JOURNAL OF IMAGING SCIENCE AND TECHNOLOGY® • Volume 49, Number 6, November/December 2005

Application of a Colorimetric Evaluation Model to Multispectral Color Image Acquisition Systems

Noriyuki Shimano
Department of Informatics, School of Science and Engineering, Kinki University, Osaka, JAPAN

With the recent advances in color management systems, the estimation of accurate colorimetric values of objects being imaged by the use of sensor responses becomes an important function of color image acquisition devices such as digital cameras and color scanners. Therefore, colorimetric evaluation of a set of sensors is important to evaluate the colorimetric performance of the sensors. It is well known that the colorimetric quality of the sensors depends not only on the spectral sensitivities but also on the noise present in them. Although several evaluation models have been proposed, application of the models to real color image acquisition devices has not been appeared since it was impossible without prior knowledge about the noise present in the devices. In this article, a new model to estimate the noise variance of an image acquisition system is proposed based on the colorimetric evaluation model and for the first time the evaluation model was applied to real multispectral cameras by using the estimated noise variance. It is confirmed by the experiments that the proposed colorimetric quality is in good agreement with the experimental results and that the noise variance of the image acquisition system can be accurately estimated by the proposal.

Journal of Imaging Science and Technology 49: 588–593 (2005)

Introduction

With the recent advances in color management systems, the estimation of accurate colorimetric values of pixels of objects being imaged is an important function of color image acquisition devices. It is well known that the accuracy of the estimation depends on the spectral sensitivities of a set of sensors, objects being imaged, recording and viewing illuminants and noise present in the devices. If the accuracy can be evaluated *a priori* using the factors described above, the evaluation will be very useful since it provides a measure to select a set of sensors suitable for the applications and to optimize the sensors. Therefore several models to evaluate the colorimetric performance of a set of sensors have been proposed.[1–5] Neugebauer's colorimetric factor was the first proposal to evaluate a single sensor.[1] However, it is impossible to use the model for the evaluation of a set of sensors. To overcome the drawbacks of the Neugebauer's model, Vora and Trussell proposed a model to evaluate a set of sensors for the first time.[2] In their model, a random variable assumption was used for the statistical properties of reflectance spectra of objects and the noise present in the devices was not taken into account. Spectral reflectances of natural objects are smooth over the visible wavelengths and fall into a subspace spanned by a few orthogonal vectors.[6–9] Therefore their assumption was not correct.

Recently three models have been proposed by taking the noise and statistical properties of reflectance spectra into account.[3–5] Sharma and Trussell proposed a comprehensive analysis to establish the colorimetric quality (they used the term "figure of merit") of an image acquisition device by taking account of the signal independent noise and the statistical properties of spectral reflectances of samples in the tristimulus values, the orthogonal color space, and the linearlized CIELAB color space.[3] Although they evaluated many sets of sensors at various color space and SNR's by computer simulations, to the author's knowledge the application of the model to real devices has not been appeared. Quan, Ohta, Berns, Jiang, and Katoh also proposed an evaluation model by taking the signal dependent noise into account.[4] However, the evaluation of a set of sensors by their proposal was performed assuming signal independent noise.[4] The estimation of the noise levels of a set of color sensors is essential to evaluate the colorimetric quality or to obtain optimal spectral sensitivities of a set of sensors. A simple formula is desirable to give an intuitive insight into the influence of noise on color correction[10] and to predict new phenomena.[11] However, these two models were not sufficient. Shimano proposed a simple formula to evaluate the colorimetric quality of a set of color sensors by considering the statistical properties of spectral reflectance of samples and signal independent noise.[5] The model predicts that the increase in the color error by the presence of noise can be suppressed by properly designed spectral sensitivities. Since color errors are separated into noise dependent and independent terms

Original manuscript received July 15, 2004

Corresponding Author: N. Shimano, Shimano@info.kindai.ac.jp

Supplemental Material—An Appendix can be found on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.

in his formulation, his model provides a novel method for estimating the noise variance of the devices.[10]

