Multiprimary displays for natural color reproduction

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Abstract

This paper presents the color displays using more than three primary colors, for the reproduction of wider color gamut, and high-fidelity color reproduction. First, Natural Vision system, which is currently under development for the natural color reproduction in visual telecommunication applications, is introduced, The natural vision is based on spectrum instead of trichromatic color space, and enables high-fidelity color reproduction using multispectral and multiprimary technologies. Then, six-primary color projection displays using LCD and DLP, and a four-primary color flat panel display are shown. It is experimentally demonstrated that the color gamut becomes much larger than conventional RGB-based display. In addition, it is proved that the spectral color reproduction using multiprimary display suppresses the influence of observer metamerism, and as a result, the color matching between the display and the real object is well improved.

1. Introduction

When we encounter beautiful scenery, we take photographs to archive them. Digital still cameras are often used recently, and the pictures are viewed on the PC screen. However, we sometimes realize that the reproduced image gives somewhat different impression to the actual scenery. Also, when we come to a home appliance shop and at the corner displaying television sets, we see the same program displayed on the screens of various manufacturers. Then we notice that the colors on every screen are slightly different each other. These experiences mean that conventional color imaging systems are not necessarily reproducing the real world faithfully.

The reproduction of realism is one of the key issues in the visual telecommunications for electronic commerce, telemedicine, digital museum and so on. Recently, great progress has been made toward the reproduction of images with high-reality, for example, high resolution, large screen, or head mounted displays. However, the capability of natural color reproduction is still limited in the current display systems.

Color management technology, which receives wide attention recently, enables to exchange the color information in common color spaces between different devices. Although an equivalent color can be reproduced on the devices that have different characteristics by the color management technology, it is still difficult to reach the complete solution against above problems, since most color imaging systems are essentially based on RGB three-primary colors.

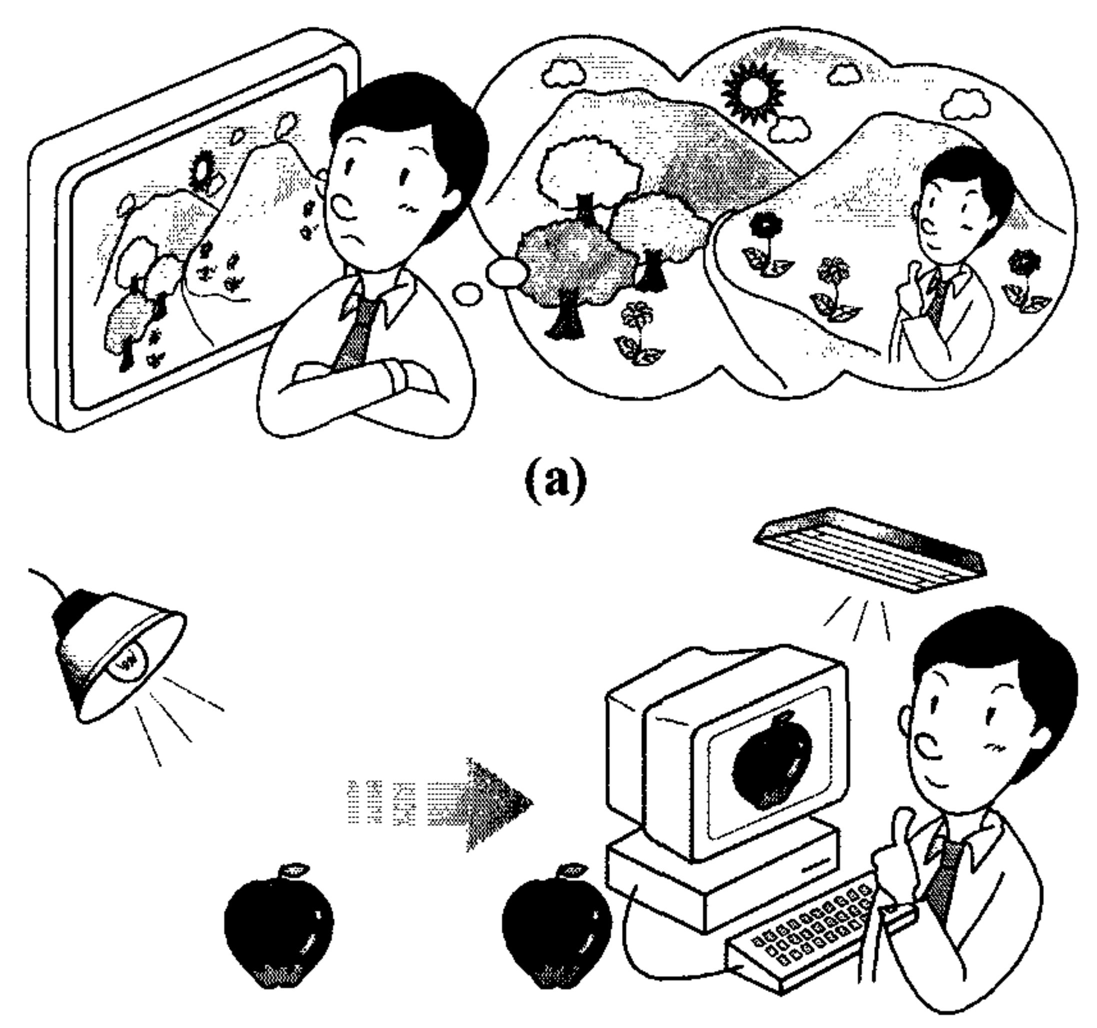
Under such background, Akasaka Natural Vision Research Center (NVRC) (established by Telecommunication Advancement Organization (TAO) is exploiting natural color reproduction technologies for visual telecommunication systems, based on multispectral and multiprimary imaging, which is not restricted to RGB trichromatic system.

