Six-Band HDTV Camera System for Color Reproduction Based on Spectral Information

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Abstract

The architecture of 6-band HDTV camera system, which is newly developed for accurate color reproduction of motion picture based on spectral information is presented. The 6-band HDTV camera is constructed by an optical system connecting the objective lens and two sets of conventional HDTV cameras whose spectral sensitivities are modified differently by interference filters inserted between the optical system and each camera. We evaluated the accuracy of the color estimations achieved by the 6-band and a conventional RGB (i.e. 3-band) HDTV camera. The evaluations are conducted using simulated camera signals and those obtained by experimental measurements. It is confirmed that the 6-band camera achieves the accurate color estimation for the use in extensive applications. In the experimental evaluation the average color difference of dE_{ab} obtained from the 6-band camera signals and the RGB camera signals became 1.43 and 4.12 respectively.

Introduction

Recent advancement of multimedia technology introduced the possibility to realize electronic art museum, electronic commerce, telemedicine and so on. In such systems the image display with accurate color is one of the most important technologies. Current color imaging systems for both of still image and motion picture are based on RGB (3-band) camera and RGB (3-primary) display, but it is quite difficult to achieve the accurate color estimation of objects under arbitrary illumination with the 3-band acquisition. The difficulty to estimate colorimetric values under the same illumination as that used for image acquisition is caused by the deviation between the spectral sensitivities of camera sensors and those of human vision. In other words the camera whose spectral sensitivities are equivalent to those of human vision realizes accurate color estimation. However, even if the camera has such characteristics, it is impossible to estimate the color accurately under the different illuminations.

Recently multi-spectral color reproduction systems which estimate spectrum using multi-band camera as input device have been actively studied in the fields of still images. It was revealed that by increasing the band number of input device it becomes possible to estimate spectrum more accurately and accordingly to refine the estimation accuracy of color under arbitrary illumination spectrum.[1)] In the case of spectral estimation of natural objects the accurate estimation can be achieved with not so large number of camera bands taking the fact that the spectral reflectance is well represented by a linear combination of small number of basis functions into account.[2]

Considering the multi-band camera for motion picture the time-multiplexed type such as one using filter-wheel cannot realize the acquisition of multi-band images as motion picture with enough time-resolution in current technologies. So we newly developed a 6-band HDTV camera for this aim using two sets of RGB HDTV cameras with an additional optical system for division of the incident light and two kinds of interference filters to modify the spectral sensitivities of the RGB cameras.

In this paper we present the architecture of the 6-band HDTV camera and the results of the evaluations regarding the accuracy of the color estimations calculated by computer simulation and those obtained by experimental measurements. The spatial distribution of color estimation error caused by non-uniformity of spectral characteristics of optical components including the interference filters and the camera sensor is also evaluated.

Architecture of the 6-Band Camera System

The 6-band camera system is constituted of the 6-band camera, camera control unit (CCU), and data storage. The CCU, which controls the 6-band camera unit, is connected to the data storage by 2 sets of HD-SDI cables to send captured 6-band image data from the 6-band camera with relative information regarding camera setting. The architecture of each unit is described.

6-Band Camera Architecture

The 6-band HDTV camera is constructed by the objective lens, the L-shape branch connection optical unit and two sets of HDTV camera heads. The optical unit connects the objective lens and two sets of HDTV cameras. Fig. 1 shows a picture of the 6-band HDTV camera. As is shown in Fig. 2 the half mirror in the optical unit divides the incident light from the objective lens to reflected light and to transmitted one. Each of the divided light from the half mirror is focused on the RGB CCD sensors of the camera head. The two sets of the RGB sensors in HDTV cameras have same spectral sensitivities in design. They are modified by different kind of interference filters to make 6 kinds of independent spectral sensitivities. The two HDTV cameras capture the 3-band images in sync to bring each frame of 6-band image. The total spectral sensitivities of the 6-band camera are determined by the spectral characteristics of the camera lens, IR cut filter, the 6-band separation filters, the CCD sensors, and all the other optical components of the camera system. Figure 3 shows the spectral transmittances of the 6-band separation filters and the spectral sensitivities of the HDTV cameras, which are provided by their manufactures. The spectral transmittances of the interference filters for 6-band separation are designed to form the 6-band spectral sensitivities having almost equal band-width. One of the interference filters is composed of long-pass filter with minus filter (solid line in Fig. 3(a)). This filter changes the original RGB spectral sensitivities to those of the longer wavelength part of the R, the shorter wavelength part of the G, and the longer wavelength part of the B sensitivities. The other filter is composed of short-pass filter with minus filter (dotted line in Fig. 3(a)). This filter changes the original RGB spectral sensitivities to those of shorter wavelength part of the R, longer wavelength part of the G, and shorter wavelength part of the B sensitivities. The 6-band separation filters are exchangeable depending on the condition of the camera use. Figure 4 shows the location for the setting of the filter in the optical unit. The spectral transmittance of the 6-band separation filter changes depending on the angle of the incident light. It introduces spatial non-uniformity of the spectral sensitivities of the camera. The influence to the color estimation accuracy will be examined later.

