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Six-primary color projection display for expanded color gamut reproduction

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ABSTRACT

A range of the reproducible color, i.e., color gamut, of the conventional display devices such as CRTs (cathode ray tubes) and LCDs (liquid crystal displays) is sometimes insufficient for reproducing the natural color of an object through color imaging systems. In this paper, a six-primary color display is developed to reproduce the expanded color gamut, by using two conventional RGB projectors and six interference filters. The filters are designed to maximize the volume of color gamut in CIE-LUV uniform color space. The experimental result is also demonstrated to confirm that 99.6 percent of the Pointer gamut (referred as the maximum gamut of real surface colors) is covered by the prototype system.

1. INTRODUCTION

Recently, rapidly evolving multi-media technologies are applied to electronic commerce, telemedicine, electronic art museum, on-line shopping, and so on. In such systems, visual communication systems reproducing the original color of an object (natural color) is extremely important and is being currently developed[1,2]. The compensation of device-dependent characteristics becomes possible by the color management technologies[3]. However, the color gamut of conventional display devices, such as CRTs and LCDs can not reproduced highly saturated colors, because real surface colors are not covered by the gamut of CRT[4,5,6]. Therefore gamut-mapping techniques are studied to compensate differences in the gamut between such display devices[7]. However, it is not possible to reproduce the same color as the original one. Thus, a display device that enables reproducing a more extensive color gamut is expected in such systems. In order to expand the color gamut in conventional RGB displays, the color triangle spanned by the RGB primaries in the chromatic diagram is enlarged by using purer RGB primary set[6]. However, the color gamut is still limited within the triangle, or hexahedron of the 3-D color space.

The approach presented in this paper is multiprimary color display, i.e. using the more than three primaries, to reproduce the expanded color gamut. In this paper, a prototype of the six-primary color projection display is developed using two conventional RGB projectors and six interference filters. The filters are designed to maximize the volume of the color gamut in CIE-LUV uniform color space. The capability of reproducing the expanded gamut by experimental system is also evaluated by comparing with the conventional CRTs and projectors.

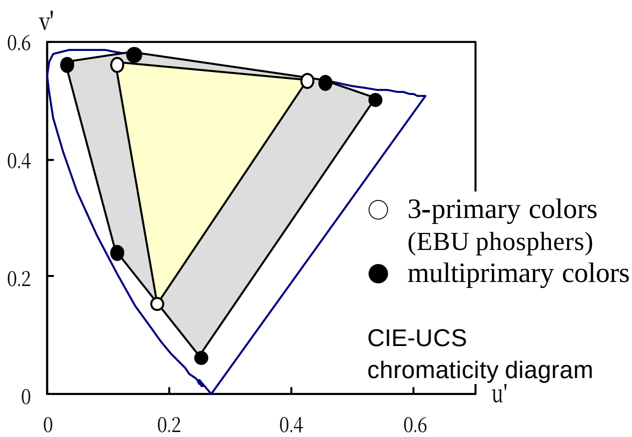

Fig.1 Concept for the color gamut expansion.
The gamut of multiprimaries became polygon.

2. MULTIPRIMARY DISPLAY

By the multiprimary display, the region of reproducible color by multiprimaries becomes a polygon in the chromatic diagram (as shown in Fig.1) and a polyhedron in 3-D color space. To realize the multiprimary color display for gamut enlargement, the multiple narrow-band lights are generated by several ways, such as the various narrow band filters, diffractive optical element[8] and so on. When N primaries are used, N narrow-band lights modulated by SLMs are composed on the screen, so that the color is reconstructed by additive mixture of N primary colors. Let the spectral intensity of each narrow-band spectral lights be $S_i(l)$ [i=1,2,…,N], then the spectral intensity of reconstructed light by N narrow-band lights is given by:

$$C(l) = \sum_{i=1}^{N} a_i S_i(l), \quad 0 \le a_i \le 1 \qquad (1)$$

where a_i [i=1,2,…,N] is the transmittance of each pixel for i-th primary. Then, using CIE-XYZ color matching functions $\bar{x}(l), \bar{y}(l), \bar{z}(l)$, the color in CIE-XYZ color coordinates $\mathbf{c}=[C_x,C_y,C_z]^t$ reconstructed by N-primaries are given by:

$$\mathbf{c} = \sum_{i=1}^{N} a_i \mathbf{P}_i, \qquad \mathbf{P}_i = \begin{bmatrix} \int S_i(l)\bar{x}(l)dl \\ \int S_i(l)\bar{y}(l)dl \\ \int S_i(l)\bar{z}(l)dl \end{bmatrix} \qquad (2)$$

$\mathbf{P}_i$ is the color coordinates in CIE-XYZ space of i-th primary color. The color gamut becomes a polygon in a chromaticity plane and a polyhedron in the three-dimensional color space, where its apices are $\mathbf{P}_i$.