However the application of the evaluation model to real color imaging devices has not appeared since it is impossible without prior knowledge of the noise present in the devices. Indeed, spectral sensitivities of a device, spectral power distributions of illuminants and spectral reflectances of objects can be measured by experiments but noise is very difficult to measure. To solve the inverse problem, e.g., the estimation of colorimetric values[12,13] or the reconstruction of reflectance spectra[14–16] through the use of sensor responses or the recovery of a blurred image,[17,18] only the noise originating from a sensor such as a CCD alone[19,20] is not sufficient. The measurement errors induced during measurements of spectral characteristics of a set of sensors, an illuminant, reflectance spectra of objects, etc., also must be considered as noise to solve the inverse problems, for instance by the use of the Wiener filter.[21] In this study, the noise is defined to include all sensor response errors that originate not only from the CCD itself but also from measurement errors in spectral characteristics of sensitivities, illuminants, surface reflectances, etc., and these combined errors are denoted as the system noise, below. Hereafter the application of colorimetric evaluation models to real devices and the optimization of a set of sensors under the image acquisition system's real signal-to-noise ratio (SNR) have not appeared.

In this study the system noise variance of a multispectral imaging device was estimated following this new proposal for the first time and it was applied to the colorimetric evaluation of the multispectral image acquisition systems. The experimental results from the evaluation agree fairly well with the proposed model.

This article is organized as follows. The outline of the colorimetric evaluation model and the method to estimate the noise variance are introduced. In the following section, the experimental procedures and results to demonstrate the trustworthiness of the proposal are described. The final section presents conclusions.

Model

In this section a brief sketch for the derivation of the colorimetric evaluation model and a model to estimate the system noise variance of an image acquisition system is described. For more detail see Refs. 5 and 10.

Colorimetric Evaluation Model

A brief sketch for the derivation of the colorimetric evaluation model is presented below. A sensor response vector from a set of color sensors for an object with a $N \times 1$ (where, N represents the sampling number over the visible wavelengths from 400 nm to 700 nm) spectral reflectance vector $\mathbf{r}$ can be expressed by

$$\mathbf{p} = SL\boldsymbol{r} + \boldsymbol{e}, \tag{1}$$

where $\mathbf{p}$ is a $M \times 1$ sensor response vector from the M channel sensors, S is a $N \times N$ matrix of a set of spectral sensitivities in which a row vector represents a spectral sensitivity, L denotes a $N \times N$ diagonal matrix for recording illuminant. $\mathbf{e}$ is a $M \times 1$ additive system noise vector which includes all the sensor response errors originated not only from a CCD itself but also from the measurement of the spectral characteristics of a system as described above. For abbreviation, let $S_L = SL$ below. Denote the projection matrix onto the human visual subspace (HVSS) as P_v. The projected vector $P_v\mathbf{r}$ is termed a fundamental vector[22] below, since the visual system is dependent only on the component of the vector that lies in the HVSS. If $\hat{\mathbf{r}}$ represents a spectral reflectance recovered by Wiener estimation,[21] the vector error $\Delta\mathbf{r}_h$ between the recovered and actual fundamental vector is given by

$$\Delta\mathbf{r}_h = P_v\mathbf{r} - P_v R_{SS} S_L^T (S_L R_{SS} S_L^T + \sigma_e^2 I)^{-1}\mathbf{p}\,, \tag{2}$$

where R_{SS} is an autocorrelation matrix of the spectral reflectance of samples, σ_e^2 is the noise variance for the Wiener estimation and I represents the identity matrix. Usually the value of the noise variance is unknown. Since R_{SS} is symmetrical, it is represented by a set of eigenvectors and eigenvalues of the matrix $R_{SS} = V\Lambda V^T$ where V represents a $N \times N$ basis matrix; Λ is a $N \times N$ diagonal matrix of eigenvalues of the matrix.

Let $S_L^V = S_L V \Lambda^{1/2}$. The singular value decomposition (SVD) of the matrix is given by

$$S_L^V = \sum_{i=1}^{\beta} \kappa_i^v \mathbf{d}_i^v \mathbf{b}_i^{vT}\,,$$

where $\beta = \mathrm{Rank}\,(S_L^V)$, and κ_i^v, $\mathbf{b}_i^v$, and $\mathbf{d}_i^v$ represent the ith singular value, the ith right and left singular vectors, respectively. By substituting these relations into Eq. (2) and averaging the square of the Euclid-norm of the error vectors $\|\Delta\mathbf{r}_h\|^2$ over the surface reflectances, if the noise variance used for the Wiener estimation σ_e^2 is equal to the noise variance of the system noise $\mathbf{e}$, then we obtain the mean square error (MSE) given by[5]

