

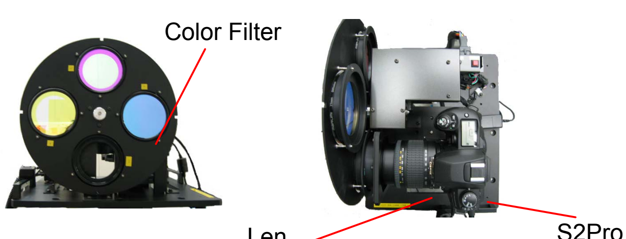

***Figure1**. System.*

Spectral design of color filters

To achieve colorimetric color reproduction, image data captured by the monochromatic digital camera and the three color filters must be converted to tristimulus values X, Y and Z. For this purpose, it is ideal that the spectral sensitivities corresponding to the three color filters are linear transformation of the CIE color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, respectively (the Luther condition). The spectral sensitivities of the color filters were designed so that the errors of the colorimetric values obtained by linearly transforming the spectral sensitivities of the image-capturing system including the spectral transmittances of the filters, the spectral sensitivity of the CCD, etc. from those obtained by the color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are minimized. The transmittance of each of the color filters thus designed is shown in Figure 2. The color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ and $\bar{x}'(\lambda)$, $\bar{y}'(\lambda)$ and $\bar{z}'(\lambda)$ obtained by linear transformation of the spectral sensitivities of the image-capturing system are shown in Figure 3.

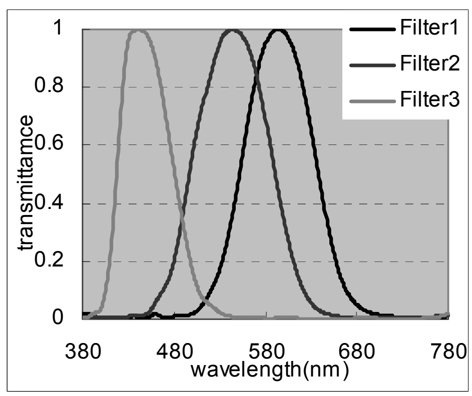

***Figure 2.** Transmittance spectra of the color filters.*

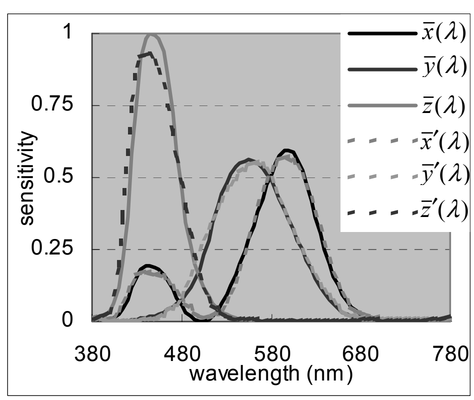

***Figure 3.** CIE color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, (2 degrees) and $\bar{x}'(\lambda)$, $\bar{y}'(\lambda)$, $\bar{z}'(\lambda)$.*

Evaluation of the spectral sensitivities

Generally speaking, the spectral sensitivities of an image-capturing system for a color image input device such as digital cameras, etc. should satisfy the Luther condition. There are a number of methods for evaluating the degree to which this condition is met: Neugebauer's quality factor [2] and measure of goodness by Vora and Trussell [3].

When Neugebauer's quality factor q, which is calculated by equation (1), is equal to 1, the Luther condition is satisfied

$$q = \sum_{i=1}^{3} a_i^2 \Big/ |\bar{s}|^2 \tag{1}$$

In this equation, $\bar{s}$ is the spectral sensitivity of the sensor, and $\{a_i\}$ is the expansion coefficient for the expansion of S on the normalized orthogonal basis of the visual subspace extended by human cone sensitivity. The concept is shown in Figure 4, in which, for simplicity, the three-dimensional visual sub-space is illustrated as a two-dimensional model.

