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Invited Paper

High-fidelity video and still-image communication based on spectral information: Natural Vision system and its applications

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ABSTRACT

In addition to the great advancement of high-resolution and large-screen imaging technology, the issue of color is now receiving considerable attention as another aspect than the image resolution. It is difficult to reproduce the original color of subject in conventional imaging systems, and that obstructs the applications of visual communication systems in telemedicine, electronic commerce, and digital museum. To breakthrough the limitation of conventional RGB 3-primary systems, "Natural Vision" project aims at an innovative video and still-image communication technology with high-fidelity color reproduction capability, based on spectral information. This paper summarizes the results of NV project including the development of multispectral and multiprimary imaging technologies and the experimental investigations on the applications to medicine, digital archives, electronic commerce, and computer graphics.

1. INTRODUCTION

Digital images are widely used at present in digital broadcasting, digital still cameras (DSC's), and the image delivery through the broadband network, and are being applied to the extended fields such as telemedicine, electronic commerce, and electronic museum. The natural color reproduction is one of the key issues in these applications, as well as the high-resolution or large-screen display technologies. However, many of conventional color imaging systems are designed for user preference, and it is difficult to reproduce the original color of the object. The color management technology is greatly progressed, but there still remains a limitation in color reproducibility in RGB 3-primary color systems.

As a breakthrough to this limitation, multispectral imaging technology is promising, and the research and development of multispectral imaging are gaining remarkable attention recently [1-6]. In the printing and the display of color images, there have also been the attempts to improve the color reproducibility by increasing the number of primary colors. For high-fidelity color reproduction in the image communication, total multispectral system was proposed [4-6], but there has been no implementation of integrated multispectral system, and neither has multispectral video.

To get those multispectral and multiprimary imaging technology into widespread use, it is required to establish the total system for the video and still-image communication based on spectral information. Natural vision (referred as NV hereafter) is an industry-government-academy joint project aiming at the development of visual telecommunication system that enables the high-reality image reproduction with natural color. The NV project, started 1999, is completed by March 2006 as scheduled. This paper reports the results of the seven years activity of NV project, including the multispectral and multiprimary imaging technologies and the experimental investigations on the applications to medicine, digital archives, electronic commerce, and computer graphics.

2. OVERVIEW OF NATURAL VISION PROJECT

2.1 Concept

The basic concept of NV is to shift the role of color imaging system from observation to measurement, and to reproduce the image as the physical or psychophysical quantity, such as the spectral radiance or the colorimetry. Then the fundamental requirements in NV system are (a) a digital system that enables the exact data management, transmission, and preservation, (b) a spectrum-based system instead of RGB digital counts, and (c) a capability to handle additional information such as the spectral profile of imaging devices and the illumination spectra along with the image data.

Then, why spectrum-based processing? The RGB values obtained in conventional imaging systems often have different meanings. Even if the RGB signal is compliant to the CIE standard, most of the color cameras do not satisfy Luther

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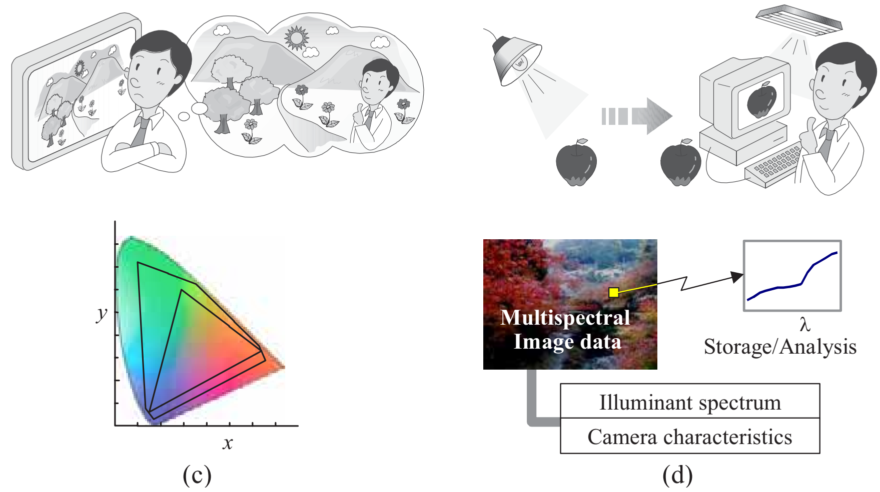