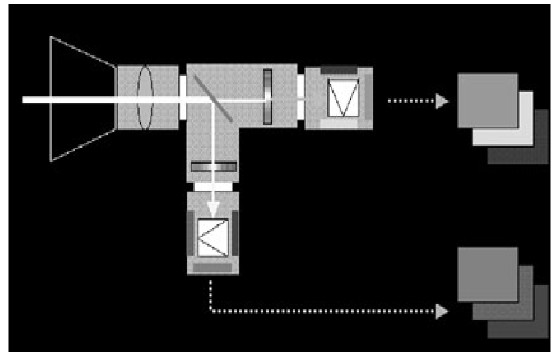

Figure 2. Schematic diagram of 6-band HDTV camera architecture

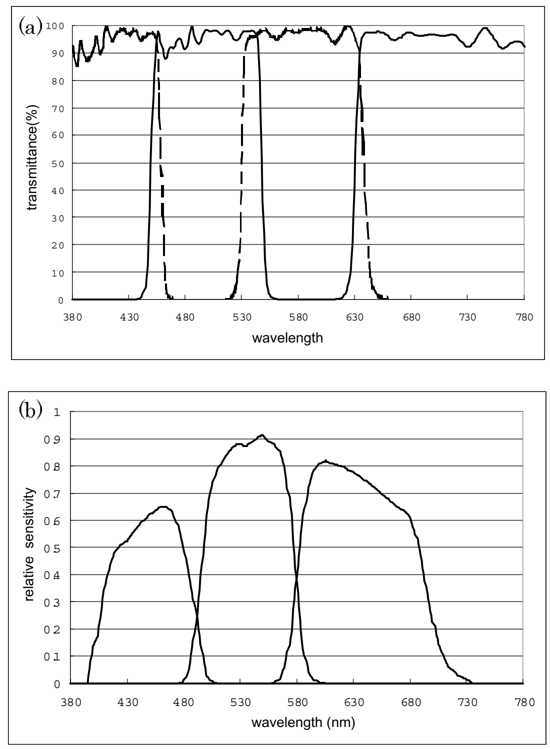

Figure 3. Spectral characteristics (a) Spectral transmittance of 6-band separation filters (b) Spectral sensitivities of the HDTV camera