$$MSE = \sum_{i=1}^{\alpha} \left\|\mathbf{a}_i^v\right\|^2 - \sum_{i=1}^{\alpha} \left\|P_{CV}\mathbf{a}_i^v\right\|^2 + \sum_{i=1}^{\alpha}\sum_{j=1}^{\beta} \left(\frac{\sigma_e^2}{\kappa_j^{v^2} + \sigma_e^2}\right)\left(\mathbf{b}_j^{v^T}\mathbf{a}_i^v\right)^2 \tag{3}$$

where P_{CV} is the projection matrix onto the subspace spanned by a set of basis vectors

$$\left\{\mathbf{b}_i^v\right\}_{i=1-\beta}.$$

A column vector $\mathbf{a}_i^v$ is given by $\mathbf{a}_i^v = \Lambda^{1/2}V^T\mathbf{a}_i$, where $\mathbf{a}_{i,i=1,\ldots,\alpha}$ represent orthonormal basis vectors which span the HVSS. The first and second terms on the right hand side of Eq. (3) represent the MSE for the noiseless case and the third term represents the increase in the MSE in the presence of noise.

If the square of the singular values κ_i^{v2} is larger than the system noise variance σ_e^2, i.e., $\kappa^{v2}_{i,i=1,\cdots,\beta} >> \sigma_e^2$, then the third term is negligible. Therefore, if a set of sensors with large values of κ_i^v is used, the noise effect will be suppressed.[5]

To relate the above argument to evaluate colorimetric quality, Eq. (3) can be rewritten as

$$MSE = \sum_{i=1}^{\alpha}\left\|\mathbf{a}_i^v\right\|^2 \left(1 - \frac{\sum_{i=1}^{\alpha}\left\|P_{CV}\mathbf{a}_i^v\right\|^2 - \sum_{i=1}^{\alpha}\sum_{j=1}^{\beta}\left(\frac{\sigma_e^2}{\kappa_j^{v^2} + \sigma_e^2}\right)\left(\mathbf{b}_j^{v^T}\mathbf{a}_i^v\right)^2}{\sum_{i=1}^{\alpha}\left\|\mathbf{a}_i^v\right\|^2}\right). \tag{4}$$

Therefore, the *MSE* is expressed as

$$MSE = \sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|^2 \left(1 - Q_S\right), \tag{5}$$

where Q_S represents the colorimetric quality and therefore the quality is defined as

$$Q_S = \frac{\sum_{i=1}^{\alpha} \left\| P_{CV} \mathbf{a}_i^v \right\|^2 - \sum_{i=1}^{\alpha} \sum_{j=1}^{\beta} \left(\frac{\sigma_e^2}{\kappa_j^{v2} + \sigma_e^2} \right) \left(\mathbf{b}_j^{vT} \mathbf{a}_i^v \right)^2}{\sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|^2}. \tag{6}$$

This equation shows that the *MSE* has a linear relation to Q_S and the slope of the line depends on

$$\sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|.$$

The values of

$$\sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|^2$$

are dependent on the viewing illuminant, the CIE color matching functions and the surface spectral reflectances of the objects being captured.[23]

A Model to Estimate Noise Variance

Usually it is difficult to use the Wiener filter correctly without prior knowledge of the noise present in a device. As described above, to solve the inverse problem not only the noise originated from a CCD itself but also the errors caused during the measurement of the spectral characteristics of an imaging system (the spectral sensitivities of sensors, spectral power distribution of illuminants, spectral reflectances, etc.) must be considered as system noise. Let us consider how to estimate the system noise variance as follows. If we let the noise variance $\sigma_e^2 = 0$ for the Wiener filter in Eq. (2), the $MSE(\sigma_e^2 = 0)$ for the signal by Eq. (1) is given by (for details see Appendix, *available as Supplemental Material on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication).*

$$MSE\left(\sigma_e^2 = 0\right) = \sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|^2 - \sum_{i=1}^{\alpha} \left\| P_{CV} \mathbf{a}_i^v \right\|^2 + \sum_{i=1}^{\alpha} \sum_{j=1}^{\beta} \left(\frac{\sigma^2}{\kappa_j^{v2}} \right) \left(\mathbf{b}_j^{vT} \mathbf{a}_i^v \right)^2, \tag{7}$$

where σ^2 represents the variance of the system noise $\mathbf{e}$ (for detail see Appendix). Therefore, the system noise variance σ^2 can be formulated as[10]

$$\hat{\sigma}^2 = \frac{MSE\left(\sigma_e^2 = 0\right) - \sum_{i=1}^{\alpha} \left\| \mathbf{a}_i^v \right\|^2 + \sum_{i=1}^{\alpha} \left\| P_{CV} \mathbf{a}_i^v \right\|^2}{\sum_{i=1}^{\alpha} \sum_{j=1}^{\beta} \frac{\left(\mathbf{b}_j^{vT} \mathbf{a}_i^v \right)^2}{\kappa_j^{v2}}}. \tag{8}$$