In general, a color image input device has three sensors each having spectral sensitivity $\bar{s}_1$, $\bar{s}_2$ or $\bar{s}_3$ and outputs three kinds of signals S1, S2 or S3. Using a matrix having the optimal coefficients $\{a_{ij}\}$, linear transformation expressed by equation (2) is carried out, and the transformed result is displayed on a RGB monitor.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} \tag{2}$$

In the case explained above, the spectral sensitivities $\bar{r}$, $\bar{g}$ and $\bar{b}$ in the final RGB system are assumed to be linear transformation of $\bar{s}_1$, $\bar{s}_2$ and $\bar{s}_3$. And the evaluation of color reproducing capability of this set of sensors should be equivalent to that of $\bar{s}_1$, $\bar{s}_2$ and $\bar{s}_3$.

The measure of goodness ν proposed by Vora and Trussell in 1993 was defined according to equation (3).

$$\nu \equiv \sum_{i=1}^{3} q_i \Big/ 3 \tag{3}$$

In this equation, q_i is the Neugebauer's quality factor to the normalized orthogonal basis of the subspace extended by the sensor sensitivities. Again in this expression, when ν is equal to 1, the Luther condition is satisfied.

Here, ν thus defined evaluates the angle between the two sub-spaces as shown in Figure 5, and is invariant for the conversion represented by equation (2). In Table 1, the quality factor and measure of goodness for each of NEDO-DSC and two commercially available DSC's are shown. It is evident that NEDO-DSC has extremely good colorimetric capability.

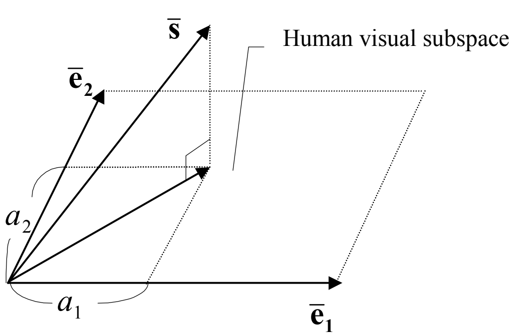

***Figure 4.** Neugebauer's quality factor.*

Color registration

Registration is a concern when a set of color filters is rotated to acquire color-interleave images sequentially. The main cause of registration error is the difference in slant of the filter for each color causing the optical axis to deviate from the actual ray of light as illustrated in Figure 6. Vibration accompanied by rotation may also cause registration error.

To determine the degree of the registration error, image shooting was carried out with four B/W cross marks arranged at the corners of the frame as shown in Figure 7. Table 2 shows the positional errors between the G, R and B channels obtained by making two sets of measurements. In general, for the registration of a pair of images, affine transformation is used, whereby three parameters, i.e., the shifts in X (horizontal) and Y (vertical) directions and the angular shift in the rotational direction, are used.

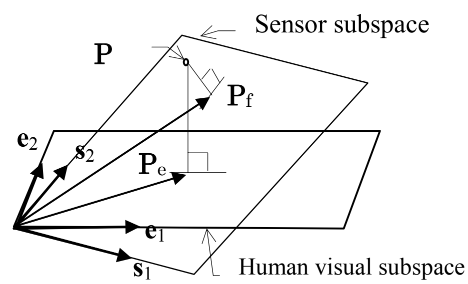

***Figure 5.** Geometric meaning of ν.*

Table 1. Q-factor and ν.

