Feature Article

Six Band HDTV Camera System for Spectrum-Based Color Reproduction

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We present the architecture of a six band high-definition television (HDTV) camera system newly developed for accurate color reproduction of motion pictures based on spectral information. The camera has an optical component connecting the objective lens to two conventional HDTV camera heads whose spectral sensitivities are individually adjusted by placing different interference filters between the objective lens and each camera. Evaluation of the accuracy of the color estimation obtained using the six band camera and a conventional RGB, i.e., three band, HDTV camera using simulated and experimentally obtained camera signals showed that the six band camera achieves accurate color estimation. In the experimental evaluation, the average color differences for the 24 color patches of the GretagMacbeth Color Checker for the six band and RGB camera signals were 1.43 and 4.12 delta-E_{ab}. This system should thus be suitable for a wide variety of applications.

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Introduction

Recent advances in multimedia technology have opened the door to achieving electronic art museums, electronic commerce, telemedicine, etc., and systems in these areas require accurate color display. However, it is quite difficult to accurately estimate the color of objects under arbitrary illumination conditions using current imaging systems based on three band acquisition. Color estimation under illumination the same as that used for image acquisition is difficult due to the differences in spectral sensitivities between the input device and the human eye. Even if the input device had sensitivities equivalent to those of the human eye, it would still be difficult to estimate the color accurately under different illuminations.

Recent studies of multispectral color reproduction systems, which estimate the spectrum using a multiband input device, in the field of still images[1–8] have revealed that increasing the number of bands in the input device enables the spectrum to be estimated more accurately. This makes it possible to improve the accuracy of color estimation under arbitrary illumination spectrum. While motion pictures should be more effective than still images in conveying the reality of an object, a time-multiplexed multiband camera for capturing motion pictures, such as a monochrome camera with a rotating filter wheel, cannot acquire multiband images as a motion picture with sufficient time-resolution with current technologies.

We have developed a six band high-definition television (HDTV) camera system that captures six band motion pictures using two HDTV cameras. These cameras acquire the image through an objective lens; the image is reflected or transmitted by an optical component connecting the lens and the two cameras. The spectral sensitivities of the cameras are adjusted by placing different interference filters between each camera head and the optical component, thereby achieving six narrow-band sensitivities.

In this article we present the architecture of the six band HDTV camera system and the results of evaluating its color estimation accuracy using simulated and actual signals. The spatial distribution of the color estimation errors in the imaging area, which are caused by the angular dependency

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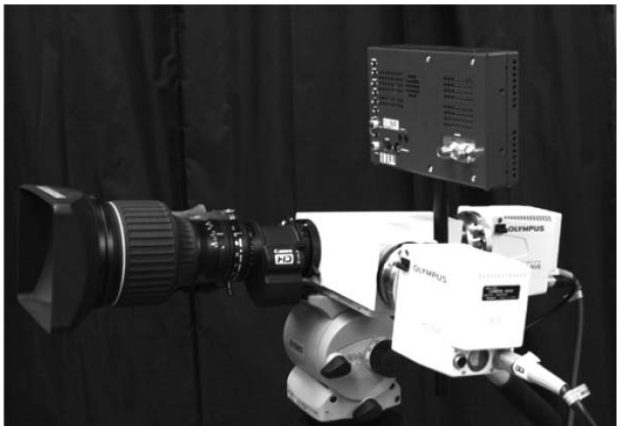


Figure 1. Appearance of six band HDTV camera

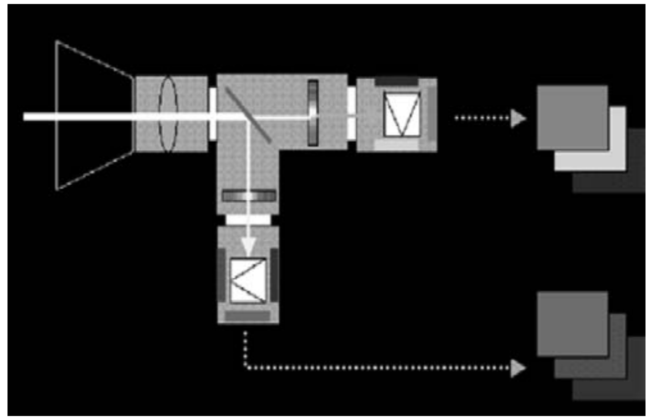


Figure 2. Principle of six band signal acquisition

of the spectral transmittance of the interference filters and the other optical components, is also presented.

Architecture

The six band camera system consists of a six band camera unit, a camera control unit (CCU), and a data storage unit. The CCU controls the camera unit and sends the captured image data from the camera unit to the data storage unit through two HD-SDI cables along with the camera setting information for each frame.

Camera Unit

The six band HDTV camera unit consists of an objective lens, a branch optical component, and two HDTV camera heads. The branch optical component connects the objective lens to the camera heads. The appearance of the six band HDTV camera unit is shown in Fig. 1. As is shown in Fig. 2, a half mirror in the branch optical component divides the incident light from the objective lens into reflected and transmitted beams, which are then focused on the RGB CCD sensors of each camera head. The two sets of RGB sensors in the camera heads are designed to have the same spectral sensitivities. The beams are modified using different interference filters to separate them into six independent spectral sensitivities. The two HDTV cameras capture three band images in sync to compose each frame of the six band image. The total spectral sensitivities of the six band camera are the convoluted spectral characteristics of the optical components: the objective lens, the half mirror, the IR cut-off filter, the interference filters, the CCD sensors, etc.