Fig.1 The role of natural vision system. (a) Reproducing the color as if the observer were at the remote site, (b) repro the ducing the color as if object were placed at the site of observer, (c) expanding color gamut of the display (the hexagon denotes the gamut of 6-primary projector [16]), and (d) enabling the storage and analysis of the image with quantitative spectral information.

condition, i.e., RGB signal does not have one-by-one correspondence to the tristimulus values. Moreover, to reproduce the color image under different illumination environment, spectral reflectance of object and the spectral distribution of illuminant are required for accurate calculation. In the display side, the color gamut achieved by 3-primary colors is limited. Also, the observer metamerism effect cannot be ignored in high-accuracy color reproduction, for example, in the color proofing of printed materials using color monitors. The target of NV project is to overcome these problems in the imaging systems based on the multispectral and multiprimary technology, and to realize following functions;

(a) For the natural color reproduction of real scene as if the observer were at the site as shown in fig.1(a), the colorimetric or spectral information is accurately captured and reproduced on a screen.

(b) To reproduce the color as if the object were in the presence of the observer as shown in fig.1(b), the spectral reflectance of the object captured as an image is multiplied by the illumination spectrum of observation environment, and the color under the illumination of observing environment is reproduced on a screen.

(c) The wider color gamut becomes available using multiprimary color display [Fig.1(c)].

(d) The original attribute of object that generates color, ex., spectral radiance, reflectance or transmittance information of the object, is captured and preserved by means of multispectral imaging [Fig.1(d)]. Such information is useful for the analysis or the recognition of object, in the digital archives of cultural heritage, artworks, and clinical cases in medicine.

2.2 Project organization and schedule

NV project is performed at Akasaka Natural Vision Research Center (NVRC), established by Telecommunication Advancement Organization (TAO), currently conducted by National Institute of Information and Communications Technology (NICT) under the support of the Ministry of Internal Affairs and Communication of Japan. Researchers from two academic institutes (Tokyo Institute of Technology and Chiba University) and industry (NTT Data, Olympus, NTT, etc.) are participated in the NV project, and have addressed the spectrum-based color reproduction technologies for still image (1999-2003) and motion picture (2001-2006). It is scheduled to be completed on March 2006. The subject of research in NVRC includes multispectral image acquisition, compression, transmission, storage, analysis, and the color reproduction on multiprimary and 3-primary display for both video and still-images. It is also an important mission to integrate the components as a model system and to experimentally demonstrate the effectiveness of the spectrum-based technology in various fields of applications.

3. SPECTRUM-BASED COLOR REPRODUCTION SYSTEM IN NATURAL VISION

3.1 System overview

The concept of the spectrum-based color reproduction system is depicted in fig.2. To obtain enough information for spectrum-based processing, multispectral camera (MSC) is desired as an input device. The profile of the input device including the spectral sensitivity, tone curve, and dark current level of the camera, and the spectral energy distribution of illuminant are attached to multispectral image (MSI) data. In image processing, transmission, and storage, the image is accompanied with the profile data, so that the spectral radiance, reflectance or transmittance can be retrieved. In image display, the image of tristimulus values or spectral radiance is reproduced on 3-primary or multiprimary color display with calibrating the display device. Although the color reproduction for printer is out of scope in NV project, the system