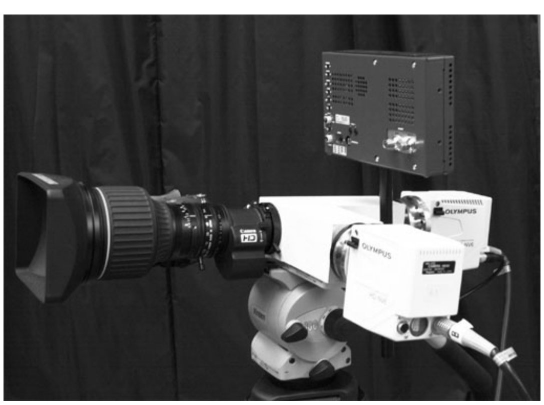

Figure 1. 6-band HDTV camera

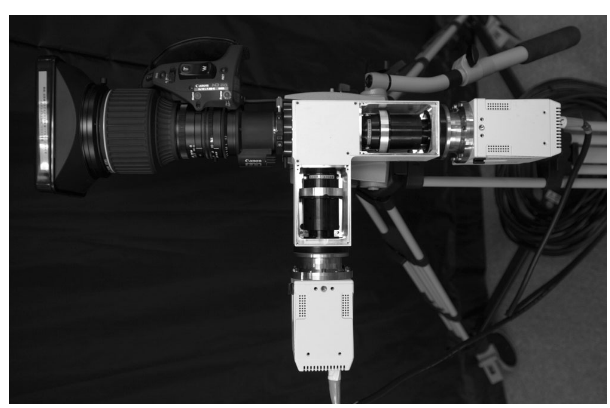

Figure 4. The 6-band separation filter location in the 6-band camera

Camera Control Unit and Data Storage Architecture

The 6-band camera is controlled by two sets of CCUs for the use of conventional HDTV camera in sync. The knee and gamma characteristics set in the CCUs are set off to make the camera response linear for the purpose of the accurate color characterization of the camera. The CCUs send the 6-band image with the camera setting data as not-sub sampled 4:4:4 data in the form of HD-SDI Dual Link signals[4] by two sets of HD-SDI cables to the data storage unit. The data storage unit has 2.5 TB data capability. The captured motion picture data is recorded in this storage unit as 10 bits 4:4:4 data with camera setting information corresponding to each frame embedded in the two lines following the HDTV 1920 by 1080 image data.

Camera Characterization

The color estimation from the camera signals is based on the camera characterization, which provides the camera signals given spectral reflectance of the object, the illumination spectrum, and the spectral sensitivities of the camera. The mathematical camera model provides a calculation method of the camera signals using these data.

Measurement of Spectral Sensitivity

One of the most important factors in the camera characterization is the set of spectral sensitivities of the camera. However, the spectral data provided by the manufacture is not always available or accurate enough to be useful for color estimation. So we measured it using a narrow-spectrum light emitter and a spectrophotometer. In the measurement, the digital counts of the 6-band camera are obtained by capturing the narrow-spectrum light and the light energy is measured by the spectrophotometer at same condition as capturing the light. The spectrophotometer used in this measurement is TOPCON SR-2A with the measuring wavelength interval of 5 nm. The measurement light ranges from 380 nm to 780 nm with interval of 5 nm. From these data the spectral sensitivities are calculated as the camera signals corresponding to the incident light with unit energy. The narrow-spectrum light is reflected by a diffuser and the reflected light is captured by the 6-band camera as image and is measured by the spectrophotometer. The captured image has non-uniform signal distribution in the image. So some extent of the central part of the signal distribution in the image is used to calculate the average camera signals of i-th camera band $g_{i\lambda}$(i = 1 ~ 6). The spectral sensitivities $h_i(\lambda)$ (i = 1 ~ 6) at the wavelength λ are calculated by the Eq. (1).

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

where I_λ represents the light energy measured by the spectrophotometer and g_{i0} represents the bias signal. In this measurement the gamma and the knee is set off to make the camera response linear. The spectral sensitivities of a conventional HDTV camera are also measured same way. Fig. 5(a) and Fig. 5(b) show the spectral sensitivities of the 6-band camera and the conventional HDTV camera respectively. The 6-band camera has 6 narrow-band sensitivities as is expected by its spectral characteristics shown in Fig. 3. It should be noted that the gain of each band is adjusted independently and there are some optical parts not common to the 6-band camera and the conventional HDTV camera.

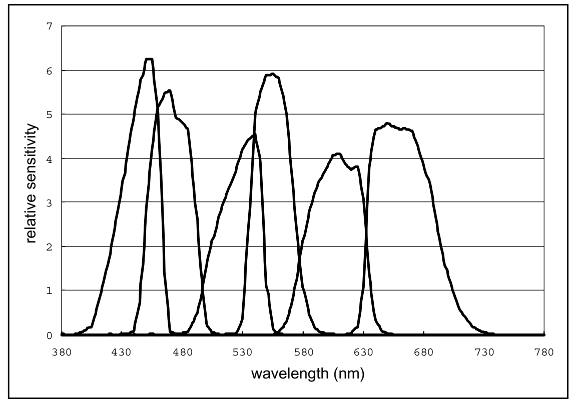

Figure 5 (a). Spectral sensitivities of the 6-band camera

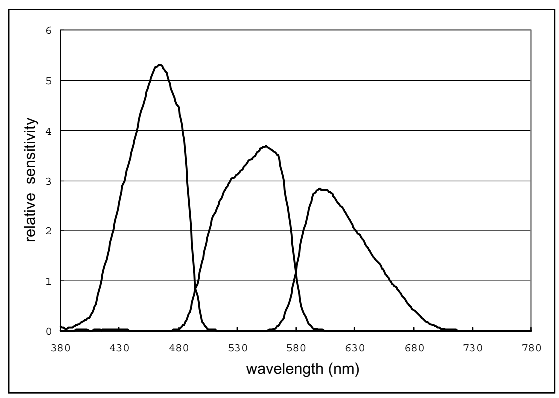

Figure 5 (b). Spectral sensitivities of the RGB camera

Mathematical Camera Model

The mathematical camera model provides a calculation method of the camera signals using the spectral sensitivities of the camera, the illumination spectrum, and the spectral reflectance of the object to be captured. We adopt the following equations as the mathematical camera model.