Figure 3 shows the spectral characteristics of the key components forming the camera unit, as provided by their manufacturers. The conventional IR cut filter with a cut-off wavelength of around 700 nm was replaced with one having a cutoff wavelength of around 750 nm, taking the effective sensitivities of the camera sensors and those of the human eye into account. The spectral transmittances of the interference filters used for the six band separation were specifically designed so that two different interference filters divide each of the spectral sensitivities of the R, G, and B sensors into two different parts in the spectrum region. One of the interference filters is composed of a long-pass filter with a minus filter. The spectral transmittance of this filter is shown in Fig. 3(c) (solid line). This filter changes the spectral sensitivities of the original R, G, and B sensors to those of the longer wavelength region of the R, the shorter wavelength region of the G, and the longer wavelength region of the B sensors. The other filter is composed of a short-pass filter with a minus filter; its spectral transmittance is shown by the dotted line. This filter changes the spectral sensitivities of the original R, G, and B sensors to those of the shorter wavelength region of the R, longer wavelength region of the G, and shorter wavelength region of the B sensors. The interference filters play a vital role in designing the total spectral sensitivities of the six band camera and determining the performance of the color estimation. The user can replace the interference filters with other filters without difficulty. Figure 4 shows the locations of the interference filters in the branch optical component.

Camera Control Unit and Data Storage Unit

The two HDTV camera heads are synchronously controlled by two CCUs designed for a conventional HDTV camera system. The knee and gamma are switched off by the CCUs to make the camera response linear for the purpose of accurately characterizing the color signals captured by the cameras. The CCUs send the six band HDTV image as not-sub sampled 4:4:4 data in the form of HD-SDI dual link signals[9] through two HD-SDI cables to the data storage unit. Camera setting information, including the exposure time and *f*-number, is added to the image data as metadata in each frame for use in the subsequent color estimation process. The data storage unit can hold 2.5 TB of data. The captured motion picture data is recorded in this unit as six band 10-bit 4:4:4 data with the camera setting metadata corresponding to each frame embedded in the two lines following the HDTV 1920 by 1080 image data.

Camera Characterization

Estimation of the color from the camera signals is based on the camera characterization that provides the camera signals by mathematical formula when the spectral reflectance of the object, the illumination spectrum, the spectral sensitivities of the camera, etc., are given.

Measurement of Spectral Sensitivities

One of the most important factors in camera characterization is the set of spectral sensitivities. However, compared with other characteristics, it is difficult to measure actual sensitivities accurately. To obtain the spectral sensitivities of the camera, 81 images of sampled narrow band light were captured. The peak wavelengths of the light were sampled from 380 to 780 nm in 5 nm increments. The narrow band light was emitted by a monochromator consisting of a light source and grating, designed and manufactured specifically for this purpose. The light was reflected by a diffuser and captured by the six band camera as an image; it was also measured by Topcon