In this paper, the basic concept and technology of natural vision are presented, focusing especially on the multiprimary color displays. Several examples of multiprimary projectors and flat panel display are shown along with the experimental results using a prototype 6-primary projector.

2. Natural Vision

For the natural color reproduction through network system, it is required to (a) reproduce images as if the

[1] URL: http://www.akasaka.tao.go.jp



(a)

(b)

Figure 1 The concept of high-fidelity image reproduction.
(a) Reproducing images as if the observer were at the remote site.
(b) Reproducing images as if the object were placed at the front of the observer.

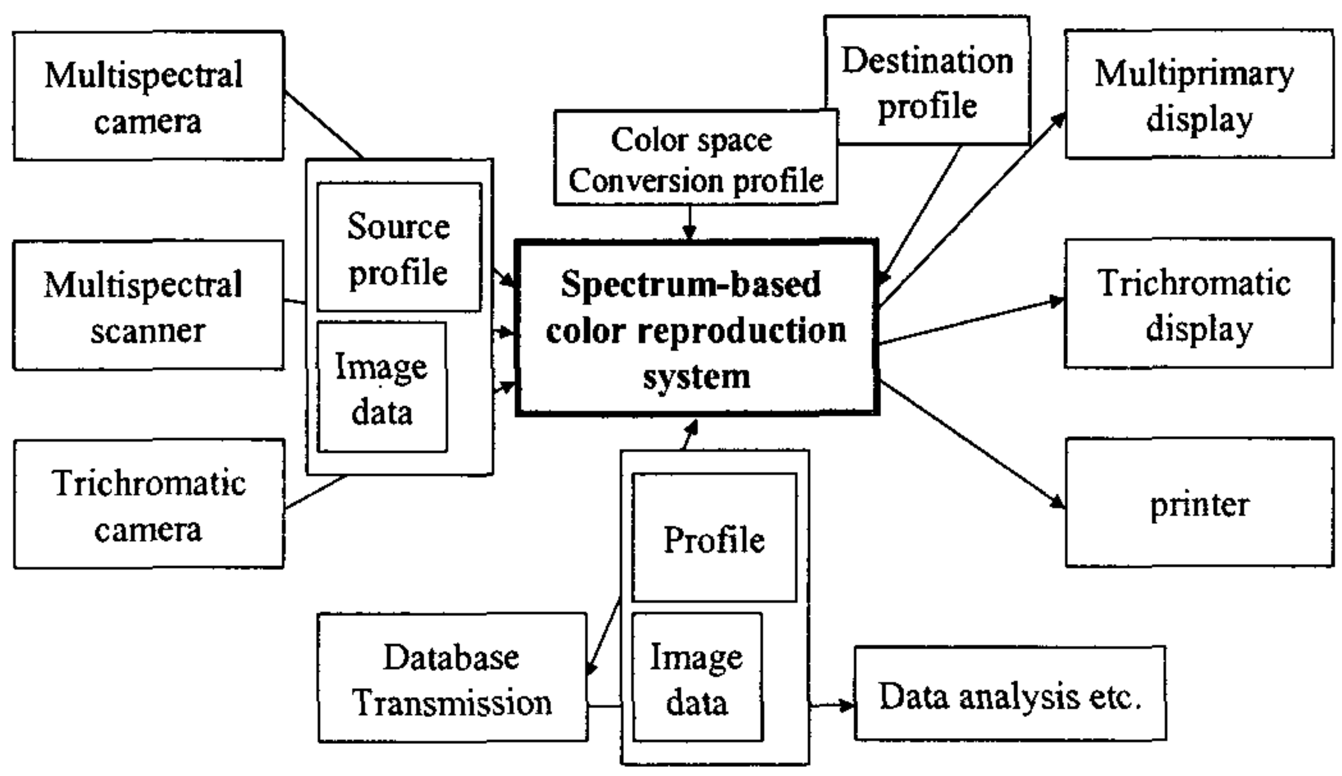


Figure 2 The concept of natural vision system.