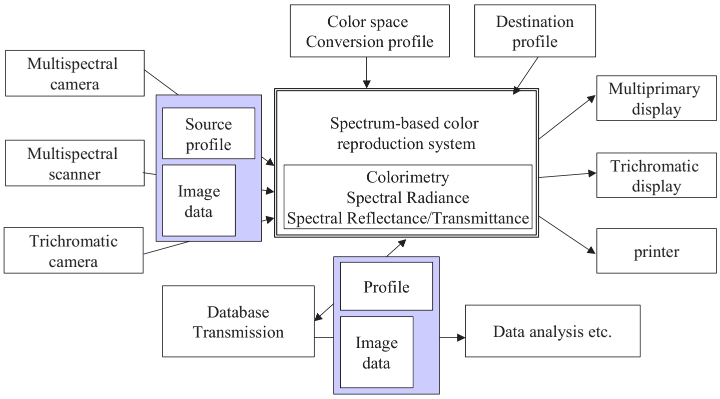


Fig.2 The scheme of spectrum-based color reproduction system

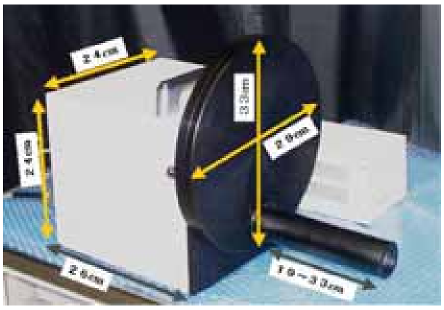


Fig.3 16-band MSC (4M pixels/band)

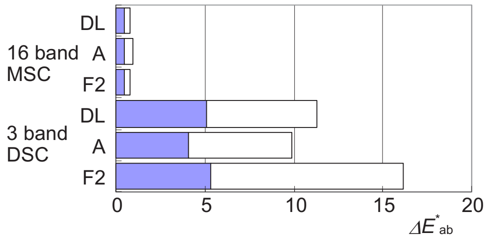


Fig.4 The color estimation accuracy of 16-band MSC and 3-band DSC, under daylight (DL), CIE A and F2 illuminants, where DL was used in the image

can provide data to color printing system in the form of CIE XYZ tristimulus values or the spectral reflectance.
The architecture of spectrum-based color reproduction system [7] is similar to the ICC (International Color Consortium) color management system, but the profile connection space (PCS) is based on physical model instead of color appearance model, i.e., spectrum-based PCS (SPCS). This can be any of CIEXYZ under arbitrary illumination, spectral radiance, or spectral reflectance. The information required for the transform to SPCS is held in the profile data. The profile data format is defined as NV image data format [7], which was proposed to CIE TC8-07 [8]. The XML version NV format was also developed for easier handling [9].
In this system, the numbers of channels in the image capture and the display are independent, and the input and output devices with the arbitrary numbers of channels can be employed. Three-channel devices can also be used in this system with proper device characterization, even though there arise restrictions in the color reproduction capability or accuracy.

3.2 Multispectral image capture

(1) Multispectral camera

In NV project, 16-band MSC's with rotating filter wheels are developed [10,11] as shown in fig.3. The spectral sensitivity of the camera is measured by using monochrometer, and the device model is carefully characterized. Then, the color reproducibility is evaluated according to the fixed procedure defined in this project. The result of evaluation using GretagMacbeth Color Checker is shown in fig.4. The accuracy obtained by MSC is high and almost equivalent of color measurement devices, while visually apparent error is observed in 3-band DSC even with the spectral characterization, and especially it is worse when the color rendering property of illuminant is poor.
Note that the precise device characterization is essential for high accuracy color estimation, namely, the error in device signals between the actual device and the model have to be kept less than about 1% to achieve CIELAB color difference $\Delta E^*_{ab} < 1.0$. Incidentally, the results given in fig.4 are obtained at the central area of the image; slightly larger error are observed around the peripheral region in the image.
For the acquisition of motion picture, 6-band HDTV camera is also developed [12] [Fig.5]. In the 6-band camera, the light is divided into two optical paths by a half mirror, and incident on two conventional 3-CCD cameras after transmitting through the special color filters inserted in each paths. Six-channel uncompressed HDTV video signal is captured and recorded in the magnetic hard disk. As a result of evaluating the color reproducibility of this 6-band HDTV camera, the CIELAB color difference ave. and max. ΔE^*_{ab} = 1.4 and 4.2, respectively, almost smaller than the discriminable level of human vision. In the case of the conventional HDTV camera with spectral characterization, ave. and max. ΔE^*_{ab} = 4.1 and 8.2, respectively.