To summarize, the system noise variance can be estimated following steps: (1) After the preparation of a color chart, an image acquisition device and a recording illuminant, of which all the spectral characteristics are known, we take a picture of the chart. (2) It is possible to compute the second and third terms of the numerator and the denominator of Eq. (8) since the spectral sensitivities of the set of sensors, spectral power distribution of the illuminant and spectral reflectances of the chart are known. (3) The ($MSE(\sigma_e^2 = 0)$ can then be obtained from Eq. (2) with the application of Wiener filter with $\sigma_e^2 = 0$ to sensor responses and by averaging the square of Euclid-norm $\| P_v \mathbf{r} - P_v \hat{\mathbf{r}} \|^2$ over color samples, where $\mathbf{r}$ and $\hat{\mathbf{r}}$ represent the actual (measured) surface reflectance of a color and the recovered surface reflectance by the Wiener filter with $\sigma_e^2 = 0$, respectively. Then the noise variance can be estimated by using Eq. (8).

Experimental Results

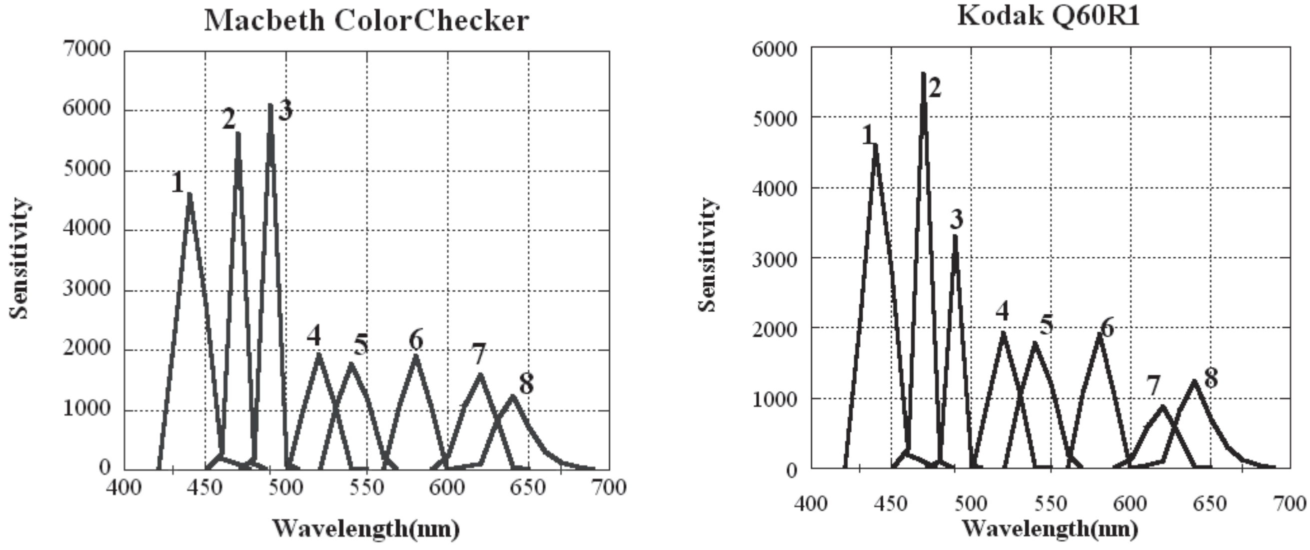
Experimental Procedures

A color image acquisition system was assembled by using eight interference filters (Asahi Spectral Corporation) in conjunction with a monochrome video camera (Sony XC-75) with an optical lens (Canon zoom lens V6 × 16). Image data from the video camera were converted to 8 bit-depth digital data by an analog-to-digital converter. The spectral sensitivity of the video camera with the optical lens was measured over the wavelengths from 400 to 700 nm at 10 nm intervals. The multiplication of the sensitivities of the video camera with the measured transmittance of the filters at each sampled wavelength gives the spectral sensitivities of the multispectral color image acquisition device. The measured spectral sensitivities for the acquisition of the images of the Macbeth ColorChecker and Kodak Q60R1 are illustrated in Fig. 1, where the eight sensors were numbered from one to eight to distinguish each sensor. By the combination of these sensors, plural multispectral color image acquisition systems were assembled and they were used for the evaluation. The small differences between the two sets of spectral sensitivities as illustrated in Fig. 1 are due to the use of neutral density (ND) filters to prevent sensor responses for given color chart from saturating. The illuminant used for image capture was a halogen lamp. The spectral power distribution of the halogen lamp was measured by the spectroradiometer and the result is presented in Fig. 2. In this study, the CIE-D65 was used as a viewing illuminant.

