Beyond Red–Green–Blue (RGB): Spectrum-Based Color Imaging Technology

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Abstract. This article presents a comprehensive study on the spectrum-based color reproduction system, called Natural Vision (NV), which aims to break through the limitation of red–green–blue (RGB) three-primary schemes. After a basic discussion on the motivation for color imaging technology beyond RGB, the method for systematizing the multispectral and multiprimary color imaging technologies, including image capture, processing, storage, printing, and display, is presented. Then experimental multispectral systems for both still image and video are introduced, and the following features of spectrum-based scheme are revealed: a) highly accurate color reproduction is possible even under different illumination environment, b) an expanded color gamut can be reproduced by multiprimary color displays, c) the influence of observer metamerism can be reduced by the spectral color reproduction, and d) the quantitative spectral attributes of an object, useful for its analysis or recognition, can be captured and preserved. Finally, the effectiveness of the system is also demonstrated through experiments in fields of application, such as medicine, digital archives, color printing, electronic commerce, and computer graphics. © 2008 Society for Imaging Science and Technology. [DOI: 10.2352/J.ImagingSci.Tecnol.(2008)52:1(010201)]

INTRODUCTION

Digital images are widely used at present in digital broadcasting, digital still cameras (DSCs), and image delivery over the broadband network and are being applied to extended fields such as telemedicine, electronic commerce, and electronic museum. The natural color reproduction is one of the key issues in these applications, in addition to high-resolution or large-screen display technologies. However, many of the conventional color imaging systems are designed for user preference, and thereby it is difficult to reproduce the original color of an object. Color management technology has greatly progressed, especially in color printing, but there still remains a limitation in color reproducibility, employing red–green–blue (RGB) three primary color systems.

An approach to break through this limitation is going beyond RGB, i.e., using a spectrum-based system instead of RGB. It has been reported that the use of multispectral imaging significantly improves the color accuracy.1–5 In the display industry, the multiprimary color approach becomes one of the choices for expanding color gamut,6–12 but it is difficult to take full advantage of multiprimary color technology because a wide gamut image source is not available for such displays. A total system based on spectral information has not yet been established. A few papers13–17 were devoted to multispectral systems, including both input and output, for hardcopy applications14,16,17 or still image display,13–15 but no systematized implementation of the multispectral and multiprimary color imaging technologies has been reported.

This article presents the concepts for systematization, implementation, and applications of video and still image systems with spectrum-based color image reproduction, including multispectral image capture, processing, compression, transmission, storage, printing, and display. The system presented in this article enables exploitation of the advantages of multispectral and multiprimary technologies. In addition, conventional imaging devices based on RGB can be also employed in the proposed spectrum-based system, though the color reproduction accuracy is not very high. With the integrated model system, the effectiveness of the spectrum-based technology is also demonstrated in various fields of application. The results shown in this article are primarily obtained from the project Natural Vision (referred to as NV hereafter), an industry-government-academic joint project (1999–2006), aimed at the development of a visual telecommunication system that enables high reality image reproduction with natural color.18–21 Although some results were previously published, this article comprehensively sum-

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marizes the study on the spectrum-based system for color image reproduction.

**SPECTRUM-BASED COLOR REPRODUCTION SYSTEM**

*Why is a Spectrum-Based System Needed?*

Let us briefly review the limitations of conventional RGB-based systems in this section to make clear the advantage of spectrum-based color reproduction.

1. The RGB values obtained in conventional systems often have different meanings, depending on the device characteristics or color processing. For example, many conventional color imaging systems are designed for user preference, and the RGB values do not represent objective color information. Even if colorimetric color calibration is applied, most color cameras do not satisfy the Luther condition; i.e., the spectral sensitivity is different from that of human vision.22 Thus the RGB signal does not have one-to-one correspondence to the tristimulus values perceived by human vision. If the spectral sensitivity is closer to that of human vision, the color fidelity is improved, but noise behavior may become worse. Spectral considerations are thus essential in the color acquisition process.

2. The RGB or any other three primary color signals that comply with the color space, such as sRGB or YCbCr, are defined under a white point such as CIE D65 or D50 standard illuminant. When the illuminant of the observation environment is different from that of image capture, the color under the different illuminant should reproduce the color as if the object were placed at the site of the observer. White balance adjustment in conventional color imaging is performed in RGB space, sometimes introducing a color appearance model. But the colorimetric accuracy is not high, because the spectral reflectance of the object and the spectral distribution of illuminant are required in principle in order to calculate the color under the different illuminant. When images are displayed on softcopy monitors, it is possible to reproduce the color under different illuminant based on spectrum-based color conversion.16 However, there is an additional issue: the standard color spaces are defined for a certain standard illuminant and do not support the color under an arbitrary illuminant. In the hardcopy applications, moreover, spectral printing is required to solve this problem of illuminant metamerism.23

3. In the color image display, the color gamut does not cover all the existent colors, and some high-saturation colors cannot be reproduced. To enlarge the color gamut, the saturation of primary colors can be increased, but the gamut is still limited within a triangle. The multiprimary color approach, i.e., using more than three primary colors, was proposed for a larger color gamut.6–8 The gamut then becomes a polygon, where its vertices correspond to the color coordinates of the primaries, or a polyhedron in three-dimensional color space. Even if the display device allows the display of a wider color gamut, conventional color signals such as sRGB or ITU-R BT.709 do not support a wider gamut color signal. Wide gamut color spaces have recently become available,24 such as AdobeRGB and xvYCC, but most of the color input devices cannot capture high-saturation colors correctly for the reason explained previously.

