Color image reproduction based on the multispectral and multiprimary imaging: Experimental evaluation

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ABSTRACT

Multispectral imaging is significant technology for the acquisition and display of accurate color information. Natural color reproduction under arbitrary illumination becomes possible using spectral information of both image and illumination light. In addition, multiprimary color display, i.e., using more than three primary colors, has been also developed for the reproduction of expanded color gamut, and for discounting observer metamerism. In this paper, we present the concept for the multispectral data interchange for natural color reproduction, and the experimental results using 16-band multispectral camera and 6-primary color display. In the experiment, the accuracy of color reproduction is evaluated in CIE ΔEa^*b^* for both image capture and display systems. The average and maximum $\Delta Ea^*b^* = 1.0$ and 2.1 in 16-band mutispectral camera system, using Macbeth 24 color patches. In the six-primary color projection display, average and maximum $\Delta Ea^*b^* = 1.3$ and 2.7 with 30 test colors inside the display gamut. Moreover, the color reproduction results with different spectral distributions but same CIE tristimulus value are visually compared, and it is confirmed that the 6-primary display gives improved agreement between the original and reproduced colors.

Keywords: Color Reproduction, Spectral imaging, Multispectral image, Multiprimary color display, Color gamut, Color matching function, Observer metamerism, color image interchange

1. INTRODUCTION

High-fidelity color image reproduction is one of key issues in visual telecommunication systems, for electronic commerce, telemedicine, digital museum and so on. For this purpose, multispectral imaging is substantially effective. Multispectral imaging enables to obtain the spectral radiance or reflectance, to greatly improve the colorimetric accuracy, and to reproduce colors under different illuminations. It thus is an important technology for high-fidelity color reproduction, and multispectral cameras and scanners have been developed for digital archive [1], medical imaging [2,3], hardcopy reproduction [4], and manufacturing industry [5].

Multiprimary color display, i.e., using more than three primary colors, has been also developed. Wider color gamut can be obtained without using special high-intensity light of narrow-band spectrum (ex. laser light) [6-8]. In addition, spectral reproduction will be realized using the multiprimary display. It has been pointed that the variation of color matching function (CMF) among the observers cannot be ignored for accurate color reproduction [9]. Suppression of observer metamerism can be realized using multiprimary display, and several methods were proposed [10,11], but experimental evaluation is not reported until now.

Moreover, for the natural color reproduction using multispectral and multiprimary imaging, spectrum-based color reproduction system is required. There have been reported several methods for color reproduction using multispectral imaging [2,4,12,13], but the general and practical model for the spectrum-based natural color reproduction system through communication network has not yet been established.

In this paper, the concept for the multispectral data interchange for natural color reproduction is presented, and then the models for the data transmission system are illustrated. The experimental results using 16-band multispectral camera and 6-primary color display are also shown.

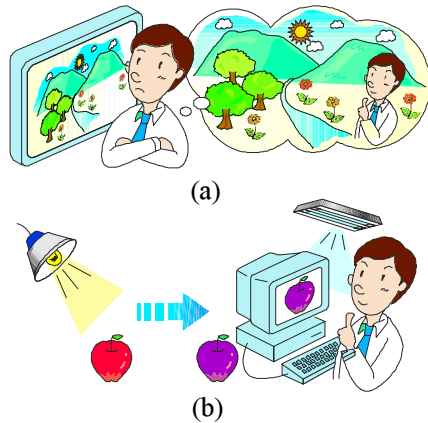* Correspondence: *guchi@isl.titech.ac.jp*
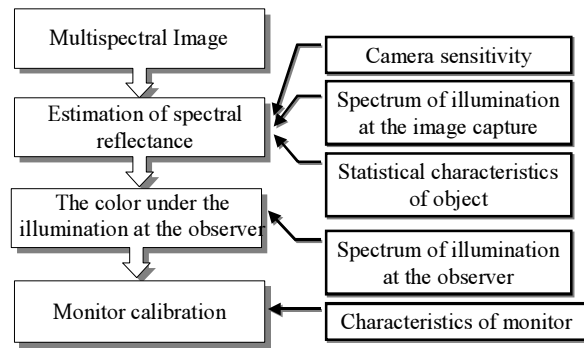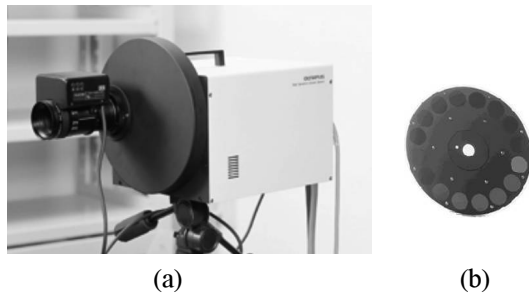
Fig.1

Fig.2

(a)   (b)

Fig.3

Fig.1   Concept of natural color reproduction
        (a) Reproducing colors as if the observer were at the site.
        (b) Reproducing colors as if the object were placed at the front of observer.
Fig.2   The color reproduction method with illumination difference correction
Fig.3   Photographs of (a) 16-band multispectral camera, and (b) color filters attached on a rotating tablet.