DSC	R	G	B	ν
NEDO-DSC	0.999	0.992	0.983	0.991
DSC(Company A)	0.776	0.996	0.874	0.882
DSC(Company B)	0.813	0.941	0.848	0.867

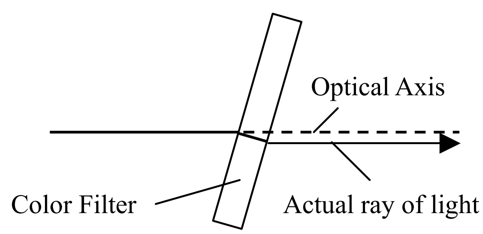

***Figure 6.** Main cause for registration error.*

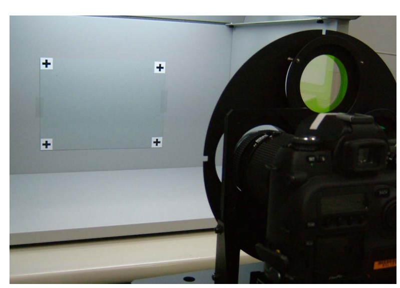

***Figure 7.** Registration checking method.*

Table 2. Registration error.

Filter	X (pixel)	Y (pixel)	Rotation (deg.)
R	0.025514	0.099484	0.0010
B	-0.024398	-0.014183	0.0005
R	-0.033403	0.038653	-0.0001
B	-0.074217	-0.020859	-0.0002

In Table 2, the degrees of shift in X (horizontal) and Y (vertical) directions are shown in terms of the quantities normalized by the pixel size of the CCD used for image capture. The unit for the angular shift in the rotational direction is degree. The degrees of shift in the horizontal and vertical directions did not exceed 10% of the CCD pixel size, while that in the rotational direction was 0.001 degrees or less. Thus, correction of the registration error in the captured images was judged unnecessary.

Data processing procedure

NEDO-DSC produces calibration data from the data obtained by the image-capture and measurement of color charts to achieve colorimetric recording of actual scenes. The procedure up to the completion of colorimetric image reproduction is shown in Figure 8. The initially captured data are acquired from RAW-DSC images.

Calibration data

The calibration data are produced from the initially captured image data and tristimulus values measured with a spectro-radiometer for the color charts and a diffuse-white plate. First of all, tristimulus values measured with a spectro-radiometer and normalized are given by

$$\begin{aligned} X &= \int R(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda \\ Y &= \int R(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda \\ Z &= \int R(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda \\ k &= 100/\int P(\lambda)\bar{y}(\lambda)d\lambda \end{aligned} \qquad (4)$$

wherein, $R(\lambda)$: spectral reflectance of an object, $P(\lambda)$: spectral distribution of the illuminant, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$: color matching functions.

In general, the spectral power distribution obtained with a spectro-radiometer is a product of $R(\lambda)$ and $P(\lambda)$ (= $S(\lambda)$), and $P(\lambda)$ can be derived by equation (5) when $R(\lambda)$ is known.

$$P(\lambda) = Sw(\lambda)/Rw(\lambda) \qquad (5)$$

Here, $Rw(\lambda)$ is the reflectance of a diffused-white plate with a known spectral reflectance, and $Sw(\lambda)$ is the spectral power

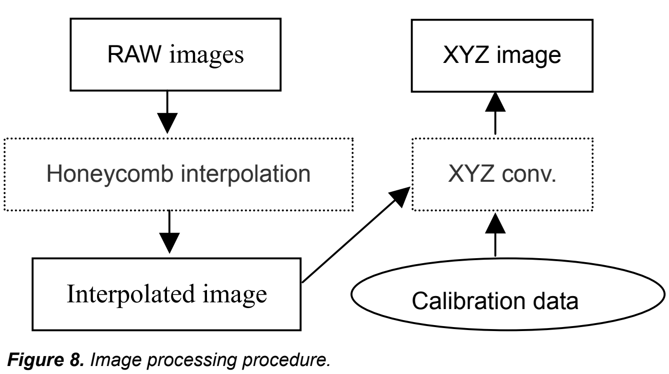

Figure 8. *Image processing procedure.*

distribution of the diffuse-white plate obtained with a spectro-radiometer.

Calibration data are produced as a 3x3 linear matrix A and correction terms α, β and γ. The production method is as follows.