4. In highly accurate color reproduction, the effect of observer metamerism cannot be ignored, which has its origin in the difference of color matching functions among individuals. When the color displayed on a monitor is compared with the real objects, such as printed materials, the observed colors may disagree with each other due to the observer metamerism effect, even if the colorimetric accuracy is high. The multispectral and multiprimary approach solves this problem by means of spectral color reproduction.16,25

5. In the image archive, database, or analysis, the utilization of color information is limited, since the RGB signal depends on the devices, illuminants, and preprocesses involved in the imaging systems. For example, in the image retrieval using color information, the target object cannot be found if the illumination condition is different. In contrast to this, the original attribute of an object that generates color, i.e., spectral radiance, reflectance, or transmittance information, is captured and preserved with multispectral imaging. The quantitative color information is useful for the analysis or the recognition of the object in the image database of the digital archives26,27 of cultural heritage, artworks, and clinical cases in medicine. Moreover, the exploration of invisible features becomes possible from spectral images.

The spectrum-based color reproduction provides the solution to these problems, as shown in Figure 1, but it is necessary to integrate the system so as to take advantage of it in image and video communication systems.

**Background**

It is known that spectral measurement provides accurate colorimetry, and the spectral color acquisition is also utilized in imaging applications. In addition to accurate imaging colorimetry, multispectral imaging has been employed for computational color constancy7,28 and color image analysis.26,27,29,30

Although there have been numerous reports on theoretical and experimental aspects of multispectral imaging, few works can be found on the system architecture for spectral color imaging including input and output. A significant contribution to the system architecture was made by Keusen15
and Hill. In the proposed architecture, the spectral stimulus, which is an output of the spectral scanner, is expanded by a set of basis functions, and encoded as $K$-channel coefficients for the basis functions. The first three components of the encoded data correspond to the tristimulus values under a standard illuminant, and the remaining $K-3$ channels represent invisible spectral components. It was suggested to employ such spectral data for multispectral display and printing.

Rosen et al. revealed the concept of spectral color management including both input and output, and a spectral profile connection space (PCS) was introduced instead of the conventional PCS used in the color management system. The architecture mainly deals with the spectral printing, though an example of a spectral image visualization tool was reported. In addition, to reduce the dimensionality of the data for spectral printing, an interim connection space (ICS) was introduced, called LABPQR, where the first three channels (LAB) corresponds the color space under standard illuminant and the additional three channels (PQR) corresponds to the “invisible” components. The concept is quite similar to the one of Keusen and Hill, but the spectral PCS is a more flexible approach for the interchange of spectral color information.

The spectrum-based color reproduction system described in the following section was also presented in this context from the NV project. The concept of the spectrum-based color reproduction system is depicted in Figure 2. To obtain sufficient information, a multispectral camera (MSC) is desired as an input device. The profile of the input device, including spectral sensitivity, tone curve, and dark current level of the camera, and the spectral energy distribution of the illuminant are attached to multispectral image (MSI) data. In image processing, transmission, and storage, the image is accompanied by the profile metadata, so that the spectral radiance, reflectance, or transmittance can be retrieved. In the image display, the image of tristimulus values or spectral radiance is reproduced on three-primary or multiprimary color displays with device calibration. The system can also provide data to a color

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The role of spectrum-based color reproduction in the video and still-image systems. (a) Reproducing the color as if the observer were at the remote site, (b) reproducing the color as if object were placed at the site of observer, (c) expanding color gamut of the display (the hexagon denotes the gamut of six-primary projector), and (d) enabling the storage and analysis of the image with quantitative spectral information.}
\end{figure}
printing system in the form of CIE XYZ tristimulus values or the spectral reflectance under D50 standard illuminant.

The architecture of our spectrum-based color reproduction system is similar to the ICC (International Color Consortium) color management system, but the PCS is based on a physical model, i.e., spectrum-based PCS (SPCS) instead of a color appearance model. This can be any CIE XYZ under arbitrary illumination, spectral radiance, or spectral reflectance (or transmittance). The information required for the forward or inverse transform to SPCS is held in the profile data. The profile data format was defined as NV image data format. The XML version NV format was also developed for easier handling. Table I shows the summary of the data items used in the NV profile data by XML format.