(2) Illumination spectrum measurement

In the image-capturing step, the spectral distribution of illumination light is also measured to estimate the spectral reflectance or the transmittance of the object, by using either of following methods; a) the reflected light from standard white is measured by a spectroradiometer or the MSC, or b) the ambient illumination is directly measured by a compact fiber-optic spectrophotometer. For the correction of the spatial nonuniformity of illumination, white plate (in the case of

Fig.5 6-band HDTV camera

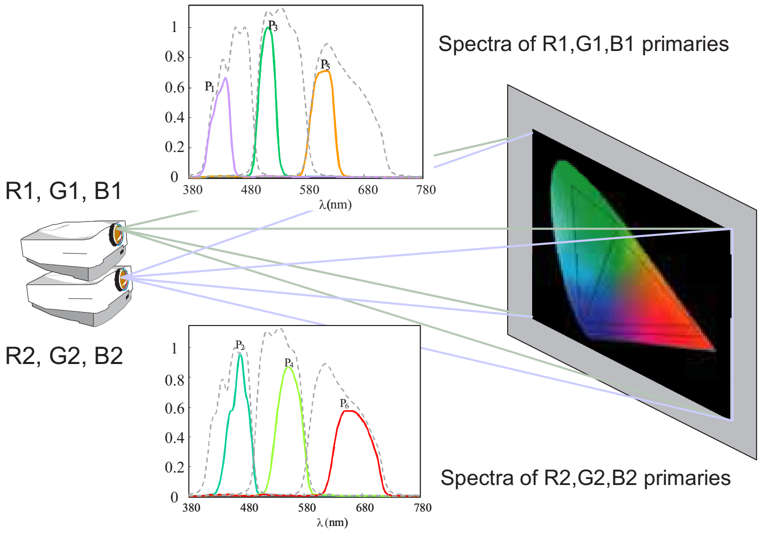


Fig.6 The 6-primary projection display using two modified projectors. The spectral intensities of each projector are also shown.

Fig.7 6-primary DLP rear-projection display

reflective object) or transparent glass plate (in the case of transmissive object) is captured by the MSC. For practical use, it is expected to make available more easy-to-handle device for the measurement of illumination spectrum.

(3) Spectrum estimation

In the spectrum-based color reproduction system, the spectral radiance, reflectance or transmittance is estimated from the MSI data. The estimation method can be arbitrarily chosen in this system, as the original MSI data can be preserved along with the spectral sensitivity of MSC. There have been huge reports on the spectral estimation [13-15], and among them, the method based on Wiener estimation is both practical and accurate. When available, the covariance function of spectral reflectance of target object is used and good accuracy is achieved even though the number of channels is small. However, in general case, it is not necessarily possible to obtain the covariance function in advance. In such case we can use a convenient approximation; the covariance is modeled as a first-order Markov process [14], and fairly good accuracy is obtained for most natural object. It is because the spectral reflectance of natural object is mostly smooth except for special cases such as the Aurora explained in sec. 4.4.

