An Active Illumination Method for Tristimulus Image Display

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Abstract

The present paper proposes a method for producing the XYZ images of objects observed under arbitrary illumination on a display device. A realistic appearance of object surfaces is realized on the display directly without any color conversion. First, we describe the system construction with a programmable light source, a high speed monochrome camera, a display device, and two personal computers. The illuminant spectra are produced in a linear combination of narrow-band basis spectra. Next, we describe the principle of tristimulus image display. The theoretical equations of the active illuminant are derived for producing the tristimulus values of object surfaces observed under a target light source. The ideal illuminant spectra, however, have negative portions that are not physically realizable. Then, we design the practical illuminant spectra that make compensation for the negative portions. The feasibility of the proposed active illumination method is confirmed in experiments of color image rendering for real color patches.

Introduction

Image reproduction of objects existing in a natural scene is normally performed using a color camera and a color-calibrated display device. In such a case we take account of the characteristics of the camera and the display for accurate color reproduction. The typical device characteristics are (1) the spectral-sensitivity functions, the input-output linearity, and the dynamic range for the camera, and (2) the spectral-power distributions, the RGB chromaticity coordinates, and the input-output nonlinearity for the display. Because the camera spectral sensitivities cannot satisfy the Luther condition, a multi-spectral imaging system is often used for improving color reproduction. However, the traditional system for multi-spectral imaging has essential problems such as time consumption and system complexity.

In a previous paper, we proposed a high-speed spectral imaging system using an active spectral illumination [1]. The synchronous imaging system was constructed by combining a programmable light source and a high-speed monochrome camera. Then illuminant distribution with arbitrary spectral shape can be produced as a time sequence. We also presented a control algorithm for effectively producing arbitrary illuminants [2]. This imaging system has a wide range of applications. Real-time colorimetry is a potential application of this system [3]. The colorimetric technique is based on projection of the color-matching functions as illuminant. When the color-matching functions are projected onto object surfaces, the CIE-XYZ color values can be obtained at every point on the surface directly from the camera outputs. This system can be called the CIE tristimulus imager or the CIE-XYZ imager. However, when the camera outputs are displayed onto a display device, we still need a traditional color conversion from the XYZ values to the display RGB values.

The present paper proposes a method for producing the XYZ images of objects observed under arbitrary illumination environment on a display device. A realistic appearance of object surfaces is realized on the display directly without any color conversion. Figure 1 illuminates the entire system that combines an active spectral imaging system and a display device. We design an active illumination containing both the characteristics of the camera and the display. The color-matching functions with the devise characteristics are projected onto the objects in time sequence. Then the corresponding tristimulus images captured by a monochrome camera in three times are transmitted to a display device in the form of tri-signal without color conversion. The display device produces the XYZ image directly. That is, the CIE tristimulus values are obtained at every pixel of the display. Several merits of the proposed system are as follows:

(1) A realistic appearance of real objects in a scene observed under a light source with arbitrary spectral-power distribution can be rendered on a display device.

(2) We enable high-speed image rendering including image capturing and displaying.

(3) Color conversion is not necessary from the camera to the display, but the color signals are sequentially passed through the camera to the display device.

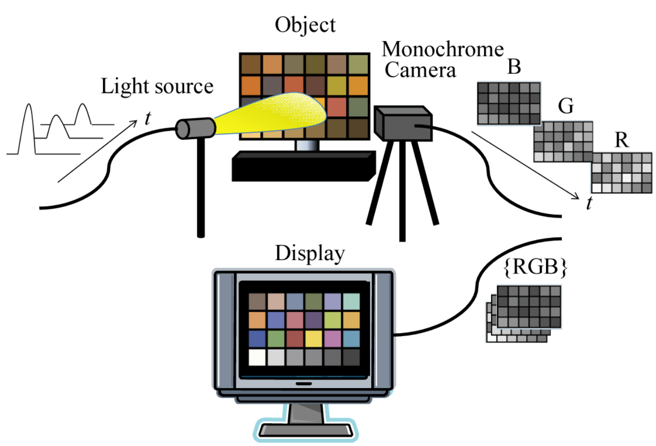

Figure 1 Entire system combining an active spectral imaging system and a display device.