Figure 3 shows the schematic presentation of the workflow of the spectrum-based color reproduction system. Once a MSI is captured by an input device, raw image data and the characteristics of the input device are obtained. The spectrum of the illuminant can be also attached to the data. Applying the spectral estimation technique described in “Spectral Estimation,” the matrix to estimate the spectral reflectance, transmittance, or radiance is derived and attached to the profile data. Artificial spectral image is also supported, where it is accompanied by the characteristics of the virtual input device, or the spectral reconstruction matrix. It is also possible to assign the matrix to estimate the tristimulus values under a certain illuminant for convenience. To make use of the stored MSI data afterward, it is often important to know the profile of the input device. For this purpose, the profile data as shown in Table I are attached to the image data in the database or in the system for interchanging images. In image display or printing, the device profile of the output device, as well as the illumination spectrum of the assumed output environment, is presented to the color conversion system. By this system, the color reproduction under an arbitrary illumination environment as shown in Fig. 1(b) is possible, while the standard illuminant (such as CIE D65 or D50) can be specified for output to the conventional color display or printing devices.

Accordingly, the system is capable of output of the image data compatible with the standard color space.

In this system, the number of channels in the image capture and the display are independent, and input and output devices with arbitrary numbers of channels can be employed. Color conversion can be performed without loss of information contained in the MSI. Three-channel devices can also be used in this system with proper device characterization, although there arise restrictions in the color reproduction capability or accuracy.

MULTISPECTRAL AND MULTIPRIMARY TECHNOLOGY

Multispectral Image Capture

For high-fidelity color reproduction with the spectrum-based color reproduction system, it is crucial to increase the number of bands in the image input device. There have been various reports on devices for the acquisition of multispectral images, for example, a monochrome camera with a rotating filter wheel, a grism (grating-prism), or a liquid crystal tunable filter. Capturing a multichannel image with modulating illumination light is also a useful technique to obtain the spectral reflectance of an object. The use of dichroic mirrors to separate the spectral components provides highest signal-to-noise ratio, though the optical system becomes relatively complex. In the experiment explained next, the MSCs for still image and video developed in the NV project are used.

Figure 4(a) shows the 16-band MSC with a rotating filter wheel developed in the NV project. The color reproducibility evaluated using a GretagMacbeth color checker is shown in Figure 4(b). The accuracy by MSC is high and the error is smaller than the discriminable level of human vision, while visually apparent error is observed in three-band DSC.

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Figure 5(a) shows a six-band HDTV camera for the acquisition of motion picture. In the six-band camera, the light is divided into two optical paths by a half mirror, and incident on two conventional three–charge coupled device (CCD) cameras after transmission through the special color
filters inserted in each path. Six-channel uncompressed HDTV video signal is captured and recorded on a magnetic hard disk. As a result of evaluating the color reproducibility of this six-band HDTV camera using the GretagMacbeth color checker, the CIELAB color difference average and maximum \( \Delta E_{ab} \) were 1.4 and 4.2, respectively, where \( \Delta E_{ab} \) were 4.1 and 8.2 in the case of the conventional HDTV camera. The same Wiener estimation technique mentioned in the next section was used in the evaluation of both devices.

Figure 5(b) shows the estimation results of high saturation colors. In this experiment, the interference filters of the 16-band MSC were illuminated by a light box (DNP, Hi-Vision Color Viewer) and employed as test colors. The colors were captured with the six-band camera and the

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**Table 1. Summary of the sample profile data in XML version of NV format. The mark ... represents the omitted numerical data.**