3.3 Multiprimary display system

(1) Multiprimary displays

NV project developed new display systems that significantly expand color gamut by using more than three primary colors, called multiprimary display [10,16,17]. Although there were few previous works on 4-primary and 7-primary color displays for larger color gamut [18,19], the system development and evaluation of muliprimary display had been originally started by NV project. In the projection-type multiprimary display developed in NV, the images from two projectors, each of which is adapted to produce different 3-primary colors, are overlaid on the screen [Fig.6]. We have developed 2x2 tiled large-screen (120inch) 6-primary rear-projection display, in which eight projectors are used [10], 6-primary front-projection DLP display [20], and smaller version of rear-projection 6-primary display, which can be used in lighted room environment (Fig.7). As a flat-panel type multiprimary display, an LCD with LED backlight of two different colors is used, 4-primary flat-panel LCD was implemented by means of time sequential display [21,22].

Fig.8 shows the color gamut of 6-primary DLP display, conventional RGB 3-primary DLP display, and natural objects. As for the gamut of natural objects, we investigate Pointer gamut [23] and SOCS spectral database (except for fluorescent object) [24] and found that some of the objects in SOCS are out of the Pointer gamut. Thus we have defined the gamut of natural objects as the combination of the ones from Pointer and SOCS database (Pointer + SOCS). Six-primary DLP display almost covers the gamut of natural objects and the gamut volume in CIELAB space is about 1.8times larger than the normal RGB DLP projector. The gamut of 6-primary display is enlarged in the dark red, cyan, purple regions and bright orange, as compared with conventional RGB display.

Recently, large gamut color displays are developed using high-saturation RGB primaries. The features of multiprimary approach compared with high-saturation RGB are the larger gamut covered by color polygon, less energy need for each

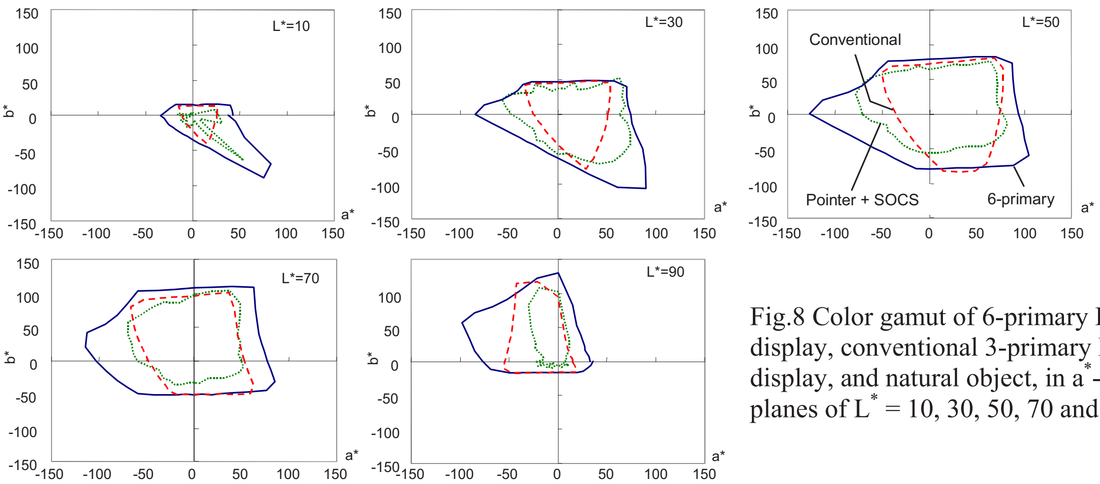


Fig.8 Color gamut of 6-primary DLP display, conventional 3-primary DLP display, and natural object, in a^*-b^* planes of L^* = 10, 30, 50, 70 and 90.

primary color, and better efficiency depending on the implementation. There have been announcements of development of multiprimary displays also from other groups lately. Evolution of multiprimary approach is expected as a way to enhance the color reproducibility in the next-generation displays.

(2) Spectral color reproduction by multiprimary display

It is known that the variability in color matching functions of human observers exists; originated from the macular pigments, lens absorption, and cone sensitivity. Due to the individual difference of color matching functions, the 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 CIE standard observer, this 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 [25].