The Macbeth ColorChecker (24 colors) and Kodak Q60R1 (228 colors) were used as color charts and were illuminated from the direction of about 45° to the surface normal. Then the images were captured by the video camera from the normal direction. Usually sensor responses as a function of the light intensity are nonlinear due to the saturation of the CCD's output at higher exposures. Therefore the nonlinearity was corrected by using a look-up table (LUT) which was prepared by using a pre-measured relation between sensor responses and the light intensity. The linearlized image data were transformed to correct the non-uniformity of the illumination over the chart and of the sensitivities of each pixel of a CCD by using the next relation

$$\hat{p}_{i,j,k} = \frac{F(p_{\mathrm{i,j,k}} - d_{\mathrm{i,j,k}})}{F(w_{\mathrm{i,j,k}} - d_{\mathrm{i,j,k}})}, \tag{9}$$

where $p_{\mathrm{i,j,k}}$, $w_{\mathrm{i,j,k}}$, $d_{\mathrm{i,j,.k}}$ and $p_{\mathrm{i,j,.k}}$ represent a sensor response to a color chart, a sensor response to a white calibration



(a) (b)

Figure 1. Spectral sensitivities of sensors used for the acquisition of the images of (a) Macbeth ColorChecker and (b) Kodak Q60R1.

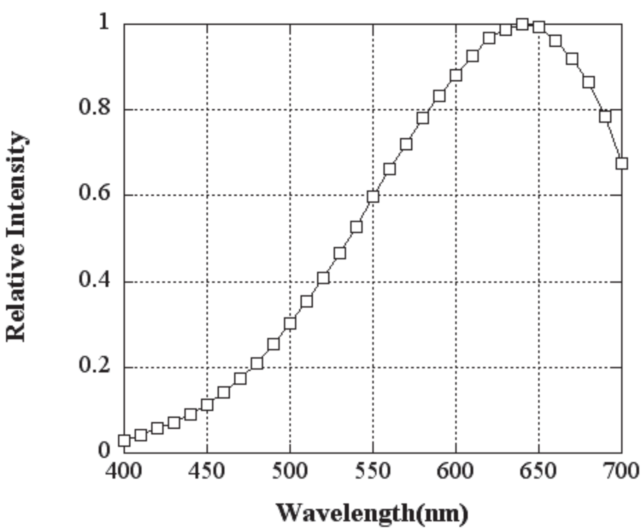


Figure 2. Spectral power distribution of the halogen lamp used for image capture.

paper placed on the color chart, a dark signal of the CCD and a corrected sensor response for the ith channel at the (j, k) th pixel. $F(\bullet)$ in Eq. (9) represents the transformation from nonlinear to linear response characteristics as a function of exposures using the LUT. Since the absolute values of spectral sensitivities of a camera depend on the camera gain, the camera's responses to a color computed by using the measured spectral characteristics of the sensors, the illumination and the surface reflectance of the color does not equal to the actual sensor responses. Therefore, the sensitivities were calibrated using an achromatic color in the charts.

The system noise variance $\hat{\sigma}^2$ of the multispectral color image acquisition system was estimated by the procedures described above. The value was computed with the constraint $\rho = Tr(S^{L}R_{SS}S_{L}^{T}) = 1$ for each sensor set, since the intensity of the signals is limited practically.[3,5] The estimated noise variance $\hat{\sigma}^2$ was used to compute the colorimetric quality Q_S defined in Eq. (6) and also used in Eq. (2) to compute the MSE by averaging the square of the Euclid-norm of the error vectors $\|\Delta\mathbf{r}_h\|^2$ over the colors. The values of the MSE, Q_S and average color difference ΔEab^* in the CIELAB space were computed for each combination of sensors by selecting three to eight sensors as represented in Fig. 1.