<table>
<thead>
<tr>
<th>XML</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Nvision xmlns=&quot;http://.../NvXmlSchema.xsd&quot;&gt;</td>
<td>Basic information of image data</td>
</tr>
<tr>
<td>&lt;NvisionInput d2p1:InputDate=&quot;2006-12-31T00:00:00.0000000+09:00&quot;&gt;</td>
<td>Input profile tag</td>
</tr>
<tr>
<td>&lt;DarkCurrentData d2p1:ID=&quot;1&quot;&gt;</td>
<td>N-Component bias digital counts</td>
</tr>
<tr>
<td>&lt;ToneCurvesData d2p1:ID=&quot;2&quot;&gt;</td>
<td>N-Component tone reproduction curves</td>
</tr>
<tr>
<td>&lt;ExposureTimeData d2p1:ID=&quot;3&quot;&gt;</td>
<td>Coefficients of N-component sensitivity level for the correction of exposure time setting</td>
</tr>
<tr>
<td>&lt;SpecSensiData d2p1:ID=&quot;4&quot;&gt;</td>
<td>Spectral Sensitivity of P-channel input device</td>
</tr>
<tr>
<td>&lt;NoiseData d2p1:ID=&quot;5&quot;&gt;</td>
<td>N-channel noise levels of Input device</td>
</tr>
<tr>
<td>&lt;InputIllum d2p1:ID=&quot;6&quot;&gt;</td>
<td>Spectral radiance of Q-input illuminants</td>
</tr>
<tr>
<td>&lt;AutoCorrelationMatrix d2p1:ID=&quot;7&quot;&gt;</td>
<td>Principal components of object's spectral reflectance</td>
</tr>
<tr>
<td>&lt;NvisionConversion d2p1:ConvDate=&quot;2006-12-31T00:00:00.0000000+09:00&quot;&gt;</td>
<td>Relative colorimetric values estimation matrix</td>
</tr>
<tr>
<td>&lt;XYZConvData d2p1:ID=&quot;8&quot;&gt;</td>
<td>Relative spectral reflectance estimation matrix</td>
</tr>
<tr>
<td>&lt;SpecStimuliData d2p1:ID=&quot;10&quot;&gt;</td>
<td>Relative spectral radiance estimation matrix</td>
</tr>
<tr>
<td>&lt;ColorMatchingFuncData d2p1:ID=&quot;11&quot;&gt;</td>
<td>Relative colorimetric values estimation matrix</td>
</tr>
<tr>
<td>&lt;RenderingIllum d2p1:ID=&quot;12&quot;&gt;</td>
<td>Relative colorimetric values estimation matrix</td>
</tr>
</tbody>
</table>

---
tristimulus values were calculated by the spectrum-based method explained next. The results are compared with the colors measured by a spectroradiometer in Fig. 5(b). The simulated results with a three-band camera are also shown in the Fig. 5(b). It can be seen that the colors estimated from the three-band camera clusters around RGB pure primaries, that is, the vertices of the camera analysis gamut. The six-band camera offers considerably better color tones in these high-saturation colors in comparison to the three-band camera. The color differences are relatively large for green objects, but they are out-of-gamut of the output devices, even in the case of wide-gamut displays. The results clearly show the advantage of multispectral imaging, especially in the case of high-saturation colors. The camera was employed...
for the experiment of real-time video reproduction described next.

In image capture, the spectral distribution of the illumination is also measured to estimate the spectral reflectance or the transmittance of the object. For example, the reflected light from a standard white plate is measured by a spectroradiometer or the MSC, or the ambient illumination is directly measured by a compact fiber-optic spectrophotometer. For correction of the spatial nonuniformity of illumination, a white plate (in the case of reflective object) or a transparent glass plate (in the case of transmissive object) is captured by the MSC. For practical use, it is expected that more easily handled devices will become available for the measurement of the illumination spectrum.

### Spectrum Estimation

In the spectrum-based color reproduction system, the spectral radiance, reflectance, or transmittance is estimated from the MSI data. An arbitrary estimation method can be used in this system, as the original MSI data can be preserved with the spectral sensitivity of MSC. Among various techniques for spectral estimation, the method based on Wiener estimation is practical and accurate. If the covariance function of spectral reflectance of the target object is available, it considerably improves the accuracy. However, it is not necessarily possible to obtain the covariance function, and we can alternatively use an approximation in which the covariance is modeled as a first-order Markov process. This model works fairly well for most natural objects, because the spectral reflectance of natural objects is for the most part smooth, except in special cases.

Even though spectrum estimation may be used in the color conversion where the spectrum space requires high dimensionality, the implementation of the spectrum-based color conversion is not so difficult in many cases, insofar as the spectral estimation may be be formulated by a linear model. For example, to display the color under an illuminant different from the image capturing environment, the image spectral reflectance is estimated from the multispectral image and the illuminant spectrum of the image capturing environment. Then the tristimulus values are calculated by multiplying the illuminant spectrum of image display environment and the color matching function. Then the device RGB signal is obtained by multiplying the matrix for color conversion. After the nonlinearity of the image capturing device is corrected, the spectrum-based color conversion from the multispectral image to the device RGB signal can be realized with the matrix operation of \( N \times 3 \), and following tone curve correction which can be implemented by one-dimensional look-up tables. Therefore, computation in the spectral space is needed only when changing the color conversion matrix.

In color reproduction for video images, the gain parameter noticeably impacts the color accuracy and the image quality. The gain parameter should be set such that the six-band signals from a reference white object become constant, in order to set the signal levels within the dynamic range of every band. Then the gain parameters are required in the color estimation step to correct the magnitudes of the output signals, as well as to set the noise variance in the derivation of a Wiener estimation matrix, since the noise levels of the camera output depend on the gain setting.