Let us now consider the color reproduction method using the multiprimary display. Once the chromaticity data in three-dimensional color-space is given, we have to compute the signals corresponding to the transmittance a_i [i=1,…,N] for primaries to be applied to pixels for i-th primary. The six-primary color signals could be calculated by the inversion of eq.(2), considering the dynamic range of the display devices. Although the conversion to six-dimensional primary signal space from three-dimensional color space involves a degree of freedom due to the metamerism, the inversion of eq.(2) should be kept under the restraint as $0 \le a_i \le 1$. One of the solutions to realize the conversion considering the constraint is to use a look-up-table (LUT). However, the LUT size is very large, so further investigations are required to realize the efficient conversion for the display device.

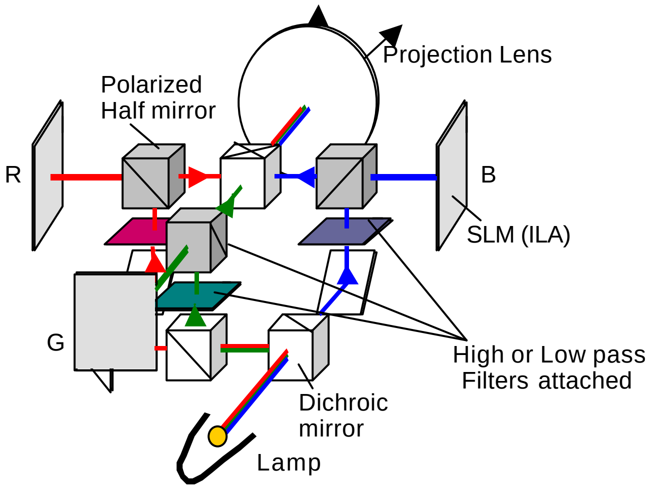

Fig.2 The optical setup for the six-primary projection display prototype (on the one projector's side).

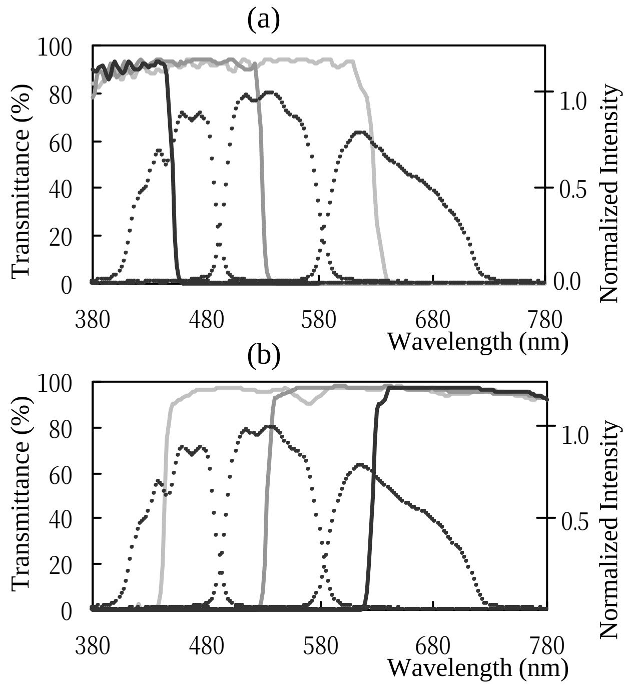

Fig.3 The spectral transmittances of (a)low-pass and (b)high-pass filters. The spectral intensities of RGB lights are also shown (dotted line), respectively.

3. PROTOTYPE SIX PRIMARY DISPLAY

3.1 Optical Setup

In this section, the six-primary projection display prototype constructed by using two conventional projectors and six interference filters is introduced. In this prototype, two projectors (Victor, D-ILA projectors), which have three reflection-type SLMs, are used. In each projector, the light emitted from the lamp is separated into RGB lights by dichroic mirrors, as shown in Fig.2. To illuminate the SLMs by the lights of narrow-band spectrum, the six interference filters are attached (see Fig.2) to modulate these RGB lights of the two projectors. The spectral transmittances of the six interference filters are shown in Fig.3. Three high-pass filters are attached on the one projector and the three low-pass filters are attached on the other. The six band images of two projectors are superposed on the screen, so that the color of the image on the screen is reconstructed by additive mixture of six primaries.

To superpose the image projected by the two projectors, the distortion due to the disparity between the two projectors should be compensated. For this purpose, the mesh images projected by each projector are captured by CCD camera to find the characteristics of the distortion, and the image for each projector is pre-distorted to compensate it.

3.2 Filter set

To obtain the enhanced color gamut size of the display system, the cut-off wavelengths of the filter set used in this prototype are determined to maximize the volume of the gamut in CIE-LUV uniform color space. The cut-off wavelengths of high-pass filter modulating the R, G and B lights of one projector are 620, 540 and 440(nm), respectively. The cut-off wavelengths of low-pass filters modulating the R, G and B lights of the other are 620, 540 and 450(nm). As a result, the spectral intensities of the primary lights shown in Fig.4 are obtained. The bandwidth of each primary light becomes small contented at different wavelength, as shown in Fig.4. In Fig.4, S_1 and S_2 are generated from blue light, S_3 and S_4, S_5 and S_6 are from green and red lights, respectively.