Table I represents typical examples of the estimated parameters for the acquisition of Kodak Q60R1 by various combinations of sensors. In this table the values of $MSE(\hat{\sigma}^2)$, $MSE(\hat{\sigma}^2 = 0)$ and $MSE(\hat{\sigma}^2_{opt})$ represent the $\hat{\sigma}^2_{opt}$ MSE at $\sigma_e^2 = \hat{\sigma}^2$, $\sigma_e^2 = 0$ and $\sigma_e^2 = \hat{\sigma}^2_{opt}$, respectively, where represents the system noise variance which minimizes the MSE. From the results, it is confirmed that the values of the $MSE(\hat{\sigma}^2 = 0)$ decrease to those of the $MSE(\hat{\sigma}^2)$, which agree quite well with those of the $MSE(\hat{\sigma}^2_{opt})$, by using the estimated system noise variance $\hat{\sigma}^2$, and that the estimated noise variances agree fairly well with the values of $\hat{\sigma}^2_{opt}$. The aim of the determination of noise variance is to recover the surface reflectance spectra accurately, therefore the experimental results are considered to be satisfactory. The signal-to-noise ratio (SNR) was computed by the relation of $SNR = 10\log(\rho/\hat{\sigma}^2)$. The SNR's of the multi-spectral image acquisition systems are about 30 dB. From Table I, it is also confirmed that the value of the colorimetric quality Q_S decreases with an increase in $MSE(\hat{\sigma}^2)$.

To check the trustworthiness of the proposed colorimetric quality Q_S, the MSE as a function of the Q_S is given in Fig. 3. The values of the MSE (MSE corresponds to $MSE(\hat{\sigma}^2)$ in Table I) and Q_S in this figure were computed by using the estimated system noise variance . The two lines in this figure are the theoretical lines which are given by Eq. (5). The slope of the line is determined by the value of

$$\sum_{i=1}^{\alpha}\left\|\mathbf{a}_i^v\right\|.$$

TABLE I. Estimated Parameters for the Acquisition of the Kodak Q60R1 by Multispectral Cameras

Filters	Q_S	$MSE(\hat{\sigma}^2)$	$MSE(\hat{\sigma}_e^2=0)$	$MSE(\hat{\sigma}_{opt}^2)$	SNR	$\hat{\sigma}^2$	σ_{opt}
12345678	0.996083	0.009213	0.010480	0.009196	29.56	1.11e-003	1.40e-003
1234567	0.996130	0.008951	0.010755	0.008931	29.73	1.06e-003	1.38e-003
124567	0.995329	0.009631	0.010717	0.009614	29.16	1.21e-003	9.00e-004
14567	0.993579	0.012683	0.016461	0.012523	28.40	1.44e-003	2.25e-003
1567	0.993742	0.013102	0.013175	0.013101	28.68	1.35e-003	1.46e-003
157	0.993266	0.012872	0.013715	0.012770	26.95	2.02e-003	3.09e-003

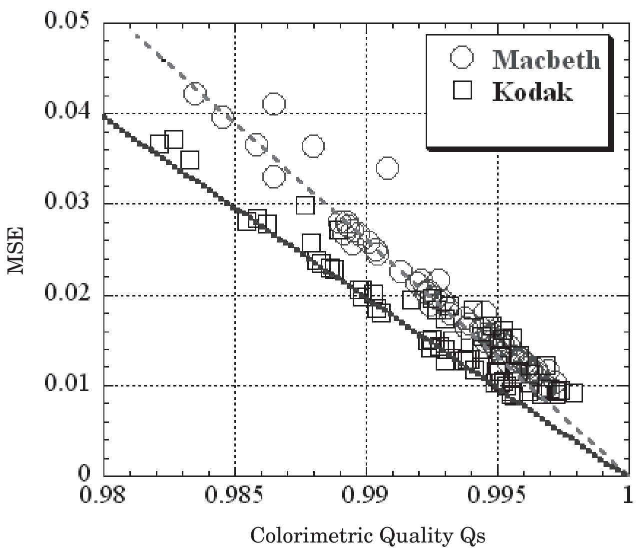


Figure 3. The MSE as a function of Q_S for the Kodak Q60R1 and Macbeth ColorChecker when the estimated system noise variance was used.