observer were at the image-capturing site [Figure 1(a)], or (b) reproduce images under the illumination environment of the observation site. [Figure 1(b)]. For these purposes, multispectral imaging technology is quite advantageous [1-4], which enables natural color reproduction with high accuracy. In the project at NVRC, multispectral cameras, 16-band camera with rotating wheel and 6-band HDTV camera for motion picture have been developed [5]. In addition, to extend the range of reproducible colors (color gamut) of color display device, multiprimary color display, i.e., using more than three primary colors, has been developed [6-11].

The concept of Natural Vision system is illustrated in figure 2. The image data are accompanied by the information of image capturing condition (source profile), i.e., spectral sensitivity of the camera, illumination spectrum, etc. The architecture is similar to the ICC color management system [12], but the profile connection space (PCS) is not based on the color appearance model, but the physical model, i.e., the spectrum-based PCS (SPCS), which can be any of CIEXYZ under arbitrary illumination, spectral radiance, or spectral reflectance. Destination profile specifies the observation condition, including the observation illumination spectrum as well as the device characteristics. Also a color-space conversion profile is defined, as the information describing the relation from spectral reflectance or radiance to colorimetry.

Although the feature of the system is the use of multispectral camera and multiprimary color display, trichromatic devices can be also used, in spite that the accuracy is rather limited, with doing appropriate device characterization.

Spectrum-based color reproduction system allows following functions;

(a) Color reproduction based on colorimetric match using arbitrary color imaging devices that have 3 or more channels.
(b) Reproduction of color images under arbitrary illumination different from that of image capture.
(c) Display more vivid colors of high-saturation using multiprimary colors.
(d) Reproduction of color images based on unconventional color matching functions (CMFs) including extended multidimensional CMF or spectral basis for discounting the observer metamerism.
(e) Acquisition of quantitative information as multispectral images, which can be employed for the image analysis using spectral information, such as the object recognition and spectral feature extraction.

3. Multiprimary Color Display

3.1 Method for Multiprimary Color Display

In the conventional display devices, such as CRTs and LCDs (liquid crystal displays), the display color gamut does not cover all the existent colors. To enlarge the color gamut, the saturation of primary colors can be increased, but the gamut is still limited within a triangle, or hexahedron in three-dimensional (3-D) color space, and it is impossible to cover all the visible colors by a triangle. Moreover, narrow band spectrum of the light for each primary color is required, and it becomes difficult to realize a bright