In the following, we first describe the system construction with a programmable light source, a high speed monochrome camera, a display device, and two personal computers. The illuminant spectra are produced in a linear combination of narrow-band basis spectra. Next, we describe the principle of tristimulus image display. The theoretical equations of the active illuminant are derived for producing the tristimulus values of object surfaces

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observed under a target light source. The ideal illuminant spectra, however, have negative portions that are not physically realizable. Then, we design the practical illuminant spectra that make compensation for the negative portions. The feasibility of the proposed active illumination method is examined in experiments of color rendering using the present system in detail.

System construction

The spectral imaging system is constructed with a high speed monochrome CMOS camera (Epix SV642M) and a programmable light source (Optronic Laboratories OL490) [4], which are controlled by two computers in order to capture image sequences synchronously with the strobo light. The programmable light source is composed of a xenon lamp, a grating, and a digital micromirror device (DMD) chip. The wavelength and intensity information of the emitted light is controlled using the two-dimensional DMD chip. The monochrome camera is operated with 320x240 resolution and 10-bit quantization at 20-200 fps. Since the operation of the camera is much slower than the light source, the camera is the master device in the relationship to the light source for their synchronization. Before capturing images, we create a sequence of frames forming lighting conditions such as wavelength, bandwidth, and relative intensity in advance. The light source software then prepares a frame by downloading the sequence to RAM and setting the frame up for hardware triggering. When the camera starts observation of a scene, the RS644 strobe signal is output by the instruction from the control PC.

We design the emission of a spectral function in a time-varying mode. In the time-varying mode, different spectra can be generated at every time. Let $E_{\lambda i}(\lambda)$ be a spectral-power distribution emitted at a central wavelength λ_i. A set of these basis spectra is generated at equal wavelength interval in the visible range. The emitted illuminant spectrum, therefore, is expressed in a linear combination of the basis spectra in the form.

$$I(\lambda)=c_1E_{\lambda 1}(\lambda)+c_2E_{\lambda 2}(\lambda)+...+c_nE_{\lambda n}(\lambda)\ . \qquad (1)$$

For colorimetry and color reproduction, three illuminant spectra $I_X(\lambda,t_1)$, $I_Y(\lambda,t_2)$, and $I_Z(\lambda,t_3)$ are produced in time sequence. Coefficients $\{c_1, c_2, \ldots, c_n\}$ of the basis spectra are estimated by an iterative calibration process in Ref. [2].

These illuminants are projected onto the object surfaces, and the monochrome camera captures the corresponding images in three times, which are transmitted to a display device in the form of tri-signal without color conversion. A display device used in this study is an EIZO ColorEdge (CG221) with the Adobe RGB color gamut. Figure 2 shows the flow of color signals in the entire system.

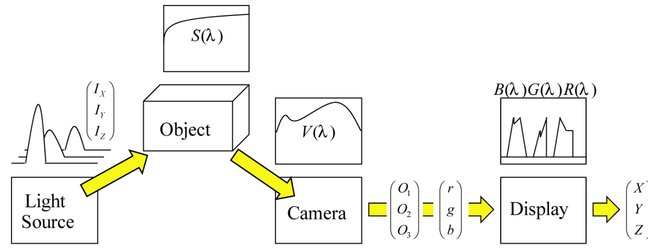


Figure 2 Flow of color signals in the entire system.

Principle of tristimulus display

Let $S(\lambda)$ and $V(\lambda)$ be the surface-spectral reflectance function of an object and the spectral-sensitivity function of the monochrome camera, respectively. The camera outputs under the illuminants $I_X(\lambda,t_1)$, $I_Y(\lambda,t_2)$, and $I_Z(\lambda,t_3)$ are described as

$$\begin{bmatrix} O(t_1) \\ O(t_2) \\ O(t_3) \end{bmatrix} = \int S(\lambda)V(\lambda) \begin{bmatrix} I_X(\lambda,t_1) \\ I_Y(\lambda,t_2) \\ I_Z(\lambda,t_3) \end{bmatrix} d\lambda\ . \qquad (2)$$