### Multiprimary Display System

There were few previous works on multiprimary color displays for larger color gamut; NHK (Japan Broadcasting Corp.) demonstrated a four-primary projection display to evaluate the wider color space in 1994. The present authors also reported a seven-primary display using a holographic optical element. However, system development and evalua-
tion of the multiprimary display had been originally started in the context of the NV project. In the multiprimary projection display developed in the NV project, the images from two projectors [liquid crystal display (LCD) or digital light processing (DLP)], each of which is adapted to produce a different set of three primary colors, are overlaid on the screen, as shown in Figure 6. As a flat-panel type multiprimary display, a four-primary flat-panel LCD with light emitting diode (LED) backlight was implemented by means of time sequential display.10

Figure 7 shows the color gamut of a six-primary DLP display.9 As for the gamut of natural objects, Pointer gamut39 and standard object color spectra (SOCS) database (excluding fluorescent objects)40 are combined/pointer+SOCS, because some objects in SOCS are out of the Pointer gamut. Six-primary DLP display almost covers the gamut of natural objects and the gamut volume in CIELAB space is about 1.8 times larger than that of the normal RGB DLP projector. The gamut of the six-primary display is enlarged in the dark red, cyan, purple and bright orange regions, as compared with the conventional RGB display.

Spectral Color Display

There exists variability in color matching functions of human observers originating from macular pigments, lens absorption, and cone sensitivity. Due to the individual difference of color matching functions, a color difference may appear to a certain observer when two color stimuli are shown, even if perceived as the same color by another observer, or the CIE standard observer. This phenomenon is called observer metamerism. It causes the color mismatch between different media, such as color printed materials and displays, even though the colorimetric match is achieved for CIE 1931 or 1964 color matching functions. It has been shown that the influence of observer metamerism due to the variation of color matching functions in color reproduction is not negligible.41,42

Based on the multispectral and multiprimary technology, spectral color display becomes possible, and the color mismatch between the display and the real object can disappear for different observers. The advantage of spectral color display was experimentally demonstrated using the six-
primary display\textsuperscript{25} with the signal processing method briefly explained in the next subsection.

**Multiprimary Color Conversion**

The multiprimary color signal is generated from the image of tristimulus values or multispectral data, called multiprimary color conversion, similar to the color decomposition for multiprimary color printers. For colorimetric color reproduction, three-dimensional tristimulus values are transformed to $M$-dimensional multiprimary color values. It involves a degree of freedom; plural combinations of multiprimary color values can reproduce a certain color.

The following methods have been developed as the multiprimary color conversion for colorimetric color reproduction:

1. The matrix switching method\textsuperscript{43} in which the polyhedral color gamut spanned by multiprimary colors is divided into pyramids, and selecting a $3^M$-matrix depending on the pyramid, we perform a linear color conversion in each pyramid.
2. Linear interpolation in equiluminance plane method\textsuperscript{44} where the multiprimary signal values are interpolated within the equiluminance plane in the solid color.
3. Metameric black method\textsuperscript{45} whereby multiprimary signal values are decomposed into visible and invisible (metameric black) components. The visible components are uniquely solved, where the metameric black components are determined such that the multiprimary signal values changes smoothly if the change of tristimulus values is smooth.
4. The spherical average method\textsuperscript{46} in which the conversion is based on the analytical solution such that the multiprimary signal values are continuous for the smooth change of tristimulus values.

The computation speed, ease of hardware implementation, and image quality depend on the conversion method. When an image with smooth color tonal change is reproduced on a multiprimary color display, a contourlike pattern sometimes appears. The observer dependence of color matching functions and the device characterization error are the sources of the artifact, and proper selection of the multiprimary color conversion process suppresses such artifacts.\textsuperscript{47} Color tone reproduction is one of the important issues for image quality in multiprimary displays.

For the spectral color reproduction explained in the previous subsection, it becomes $N$ to $M$ conversion, where $N$ is the number of channels of MSI. In the proposed $N$ to $M$ conversion method called the “spectral approximation method,” the spectral error is minimized under the constraint that the colorimetric match is attained for the standard observer. The effectiveness of this approach was confirmed experimentally.\textsuperscript{25,48}

**Multispectral Image Transmission, Compression**

The system architecture of image transmission and signal processing in the spectrum-based color reproduction system is shown in Figure 8. The signal from MSC (multispectral input signal) is converted to a signal for transmission, and converted again to the display signal for multiprimary or RGB display. The same scheme can be used in the storage of image data. There Three cases to implement the image transmission.
transmission system can be considered, and the features of these implementations are given in Table II.

The compression and encoding are also issues for MSI transmission. As an MSI compression technique considering the colorimetric accuracy, a modified Karhunen-Lueve (KL) transform called weighted KL transform was proposed and combined with the JPEG2000 scheme.\(^4\) For video compression, three methods that support multichannel images, MPEG4 studio profile, H.264/AVC, and Motion JPEG2000, were tested. The test included a coding method in which a MSI signal was converted into visible and invisible components, with the subsampling of chrominance signals. As a result, it was shown that intraplane codecs and the full-resolution formats without subsampling give better quality at higher bit rate, while a subsampled format surpasses other methods at lower bit rate.\(^5\) JPEG2000 is one of the suitable formats for high-quality encoding of both video and still MSIs. The profile data for NV format described previously can be easily implemented in JPEG2000 as an extended ICC profile or metadata using XML.