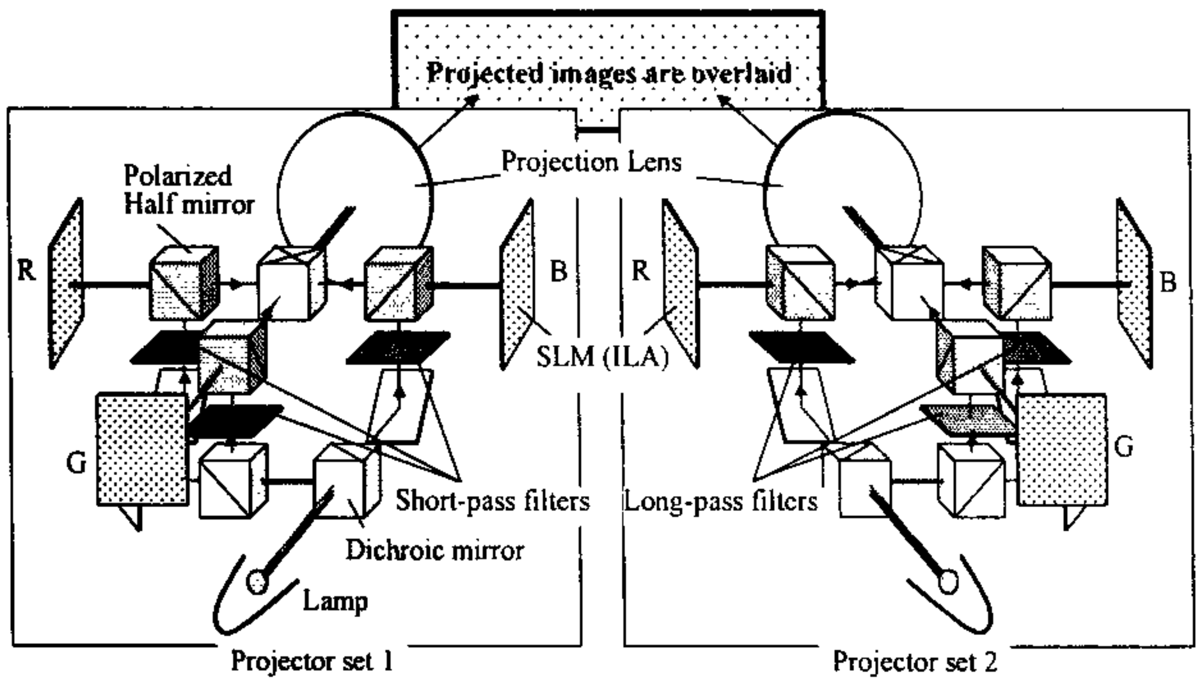


Figure 3 The optical system of 6-primary color LCD projector system.

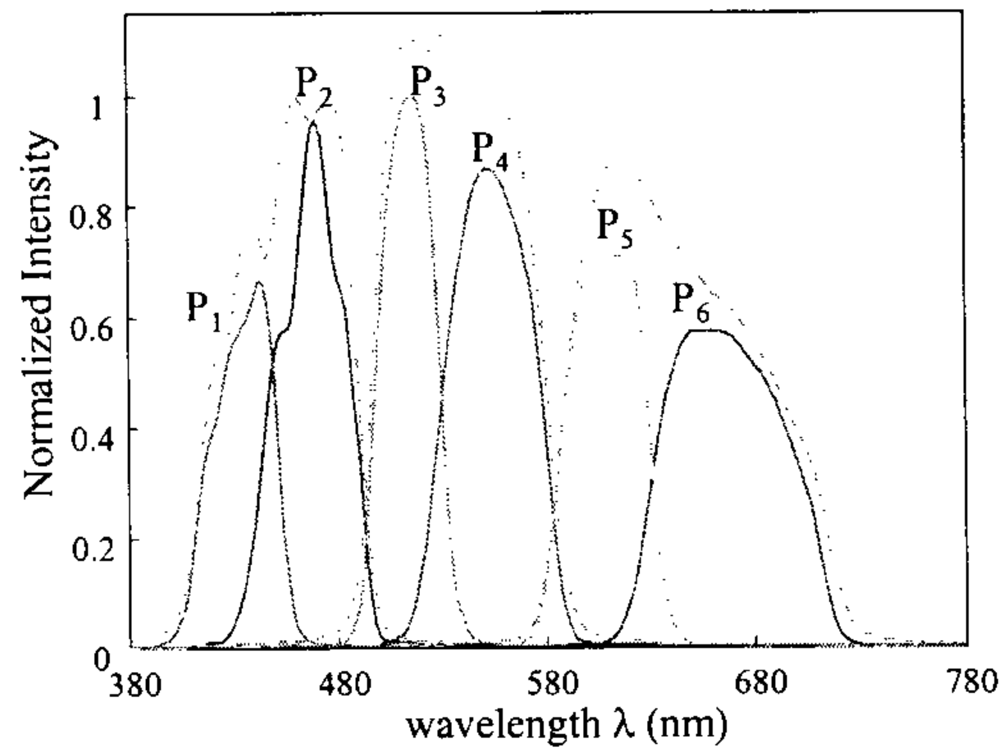


Figure 4 The spectra of six primary colors. Dotted lines are the spectra of original primaries (R, G, and B)