The time sequence of the outputs is stored in the frame buffer of RGB as $(r, g, b) = (O(t_1), O(t_2), O(t_3))$ to transmit into the display device in the form of tri-signal. Next, let $(R(\lambda), G(\lambda), B(\lambda))$ be the spectral-power distributions of three phosphors in the display device. Then, the tristimulus values of the display outputs are described as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \int (rR(\lambda)+gG(\lambda)+bB(\lambda)) \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} d\lambda\ . \qquad (3)$$

On the other hand, the tristimulus values of the same object surface under a target illuminant $E_T(\lambda)$ to be observed are calculated as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \int S(\lambda)E_T(\lambda) \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} d\lambda\ . \qquad (4)$$

For simplicity of mathematical manipulation, we use matrix notation for spectral representation. Assume that each spectral function is sampled at n points with equal interval $\Delta\lambda$ in the region [400, 700] nm. All spectral functions are then represented in n-dimensional row vectors as follows:

Active illuminants;

$\mathbf{I}_X = [I_X(\lambda_1,t_1), I_X(\lambda_2,t_1), \ldots, I_X(\lambda_n,t_1)]$,

$\mathbf{I}_Y = [I_Y(\lambda_1,t_2), I_Y(\lambda_2,t_2), \ldots, I_Y(\lambda_n,t_2)]$,

$\mathbf{I}_Z = [I_Z(\lambda_1,t_3), I_Z(\lambda_2,t_3), \ldots, I_Z(\lambda_n,t_3)]$.

Surface;

$\mathbf{S} = [S(\lambda_1), S(\lambda_2), \ldots, S(\lambda_n)]$

Phosphors;

$\mathbf{R} = [R(\lambda_1), R(\lambda_2), \ldots, R(\lambda_n)]$, $\mathbf{G} = [G(\lambda_1), G(\lambda_2), \ldots, G(\lambda_n)]$,

$\mathbf{B} = [B(\lambda_1), B(\lambda_2), \ldots, B(\lambda_n)]$.

Color matching functions;

$\bar{\mathbf{x}} = [\bar{x}(\lambda_1), \bar{x}(\lambda_2), \ldots, \bar{x}(\lambda_n)]$, $\bar{\mathbf{y}} = [\bar{y}(\lambda_1), \bar{y}(\lambda_2), \ldots, \bar{y}(\lambda_n)]$,

$\bar{\mathbf{z}} = [\bar{z}(\lambda_1), \bar{z}(\lambda_2), \ldots, \bar{z}(\lambda_n)]$.

Moreover we define diagonal matrices for the camera sensitivity function and the target illuminant as $diag\mathbf{V}$ and $diag\mathbf{E}$. Combining Eqs.(2) and (3), we obtain the input-output relationship of the entire system as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{x}} \\ \bar{\mathbf{y}} \\ \bar{\mathbf{z}} \end{bmatrix} \begin{bmatrix} \mathbf{R}^t & \mathbf{G}^t & \mathbf{B}^t \end{bmatrix} \begin{bmatrix} \mathbf{I}_X \\ \mathbf{I}_Y \\ \mathbf{I}_Z \end{bmatrix} [diag\mathbf{V}]\mathbf{S}^t, \qquad (5)$$

From a color reproduction standpoint, the above equation should be equivalent to Eq.(4). Therefore, we have the relationship

$$\begin{bmatrix}\bar{\mathbf{x}}\\ \bar{\mathbf{y}}\\ \bar{\mathbf{z}}\end{bmatrix}\left[diag\mathbf{E}\right]=\mathbf{M}\begin{bmatrix}\mathbf{I}_X\\ \mathbf{I}_Y\\ \mathbf{I}_Z\end{bmatrix}\left[diag\mathbf{V}\right] , \qquad (6)$$

where **M** indicates a 3×3 correlation matrix between the CIE color matching functions and the phosphor spectral-power distributions. The active illuminants for producing the tristimulus values of color appearance under the target light source can be determined from a solution of Eq.(6) as

$$\begin{bmatrix}\mathbf{I}_X\\ \mathbf{I}_Y\\ \mathbf{I}_Z\end{bmatrix}=\mathbf{M}^{-1}\begin{bmatrix}\bar{\mathbf{x}}\\ \bar{\mathbf{y}}\\ \bar{\mathbf{z}}\end{bmatrix}\left[diag\mathbf{E}\right]\left[diag\mathbf{V}\right]^{-1} . \qquad (7)$$