2. MULTISPECTRAL AND MULTIPRIMARY IMAGING FOR COLOR REPRODUCTION

2.1 NATURAL COLOR REPRODUCTION BY MULTISPECTRAL IMAGING

The natural color reproduction system will be utilized for (a) reproducing colors as if the observer were at the image-capturing site [Fig.1(a)], or (b) reproducing colors under the illumination environment of the observation site. [Fig.1(b)]. The aim of color reproduction system is the colorimetric match between the original and reproduced colors, though there is a problem in colorimetry as described in sec. 2.3.

To realize the color reproduction as shown in fig.1 (a), the chromaticity must be exactly determined from the output signal of an image acquisition device. However, the spectral sensitivities of conventional color cameras that have R, G, and B channels are not equivalent to that of human visual system, resulting that some objects that give the same color signal can be perceived as different colors by a human observer. Therefore, we need a color imaging device with equivalent spectral sensitivities to the human vision, i.e., satisfying "Luther condition," for exact color reproduction. Using multispectral imaging greatly reduces the deviation from the Luther condition.

When the illumination environments of image capture and observation are different, the color adaptation property of human vision must be considered. But if the colors under the observation illumination are reproduced, the observer perceives as if the object were placed at the front of the observer, as shown in fig.1(b). Reproduction of the colors under arbitrary illumination requires the spectral reflectance of the object and the spectral distribution of new illumination, and multispectral imaging is necessary for this purpose. The method to reproduce the color image under new illumination using multispectral image is shown in fig.2. After the correction of camera characteristics, the spectral reflectance of the object is estimated for each pixel of the captured image, using the illumination spectrum of the image capture. If the number of bands is not large, the use of statistical information of the spectral reflectance of target object class is effective for improving accuracy in the spectrum estimation [14]. Using the spectral reflectance of the object, the chromaticity is calculated for given illumination spectrum of observation environment.

In the hardcopy, it is not possible to change the colors adapted to the ambient illumination, but if the reproduction of spectral reflectance is realized, colorimetric match becomes possible between the original and reproduction under arbitrary illumination [4].

Several types of multispectral cameras (MSC) and scanners have been developed until now. A typical example is using a monochromatic image sensor and color filters attached on a rotating tablet [13]. The image of each spectral band is captured sequentially. Fig.3 shows this type of MSC developed by Olympus Optical Co., which can acquire 1k*1k 16-band multispecteral images. In another type of multispectral imaging device, especially scanners, the lights of different colors sequentially illuminate the object, which is imaged by monochromatic image sensor.

To capture a multispectral image of moving object, sequential acquisition is inconvenient because the object may move during the exposure. One-shot-type MSC, that is, a multispectral image is obtained by a single exposure, was also developed in the Akasaka Natural Vision Research Center [15]. In the one-shot-type 6-band MSC, two conventional RGB-type CCD cameras are used. The incident light is split by a half mirror and passes through special color filters, so that every channel of two CCD cameras has different spectral sensitivity.

2.2 MULTIPRIMARY DISPLAY FOR EXPANDING COLOR GAMUT

In the conventional display devices, such as CRT, LCD, or projectors, some of the colors of high saturation cannot be reproduced because the area of reproducible colors, i.e., color gamut, of display device does not cover all the existent colors in the world. The color gamut of the conventional display using three primary colors is inside the triangle, where three vertices are located at the coordinates of primary colors. Increasing the saturation of primary colors can enlarge the color gamut, but the gamut is still limited within a triangle, or hexahedron in three-dimensional color space, and it is impossible to cover all the visible colors by a triangle. Moreover, the spectral bandwidth should be narrowed to generate pure primary colors, and it sometimes decreases the efficiency of light energy.

The multiprimary color approach, i.e., using more than three primary colors, realizes expanded color gamut, which becomes a polygon, or tetrahedron in 3-D color space. The 6-primary projection display system was developed using two conventional RGB projectors, as shown in fig.4. Color filters are inserted into the optical paths of the R, G, and B primary lights so that the spectrum of each primary light is trimmed. Different filter sets are employed to the two projectors, and thus 6-primary colors are obtained as shown in fig.5. Projected images from two projectors are overlaid on the screen, where the pixel registration is realized by applying distortion correction technique. To reproduce a color given by chromaticity coordinates, a method for the computation the multiprimary display signal was proposed, in which several matrices are prepared and switched according to the region in the color space [16]. Fig.6 shows the 2*2 tiled 6-primary projection display system, which consists of eight projectors and reproduces about 2k*2k resolution images, developed by Akasaka Natural Vision Research Center [15].
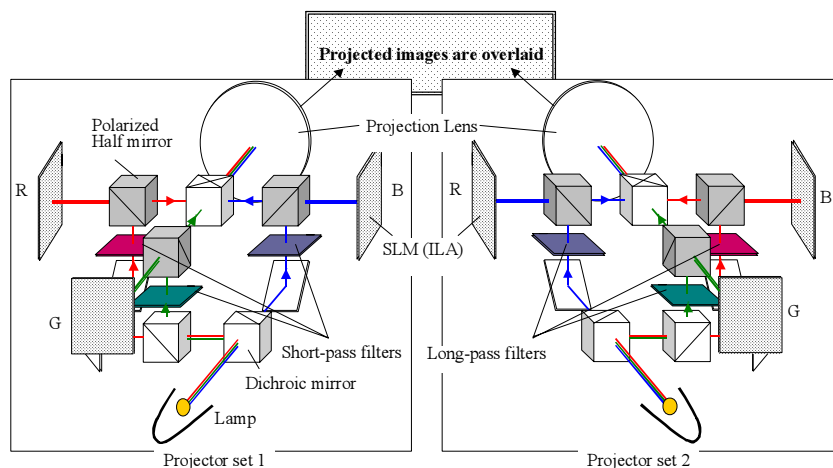