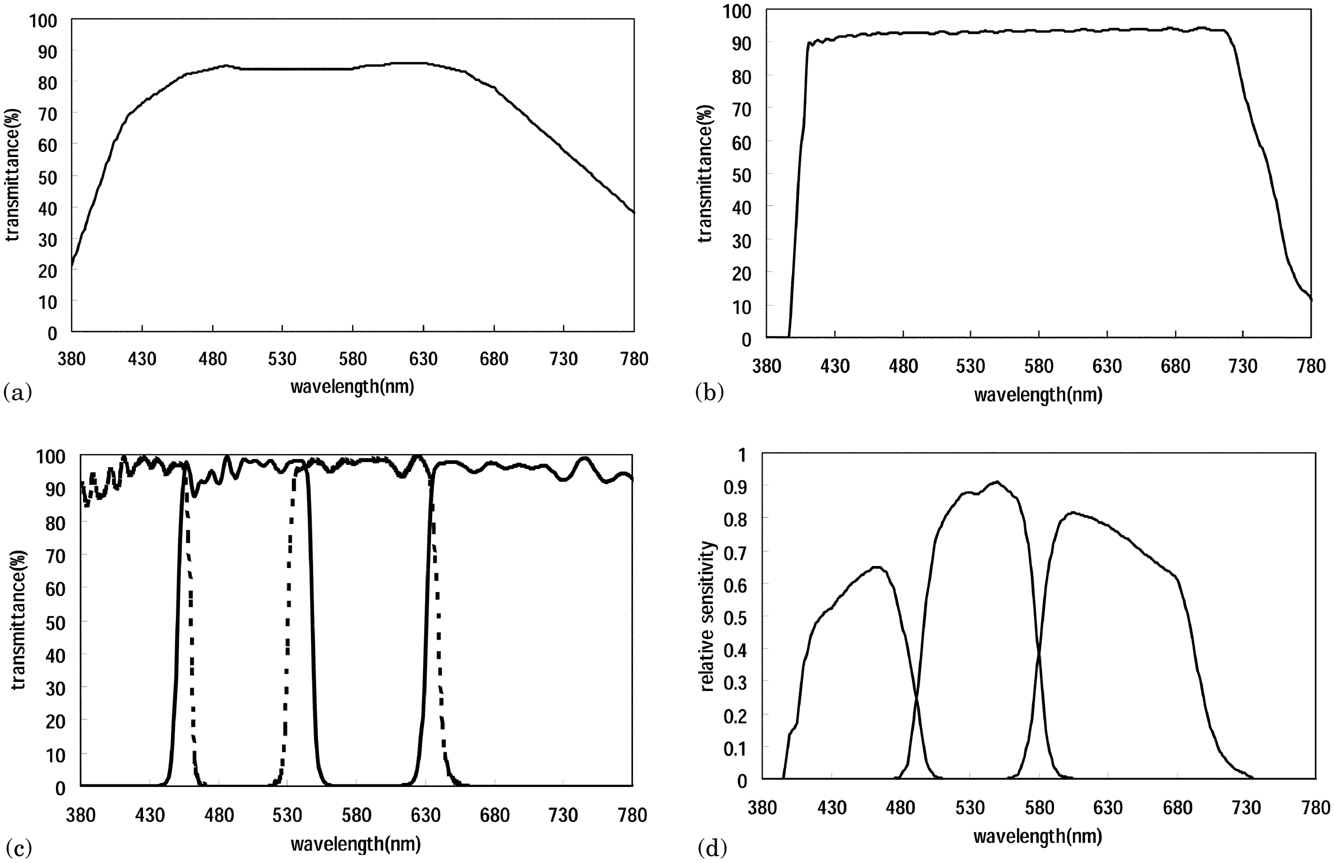


Figure 3. Spectral characteristics of optical components used in six band HDTV camera.

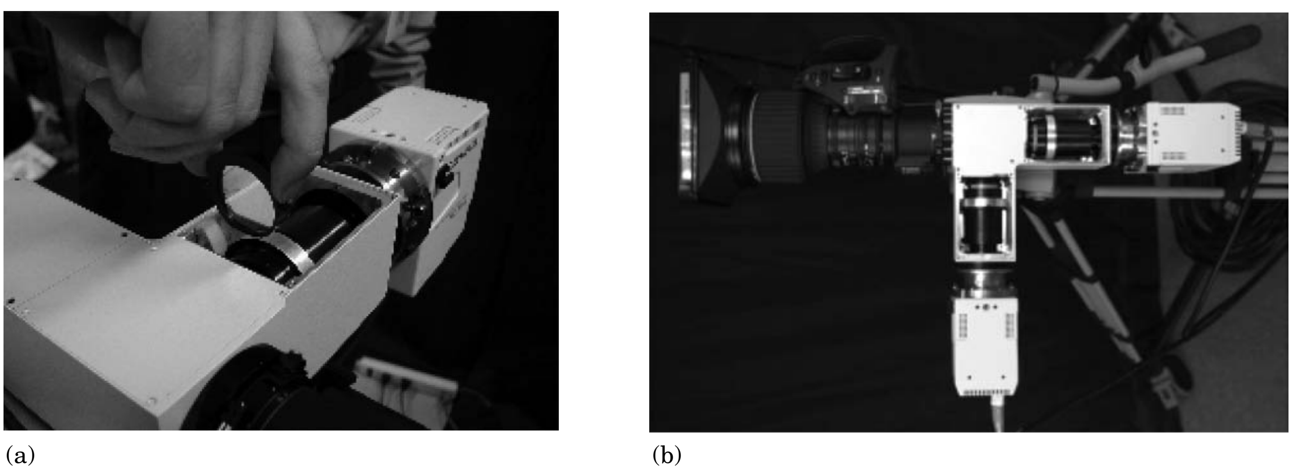


Figure 4. Locations of interference filters in branch optical component.

SR-2A, a spectrophotometer under the same conditions; the wavelength range of the measurement was from 380 to 780 nm in 5 nm increments. The image of the narrow band light captured by the diffuser was not a uniform signal distribution, so a certain area around the central part of the image was used to calculate the average camera signal of the i-th camera band $g_{i\lambda}$ (i = 1…6). The spectral sensitivities g_i (λ) (i = 1…6) at the sampled wavelength, λ, were calculated using

$$h_i(\lambda) = (g_{i\lambda} - g_{i0})/I_\lambda, \quad (1)$$

where I_λ represents the energy of the narrow band light measured by the spectrophotometer and g_{i0} represents the bias signal of the i-th band, which was measured by capturing an image with no incident light to the camera sensors. In these measurements, the gamma and knee were switched off to linearize the camera response. The data of the spectral sensitivities from 380 to 780 nm in 1 nm increments were obtained by linear interpolation using the measured data. The spectral sensitivities of a conventional HDTV camera were also measured in the same way. Figures 5 (a) and (b) show the measured spectral sensitivities of