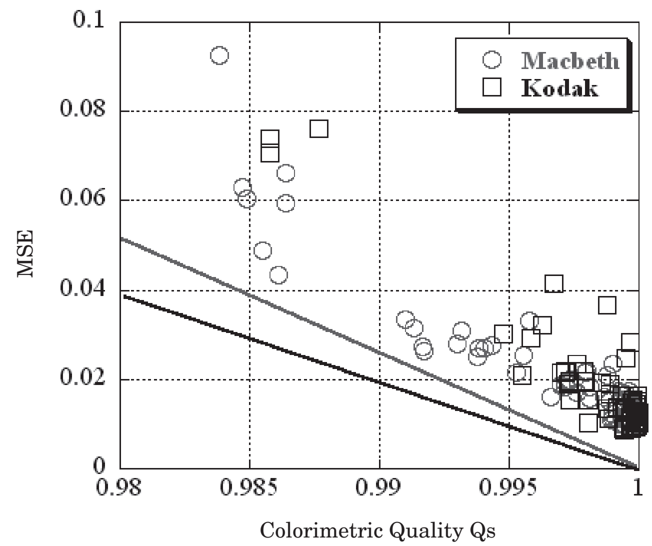


Figure 4. A typical example of the MSE as a function of Q_S for the Kodak Q60R1 and Macbeth ColorChecker when the estimated system noise variance was not used. The values of the MSE and Q_S were computed for $\sigma_e^2 = 0$.

Although the plots of the Kodak Q60R1 scatter slightly around the $Q_S = 0.995$, the experimental results are in good agreement with the model. Figure 4 shows a typical example for the MSE as a function Q_S when the estimated system noise variance was not used, i.e, in this figure the values of MSE were obtained by averaging the $\|\Delta \mathbf{r}_h\|^2$ over the colors by letting $\sigma_e^2 = 0$ in Eq. (2) and the values of Q_S were also computed for $\sigma_e^2 = 0$ using Eq. (6). From the results it is found that these plots are in disagreement with the theoretical lines. From a comparison of these results it may be concluded that the formulation of the colorimetric quality of a set of sensors is correct and that the system noise variance can be estimated accurately by the proposal. To check the correlation between the proposed colorimetric quality Q_S and the color difference ΔEab^*, the ΔEab^* as a function of Q_S is given in Fig. 5. The values of the ΔEab^* and Q_S were computed using the estimated system noise variance. Although the data for the Kodak Q60R1 scatter more compared with those of the Macbeth ColorChecker, the results show that there is a significant correlation between the Q_S and the ΔEab^*, i.e., ΔEab^* increases with decreasing Q_S and the correlation is good for the Macbeth ColorChecker over the regions of $Q_S = 0.99$.

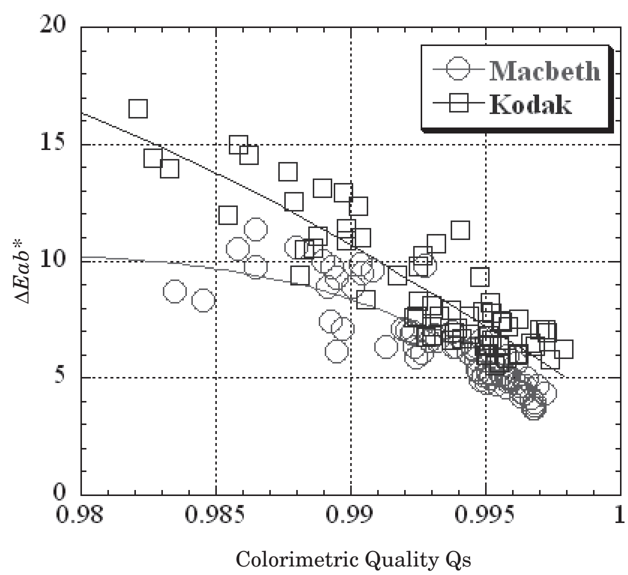


Figure 5. The ΔE_{ab}^* as a function of Q_S for the Kodak Q60R1 and Macbeth ColorChecker when the estimated system noise variance was used.

Conclusions

Application of the colorimetric evaluation model to a real color image sensor is impossible without prior knowledge of the noise present in the device. Therefore, the noise variance of a multispectral color image acquisition systems was estimated by the present proposal which was applied to a real system for the first time. It was found from the experiments and evaluation that the experimental results are in good agreement with the predictions of the colorimetric evaluation model, and that the system noise variance can be estimated accurately by the proposal.