It should be noted that Eq.(7) does not depend on the object surface S, but depend only on the spectral sensitivity of the camera and the spectral-power distributions of the phosphors.

Without using the phosphor spectra, the characteristics of a display can be expressed in the triplet of the CIE chromaticity coordinates (x, y) and the luminance as $\{(x_R, y_R), L_R\}$, $\{(x_G, y_G), L_G\}$, $\{(x_B, y_B), L_B\}$. In this case, the active illuminants equivalent to the above solution are given in the following form:

$$\begin{bmatrix}\mathbf{I}_X\\ \mathbf{I}_Y\\ \mathbf{I}_Z\end{bmatrix}=\mathbf{T}\begin{bmatrix}\bar{\mathbf{x}}\\ \bar{\mathbf{y}}\\ \bar{\mathbf{z}}\end{bmatrix}\left[diag\mathbf{E}\right]\left[diag\mathbf{V}\right]^{-1} , \qquad (8)$$

where

$$\mathbf{T}=\begin{bmatrix}\frac{255}{L_{R\max}} & 0 & 0\\ 0 & \frac{255}{L_{G\max}} & 0\\ 0 & 0 & \frac{255}{L_{B\max}}\end{bmatrix}\begin{bmatrix}\frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B}\\ 1 & 1 & 1\\ \frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B}\end{bmatrix}^{-1} , \qquad (9)$$

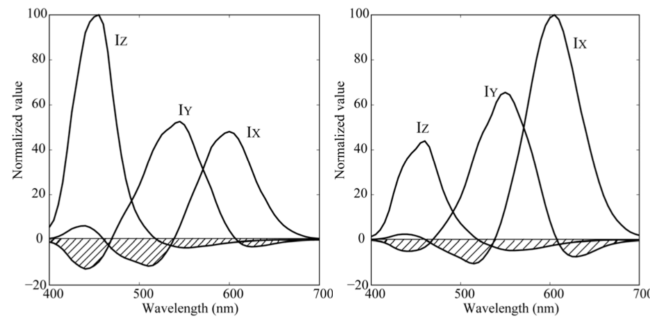
Here we assume the display of 8-bit quantization and the maximum luminance values of ($L_{R\max}$, $L_{G\max}$, $L_{B\max}$). This expression is much more useful than Eq.(7) when the profile of the display device is available. Even for application of color management where the device profile of each display is not available, we can utilize default standards such as sRGB and Adobe RGB.

So far, a linear relation has been assumed between the input signals and the output signals at both the camera and the display. The monochrome camera used in this study has a good linear relationship. However, the luminance outputs from the display device are not linear to the input RGB signals. Correction of this display nonlinearity (gamma correction) is performed by a lookup table representing the inverse function. Let **F** be a 3×3 diagonal matrix of the correction function f. Thus, the active illuminants with the effect of gamma correction are given by

$$\begin{bmatrix}\mathbf{I}_X\\ \mathbf{I}_Y\\ \mathbf{I}_Z\end{bmatrix}=\left[diag\mathbf{F}\right]\mathbf{T}\begin{bmatrix}\bar{\mathbf{x}}\\ \bar{\mathbf{y}}\\ \bar{\mathbf{z}}\end{bmatrix}\left[diag\mathbf{E}\right]\left[diag\mathbf{V}\right]^{-1} . \qquad (10)$$

Design of practical illuminant

We have calculated the active illuminant spectra for the present system by substituting all device characteristics into Eq.(10). Figure 3 shows the illuminants $\mathbf{I}_X$, $\mathbf{I}_Y$ and $\mathbf{I}_Z$ needed for realizing the tristimulus display of any objects under the viewing conditions of Illuminant D65 and Illuminant A. It is noted that all three spectral curves have negative portions in both illuminant conditions. The ratio of the negative portions is larger in Illuminant D65 compared with Illuminant A. The largest is the negative portion of $\mathbf{I}_X$ in the blue-green parts of the spectrum. The negative parts of the illuminant spectrum are not physically realizable in the present programmable illumination system. In practice they may be ignored. However the accuracy of color image display certainly decreases in ignoring them.