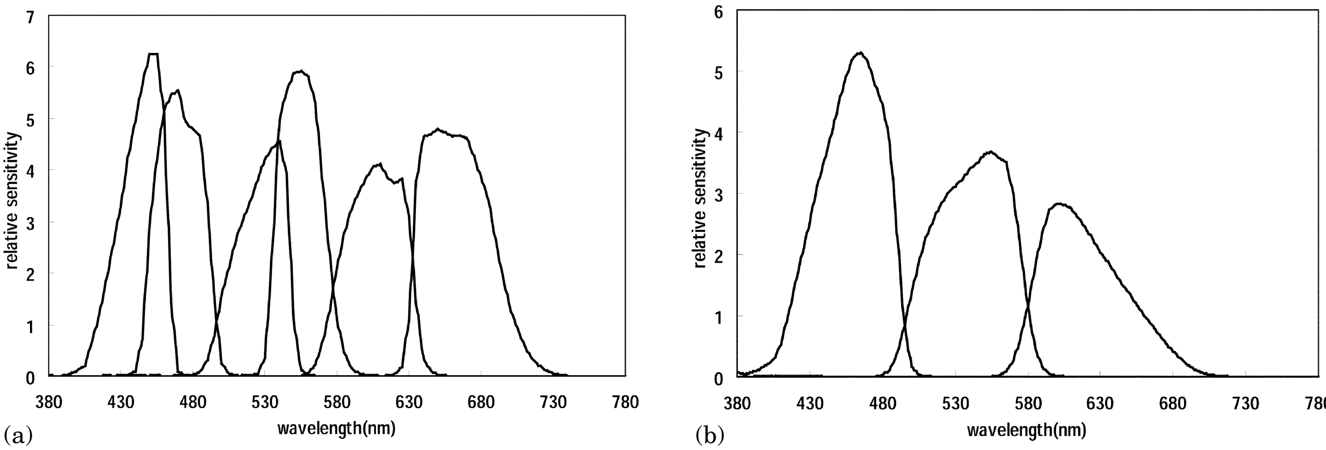


Figure 5. Measured spectral sensitivities of (a) six band camera system and (b) conventional HDTV camera.

the six band camera and the conventional HDTV camera. The six band camera had six narrow-band sensitivities, as expected from the spectral characteristics shown in Fig. 3. Note that the gain of each band is adjusted differently.

Mathematical Camera Model

A mathematical model was used to calculate the camera signals using the spectral sensitivities of the camera, the illumination spectrum, the spectral reflectance of the object to be captured, etc. The model of the six band camera is given by

$$g_i' = \int_{\lambda=380}^{780} h_i(\lambda)E(\lambda)f(\lambda)d\lambda \quad (i = 1...6) \tag{2}$$

$$g_i = \gamma_i(g_i') + g_{i0}, \tag{3}$$

where h_i (λ) (i = 1…6) are the spectral sensitivities of the six band camera shown in Fig. 5 (a), $E(\lambda)$ is the spectrum of the light illuminating the object to be captured, and $f(\lambda)$ is the spectral reflectance of the object. The function $\gamma_i(\,)$ in Eq. (3) represents the characteristics of the tone curve of the i-th band. It is not measured but assumed to be linear, as set in the CCUs.

Theory of Spectrum-Based Color Estimation

The CIE colorimetric values, X, Y, and Z, of an object, the spectral reflectance of which is $f(\lambda)$ under illumination spectrum $E'(\lambda)$, are given by

$$\begin{aligned} X &= \int_{\lambda=380}^{780} x(\lambda)E'(\lambda)f(\lambda)d\lambda \\ Y &= \int_{\lambda=380}^{780} y(\lambda)E'(\lambda)f(\lambda)d\lambda \\ Z &= \int_{\lambda=380}^{780} z(\lambda)E'(\lambda)f(\lambda)d\lambda \end{aligned} \tag{4}$$

where $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ represent the CIE 1931 XYZ color matching functions.[10] When the L-band camera signals $g_1, g_2, \ldots, g_L$ are obtained, assuming that Eqs. (2) and (3) hold, the estimated colorimetric values, $\tilde{X}, \tilde{Y}, \tilde{Z}$ are given by

$$g'_i = \gamma^{-1}_i(g_i - g_{i0}) \tag{5}$$

$$\tilde{\mathbf{C}} = \mathbf{M}\mathbf{G}', \tag{6}$$

where –1 represents the inverse operation, $\tilde{\mathbf{C}} = [\tilde{X}, \tilde{Y}, \tilde{Z}]^T$ and $\mathbf{G}' = [g'_1, g'_2, \ldots, g'_L]$. Matrix **M** is determined using the least squares method: minimizing $\|\tilde{\mathbf{C}} - \mathbf{C}\|$, where $\mathbf{C} = [X,Y,Z]$, as

$$\mathbf{M} = \mathbf{A}\mathbf{B}^{-1}, \tag{7}$$

where the elements of matrixes **A** and **B** are given by Eqs. (8) and (9), respectively.

$$a_{jk} = \int_{\lambda=380}^{780} \int_{\lambda'=380}^{780} c_j(\lambda)E'(\lambda)\langle f(\lambda)f(\lambda')\rangle h_k(\lambda')E(\lambda')d\lambda d\lambda' \tag{8}$$

$$b_{jk} = \int_{\lambda=380}^{780} \int_{\lambda'=380}^{780} h_j(\lambda)E(\lambda)\langle f(\lambda)f(\lambda')\rangle h_k(\lambda')E(\lambda')d\lambda d\lambda' \tag{9}$$

where < > represents ensemble average, and $c_1(\lambda) = x(\lambda)$, $c_2(\lambda) = y(\lambda)$, and $c_3(\lambda) = z(\lambda)$. If illumination spectrum $E(\lambda)$ is equal to $E'(\lambda)$, it is possible to estimate the colorimetric values of arbitrary combinations of objects and illuminations exactly by linearly transforming the camera signals only when $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ can be represented by a linear combination of the spectral sensitivities of the camera. The color reproduction of conventional television systems is based on this theory, and the spectral sensitivities of the camera are standardized. However, when $E(\lambda)$ is not equal to $E'(\lambda)$, the theory no longer holds. In this case, estimation matrix **M** is calculated based on the spectral information of the illumination and the statistical characteristics of the object.