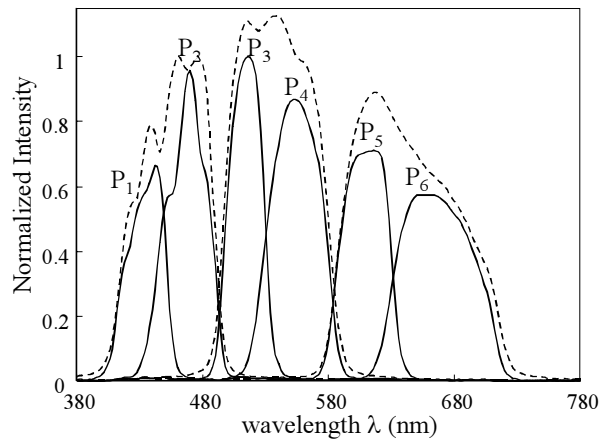Fig.4   The optical system of six-primary color projector

Fig.5 The spectra of six primary colors.

Fig.6 The photograph of 2x2 tiled 6-primary projection display system used in the experiment.

2.3 SUPPRESSION OF OBSERVER METAMERISM

In the color reproduction scheme for the colorimetric match, CIE 1931 XYZ color coordinate system is usually used. However, the spectral sensitivity of human vision, i.e., color matching function (CMF) varies depending on observers, due to the racial or genetic difference, aging, and so on. Also the CMF changes according to the size of stimuli. It has been reported that these variations of CMF cannot be ignored in the highly accurate color reproduction [9].

If the CMF of an observer is different from that of CIE standard observer, the colors of the original object and displayed image becomes different, even though the colorimetric match is carried out based on the CIE XYZ space. This is due to so-called observer metamerism. If we can acquire the CMF of each observer, the color matching can be realized for each observer. However, it is impossible to suppress the observer metamerism by using conventional three-primary displays, i.e. RGB-based displays. It was also revealed that using multiprimary display would solve this problem, namely, the object and image can be observed as the same color for the observers who have different CMF. For this purpose, it is required to apply multispectral image acquisition and the multiprimary display using multidimensional CMF or spectral basis for discounting the CMF variation.

3. SPECTRUM-BASED COLOR REPRODUCTION ARCHITECHTURE

3.1 COLOR REPRODUCTION SYSTEM

Conventional color management systems are based on three-dimensional color space, and thus it is not possible to implement the illumination conversion and spectral color reproduction. In this paper, we present a system for spectrum-based color reproduction, as shown in fig.7. The image data is accompanied by the information of image capturing condition, i.e., spectral sensitivity of the camera, illumination spectrum, etc. The attached information enables the image signal to be transformed to standard tristimulus values, spectral intensity, or spectral reflectance. The image data can be then converted to the output signal for arbitrary display devices by the software module for color reproduction.

The architecture is similar to the ICC color management system, but the profile connection space (PCS) is not based on the color appearance model, but the physical model, which basically corresponds spectral reflectance or radiance. In addition to the spectral color management system presented by Rosen et al [4], multiprimary signal is handled as the display data, and the method to specify the illumination condition is also extended.

The features of this system is illustrated as follows; The PCS of the proposed system is spectrum-based PCS (SPCS), which can be any of CIEXYZ under arbitrary illumination, spectral radiance, or spectral reflectance. The source profile
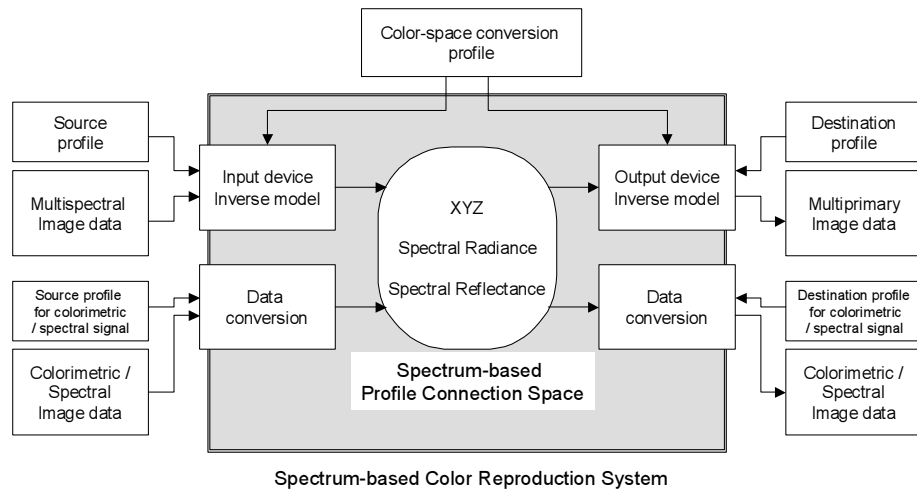
Fig.7 The schematic architecture of spectrum-based color reproduction system

is attached to an image instead of a device, and thus it is enabled to make use of the multispectral image data in various applications. Destination profile specifies the observation condition, including the observation illumination spectrum as well as the device characteristics. We here also define a color-space conversion profile, which contains the information for describing the relation from spectral reflectance or radiance to colorimetry. Then the proposed system offers following functions:

(a) Color reproduction based on colorimetric match using arbitrary color imaging devices that have 3 or more channels.