The multispectral and multiprimary imaging technique can solve this problem, because spectral color reproduction becomes possible. Namely, the color mismatch between the display and the actual object can be disappeared for different observers. The advantage of spectral color reproduction on 6-primary display was experimentally demonstrated [10, 26, 27]. The signal processing method is briefly explained in the subsection (3).

(3) Multiprimary color conversion

The multiprimary color signal is generated from the image data of tristimulus values or multispectral data, which is called multiprimary color conversion. Let the number of primary colors be *M*. For the colorimetric color reproduction, 3-dimensional tristimulus values are transformed to *M*-dimensional multiprimary color values. Since there exists a degree of freedom; plural combinations of multiprimary color values can reproduce a certain color. To solve this problem, we developed several methods for 3to*M* color conversion [28-31]. The computation speed, the easiness of hardware implementation, and the image quality depend on the method of multiprimary color conversion.

For the spectral color reproduction explained in the previous subsection, it becomes *N*to*M* conversion, where *N* is the number of channels of MSC. As the *N*to*M* conversion methods, the spectral error is minimized under the constraint that the colorimetric match is attained for the standard observer, and it is confirmed to be effective for the suppression of color mismatch due to the observer metamerism [26,27].

(3) Evaluation of color reproducibility

After applying the spectral characterization of 6-primary display, the color reproduction accuracy was evaluated. The average and maximum color differences ΔE^*_{ab}, ≈ 1.2 and 2.5, respectively, although the accuracy is slightly worse in the marginal area. The reproducible color gamut is also evaluated and the results shown in fig.8 are obtained.

When an image with a smooth color tonal change is reproduced on a multi-primary color display, a contour-like pattern is sometimes appeared. This is caused by the use of metameric colors, though a standard observer does not observe the difference. The observer dependence of color matching function and the characterization error produce unexpected color difference, and is observed as a contour-like artifact. Its appearance depends on the method of multiprimary color conversion; it is suppressed when using the methods in ref.28 or 29 according to the result of evaluation experiments [32]. The smoothness of color tonal change is also an important item of evaluation in multiprimary display.

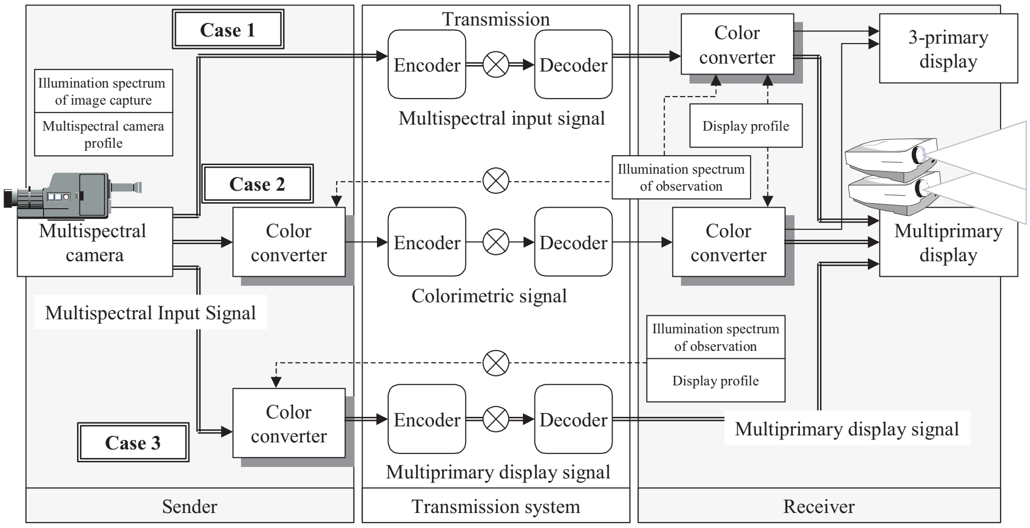


Fig.9 The system architecture of multispectral video transmission.