(a) Viewing condition of D65 (b) Viewing condition of A

Figure 3 Theoretical illuminant spectra for realizing the tristimulus display of any objects.

In order to solve this problem, we design the illuminant spectra that make compensation for the negative portions. In the field of color television, it is known that the ideal color-matching functions of color television have negative portions that are not physically realizable [5]. So far, practical methods were developed for approximating the color-matching functions. The approximated functions were designed by taking account of non-negativity, color separation, and single peak. Such a correction method of the color-matching functions provides us a useful idea for designing practical functions of active illuminant spectra. There are three correction methods that we have examined in this study. These are Epstein's approximation, the nearest neighbor approximation, and the linear scaling approximation. Epstein's approximation was proposed for compensating negative portions of an equivalent color response curve for RCA color television system [6]. His idea was to compensate the negative portion of a spectral curve by deleting a certain positive area near the negative part. The nearest neighbor approximation was used as an electric compensation algorithm for the television system. The algorithm compensates the negative portion by deleting a positive area near the negative part. The different point from Epstein's approximation is that the negative portion can be deleted from other color channels. The linear scaling approximation compensates the negative portion by deleting positive area linearly in all wavelengths. Our examination of three methods showed that Epstein's approximation was better than the others. Therefore, in this paper, we develop a compensation algorithm for the negative illuminant problem based on Epstein's approximation.

Figure 4 illustrates the concept of our compensation method. An example in Figure 4(a) depicts a partial spectral curve of the original illuminant with a negative lobe. Figure 4(b) shows a design for illuminant compensation. According to the negative portion of a spectral curve, a certain amount of positive area near the negative part is deleted as shown in Figure 4(b). This solution process can be formulated as follows:

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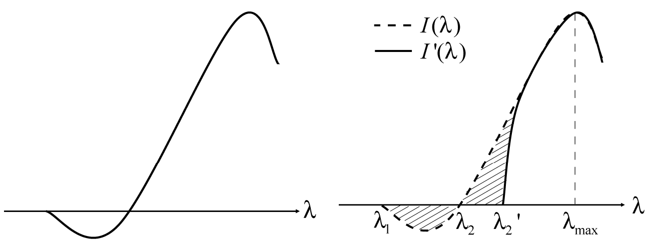
$$\begin{cases} I(\lambda)=0, & (\lambda \le \lambda_1) \\ I(\lambda)<0, & (\lambda_1<\lambda<\lambda_2) \Rightarrow \begin{cases} I'(\lambda)=0 & (\lambda \le \lambda_2') \\ I'(\lambda)\ge 0 & (\lambda_2'<\lambda) \end{cases}, \\ I(\lambda)>0, & (\lambda_2 \le \lambda) \end{cases} \tag{11}$$

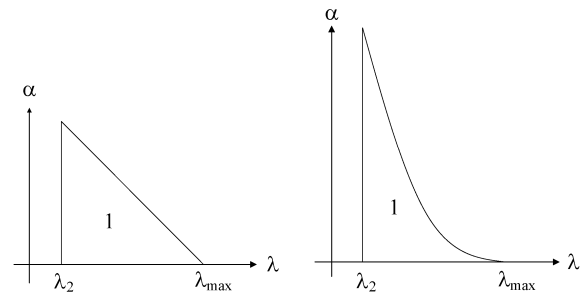
where $I'(\lambda)$ indicates the illuminant spectrum after the compensation, and the wavelengths λ_1, λ_2' and λ_2 are defined as in the figure. We design so that the area removed from the positive spectral curve within $[\lambda_2, \lambda_{\max}]$ (shown by hatching in the figure) has the same area as the negative portion within $[\lambda_1, \lambda_2]$. Therefore we have a constrained relation

$$\int_{\lambda_1}^{\lambda_2} I(\lambda)d\lambda + \int_{\lambda_2}^{\lambda_{\max}} \{I(\lambda)-I'(\lambda)\}d\lambda = 0\ . \tag{12}$$



(a) Spectral curve with negative portion *(b) Design for illuminant correction*

Figure 4 Compensation of illuminant with negative portions.