Let the initial image data for n-th patch of color chart and the diffuse-white plate be (R_n, G_n, B_n) and (R_w, G_w, B_w) and the tristimulus values thereof measured with a spectro-radiometer be (X_n, Y_n, Z_n) and (X_w, Y_w, Z_w). Then, $A(\alpha,\beta,\gamma)$ can be obtained by equation (6) in which any value of α, β and γ are substituted.

$$A(\alpha,\beta,\gamma) = \begin{pmatrix} X_1 & \cdots & X_n & X_w \\ Y_1 & \cdots & Y_n & Y_w \\ Z_1 & \cdots & Z_n & Z_w \end{pmatrix} \begin{pmatrix} R_1' & \cdots & R_n' & R_w' \\ G_1' & \cdots & G_n' & G_w' \\ B_1' & \cdots & B_n' & B_w' \end{pmatrix}^{-1} \qquad (6)$$

$$\begin{cases} R_n' = (R_n - \alpha)/(R_w - \alpha) \\ G_n' = (G_n - \beta)/(G_w - \beta) \\ B_n' = (B_n - \gamma)/(B_w - \gamma) \end{cases}$$

The resulting $A(\alpha,\beta,\gamma)$ is substituted into equation (7).

$$\begin{pmatrix} X_n' \\ Y_n' \\ Z_n' \end{pmatrix} = A(\alpha,\beta,\gamma) \begin{pmatrix} R_n' \\ G_n' \\ B_{n'} \end{pmatrix}$$

(7)

Then, with illuminant tristimulus values of (X_l, Y_l, Z_l), (X_n', Y_n', Z_n') and (X_n, Y_n, Z_n) obtained from equation (7) are substituted in equation (8).

$$\begin{pmatrix} L_n' \\ a_n' \\ b_n' \end{pmatrix} = \begin{pmatrix} 0 & 116 & 0 \\ 500 & -500 & 0 \\ 0 & 200 & -200 \end{pmatrix} \begin{pmatrix} (X_n'/X_l)^{1/3} \\ (Y_n'/Y_l)^{1/3} \\ (Z_n'/Z_l)^{1/3} \end{pmatrix} \qquad (8)$$

In addition, (α,β,γ) that minimizes $E(\alpha,\beta,\gamma)$ obtained from equation (9) is derived to give calibration data A from equation (6).

$$E(\alpha,\beta,\gamma) = \sum_{i=1}^{n} \sqrt{(L_i - L_i')^2 + (a_i - a_i')^2 + (b_i - b_i')^2} \Big/ n \qquad (9)$$

Experiments and results

Colorimetric accuracy

Under the illumination of the three kinds of illuminant shown in Figure 9, the colorimetric values of NEDO-DSC obtained using the calibration data derived by the aforementioned calibration method were compared with those actually measured with a spectro-radiometer CS-1000 (Konica-Minolta). The spectral data of the illuminants used are shown in Figure 9, in which the ordinate plots radiant energy normalized so that Y of the illuminant is equal to 100. Table 3 shows the CIELAB average color difference between NEDO-DSC and CS-1000 for the 64 color patches in Macbeth ColorChecker and NCS-chart ($\Delta\overline{E}$), the average color difference for gray ($\Delta\overline{E}_g$), and the maximum color difference ΔE_{max} under each illuminant. Sufficiently small average color differences with weak illuminant dependence were obtained. Meanwhile, under illuminant 2, the average color difference between Prometric Color 1400, a 2D-XYZ spectral colorimeter of Radiant Imaging, Inc. applied to the present calibration method and

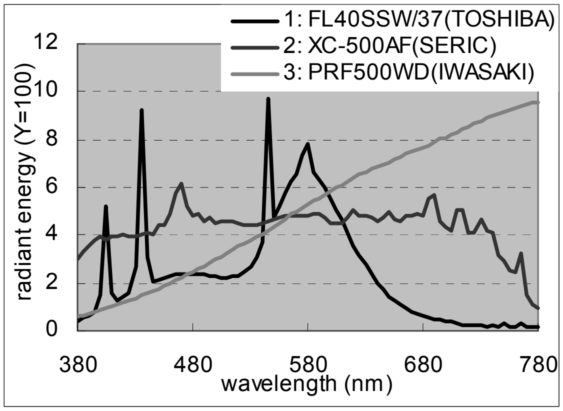

Figure 9. Spectra of the illuminants.