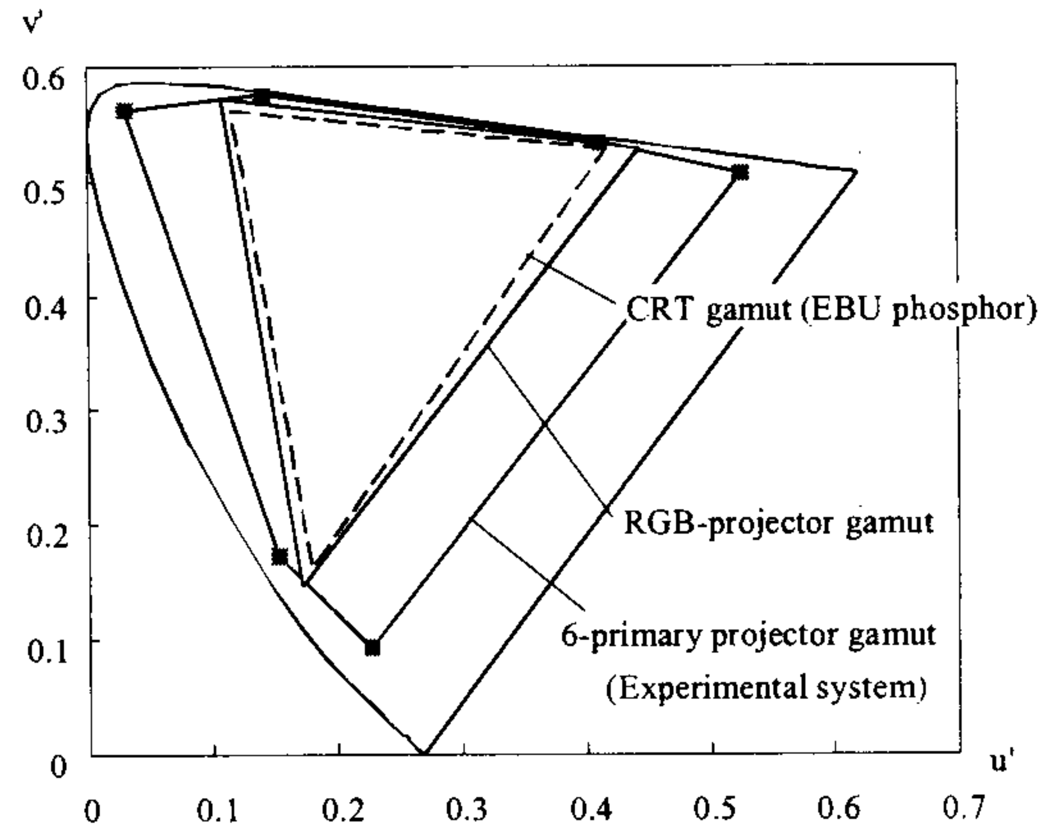


Figure 5 The color gamut obtained by the 6-primary projection system (solid line). The color gamut of the conventional CRT(EBU phosphor) (dotted line), and the liquid-crystal projector (gray line) are also shown.

display unless special light sources, such as a laser light source, are used.

The multiprimary color approach, i.e., using more than three primary colors, has been exploited for larger color gamut [6, 13]. The color gamut then becomes a polygon, where its vertices correspond the color coordinates of the primaries, or polyhedron in three-dimensional color space. If a color pixel is composed of N primary colors, then the number of faces of the polyhedral gamut is $N(N-1)$.

3.2 Multiprimary Color Display Systems

There can be considered several methods for multiprimary display. The set of primary color pixels, called color pixel, can be composed by (a) field-sequential, (b) spatial color filters, or (c) using multiple panels. Also the combination of them is useful for appropriate system configuration.

We have developed a 6-primary projection display system using two conventional RGB projectors (Victor, D-ILA). The optical system is shown in figure 3. 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. The spectrum of each primary color is shown in Figure 4.

Projected images from two projectors are overlaid on the screen. The trapezoid distortion due to the difference of projector positions is removed by a distortion correction technique, in which the input image is pre-distorted so as to compensate the distortion of the optical system.

The color gamut obtained by the experimental system is shown in figure 5. Larger color gamut is obtained, and especially red and purple colors of high-saturation, which cannot be displayed by conventional CRTs or LCD projectors, are successfully reproduced. The reproduced gamut of the 6-primary display is compared with the gamut given by Pointer and SOCS database except for the fluorescent and glossy colors, under CIE standard C illuminant. The ratio of the reproducible color within the minimum gamut covering the Pointer + SOCS colors is 95.2% by 6-primary projection system, while 80.7% and 80.9% by a conventional RGB projector and a CRT monitor.

Figure 6 shows the 2×2 tiled 6-primary projection display system, which consists of eight LCD projectors (Victor, D-ILA) and reproduces about 2k×2k resolution images, developed by Akasaka Natural Vision Research Center [5].

6-primary DLP projector system [Figure 7(a)] is also constructed using two DLP projectors, where the spectral property of dichroic prisms in each projector is designed so as to obtain large gamut [10].