Evaluation of Color Estimation

The estimated colorimetric values were evaluated based on the difference between those of the object under illumination for observation calculated by Eq. (4) and those estimated from the simulated camera signals, which were calculated using

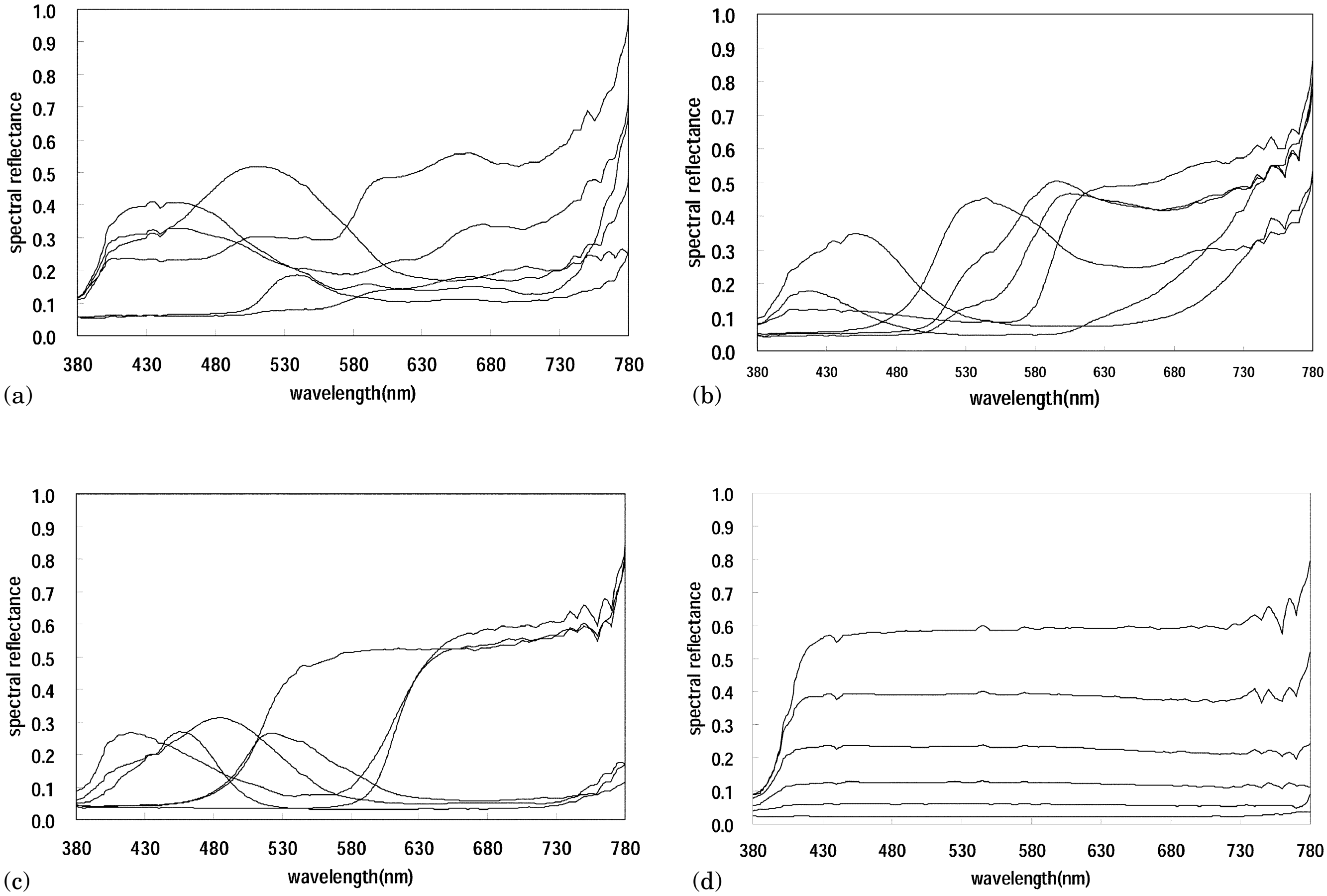


Figure 6. Measured spectral reflectance of 24 color patches of Gretag-Macbeth color checker.

the model given by Eqs. (2) and (3). Also evaluated was the color difference between the colorimetric values of the object under the illumination for observation and those estimated from the camera signals, which were obtained by capturing the image under the same illumination. The first evaluation is labeled simulation and the latter experiment. The color difference between the estimated colorimetric values of the simulation and those of the experiment due to the error in the camera model was also examined in the experiment.

Simulation

The error is defined by the color difference between the colorimetric values of each object estimated using Eq. (6), where the camera signals are simulated using Eqs. (2) and (3), and those of each object calculated using Eq. (4). The objects were the 24 color patches of the GretagMacbeth Color Checker. The illumination used for image capture and observation came from a xenon lamp (D), the spectrum of which is similar to that of daylight, an incandescent lamp (A), or a fluorescent lamp (Fl). In the estimation process, statistical information about the object, $<f(\lambda)f(\lambda')>$, was needed *a priori*. We used the data calculated from the spectral reflectance of the 24 color patches measured by a spectrophotometer as statistical information. The XYZ values were calculated using the CIE1931 XYZ color matching functions and transformed to the CIE1976 L*a*b* values assuming that the white point is the color chart white. The spectral reflectance of the color charts and the three illumination spectra are shown in Figs. 6 to 9.

The average and maximum errors of the colors estimated from the simulated six band camera signals and three band camera signals are listed in Table I. The description of the illumination conditions, e.g., D-A, represents the illumination for capture and that for observation, respectively. The six band camera had smaller errors under all three illumination conditions. It estimated the color with an average error of approximately 1 in ΔE_{ab} units, while the three band camera estimated it with an average error of approximately 2 to 4 in ΔE_{ab} units.