References

1. H. E. J. Neugebauer, "Quality Factor for Filters Whose Spectral Transmittances are Different from Color Mixture Curves, and Its Application to Color Photography", *J. Opt. Soc. Amer*, **46,** 821 (1956).
2. P. L. Vora and H. J. Trussell, "Measure of goodness of a set of color-scanning filters", *J. Opt. Soc. Amer. A* **10,** 1499 (1993).
3. G. Sharma and H. J. Trussell, "Figure of Merit for Color Scanners", *IEEE Trans .Image Processing,* **6,** 990 (1997).
4. S. Quan, N. Ohta. R. S. Berns, X. Jiang, and N. Katoh, "Unified Measure of Goodness and Optimal Design of Spectral Sensitivity Functions", *J. Imaging Sci. Technol.* **46,** 485 (2002).
5. N. Shimano, "Suppression of Noise Effect in Color corrections by Spectral Sensitivities of Image Sensors", *Opt. Rev.*, **9,** 81 (2002).
6. J. Cohen, "Dependency of the spectral reflectance curves of the Munsell color chips", *Psychon. Sci.* **1,** 369 (1964).
7. L. T. Maloney, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters", *J. Opt. Soc. Amer. A*, **3,** 1673 (1986).
8. J. P. S. Parkkinen, J. Hallikainen and T. Jaaskelainen, "Characteristic Spectra of Munsell Colors", *J. Opt. Soc. Amer. A,* **6,** 318 (1989).
9. J. L. Dannemiller, "Spectral reflectance of natural objects: how many basis functions are necessary?", *J. Opt. Soc. Amer. A*, **9,** 507 (1992).
10. N. Shimano, "Influence of Noise on Color Correction", *Proc. IS&T's, First European Conference on Colour in Graphics, Imaging and Vision,* (IS&T, Springfield, VA, 2002), p. 549.
11. N. Shimano, "Optimal Spectral Sensitivities of a Color Image Acquisition Device in the Presence of Noise", *Proc. IS&T, Second European Conference on Colour in Graphics, Imaging and Vision,* (IS&T, Springfield, VA, 2004), p. 379.
12. P. S. Hung, "Colorimetric Calibration for Scanners and Media", *Proc. SPIE* **1448,** 164 (1991).
13. H. R. Kang, "Colorimetric Scanner Calibration", *J. Imaging Sci. Technol.*, **36,** 162 (1992).
14. Y. Miyake and Y. Yokoyama, "Obtaining and Reproduction of Accurate Color Images Based on Human Perception", *Proc. SPIE* **3300,** 190 (1998).
15. K. Martinez, J. Cupitt, D. Saunders, and R. Pillay, "Ten Years of Art Imaging Research", *Proc. IEEE*, **90,** 28 (2002).
16. T. Keusen, "Multispectral Color System with an Encoding Format Compatible with the Conventional Tristimulus Model", *J. Imaging Sci. Technol.* **40,** 510 (1996).
17. W. K. Pratt, *Digital Image Processing,* (John Wiley and Sons, New York, 1991), p. 351.
18. J. W. Choi, M. G. Kang and K. T. Park, "An Algorithm to Extract Camera-Shaking Degree and Noise Variance in the Peak-Trace Domain", *IEEE. Trans. Consumer Electronics*, **44,** 1159(1998).
19. H. Haneishi, T. Hasegawa, N. A. Hosoi, Y. Yokoyama, N. Tsumura, and Y. Miyake, "System design for accurately estimating the spectral reflectance of art paintings", *Appl. Optics*, **39,** 6621(2000).
20. P. D. Burns and R. S. Berns, "Image Noise and Colorimetric Precision in Multispectral Image Capture", *Proc. IST/SID Sixth Color Imaging Conference*, (IS&T, Springfield, VA, 1998), p. 83.
21. A. Rosenfeld and A. C. Kak, *Digital Picture Processing*, (Academic Press, New York, 1982), p. 281.
22. W. A. Shapiro, "Generalization of tristimulus coordinates", *J. Opt. Soc. Amer.* **56,** 795 (1992).
23. N. Shimano, "Total Colorimetric Evaluation of a Set of Color Sensors for a Variety of Illuminants and Objects", *Opt. Rev.*, **8,** 71 (2001).