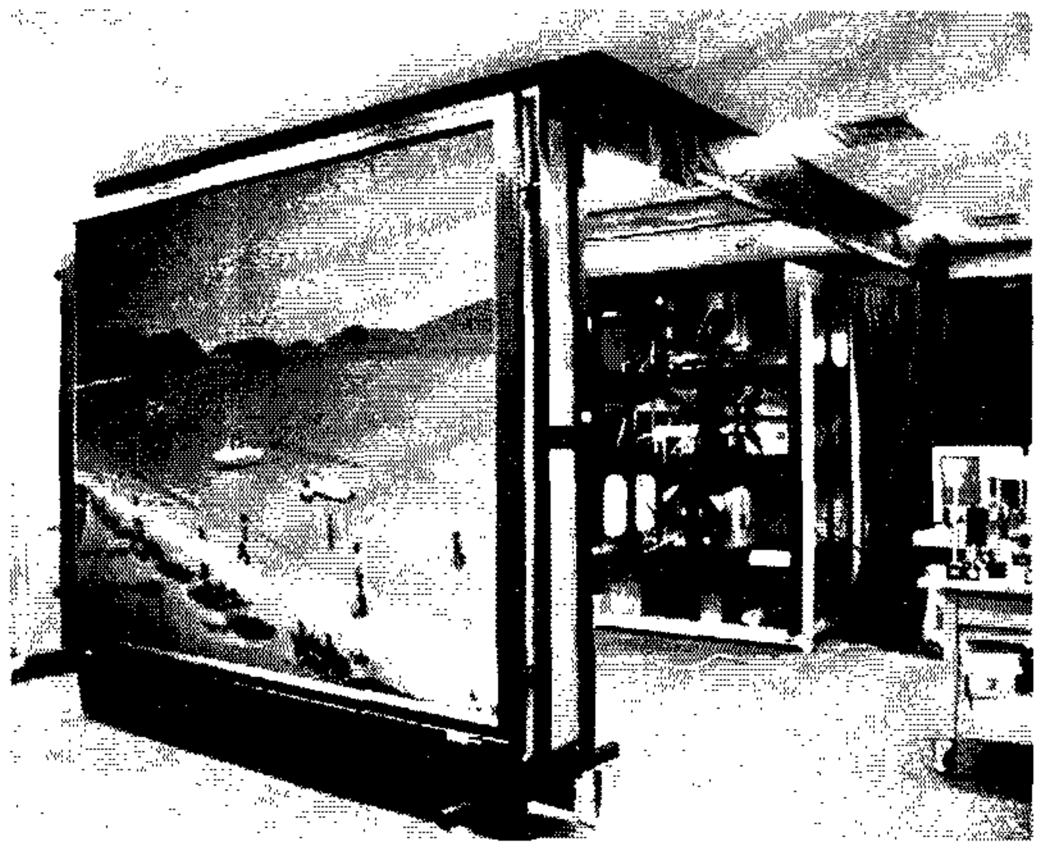


Figure 6 2x2 tiled 6-primary projection display system

Furthermore, 4-primary flat panel LCD [Figure 7(b)] is developed in the Natural Vision project [11].

3.3 Color Conversion Method

In the optical systems of figure 3, the color is reconstructed as the additive mixture of N-primary colors. Denoting the spectral intensity of transmitted light as $S_j(\lambda)$ for j-th subpixel, where $j = 1 \ldots N$, the total spectral intensity transmitted through the color pixel, $S(\lambda)$ is given by

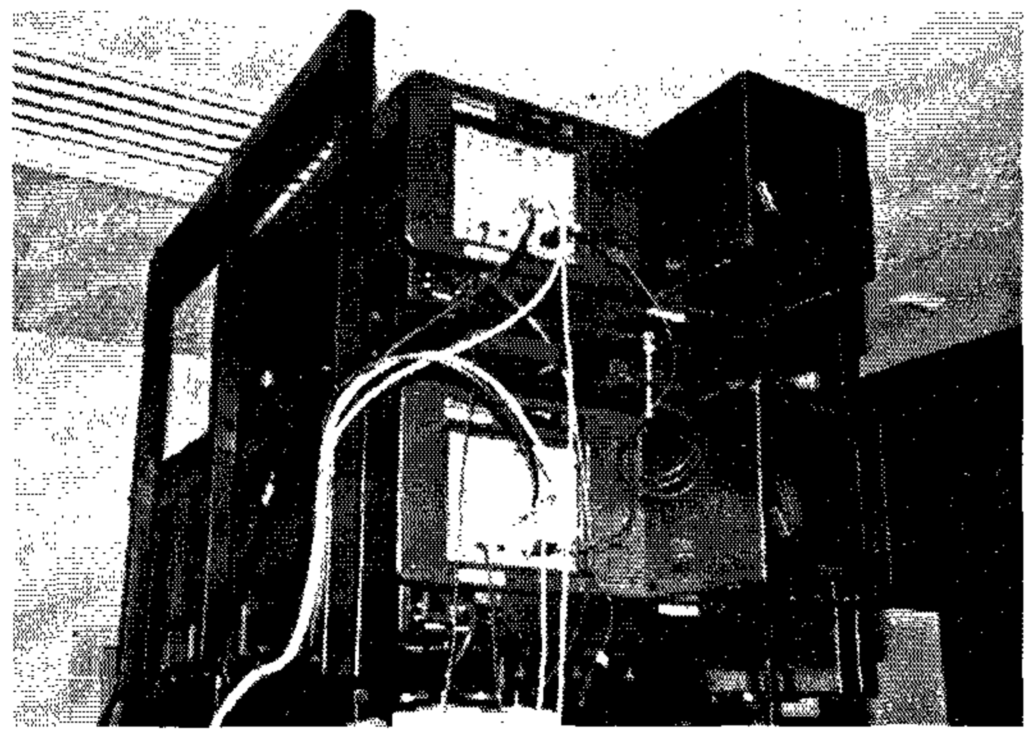
$$S(\lambda) = \sum_{j=1}^{N} \alpha_j S_j(\lambda) \;, \qquad (1)$$

where α_j is the intensity transmittance of j-th subpixel. The color in CIE XYZ color coordinates $\mathbf{x}$ becomes