**Real-Time Video Reproduction and Transmission System**

A prototype of the multispectral video transmission shown in Figure 9 was also developed.\(^5\) The six-channel video signal from six-band high definition television (HDTV) camera is converted in a six-to-three color converter to the colorimetric tristimulus values, by using a spectrum-based color reproduction technique. In the spectrum-based color reproduction, after correction of the tone reproduction curve of CCD, the spectral reflectance is calculated for every pixel by Wiener estimation with the spectral sensitivity of the camera and illuminant spectrum of the image-capturing environment measured in advance. The colorimetric tristimulus values are then generated with using the illuminant spectrum of the observation environment. All of these processes can be done by \(6 \times 3\) matrix multiplication in real-time.

For the image display, both three-primary and multiprimary displays can be employed. The color display is characterized in advance and the parameters are set into the real-time color converter. When using the six-primary color display, a three-to-six color converter consisting of six 3D LUTs is used to generate a six-primary color video signal. Figure 10 is the photograph of the demonstration of six-band real-time reproduction, along with comparison with the real objects and the three-band system. The advantage of the spectrum-based system can be easily observed from the demonstration in Figure 10.

In real-time reproduction, direct conversion from three to six channels is difficult because of the hardware complexity. Thus colorimetric color reproduction is implemented with the six-to-three color converter. In addition, it is possible to apply a limited version of the spectral approximation technique; the spectral radiance of the object is approximated from the colorimetric tristimulus signal using the spectral estimation technique with the illuminant spectrum of observation environment. The object-dependent basis functions can be employed to reconstruct the spectra from the tristimulus values if available. In this case, the spectral difference between the real object and the displayed image

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**Table II. Transmission of video signal in natural vision**

<table>
<thead>
<tr>
<th>Case</th>
<th>Transmission signal</th>
<th>Description</th>
<th>Examples of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Multispectral input signal</td>
<td>The color under the arbitrary illuminant can be computed at the receiver site</td>
<td>Image archive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Image distribution</td>
</tr>
<tr>
<td>2</td>
<td>Colorimetric signal</td>
<td>The spectrum of observation illuminant sent to the sender in advance and the color under the observation illuminant is transmitted.</td>
<td>One-to-one communication, Wide-gamut color reproduction with fixed observation illuminant</td>
</tr>
<tr>
<td>3</td>
<td>Multiprimary display signal</td>
<td>The spectrum of observation illuminant and the display profile sent to the sender in advance, and the display signal transmitted.</td>
<td>Client-server image transmission</td>
</tr>
</tbody>
</table>

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**Figure 9.** The experimental prototype system for multispectral and multiprimary video reproduction.
becomes smaller if the spectral shape of the reflectance is smooth, which is assumed in the spectral estimation. Through the visual observation in an informal manner, the effectiveness of the spectral approximation is found by direct comparison of the object and the display, for example, in the reproduction of skin colors.

The captured image is recorded on the hard disk drive (HDD) video recorder without any compression. The data volume is about 3.5 Gbps. In an experiment on real-time reproduction at a remote site, the parallel MPEG-2 encoder/decoder for transmitting video signal through the TCP/IP network was used. When the network bandwidth was 80 Mbps, the CIELAB color difference due to the codec and decoder for transmitting video signal through the TCP/IP network was smaller than unity ($\Delta E_{ab}^*\leq 2$).

**Multispectral Image Editing, Analysis, and Database**

A multispectral video editor is required to create video contents. In the multispectral video editor, it is expected to handle image data of an arbitrary number of spectral bands. It is possible to edit movies from MSI sequences of the various numbers of bands using a sort of script, but it becomes rather burdensome to handle different format images. A method was proposed to simplify the multispectral video editor in which the image data of various numbers of bands are converted to a single format with the fixed number of bands, where a virtual multispectral camera is assumed to define the fixed format. A MSI can be considered as a value-added color image because every pixel has quantitative spectral data. Thus it is possible to make use of MSI data with the image database and analysis. The techniques for spectrum-based image processing, analysis, and retrieval explained in the next section were developed for specific applications, but they can be exploited in other applications as well.

**APPLICATIONS**

**Medical Application**

The use of digital color images is extremely valuable for teleconference, teleconsultation, education, training, image analysis, and reference database in pathology, endoscopy, and dermatology. In these applications, it may also be required to reproduce the complexion of a patient through the visual communication system for telediagnosis and home care. If the reproduced color is not accurate, it may cause misdiagnosis, thus, the reliability of reproduced color is critical.