(b) Conversion of color images for the illumination of arbitrary spectrum

(c) Reproduction of the spectrum reflectance

(d) Reproduction of color images based on unconventional color matching functions including extended multidimensional CMF or spectral basis for discounting the CMF variation.

(e) Generation of the image data in standard colorimetric or spectral space, for data transmission.

(f) Using the source profile attached to the image, the multispectral image data can be employed for the image analysis using spectral information, such as the object recognition, spectral feature extraction, and spectral measurement.

The data used in this system are summarized below;

- Source profile

Source profile provides the information for transforming the input image signal to the SPCS. It can include the spectrum of illumination light when the image was captured, in addition to the input device profile such as the spectral sensitivities and the gamma characteristics of the MSC. If an image is artificially generated using a certain display device in case of computer graphics (CG), the input profile includes the device profile of the display used in creating the image.

- Image data

Multiband image (Number of band >= 3). Conventional RGB and YMCK images can be also dealt with this system if appropriate profile is attached, though the color reproduction accuracy is not so high.

- Destination profile

Destination profile provides the information required for transforming the SPCS signal to the output device signal. It can contain the observation illumination spectrum, as well as the output device profile of the multiprimary display, for example, such as the spectral intensities of primary colors and the tone reproduction curve.

- Color-space conversion profile

Sender   Receiver

(a)
Input device
Image capturing system
Input device signal
Source Profile
Spectrum-based Color-reproduction system
Destination Profile
Output device signal
Output device

(b)
Input device
Source Profile
Spectrum-based Color-reproduction system
Destination Profile
Output device signal
Destination Profile
Output device signal
Output device

(c)
Input device
Source Profile
Spectrum-based Color-reproduction system
Colorimetric or Spectral signal
Profile for colorimetric or spectral signal
Spectrum-based Color-reproduction system
Destination Profile
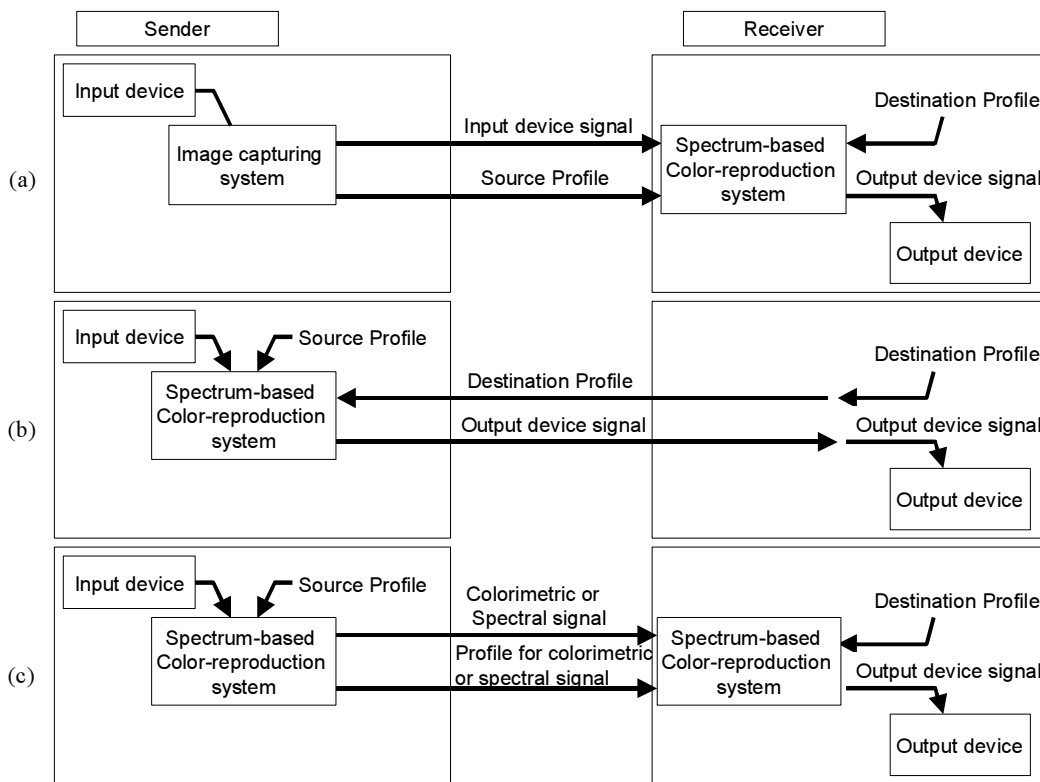Output device signal
Output device

Fig.8 The data transmission schemes for spectrum-based color reproduction

Color-space conversion profile provides the information for the transformation from spectral reflectance or radiance to colorimetry. It can specify a rendering illumination spectrum, which determines the illumination light for output image, and customized CMF including more than three-dimensional CMF.

When the SPCS is colorimetric space under a certain illuminant, for example CIEXYZ or CIELAB, multispectral image data is accompanied with any of the following profiles:
- Source profile for the transform to colorimetry
- Source profile for the transform to spectral reflectance or radiance + Color-space conversion profile
and destination profile contains the information for transforming the colorimetry to output device signal. Then the color reproduction shown in fig.2 can be realized.