Table 1 Transmission of video signal in natural vision

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

3.4 Multispectral image transmission

The system architecture of image transmission and signal processing in NV is shown in fig.9. 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 can be considered three cases to implement the image transmission system and the features of these implementations are given in table 1.

The prototype of the multispectral video transmission shown in fig.10 is developed. In the multispectral video transmission, real-time color conversion is necessary. The conversion from multispectral input signal to the colorimetric signal is realized by the combination of 1D-LUT and a matrix, and the conversion from the colorimetric signal to the multiprimary display signal needs a nonlinear transform, and it is implemented by M-sets 3-D LUT's in NV project, where M is the number of display primary colors. Real-time colorimetric reproduction is realized in NV project with 6-band MSC and 6-primary display in HDTV resolution.

The compression and encoding are the other issues on MSI transmission. As a high-quality irreversible compression technique for MSI's considering the colorimetric accuracy, modified KL transform called weighted KL transform is proposed and combined with JPEG2000 scheme [33]. For video compression, we tested several compression methods that support multichannel images, and found that Motion JPEG2000 gives good quality in high bit rate case [34]. In this experiment, the compression was evaluated with a coding method in which MSI signal is converted into visible and invisible components, considering the compatibility to the conventional colorimetric video signal.

Through these experiments, we conclude that JPEG2000 is suitable formats for high-quality encoding of both video and still MSI's. The profile data for NV format described in section 3.1 can be easily implemented in JPEG2000 as metadata with using XML [9].

3.5 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 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 rather burdensome to handle different format images. We proposed a

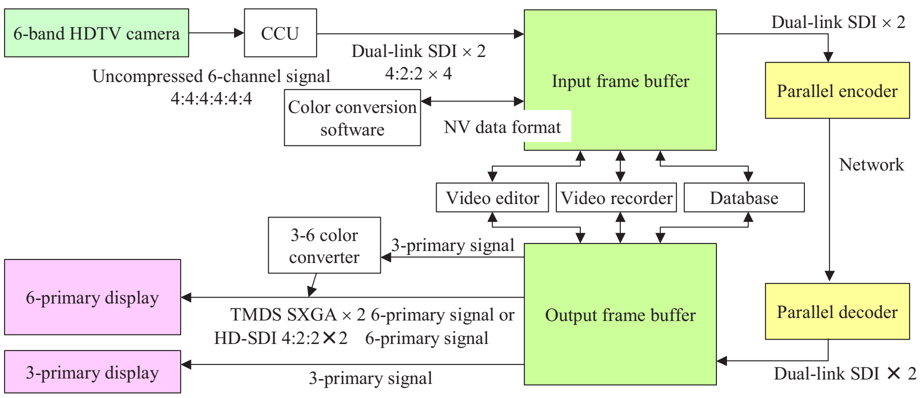


Fig.10 The experimental prototype system for multispectral and multiprimary video transmission.

method to simplify the multispectral video editor; 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 [35]. Multispectral images can be considered as a value-added color image, because every pixel has quantitative spectral data. Thus the image analysis is essentially important issue in the multispectral imaging for color reproduction. We have developed several techniques for image processing, analysis, and retrieval that utilize spectral data. Those techniques are developed for specific applications explained in section 5, but they can be applied to other applications as well.

5. APPLICATIONS OF NATURAL VISION SYSTEM

One of the important purposes of NV project is to demonstrate the effectiveness of spectrum-based color reproduction technology to exploit the potential application fields. The examples of applications are introduced in the following along with some experimental results.