4. EXPERIMENTAL RESULT

In the experiment, the color gamut reproduced by the six-primary projection display is evaluated by measuring the each primary color of the prototype system. The color obtained by this system is indicated in Fig.5. The color gamut is expansible compared with the conventional CRT and the RGB projector, especially in purple, green and red region.

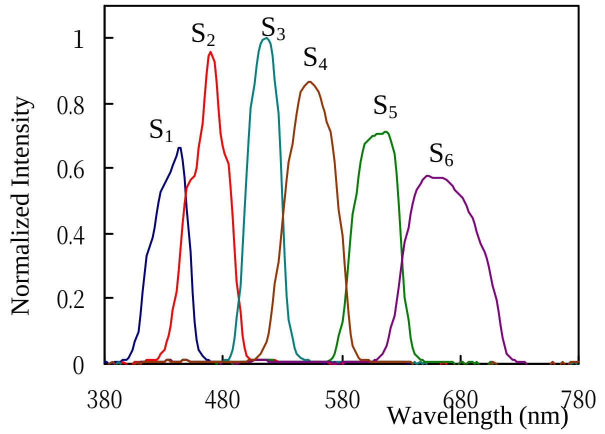

Fig.4 The spectral intensities of six-primary colors

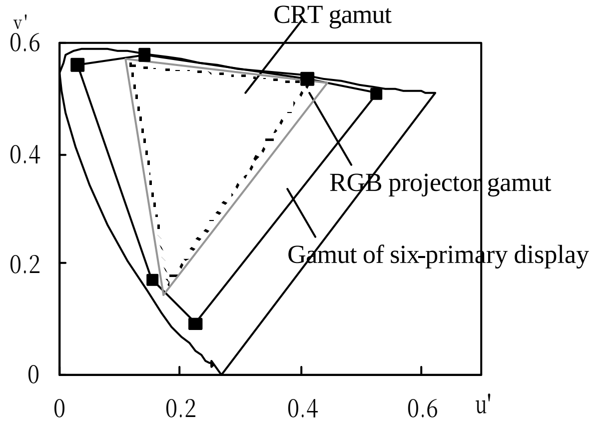

Fig.5 The color gamut by the six-primary projection system(solid line). The color gamut of the conventional EBU phospher (dotted line), and projecton display(gray line) also shown.

Table.1 shows the comparison of the volume of the gamut, (V), in CIE-LUV color space and the percentage, (W), of the reproducible color within the Pointer gamut[4], referred as the gamut of real surface colors. In this evaluation, we assume that the observer illumination is CIE standard illuminant C, and the total luminous of each display device is normalized as the reference white of the CIE-LUV space. From this result, the expanded color gamut is obtained by the six-primary projection display compared with these conventional RGB display devices, in spite that the volume of the gamut by the projection display is smaller than that of CRT monitor due to insufficiency of the contrast. Furthermore, the nearly all the Pointer gamut (99.6%) is covered by the gamut of the six-primary display.

To show the color reproduction ability of the six-primary display system, the color image of the painted wood object as shown in Fig.6 is displayed by the prototype system. The color image data of the object,

	V ($\times 10^6$)	W (%)
Experimental system	1.91	99.6
RGB Projector	1.23	84.3
CRT monitor	1.52	85.8

Table.1 Comparison of the volume, (V), of the gamut in CIE-LUV color space, and the percentage, (W), of the reproducing color within the Pointer gamut is also shown.

Fig.6. A photograph of the reproduced image by six-primary display.

represented by CIE-XYZ values, are estimated by using multi-band images taken by a multispectral camera[1], and is converted to the six primary color signals by calculating the inversion of Eq.(2) considering the constraint $0 \le a_i \le 1$. Fig.6 is the photograph of the resultant image. The colors of the paints illuminated by an incandescent lamp, including the highly saturated color out of the CRT gamut, are almost perfectly reproduced by the six-primary color projection display.

5. DISSCUSSION AND CONCLUSION

This paper presents the method for multiprimary display to reproduce the expanded color gamut, and the six-primary projection display prototype is introduced. The capability of reproducing the expanded gamut by the six-primary projection display is demonstrated through the prototype system. By calculating the volume of display's gamut in CIE-LUV uniform color space, it is confirmed that the six-primary display could almost cover the real surface colors under the condition that the luminous of the observer illumination is same as the total luminous of the display.

To expand the color gamut, pure colors of narrow bandwidth light are required for primaries. In the case of RGB transmission displays, such as LCDs, the light loss is increased if the bandwidths of RGB lights are reduced. The multiprimary display is promising approrch because expanded polyhedral gamut can be obtained without the substantial loss of illumination light, if the narrow bandwidth lights are generated efficiently by using whole spectrum of the light source.

The further enhancement of the gamut is necessarily in order to reproduce the colors of the illuminant besides the surface colors. In this prototype system, to use the filter is involved to reduce the luminous efficiency. A diffractive optical element or the holographic optical element has advantage to realize the multiprimary display without the substantial loss of illumination.

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