When the SPCS is spectrum, either reflectance or radiance, source profile provides the information for the transform to spectral reflectance or radiance, and at the destination, any of the following profiles needs to be presented:
- Destination profile for the transform from spectral reflectance or radiance to output device signal
- Destination profile for the transform from colorimetry to output device signal + Color-space conversion profile

The profile can specify either forward or inverse device model. The forward device model accompanied with a multispectral image enables to apply different algorithm for the transform from device signal to SPCS, when a new method would be developed in future. In addition it will facilitate to make use of the image data for analysis, object recognition, etc.

3.2 DATA TRANSMISSION

Let us now consider the natural color reproduction through communication network or the storage in database. We can suppose various types of use cases in such systems. It is necessary that the spectrum-based color reproduction system can be applied to all these cases. The data types for transmission can be (a) input device signal, (b) output device signal,

or (c) colorimetric or spectral signal. The transmitted data are regularly associated with the source profile of corresponding type. Then the receiver can process the image data properly. The data to be transmitted are any of followings:

(a) Input device signal

    The original data captured by a multispectral imaging device is transmitted or stored, and thus the receiver can use the image data for the illumination conversion, spectral reproduction, analysis, and so on, without any loss of information. This seems to be especially suitable for image data archiving.

(b) Output / Display device signal

    In this case, the sender bears all process of color reproduction. For example, in a client-server system, the server receives the destination profile from the client, and computes the output device signal, which is sent to the client system. The client system does not need any special software for color reproduction, other than sending the destination profile to the server.

(c) Colorimetric / Spectral signal

    Colorimetric or spectral signal, for example, CIELAB, CIEXYZ, or principal components of reflectance or radiance can be also transmitted. The profile associated with the image describes the format of such image data, in order that the receiver can convert the image data to the output device signal.

When data encoding is employed, i.e., data compression or encryption, the input device signal is encoded and transmitted. The transmitted data is decoded before presented to the color reproduction system of the receiver's site in the case of (a) in fig.8. In the cases of (b) and (c), the output data of the color reproduction system in the sender's site are encoded, and the transmitted data are decoded before the color reproduction system of the receiver's site. Suitable data transmission method depends on applications. The development of protocols for the spectrum-based color reproduction system through network is a future work.

4. EXPERIMENTAL RESULTS

4.1 DEVICE CHARACTERIZATION

(1) 16-band MSC

The 16-band MSC shown in fig.3 is used in this experiment. For the characterization of the MSC, following measurements are carried out:

  a) The gamma curve was measured by photographing gray chart, and we confirm that it can be modeled as linear.
  b) The noise level is about 0.1% of the output signal, when 50% gray is imaged.
  c) The sensitivity of the camera decreases about 35% in the marginal area of the image, due to the shading effect.
  d) The internal reflection in the optical system causes stray light yielding the increase of signal level, which is about 2% of signal level. Though this effect depends on both the average intensity of whole image and the intensity of surrounding area, considerable part of this component can be predicted from the average level of whole image.
  e) Spectral sensitivities of 16-bands are measured and the result is shown in fig.9.
  f) The dark-current is measured by checking output signal level with a lens cap attached.

From above measurements, the characteristics of the MSC cam be modeled as

$$g_j(\mathbf{r}) = K(\mathbf{r})\int S_j(\lambda)E(\lambda)f(\mathbf{r},\lambda)d\lambda + b_j(\mathbf{r}) + Q_j\{\int g_j(\mathbf{r})d\mathbf{r}\} \qquad (1)$$

where $g_j(\mathbf{r})$ is the output device signal of j-th channel ($j=1, .. N$) for N-band MSC, and $\mathbf{r}$ denotes the spatial coordinates on image plane. $f(\mathbf{r}, \lambda)$ is the spatial distribution of spectral reflectance corresponding to the captured image, $S_j(\lambda)$ and

$E(\lambda)$ are the spectral distributions of sensitivity and illumination light, respectively. $b(\mathbf{r})$ is the bias signal caused by dark current, depending on the location of CCD sensor, and $K(\mathbf{r})$ is a term for the correction of shading. The term of $Q_j\{\int g_j(\mathbf{r})d\mathbf{r}\}$ is used to compensate the stray light effect, while only the component uniformly added to the whole image is taken into account. The output signal is quantized to 10bits digital data. The parameters in eq.(1) are obtained from above measurement. The model accuracy is evaluated with the error between the output signal and predicted signal, and the error is about 2% of the signal level.

(2) 6-primary projection display

The 6-primary color projection display system consists of two liquid crystal projectors (Victor D-ILA), in which special color filters are attached so as to realize six different primary colors. Hereafter the red, green and blue channels of two projectors are called (R1 G1 B1) and (R2 G2 B2), respectively, where the spectral intensities of these channels are shown in fig.5. The input digital value for driving each channel is encoded by 8bits (0-255). To characterize the projector system, following measurements are done:

a) The temporal stability is measured, and it becomes stable after 90min.
b) The contrast ratio of the display is about 100:1.
c) The spectral radiances of R1, G1, B1, R2, G2, and B2 are respectively measured by a spectroradiometer (Topcon SR-2), for 17 equally spaced digital counts [0, 16, 32, ... 240, 255].
d) The spectral radiances corresponding to R1+G1+B1 and R2+G2+B2 are measured for the same digital counts as (c). In addition, the chromaticity of each channel is also measured when applying maximum value 255 to a channel and 0 to the other channels.