Experiment

In the experiment, the six band camera and the three band camera captured images of the color patches of the GretagMacbeth Color Checker in a light booth. The illumination came from a xenon lamp whose spectral power distribution is similar to that shown in Fig. 7. The captured image area of the checker, including the 24 color patches, was smaller than half the total image area. The six band and three band signals for each color chart were obtained by averaging the camera signals for certain areas of the color patches. The colorimetric values of the 24 colors were measured with a spectrophotometer (Topcon SR-2A) under almost the same geometrical conditions as for capturing the images. The measurement wavelength was from 380 to 780 nm in 5 nm increments.

The color differences between the colorimetric values estimated from the camera signals and those measured by the spectrophotometer are listed in Table II. The

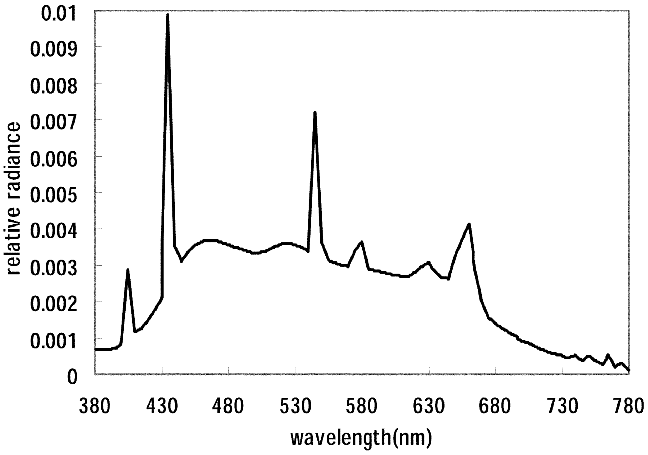


Figure 7. Spectrum of daylight

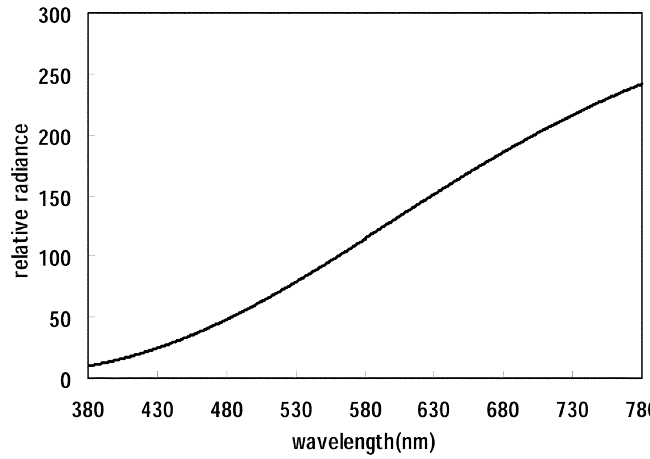


Figure 8. Spectrum of incandescent lamp

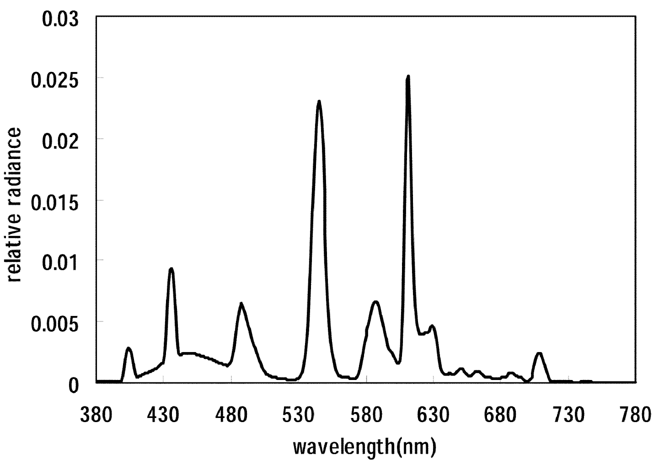


Figure 9. Spectrum of fluorescent lamp

TABLE I. Color Estimation Errors In Simulation
Average and maximum errors in color estimation using simulated six band and three band camera signals. Description of illumination conditions, e.g., D-A, represents illumination for capturing and observing, in that order.

	D-D		D-A		D-Fl	
	Ave.	Max.	Ave.	Max	Ave.	Max
6-band	0.57	1.97	0.74	2.64	0.84	2.52
3-band	2.60	8.70	1.91	7.70	2.78	9.42
	A-D		A-A		A-Fl	
	Ave.	Max.	Ave.	Max	Ave.	Max
6-band	0.56	2.23	0.68	2.42	1.03	3.57
3-band	4.11	12.5	2.16	6.94	3.71	10.54
	Fl-D		Fl-A		Fl-Fl	
	Ave.	Max.	Ave.	Max	Ave.	Max
6-band	1.38	5.92	1.33	4.75	0.47	1.94
3-band	4.27	11.72	2.75	10.36	1.89	5.46