(a) p=1 *(b) p=2*

Figure 5 Weighting functions α(λ) for p=1and p=2.

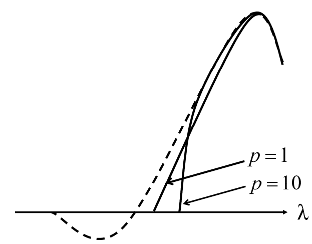


Figure 6 Illuminant spectral curves compensated with different values of the parameter p.

The following algorithm is proposed for determining the practical spectral curve of positive illuminant which results in good approximation of CIE tristimulus values on the display.

$$I'(\lambda) = \max\left(0,\ \ I(\lambda) - \alpha(\lambda)\int_{\lambda_1}^{\lambda_2} I(\lambda')d\lambda'\right), \tag{13}$$

where $\alpha(\lambda)$ indicates a weighting function of wavelength which represents the ratio of negative area to positive area. This function is defined in this paper as

$$\alpha(\lambda) = \frac{(\lambda_{\max}-\lambda)^p}{\int_{\lambda_2}^{\lambda_{\max}} (\lambda_{\max}-\lambda')^p d\lambda'}, \quad (\lambda \le \lambda_{\max}), \tag{14}$$

$$\int_{\lambda_2}^{\lambda_{\max}} \alpha(\lambda)d\lambda = 1\ , \tag{15}$$

where p is a parameter representing the dimension of the weighting. This parameter is related to the sharpness of illuminant spectral curve. The spectrum shape becomes sharp as the parameter p increases. For instance, in the case of p=1, the weighting function is rewritten as

$$\alpha(\lambda) = 2\frac{(\lambda_{\max}-\lambda)}{(\lambda_{\max}-\lambda_2)^2}, \tag{16}$$

and becomes linear as schematized in Figure 5(a). Figure 5(b) shows the weighting function $\alpha(\lambda)$ in the case p=2. The range for weighting is concentrated on a narrow range compared with p=1. Figure 6 shows illuminant spectral curves $I'(\lambda)$ compensated with different parameter values of p=1 and p=10. Note that the spectral curve of p=10 is narrower than p=1.

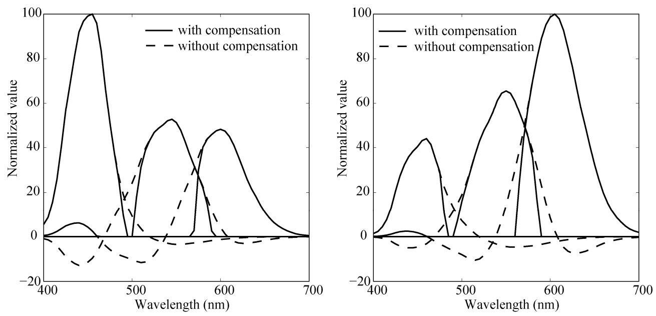
Experiments

Simulation results

The proposed compensation algorithm was applied to the active illuminant spectra with negative portions shown in Figure 3. Figure 7 shows the compensated illuminant spectra with only non-negative values. The broken curves represent the original illuminant spectra $\mathbf{I}_X$, $\mathbf{I}_Y$ and $\mathbf{I}_Z$ in Fig. 3. The bold curves represent the compensated illuminant spectra $\mathbf{I}_X'$, $\mathbf{I}_Y'$ and $\mathbf{I}_Z'$. We note that the spectral curves are sharpened and non-negative. Table 1 shows simulated results for the X-Rite Mini ColorChecker. We suppose that the set of color patches are illuminated by the compensated illuminants and the appearance of the color image is produced on the display device. The accuracy of color rendering is evaluated by the average of the CIE-L*a*b* difference for 24 color patches. In the viewing condition of Illuminant A, the xy chromaticity coordinates of three patches are outside of the Adobe RGB gamut as shown later in Figure 9(b). In this case the difference is calculated for 21 color patches except for the three patches. In both the viewing conditions, the color differences are improved by the proposed compensation algorithm.