From the results of measurement c), we confirm that the color of each primary channel is stable with respect to every gray-levels. Next, the chromaticity data of R1, G1, and B1 obtained by c) are numerically summed up and compared with the chromaticity of R+G+B obtained by the result d). The same comparison is also done for the projector set 2, and the difference is evaluated in ΔE in CIELAB space. As a result, average and maximum ΔE are 0.42 and 0.87, respectively. Therefore, it is possible to characterize that the primary channels are independent each other, and same tone reproduction curve can be used for three primary channels of each projector set. There is a small difference between the tone reproduction curves of two projectors. Finally, the relationship between the driving signal (R_1 G_1 B_1 R_2 G_2 B_2) and the reproduced color (X Y Z) in CIEXYZ space can be modeled as

$$
\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} M_X^{R1} & M_X^{G1} & ... & M_X^{B2} \\ M_Y^{R1} & M_Y^{G1} & ... & M_Y^{B2} \\ M_Z^{R1} & M_Z^{G1} & ... & M_Z^{B2} \end{pmatrix} \begin{pmatrix} \gamma_1\{R_1\} \\ \gamma_1\{G_1\} \\ \gamma_1\{B_1\} \\ \gamma_2\{R_2\} \\ \gamma_2\{G_2\} \\ \gamma_2\{B_2\} \end{pmatrix} + \begin{pmatrix} B_X \\ B_Y \\ B_Z \end{pmatrix} , \qquad (2)
$$

where $(M_X^P M_Y^P M_Z^P)^t$ are the chromaticity coordinates of a primary color P [$P = R_1, G_1, B_1, R_2, G_2, B_2$], $(B_X B_Y B_Z)^t$ are the chromaticity of bias light, and $\gamma_1\{\}$ and $\gamma_2\{\}$ are the tone reproduction curve for projector set 1 and 2, respectively. Since the spatial color variation over the projected image is observed by the visual assessment, the following experiments are done using the central part of the projected image. We confirm that the spatial inhomogeneity is caused by the nature of the original projectors, and it can be improved using newer version of projectors.

4.2 COLOR REPRODUCTION

(1) 16-band MSC

The accuracy of color reproduction using 16-band MSC is evaluated. As a test target, 24 color patches of Macbeth ColorChecker are used. The image of the test target is captured under standard D65 illuminant, and the spectral reflectance is estimated using constrained least-squares method. The colors estimated from MSC image under standard

A and D65 are compared with the actual colors measured by a spectroradiometer (Topcon, SR-2), as shown in table.1 Highly accurate color estimation is realized by using 16-band camera. Remaining error is mainly due to the prediction error, so the improvement of device characterization is desirable for better accuracy.

(2) 6-primary projection display

The color gamut of the 6-primary color projection display system is obtained from the measurement described in the section 4.1, as shown in fig.9 [8]. The gamut is compared with the gamut given by Pointer data [17] and SOCS database [18] except for the fluorescent and glossy colors, under CIE standard C illuminant. The total luminous of each display device is normalized as the reference white of the CIELUV space. The ratio of the reproducible color within the minimum gamut covering the Pointer + SOCS colors is 95.2% by 6-primary projection system, where 80.7% and 80.9% by a conventional RGB projector and a CRT monitor. The gamut of the 6-primary projector will be improved, if the contrast of the projector can be higher.

Next, to assess the color reproduction accuracy, 30 test colors are randomly selected inside the display gamut in CIELAB space. The display signal is calculated based on the characterized model expressed by eq.(2), where the lookup table for $\gamma^{-1}\{\}$ is quantized as 10bits to 8 bits conversion. For the matrix inverse of eq.(2), matrix switching algorism described in ref.16. The result of color reproduction is shown in table.2.
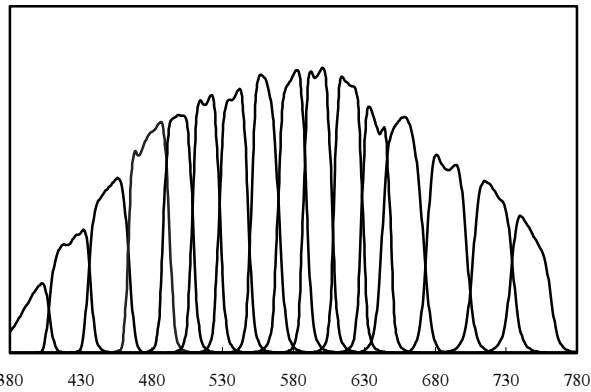

Fig.9 The spectral sensitivities of 16-bands of the MSC used in this experiment

Table.1 The ΔE^*ab of estimated colors by 16-band MSC and conventional digital still camera.

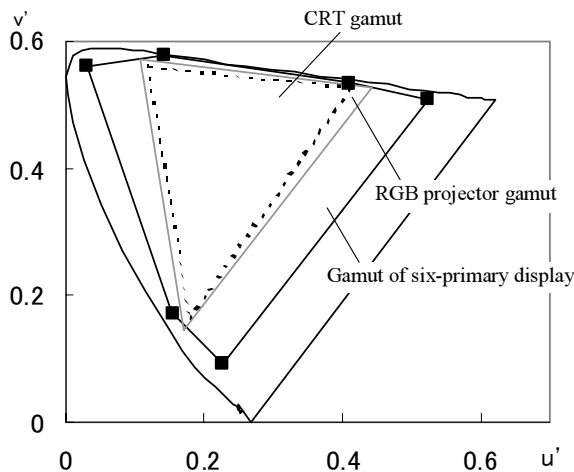|	illuminant	A	D65
Experiment	Average ΔE	0.9	1.0
	Max. ΔE	1.9	2.1
Simulation	Average ΔE	0.1	0.1
	Max. ΔE	0.4	0.4

Fig.10 The color gamut by the 6-primary projection system (solid line). The color gamut of the conventional EBU phosphor (dotted line), and projection display (gray line) are also shown.