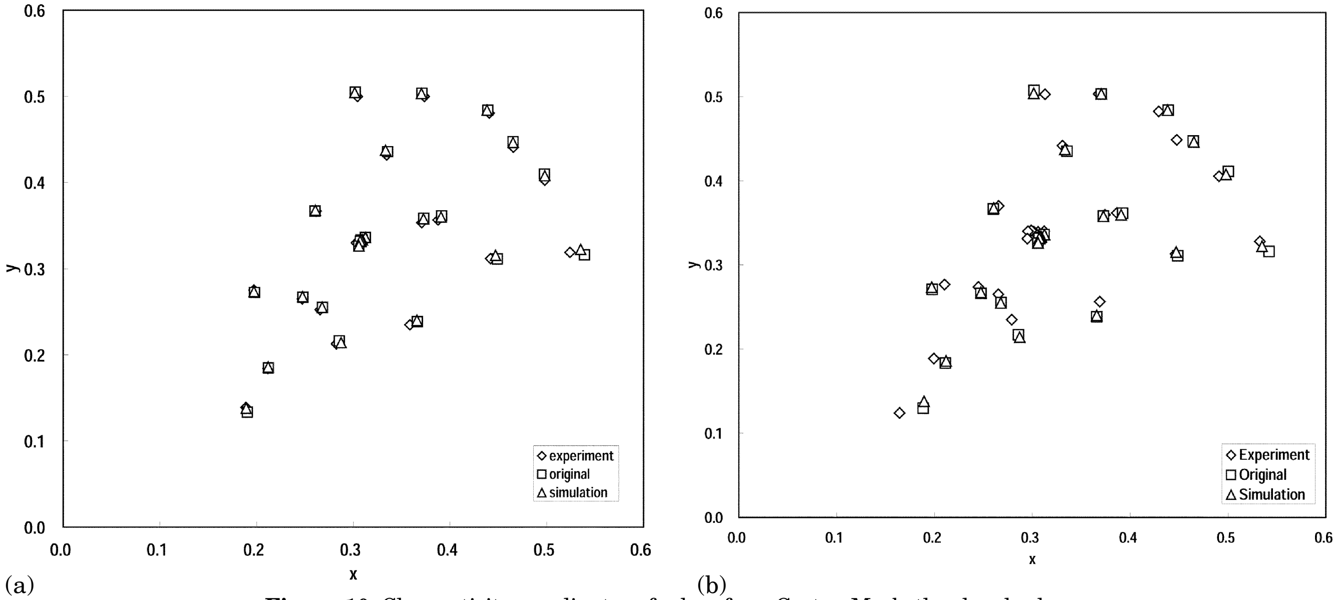
average error of the six band camera was 1.43, and the maximum error was 4.24. The average error of the three band camera was 4.12, and the maximum error was 8.22. The average and maximum errors of the color estimated from the simulated camera signals, which were calculated using the spectral data measured in the experiment as described in the simulation method, are also shown in Table II. The difference between the colors estimated from the captured camera signals and from the simulated ones indicates the extent to which error in the camera model contributes to the experimental error. The average and maximum contributions due to this error are also shown in Table II. The *xy* chromaticity coordinates of the colorimetric values estimated from the captured camera signals, the simulated camera signals, and those measured by the spectrophotometer are shown in Fig. 10; Fig. 10 (a) shows the estimated color distribution of the six band camera and (b) shows that of the three band camera.

TABLE II. Color Estimation Errors
Average and maximum errors in the color estimation using six band and three band camera signals. Experimentally color was estimated from captured camera signals, whereas in simulation it was estimated from simulated camera signals. Model error is color difference between colors estimated from captured camera signals and from simulated ones. It indicates the extent to which the error in camera model contributes to error in experiment. Illumination for capture and for observation came from a xenon lamp in both cases.

	Experiment		Simulation		Model Error	
	Ave.	Max.	Ave.	Max.	Ave.	Max.
6-band	1.43	4.24	0.72	2.82	1.09	2.96
3-band	4.12	8.22	1.07	4.33	3.83	9.59

Evaluation of Spatial Uniformity

In our evaluation of the color estimation we assumed that the spectral characteristics of the camera were spatially uniform. However, the spectral characteristics of actual cameras have spatial non-uniformity in the imaging area, more or less. In the case of the six band camera, this spatial non-uniformity can arise from the spectral characteristics of the interference filters used for six band separation and of the branch optical component as well as from the spectral characteristics of the other optical components and image sensors. We examined the spatial distribution of the estimated colorimetric values on the imaging area of the six band camera. An image of a white diffuser was captured



(a) (b)

Figure 10. Chromaticity coordinates of colors from Gretag-Macbeth color checker.