In the pathology application, the spectrum-based system enables not only the accurate color reproduction of stained tissue samples, but also the correction of the color variation caused by the staining procedure. By use of the spectral information in the image, the amount of dye in each pixel can be estimated based on the Lambert–Beer Law, and an image can be reconstructed by digital adjustment of the density and balance of the staining. In addition, the spectral information is valuable for the feature extraction or image segmentation. To show the results of the image analyses in a form more familiar to medical doctors, a method called "digital stain" was proposed. A colorization matrix was applied to the results of pixel classification, and an image equivalent to a physically stained specimen was generated through computer processing from the MSI data. It becomes easier to evaluate the result of image analysis using this technique in the pathology field.

In dermatology, it has been shown that MSI is useful for the diagnosis of melanoma. The experiments in the NV project dealt mainly with inflammatory skin lesions, in which a faint color difference is important for diagnosis. The MSI systems of both still image and video were tested, and the color reproducibility of the multispectral system was shown to be sufficiently high from the visual evaluation by dermatologists. It was also shown that spectral information can be utilized for image analysis that supports diagnosis in both pathology and dermatology, for example, the grading of disorders, or the quantitative evaluation of treatments.

**Digital Archive and Electronic Museum**

The color of archived images depends on the imaging device and illumination condition, if we use conventional imaging devices. Many reports are found on the multispectral imaging for digital archives. In the NV project, the digital archives created both by multispectral still imaging and video are investigated.

For the still image digital archive, the woodprint by Shiko Munakata, a famous Japanese printmaker, was captured by the 16-band MSC, displayed on a screen, and transferred to the press in collaboration with Aomori Digital Archives Association. Moreover, with Biblioteca Nacional de Antropología y Historia (BNAH) and Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE), Mexico, 16-band MSIs of "codices," pictorial documents of the Aztecan era, were captured. The result of color reproduction displayed using a 16-band multispectral image was found to be satisfactory for the art management staffs. In the capturing of historical works, it is often necessary to minimize light irradiation, so the flash lamp, whose spectral energy distribution had been measured in advance, was synchronized with 16 exposures in order to minimize exposure. For large size ob-
jects, a high-resolution image is similarly generated by tiling smaller images.

The image data can also be employed for high-fidelity color prints as explained in the next subsection. Furthermore, the spectral information in the image will be useful for the analysis of pigments or dyes, or the selection of materials for restoration.

High-fidelity natural color reproduction will be valuable for educational video and multimedia contents, promotions of a regional nature, and virtual travel simulation. Multispectral movies were created to demonstrate the feasibility of the multispectral video system, using the video editing technique explained previously. In the introduction of the technology developed in the NV project as an example of scientific video, the effectiveness of multispectral and multiprimary technologies were demonstrated using a wide-gamut multiprimary display. The content is composed of both the computer graphic (CG) images and the video captured by the six-band camera. An introduction of Okinawan regional nature and culture related to color included the aerial video captured by the six-band video camera from a helicopter. This material successfully demonstrated the feasibility of the basic technology of the video acquisition and production, though improvement in usability is strongly recommended.

In addition, the natural color reproduction of the aurora was tried experimentally in cooperation with the University of Alaska at Fairbanks. Since the luminance of the aurora is very low, multispectral image capture is difficult. Instead, high-sensitivity RGB cameras (NAC Image Technology Inc., with Texas Instruments Impactron CCD sensors), are employed with spectral characterization. The spectral characteristics of the aurora are caused by the oxygen and nitrogen ions, which can be measured by spectroradiometer, and these data are used in the spectral estimation from three-band images. The images, 30 fps video images from three cameras, 640 × 480 pixels for each camera, are tiled to obtain a larger field of view. In the display, neutral density filters are attached to the multiprimary projectors to reproduce the very low luminance of real aurora. By visual evaluation, the reproduced colors, including faint green, dark red, and light pink, appear faithful to reality.

Printing Application
Multispectral imaging greatly improves the fidelity of color prints. As a test for the printing of catalogs for product promotion, assuming a normal photographic situation for the commercial products, a 16-band MSC and professional RGB DSCs were compared in joint work with DNP Media Create Co., Ltd. In the current catalog printing process, the color adjustment by in-house color proof is essential because the color reproduction capability of conventional DSCs is not enough. If the in-house color proofing and adjustment can be omitted, the simplification of the printing workflow becomes possible along with print quality improvement. In the experiment, the object and camera setting were prepared assuming normal conditions for photography of commercial products by a professional photographer. Nine different arrangements were tried. A 16-band MSC and RGB DSCs (Sinarback 23 by Sinar, and D1X by Nikon) were used for comparison purposes. In the multispectral image capture, three flash lamps were synchronized with shutters for 16 exposure times. At first, the images obtained from the RGB DSCs were printed by an ink jet printer, which is used for normal color proofing. A professional print director puts instructions for color corrections on the printed samples. Color correction instructions were given at four to five points on average for every picture.