Table 3. Colorimetric accuracy of NEDO-DSC.

Illuminant	$\Delta\overline{E}$	$\Delta\overline{E}_g$	ΔE_{max}
1	1.77	0.38	6.27
2	1.86	0.54	6.25
3	2.08	0.72	7.44

CS-1000 was $\Delta\overline{E}$ = 3.69. NEDO-DSC gives a result better than the commercially available device.

Comparison with a commercial DSC product

In Figure 10, the colorimetric values obtained by shooting Macbeth ColorChecker with an S2 Pro, a DSC of Fuji Photo Film Co., Ltd., those obtained with NEDO-DSC, and those obtained with PR 650, a spectro-radiometer of Photo Research, Inc. are compared on the CIELAB a*b* plane. In the DSC shooting, the shutter aperture was fixed, and the other functions were automatically set. Since the image captured by S2 Pro is output as sRGB, image rendering is based on D65. For the comparison under D65, the colorimetric values obtained with NEDO-DSC were converted to those under D65 via the von Kries transformation. The data measured with the spectro-radiometer were also calculated to give the colorimetric values under a D65 illuminant. The NEDO-DSC values agree well with the measurement with the spectro-radiometer. Figure 11 compares the images recorded with NEDO-DSC and S2 Pro for a scene containing a girl and a Macbeth ColorChecker. The image data captured with NEDO-DSC is transformed into the D65 color space using a von Kries transform, and then displayed as an sRGB image and compared with the output from S2 Pro. When these two sRGB images are observed on an sRGB monitor, the NEDO-DSC image was judged an accurate reproduction of the scene.

Conclusion

This paper introduced a system capable of reproducing high-resolution, high-accuracy colorimetric images using a monochromatic digital camera and thin film interference color filters. Further, the accuracy of this system was experimentally evaluated.

In the future, using this system, we plan to define actual scene-referred color space, capture the images of fluorescent or semi-transmissive objects and put spectral sensitivity evaluation method for RAW-DSC into practice.

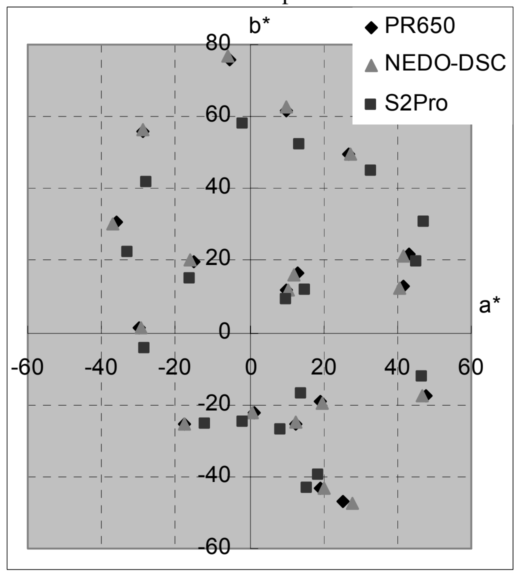

Figure 10. Comparison of NEDO-DSC with S2 Pro: color reproduction accuracy.

(a) S2Pro (b) NEDO-DSC

Figure 11. Comparison of NEDO-DSC (b) with S2 Pro (a): sRGB image appearance.

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Author Biography

Masayuki Kuramoto received his MME degree in mechanical engineering form Shizuoka University in 2003. From 2003 he is working for Fuji Photo Film Co., Ltd.. His interest is focused on colorimetric image reproduction using a digital camera.