Table 2 The color difference ΔE in CIELAB space by the experimental system of 6-primary projection display.

Average ΔE	1.3
Maximum ΔE	2.7

Light box

Color patch

Screen

6-primary projection
display

Black sheet

(a)

Observer

Color reproduced by 6-primary
projection display

Color patch illuminated by
D65 illuminant

Black sheet

(b)

Fig.11 Experimental setup for visually comparing the
original color patch and the reproduced color.

380   480   580   680   780
(a)

380   480   580   680   780
(b)

380   480   580   680   780
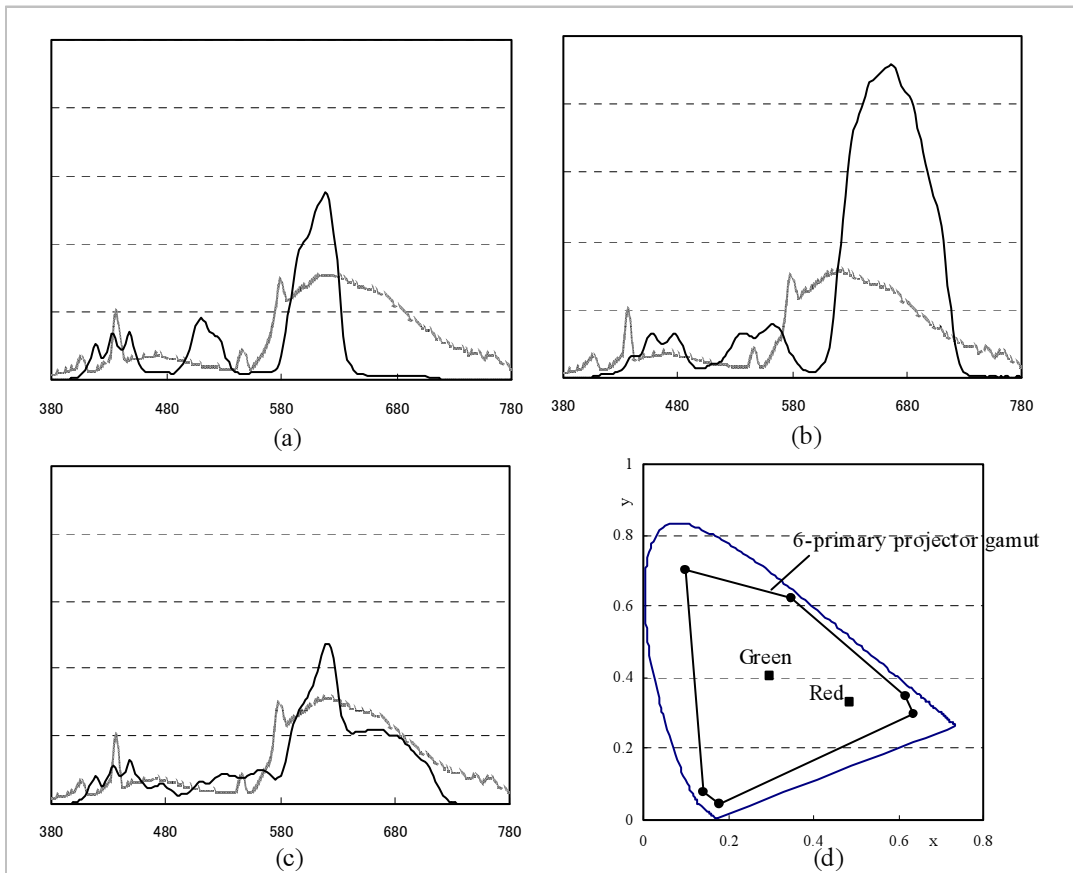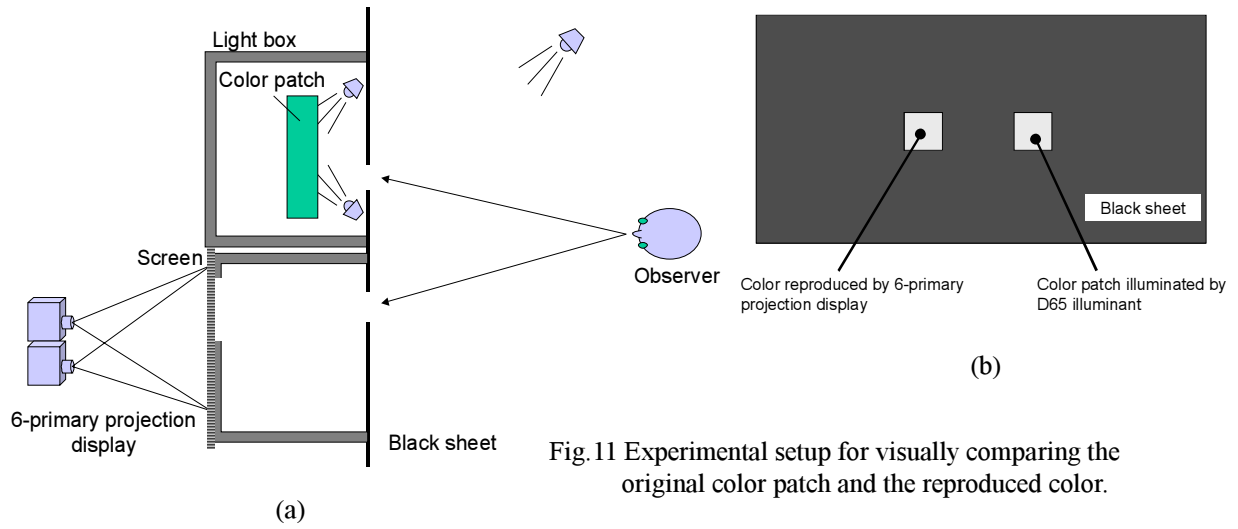(c)