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

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

where $h_i(\lambda)$ (i = 1 ~ 6) is the spectral sensitivities of the 6-band camera shown in Fig. 5(a), $E(\lambda)$ is the illumination spectrum, and $f(\lambda)$ is the spectral reflectance of the object. $\gamma_i(\,)$ in Eq. (3) represents gamma function of the camera. Usually in the actual cameras the above model does not hold strictly. We evaluate the model accuracy used in the camera characterization for the color estimation.

Theory for Accurate Color Reproduction

The CIE colorimetric values, X, Y, and Z under the illumination spectrum $E'(\lambda)$ are defined by the following equations.

$$X = \int_{\lambda=380}^{780} x(\lambda)E'(\lambda)f(\lambda)d\lambda \quad (4a)$$

$$Y = \int_{\lambda=380}^{780} y(\lambda)E'(\lambda)f(\lambda)d\lambda \quad (4b)$$

$$Z = \int_{\lambda=380}^{780} z(\lambda)E'(\lambda)f(\lambda)d\lambda \quad (4c)$$

where $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ represent the CIE color matching functions. When the L-band camera signals are obtained, the estimated colorimetric values $\tilde{X},\tilde{Y},\tilde{Z}$ are given by the 3×L matrix transformation of the camera signals.

$$\tilde{\mathbf{C}} = \mathbf{MG} \quad (5)$$

where $\tilde{\mathbf{C}} = [\tilde{X},\tilde{Y},\tilde{Z}]^t$, $\mathbf{G} = [g_1, g_2, ..., g_L]^t$.

The matrix **M** is determined by Wiener estimation minimizing

$$\left\| \tilde{\mathbf{C}} - \mathbf{C} \right\|, \textit{ where } \mathbf{C} = [X, Y, Z]^t,$$

assuming that Eq. (2) holds and rewritten as

$$\mathbf{M} = \mathbf{AB}^{-1} \quad (6)$$

where the elements of the matrix **A** and **B** are represented by Eq. (7) and Eq. (8) respectively.

$$a_{lk} = \int_{\lambda=380}^{780}\int_{\lambda'=380}^{780} c_l(\lambda)E'(\lambda) < f(\lambda)f(\lambda') > h_k(\lambda')E(\lambda')d\lambda d\lambda' \quad (7)$$

$$b_{jk} = \int_{\lambda=380}^{780}\int_{\lambda'=380}^{780} h_j(\lambda)E(\lambda) < f(\lambda)f(\lambda') > h_k(\lambda')E(\lambda')d\lambda d\lambda' \quad (8)$$

where $\langle\rangle$ represents the operator of ensemble average, and $c_1(\lambda) = x(\lambda)$, $c_2(\lambda) = y(\lambda)$, and $c_3(\lambda) = z(\lambda)$. If the illumination spectrum $E(\lambda)$ is equal to $E'(\lambda)$, it is possible for the colorimetric values of arbitrary objects to be estimated exactly by a linear transformation of the camera signals in the condition that the linear combinations of the spectral sensitivities of more than 3 bands of camera represent $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$. The color reproduction of the current television system is based on this theory in the case that the L is equal to 3 and the spectral sensitivities of the camera are standardized as ones satisfying this condition. However, when $E'(\lambda)$ is not equal to $E(\lambda)$ but arbitrary illuminant, the above theory does not hold any more. In this case it becomes effective to increase the number of the camera bands for accurate color estimation.

Results

The estimated color is evaluated by the color difference between the color of the object under the illumination for observation calculated by Eq. (4) and the color estimated from the simulated camera signals, which are calculated by the camera mathematical model given by Eq. (2) and Eq. (3). Another evaluation is the color difference between the color of the object measured under the illumination for observation and the color estimated from the captured camera signals obtained under the illumination for capturing the image. The former evaluation is denominated simulation and the latter one experiment. The color difference between the simulation and the experiment due to inadequate camera model is also evaluated in the experiment.