To process the image captured by 16-band MSC, the spectral distribution of the flash lamp was measured in advance, and then the spectrum-based color reproduction applied to obtain the image in CIEXYZ color space under standard D50 illuminant. Then it was converted to 16-bit CIELAB digital color, the "unsharp mask" filter was applied to adjust the sharpness to the DSC images, and RGB data were generated by Apple ColorSync 3.0 using an ICC profile prepared for this purpose. The printed results were evaluated again by the same print director, and no instruction for color correction was given for any of the resultant samples. The print director also commented that the printed results from 16-band MSI was even better than the proof for presentation produced from RGB DSC image after color correction.

The development of spectral printing techniques, which is expected to reduce the illumination metamerism, has been reported. Although it is not directly dealt with in the NV project, the spectrum-based color reproduction scheme explained in "Spectrum-Based Color Reproduction System" supports the use of MSIS for spectral printing. For example, spectral color management was proposed using the interim connection space called LabPQR. It can be employed with the system described in the section, Spectrum-Based Color Reproduction System, above, by incorporating the conversion from the SPCS to LABPQR.

Furthermore, spectral color display can be useful for color proofing applications using softcopy monitors, since the color matching between display and print is considerably improved thanks to spectral approximation.

Electronic Commerce Application
In electronic commerce (EC), such as online shopping using color images, color differences may lead to the return of purchased items. Furthermore, the color matching of samples between designers, factories, buyers, and sales is needed, and quantitative color information is quite beneficial. A high-fidelity natural color reproduction system should contribute to the further evolution of EC for vehicles, apparel, cosmetics, toys, and interior furnishings. A web-based server-client prototype of the electronic catalog system shown in Figure 11 was developed in the NV project. Besides color reproduction under an arbitrary observation illuminant, the features offered by the prototype system include automatic selection of the color patch index corresponding to the specified image, and the retrieval of a fabric image based on the color histogram or spectral reflectance.

The display of a wider color gamut is required in textile applications. From the experiment using 464 colors from...
SCOTDIC(R) color book (Kensaikan International Ltd.) for cotton, it was confirmed that 100% of the colors are covered by the six-primary display, while 6% are out of the sRGB color gamut. The advantage of the six-primary displays becomes clearer in consideration of the character of ambient light. According to the evaluation by color experts in the apparel industry, the color difference between the real fabric and the reproduced image is almost negligible, though the impression of surface texture is somewhat different between the display screen and the real fabrics. The use of motion pictures improves such impression, better reproducing the angular dependency of reflection in textiles, as well as in metallic or pearl automotive finishes.

Wide Gamut CG System
The expanded color gamut of the multiprimary display provides a new tool or new colors for graphics expression. Through the experiences of graphic expression with the high-chroma colors enabled by six-primary display, the significance of wide-gamut graphics was observed. This significance includes: (a) rendering of the reality of actual objects, such as flowers, butterflies, marine blue water verdant green leaves, dresses, and accessories, in vivid or splendid colors, (b) the enhanced reality based on “memory color,” which often shifts to higher saturation with time, (c) strong impact or fantastic impressions resulting from color combinations scarcely encountered in the real world, and (d) rich color tones thanks to the expansion of the color range, including depth impression by the subtle color change in these dark colors, or the expression of gloss, metallicity, or emissive colors.

Digital Prototyping—Spectral BRDF Measurement and Rendering
Digital prototyping is an important technology for the expedience and efficiency of product development, and CG technologies enable the realistic rendering of virtual products, using the bidirectional reflectance distribution function (BRDF) or Bidirectional Texture Function (BTF), but the color often disagrees with that of the real products. The multispectral BRDF/BTF measurement system and multispectral rendering technique were developed for high-fidelity color digital prototyping. The system is based on a device for the BRDF measurement (OMG-3, Digital Fashion Ltd.), and Xenon light sources to which filter wheels are attached to capture 16-band MSI. The spectral BRDF rendering is realized using the multispectral image; the image of each band is independently calculated. The result is reproduced on the six-primary display and compared with the real object to confirm high color reproducibility.

Conclusions
The concept, technology, and applications of a spectrum-based color reproduction system have been introduced in this article. Spectrum-based color reproduction enables not only high-fidelity color reproduction but also the application of image analysis based on quantitative spectral information. Moreover, multispectral information will also be of great utility in image editing for preferred color and other various image processing applications such as object extraction or image synthesis, though those were not the main topics of the NV project, which basically targets natural color reproduction. Wide gamut display is one of the most recent topics in the display industry, and presentations of multiprimary displays can also be found from other groups. But conventional color camera devices and image color spaces such as sRGB do not support wider gamut image data at present.

Going beyond RGB, significant benefits emerge in advanced imaging applications. Multiprimary printing is already available in commerce, but to make better use of devices that support innovative color reproducibility, a platform for the spectrum-based system is expected, i.e., multispectral and wide-gamut video content creation, management, distribution, and utilization.

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