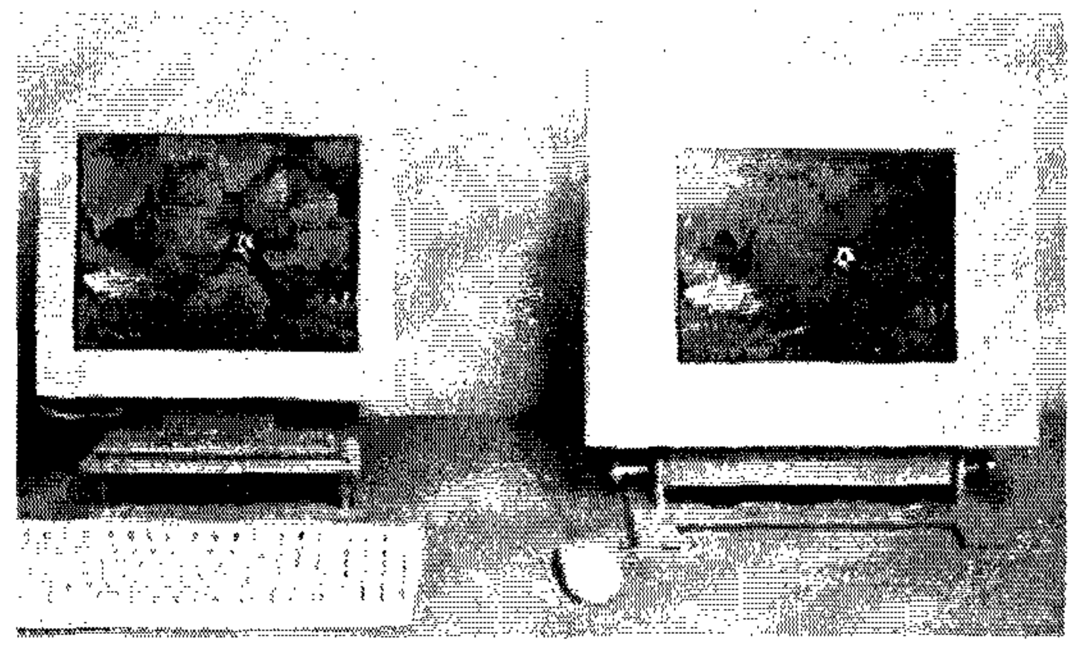
$$\mathbf{x} = \sum_{j=1}^{N} \alpha_j \begin{pmatrix} \int S_j(\lambda) C_x(\lambda) d\lambda \\ \int S_j(\lambda) C_y(\lambda) d\lambda \\ \int S_j(\lambda) C_z(\lambda) d\lambda \end{pmatrix} = \sum_{j=1}^{N} \alpha_j \begin{pmatrix} P_{xj} \\ P_{yj} \\ P_{zj} \end{pmatrix} , \qquad (2)$$

where $C_x(\lambda)$, $C_y(\lambda)$, and $C_z(\lambda)$ are the CIE XYZ color matching functions, (P_{xj}, P_{yj}, P_{zj}) are the chromaticity coordinates of j-th primary color, respectively. Therefore, the vertices of color gamut in 3-D color space are given by (P_{xj}, P_{yj}, P_{zj}).

The image data related to chromaticity in 3-D color-space is given, and the display signal to be applied to the color pixels is computed. The display signal in multiprimary space is obtained by the inversion of eq.(2), in consideration of the dynamic range of LCD. Since N-dimensional vector is computed from 3-D chromaticity data, the conversion involves the degree of freedom, which is originated from metamerism.



(a)



(b)