6-primary projector gamut

Green

Red

y

x

(d)

Fig.12* The spectral intensities of reproduced colors using (a) R1, G1, and B1,
(b) R2, G2, and B2, (c) all six channels. The spectrum of the target color
patch is also shown in every graphs (dotted lines).
(d) CIE 1931 xy chromaticity coordinates of two test colors.

4.3 OBSERVER METAMERISM

To evaluate the effect of suppressing the observer metamerism, standard color space, such as CIEXYZ and CIELAB cannot be used, because each observer perceive the color difference even if colors are matched in CIEXYZ space. If the CMF of every observer would be measured, numerical evaluation becomes possible, but it needs great effort. Instead of measurement of CMF for respective observers, we carried out a preliminary experiment, in which the colors of an actual color patch and the displayed image are visually compared by observers.

The experimental setup is shown in fig.11. A color patch is placed in a light box and illuminated by D65 illuminant. Red and green patches shown in fig.12 (d) are used in this experiment. The spectral radiance of the Green patch is plotted with gray line in figs.12 (a)-(c). The 6-primary display system is also placed adjacent to the light box. The front of the light box is covered with a black mask as shown in fig.11. There are two square apertures (35mm*35mm) on the mask, about 28mm apart each other. The observer watches two apertures at 1.6m apart from the black mask, where the color patch and the reproduced color are appeared. The observations are done with room light on and off situations.

The spectral distributions of the colors reproduced by 6-primary display are shown in figs.12. (a) and (b) are displayed by using 3-channels among 6-channels, and (c) is reproduced by all 6-channels. The input signal for 6-primary display is calculated with an algorithm that minimizes spectral difference between the original and reproduced colors under a constraint that two colors take same CIEXYZ value. The details of the algorithm will be reported at somewhere else. In the experiment, 8 observers compare two colors selected from figs.12 (a)-(c) with the original color patch, and answers that which one is close to the original color. All the combinations of (a)-(c) are compared 6 times sequentially, and the scores of matching are counted. Then the order of matching is yielded from the scores for each observer, as shown in table.3. The colors (a) and (b) sometimes look different from the original color patch. The answers if (a) or (b) is better matching depend on the observers, as can be seen in table.3, but the color shown in fig.12(c) is best matched for all observers. This means that good approximation of spectrum gives better color matching for every observer.

Table 3 The order of matching for 8 observers. The numbers in the table shows the order yielded from the scores of color matching experiments.

Observers	Green patch (Dark room)			Green patch (Room light on)			Red patch (Dark room)			Red patch (Room light on)		
1	2	3	1	2	3	1	2	3	1	2	3	1
2	2	3	1	2	3	1	2	3	1	2	3	1
3	2	3	1	3	2	1	2	3	1	2	3	1
4	2	3	1	3	1	1	2	3	1	2	3	1
5	3	2	1	2	3	1	2	3	1	3	2	1
6	2	3	1	2	3	1	3	3	1	3	2	1
7	3	2	1	2	3	1	2	3	1	2	3	1
8	3	2	1	3	2	1	2	3	1	2	3	1

5. CONCLUSION

In this paper, we present a system for high-fidelity natural color reproduction, in which multispectral and multiprimary imaging technologies are employed. In the system, the idea of device independent color space is extended to the SPCS (spectrum-based profile connection space), and the source and destination profiles defines the transforms from and to the SPCS. Then it enables that the reproduction of color images under different illuminants, spectral color reproduction, the color reproduction using extended higher-dimensional color matching functions. We also show that the presented system can be used various kinds of network applications. Actual ways of implement the system, such as protocols, software, etc., are the topic for the further investigation.

The experimental results using the multispectral camera and multiprimary display are also demonstrated. Although further improvement is expected in the device characterization, spatial uniformity, and some other factors of image quality, the accuracy of color reproduction seems to be more or less satisfactory for most color imaging applications. The visual comparison of different spectral reproduction of same chromaticity reveals that better matching of spectrum

leads the improvement of matching between the original and reproduced colors. As this is a preliminary experiment, quantitative evaluation is also required. More data about the variation of CMFs will be also helpful to make clear the effect of spectrum-based reproduction.

The standardization of the spectrum-based color reproduction system is also a future task, to facilitate the implementation of these systems, in the applications such as telemedicine, electronic commerce (BtoB, BtoC), electronic museum and so on.

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