Simulation

The error is defined by the color difference between the colorimetric values of each object estimated by Eq. (5) where the camera signals are simulated by Eq. (2) and Eq. (3) and those defined by Eq. (4). The objects are 24 color charts included in GretagMacbeth Color Checker. The illuminations used in the image capturing and the observations are a kind of xenon lamp (Day), a kind of incandescent lamp (A), and a kind of fluorescent lamp (Fl). The color is estimated by the aforementioned method using the above data. In the estimation process the statistical information on the object $<f(\lambda)f(\lambda')>$ is also necessary a priori. We used the data calculated from the spectral reflectance of the 24 color charts included in GretagMacbeth Color Checker measured by spectrophotometer as the statistical information. The XYZ values are calculated using the CIE1931XYZ color matching functions and it is transformed to the CIE1976 L*a*b* values assuming that the white point is the white chart included in GretagMacbeth color checker. The spectral reflectance of the color charts and the three kinds of the illumination spectra used in the simulations are shown in Fig. 6 to Fig. 9.

The average and maximum errors of the estimated colors from the simulated 6-band camera signals and 3-band camera signals are listed in table1. The description on the illumination condition (e.g. Day-A) represents the illumination for capturing and that for the observation in this order. Comparing the results of the 6-band camera with those of the 3-band camera, the 6-band camera achieves smaller errors than the 3-band for all the illumination conditions. The 6-band camera can estimate color with the average error of approximately 1 in ΔEab unit. On the other hand the 3-band camera estimates color with the average error of approximately 2 to 4 in ΔEab unit. The estimation errors depend whether the illumination spectrum for capturing and that for observation are same or not. Most estimation in the same illumination condition makes the average error minimum among those in the other combinations of the illumination conditions.

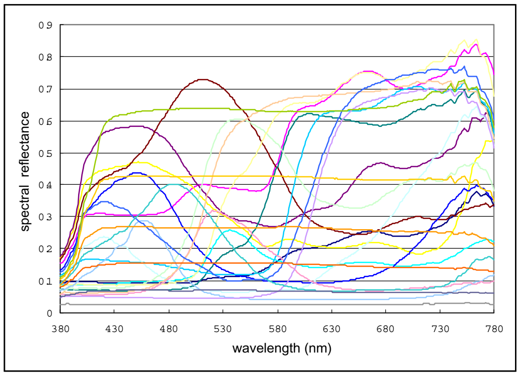

Figure 6. Spectral reflectance of the objects

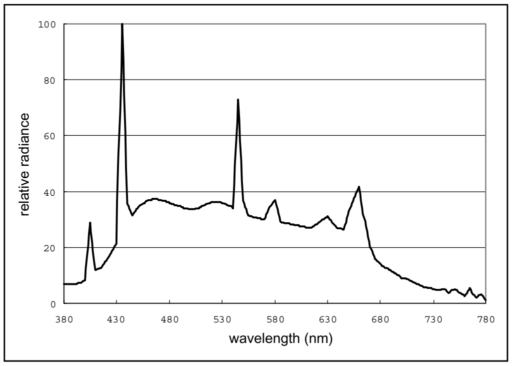

Figure 7. Spectrum of the daylight

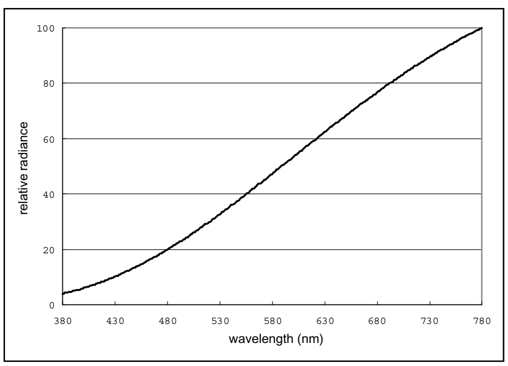

Figure 8. Spectrum of the incandescent lamp

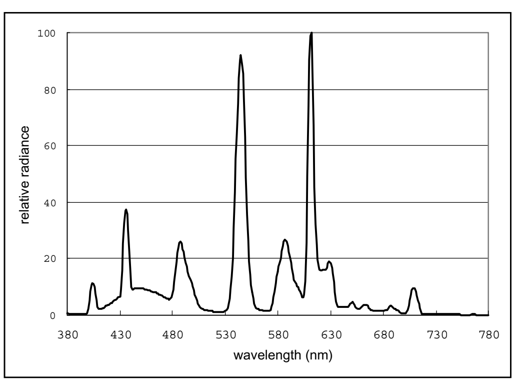

Figure 9. Spectrum of the fluorescent lamp

Table 1. Color Estimation Errors in the Simulation

	Dav-Dav		Dav-A		Dav-EI	
	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-Dav		A-A		A-EI	
	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