Experiments on real system

We have verified the feasibility of the propose method in experiments of color rendering using the present system. Figure 8 shows the illuminant spectra $\mathbf{I}_X'$, $\mathbf{I}_Y'$ and $\mathbf{I}_Z'$ produced by the active illumination system in order to render the appearance of objects observed under Illuminants D65 and A on the display device. The broken curves represent the target spectral curves that are the compensated illuminant spectra shown in Figure 7. The bold curves represent the direct measurements of the produced spectra emitted from the light source.



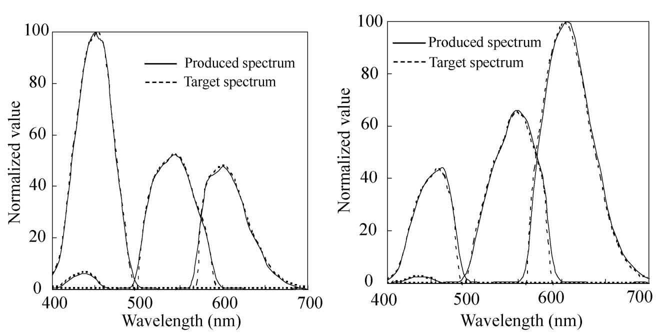
(a) Viewing condition of D65 *(b) Viewing condition of A*

Figure 7 Compensated illuminant spectra using the proposed algorithm (p=10).

Table 1 Accuracy of color rendering in CIE-L*a*b* difference (simulation)

Viewing condition	without compensation (Fig. 3)	Proposed compensation algorithm			
		p=1	*p*=2	*p*=3	*p*=10
D65	7.2	5.0	4.8	4.7	4.6
A	6.7	4.2	4.1	4.0	3.9

We have examined the accuracy of color rendering. The above illuminants were projected to the X-Rite Mini ColorChecker. The 24 color patches in all were measured by repeating the projection to the patch of 2×2 at the same time. Then the displayed patches were measured by a spectrophotometer (Photo Research Inc. PR-650). The accuracy was evaluated by color difference. The average of CIE-L*a*b* difference for the color patches under the assumed Illuminants D65 and A are shown in Table 2. The reason why the color difference increases is considered as accumulation of the measurement and device errors on the active light source, the camera, and the display.



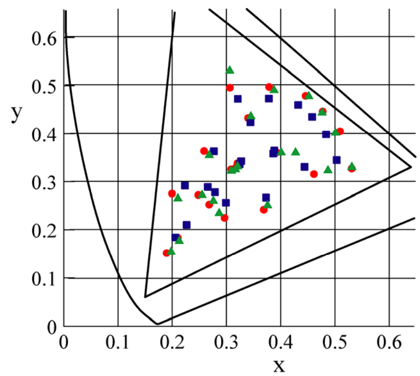
(a) Viewing condition of D65 *(b) Viewing condition of A*

Figure 8 Illuminant spectra produced by the active illumination system.