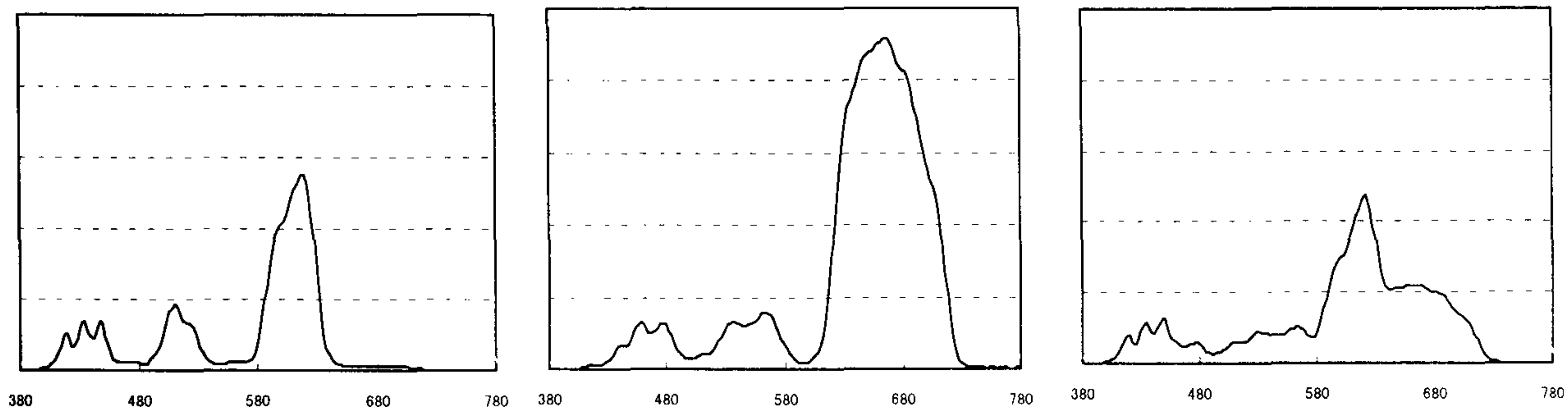
Figure 7 Prototype multiprimary displays
(a) 6-prinmary DLP projector system
(b) 4-primary flat panel LCD (right), left is conventional RGB LCD.

Therefore, it is possible to find a solution of the inversion under appropriate constraint. We have developed several methods for multiprimary color conversion, for the following cases;

1) When image data gives chromaticity,
(a) solving eq.(2) under non-negativity constraint
(b) matrix switching method, in which the 3-D color space is divided into subspaces, and a 3xN matrix is used in each subspace [7]
(c) applying constraint about the continuity of display signal
(d) using multidimensional look-up-table, which is designed by the method (a)–(c), or other principles.

2) When image data gives spectral radiance,
(e) linear programming method to find the best spectral match under the condition where eq.(2) is satisfied [14].
(f) using the CMFs in more than three dimension, i.e., multidimensional CMFs obtained as the basis functions of various observers [15,16].

In the case of 2), it becomes possible to suppress the influence of observer metamerism. The experimental demonstration is presented in the next subsection.



(a) (b) (c)

Figure 8 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).

3.4 Suppression of color difference due to observer metamerism

We have confirmed that the variation of CMF between different observers cannot be ignored for color reproduction in high accuracy [8], and multiprimary display using the method (e) effectively suppresses the effect.

In the experiment to evaluate the suppression of the observer metamerism effect, the colors of an actual color patch and the reproduced color by the 6-primary display system are visually compared. The spectral distributions of the colors reproduced by 6-primary display shown in figure 8(a) and (b) are displayed by using only 3-channels (R1 G1 B1 or R2 G2 B2) among 6-channels, and (c) is reproduced by all 6-channels. In (c), the display signals for 6-channels are calculated such that the spectral difference between the original and reproduced colors are minimized where the colorimetric match is satisfied in all cases. Eight observers compare the color patch and displayed color, and answer which one among (a)-(c) is close to the original color. As a result, the colors (a) and (b) sometimes look different from the original color patch, and the color shown in figure 8(c) is best matched for all observers. This means that good approximation of spectrum gives better color matching for every observer.

4. Concluding remark

Along with the introduction of information technology into our life, the quality of information that flows through the system becomes very important. For example, the image is used for diagnostic decision in the telemedicine system, and in electronic commerce, purchase or order items based on the digital information including images. If inaccurate images were presented, it might mislead one's decision. Exchanging objective and accurate information will be more important in our society.

In the natural vision, a color image is treated as multispectral information to breakthrough the limit of conventional trichromatic (RGB) imaging systems, resulting in the high-fidelity reproduction of reality. Then it is expected that high-reality color reproduction technology will be applied in many fields such as

- Electronic commerce, i.e., merchandise procurement, collaboration in product design, and online-shopping of textiles, cars, furniture, etc.
- Telemedicine and diagnosis supporting system in the fields of dermatology, bedsore, endoscopy and pathology, etc.
- Multimedia education, such as instructional materials and encyclopedia, which vividly introduce natural subjects.
- Natural Vision theater or electronic museum, for realistic color reproduction of nature, artworks, and historic subjects, etc.
- In multimedia contents production, from the material of recorded picture, editing, distribution, and playback of computer graphics (CG), animation, and other visual programs.
- Novel representation in graphic arts will be possible using the expanded colors, which grant images stronger impact or out-of-this-world impression.

The application to digital broadcasting is also considered in the future.

5. Acknowledgements

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