	EI-Dav		EI-A		EI-EI	
	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

Experiment

The 6-band camera and the 3-band camera captured GretagMacbeth Color Checker in a light booth. The light used in this experiment is a kind of xenon lamp whose spectral distribution is similar to that shown in Fig. 7. The captured image area of the checker including 24 color charts is smaller than a half of the whole image area. The 6-band and the 3-band signals of each color chart are averaged in the adequate region of the color chart. The colorimetric values of the 24 colors are measured by the spectrophotometer TOPCON SR-2A with the measuring wavelength interval of 5 nm on almost same geometrical condition as capturing image.

The color differences between the color values estimated from the camera signals and those measured by the spectrophotometer are listed in table 2. The average error of the 6-band camera is 1.43 and the maximum error is 4.24. The average error of the 3-band camera is 4.12 and the maximum error is 8.22. The average and maximum errors of the color estimated from the simulated camera signals, which are calculated using the spectral data measured in this experiment as described in the simulation method, are also shown in Table 2. The color difference between the colors estimated from the captured camera signals and from the simulated ones indicates how large the error of the camera model contributes to the experimental error. The average and maximum errors due to this model error are also shown in Table 2.

Table 2. Color Estimation Errors in the Experiment

	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

Discussion

In the simulation we examined the capability of the accurate color estimation by the 6-band camera comparing with a conventional HDTV 3-band camera. It is confirmed that under three kinds of illuminants typical to our daily life the 6-band camera realizes color estimation with high accuracy acceptable in large extent of applications. In the experiments the errors increased due to those of the camera model. In this experiment large part of the color estimation error is the contribution of the wrong camera model. One of the causes of the camera model error is flare inside the camera. The camera signals due to the flare should be compensated by sophisticated model for improving the color estimation performance. In the above discussion it is assumed that the spectral sensitivities of the camera are spatially uniform. However, in the case of the 6-band camera the spatial non-uniformity of the spectral sensitivity can be brought by the inserted interference filter used for 6-band color separation in addition to the non-uniformity of the spectral characteristics of the optical components and the image sensors. We examined the spatial uniformity of the estimated color of the 6-band camera. A white diffuser is captured by the 6-band camera 25 times moving the direction of it so as to adjust the image position of the white diffuser being on predetermined 5 by 5 sampled grid points. The difference of the spectral sensitivities brings the difference of the camera signals for the same object. Hence the estimated color also becomes different from point to point when the same spectral sensitivities are used in the color estimation over imaging area. The color differences relative to the color of the center in imaging area evaluated in ΔEab unit are shown in Fig.10. The farther the point of the distance from the center is larger, the larger the estimated color difference becomes. The estimated color distribution in a*-L* plane and a*-b* plane are plotted in Fig. 11.

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 10. Distribution of the estimated color difference relative to center of the image

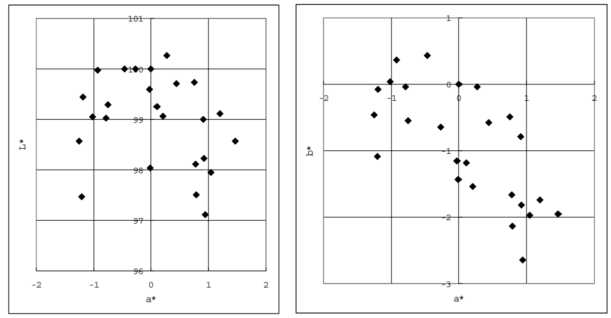

Figure 11. Estimated color distribution in a-L* and a*-b* plane*

Conclusion

We developed a 6-bnd camera for accurate color reproduction of motion picture based on spectral information. The accuracy of the estimated color of the 6-band camera comparing with a conventional RGB (i.e. 3-band) HDTV camera is evaluated. The results of the color estimations from the simulated camera signals suggest the 6-band camera has appreciable accuracy. In the experimental evaluation the average color difference of dE_{ab} obtained from the 6-band camera signals attained 1.43 although it became worse than those of the simulation due to the error of the camera model.

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