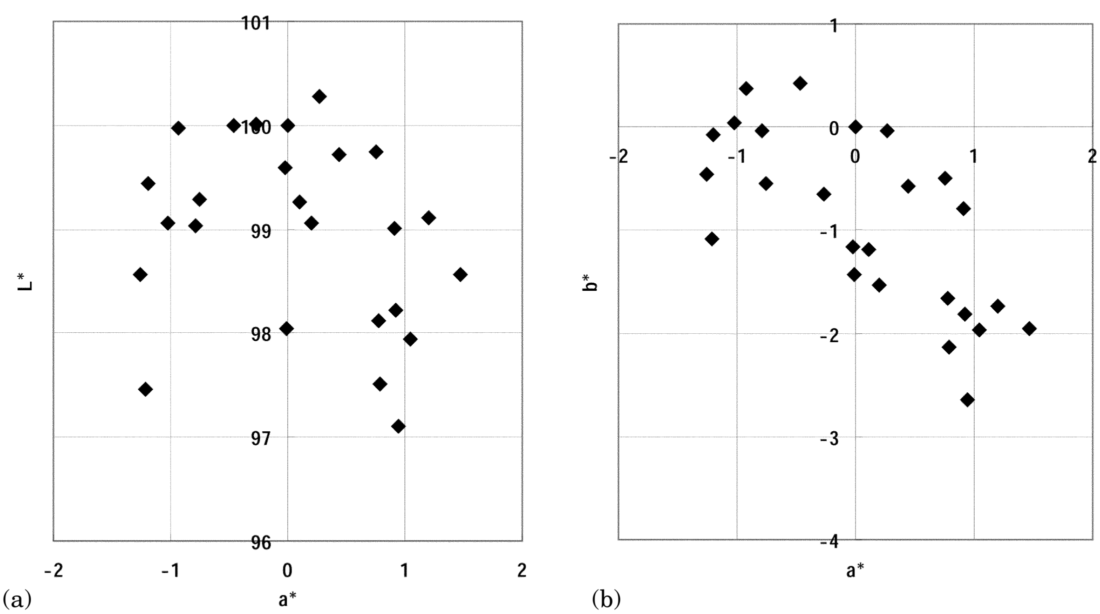
25 times by moving the six band camera so as to adjust the position of the white diffuser in the image being captured on the sampled 5 × 5 grid points. The difference in the spectral sensitivities yields the difference in the camera signals for the same object. Consequently, the estimated color differs from point to point in the imaging area when the same spectral sensitivities are used in the color estimation. The color differences relative to the color at the center of the imaging area evaluated in ΔE_{ab} units are shown in Fig. 11. The estimated color difference increased with the distance from the center. The estimated color distributions in the a*–L* and a*–b* planes are plotted in Fig. 12. The color difference around the edge of the image was comparable to the color estimation error at the center of the image.

1920 pixels

1080 pixels

4.03	2.83	2.29	1.56	2.42
2.63	0.94	0.38	0.63	1.25
2.70	0.78	0.00	1.00	1.39
3.03	1.40	0.70	1.32	1.96
3.38	1.81	1.23	1.17	3.01

Figure 11. Color differences relative to color at center of imaging area.



(a) (b)

Figure 12. Estimated color distributions in a*–L* and a*–b* planes.

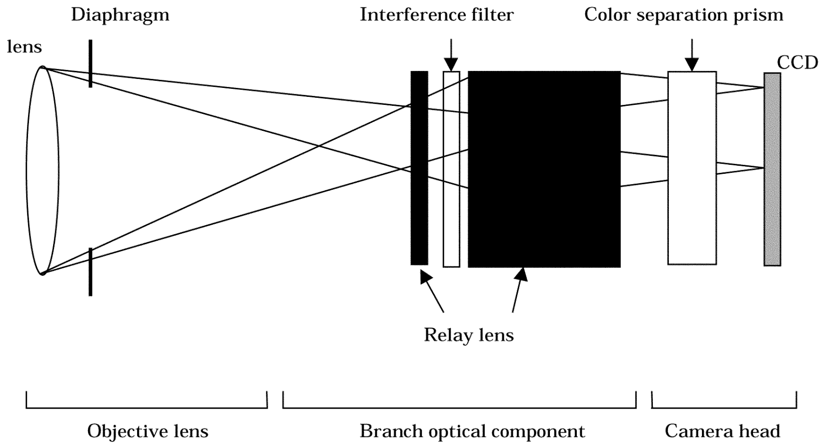


Figure 13. Schematic diagram of physical relationships of optical components

Discussion

Using simulation, we compared the color estimation performance of our six band camera with that of a conventional HDTV three band camera. Under three kinds of typical illumination, the six band camera had higher color estimation accuracy that should be sufficient for a wide range of applications. The estimation error largely depended on whether the illumination spectrum for capture and that for observation were the same. Most estimations under the same illumination conditions minimized or reduced the average error under all three types of illumination. It should be noted that the spectral reflectance of each color patch shown in Fig. 6 has artificial peaks and slopes. These artifacts result from calculating the spectral reflectance by dividing the measured spectrum of the color chart by that of the illumination. Although these characteristics may differ a little from the actual characteristics of the color charts, the difference should have little effect on the results of the evaluation.

The estimation errors in the experiments were higher than those in the simulation, suggesting that part of the color estimation error is caused by the error in the camera model. A principal cause of the camera model error could have been optical flare inside the camera. Eliminating the camera signals due to flare should improve the color estimation performance. Considering color image reproduction, the spatial performance of the camera model is important for accurate color estimation. For the six band camera, the angle dependency of the incident light of the interference filters and the half mirror can degrade the spatial performance of the color estimation. Figure 13 shows the physical relationships of the interference filter, CCD sensor, and light path after the objective lens in the six band camera. The light focused on the CCD is regarded as the integral of the infinite number of light beams passing through the interference filter with different angles. The angle distribution of this light differs from point to point on the CCD area. The spatial performance of the color estimation can be improved by using the spectral sensitivities of the six band camera determined by the image position and the diaphragm setting.

Conclusions

We have developed a six band HDTV camera system for accurate color reproduction of motion pictures based on spectral information. Specifically designed filters enable two conventional HDTV cameras to be used for six band signal acquisition. Evaluation of the accuracy of the color estimation of the six band system using simulated camera signals in comparison with that of a conventional RGB, i.e., three band, HDTV camera suggests that the six band system has sufficient accuracy for use in a wide variety of applications. However, the accuracy using captured camera signals was worse due to the error of the camera model. In the experimental evaluation, the average color differences obtained from the six band camera signals and RGB camera signals were 1.43 and 4.12 ΔE_{ab}. Evaluation of the spatial performance of the color estimation showed that the estimated color difference is comparable to the color estimation error around the center of the imaging area.

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