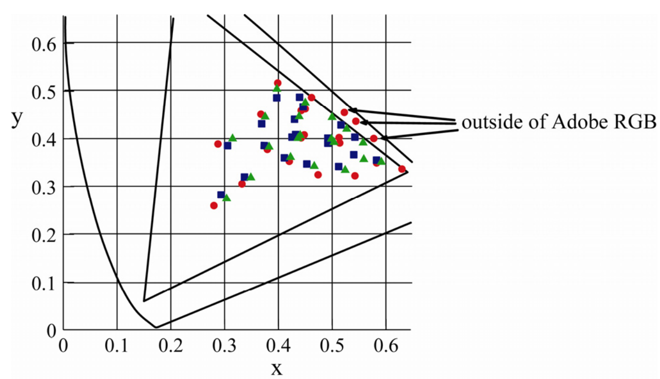
The projection time for each 2x2-paches was less than 10 milliseconds. Figure 9 summarizes the accuracy of color rendering on the xy-chromaticity diagram. Triangular lines show the gamut boundary of Adobe RGB. Three types of symbols of red circles, blue squares and green triangles show the target coordinates of color patches (the ground truth), the color patches produced by the illuminants without compensation, and the color patches produced by the proposed compensation algorithm, respectively. The chromaticity coordinates of each patch move to the desaturated direction when the negative portions of the illuminant spectra are neglected without any compensation. We note that the proposed compensation algorithm improves the deterioration of the color shift.

Table 2 Accuracy of color rendering in CIE-L*a*b* difference (real system)

Viewing condition	without compensation (Fig. 3)	Proposed algorithm *p*=10
D65	9.9	7.7
A	11.8	8.1



(a) Viewing condition of D65



(b) Viewing condition of A

Figure 9 Color rendering accuracy on the xy-chromaticity diagram. Red circles: the target coordinates of color patches (the ground truth). Blue squares: the color patches produced by the illuminants without compensation. Green triangles: the color patches produced by the proposed compensation algorithm

Discussion

We supposed in the above that three active illuminants are projected corresponding to the tristimulus values of object surfaces.

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If we can accept that four illuminants are projected sequentially onto object surfaces, the compensation for non-negativity is reduced to a simple operation of subtraction.

Figure 10 illustrates the four illuminants $\mathbf{I}_X''$, $\mathbf{I}_Y''$, $\mathbf{I}_Z''$ and $\mathbf{I}_C$ needed in the case of D65 viewing condition, where $\mathbf{I}_C$ is a constant spectrum, and $\mathbf{I}_X'' = \mathbf{I}_X + \mathbf{I}_C$, $\mathbf{I}_Y'' = \mathbf{I}_Y + \mathbf{I}_C$, $\mathbf{I}_Z'' = \mathbf{I}_Z + \mathbf{I}_C$. We note that these illuminant spectra are non-negative in the visible wavelength. After sequential projection of $\mathbf{I}_X''$, $\mathbf{I}_Y''$, $\mathbf{I}_Z''$ and $\mathbf{I}_C$, an excess of the positive values in the camera outputs (O_1, O_2, O_3) is offset by the output O_4 in the camera system as

$$(r, g, b) = (O_1 - O_4, O_2 - O_4, O_3 - O_4). \quad (17)$$

The accuracy of color rendering is much improved as $\Delta E^*_{ab} = 4.65$ under D65, compared with Table 2. We sacrifice the processing speed but improve the accuracy.

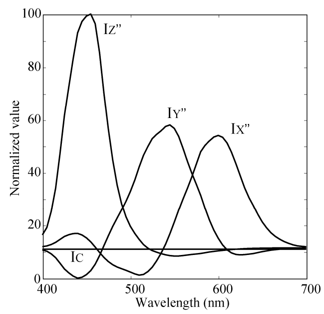

Figure 10 Four illuminant spectra for realizing the tristimulus display

Conclusion

We have proposed a method for producing the XYZ images of objects observed under arbitrary illumination on a display device. A realistic appearance of object surfaces was realized on the display directly without any color conversion. First, we described the system construction with a programmable light source, a high speed monochrome camera, a display device, and two personal computers. The illuminant spectra were produced in a linear combination of narrow-band basis spectra. Next, we described the principle of tristimulus image display. The theoretical equations of the active illuminant were derived for producing the tristimulus values of object surfaces observed under a target light source. The ideal illuminant spectra, however, had negative portions that were not physically realizable. Then, we designed the practical illuminant spectra that made compensation for the negative portions. The proposed method has several advantages of (1) image rendering of real objects under arbitrary illumination, (2) high-speed image rendering, and (3) direct transmission from the camera to the display without color conversion. The feasibility of the proposed active illumination method was confirmed in experiments of color image rendering for real color patches.

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Author Biography

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