5.1 Medical application

(1) Color management in medicine

As for the medical field, digital images are widely used in radiology, but the use of color image is still limited. Recently, digital color images begin to be used in the fields of pathology, endoscopy, and dermatology. It is also required to reproduce the complexion of a patient through visual communication system for the telediagnosis and homecare. The diagnosis through visual communication system cannot be employed without the reliability of reproduced color. If the reproduced color is not accurate, it may cause misdiagnosis. NV project demonstrate the medical applications for both high-fidelity color reproduction and the image analysis based on the quantitative spectral information, as follows.

(2) Pathology application

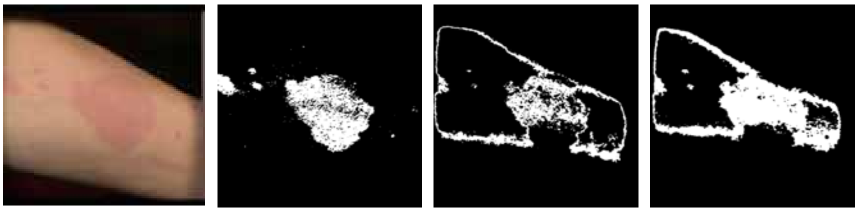
In the pathological diagnosis, the tissue specimens sampled from a lesion is stained and observed under a microscope. It is regarded as a final diagnosis, employed for the judgment of malignancy or the decision of the treatment plan. In spite of its importance, the number of pathologists is insufficient in Japan and some other countries. By the same reason, it is difficult to have the opportunity of information exchange between pathologists. Telepathology and teleconference using visual communication system is expected to overcome this problem. The use of digital color images is also extremely valuable for teleconsultation, education, training, image analysis and reference database. NV project jointly works with Tokyo Medical College and University of Pittsburgh Medical Center on the application of multispectral imaging to pathology. For this purpose, we developed MSC installed in the microscope as shown in Fig.11.

The color in the stained tissue specimen depends on not only the image acquisition device but also the staining; the type of staining technique, the variations of dye concentration, or the staining time. In this situation, pathologist must observe different colors with adjusting the color empirically. For better diagnosis and image management, the color variation due to the variations of imaging device and staining condition should be corrected.

In the Hematoxylin (H) - Eosin (E) staining in which the H and E dyes selectively colorize nucleus and cytoplasm, respectively. In the method developed by this research, the amount of dye (considering the pigment of red blood cell) in each pixel is estimated based on Lambert-Beer law. Then using the image of dye amount, we can reconstruct an image with adjusting the density and the balance of staining by digital process [36].

Moreover, a technique called "digital staining" was developed [37]. The HE staining is routinely used and special staining is employed when required. In the digital staining technique, the image of special staining is generated from routine HE

Fig.11 Filter wheel in the 16-band microscopic image acquisition system.



(a) (b) (c) (d)

Fig.12 Region extraction from 16-band MSI of drug eryption. (a) Natural color image. The area of disorder is extracted by (2) proposed spectrum-based color enhancement of 550nm band, (3) segmentation in RGB space, and (4) thresholding 550nm band image.

stained image by a digital process. The spectral information enables to discriminate tissue components from HE stained image. It has been shown that an image equivalent to Masson-trichrome staining, which selectively visualize fibrosis structure and is essential for liver cancer diagnosis, can be generated from an HE stained image. The digital staining technique is expected to promote the efficiency and quality improvements in the diagnostic process of pathology.

(3) Application to dermatology

The color of skin lesion is very important in dermatology. Photography of skin lesions is often used as a case record, and the dermatologists are highly sensitive to the color reproduced by photographs. Although DSC's come up to common recently and the image database and teledermatology [38] become practical, the color reproducibility is not enough for dermatological diagnosis [39]. In NV project, an experiment on the dermatology application of multispectral imaging is carried out in cooperation with Kagawa University [40]. The experiment mainly focuses on inflammatory and immunologic diseases, in which the subtle reddish color is important for diagnosis.

We investigate the color reproduction accuracy with using 16-band MSI captured by the camera shown in fig.3. In the first step, the images reproduced on a flat panel LCD were evaluated visually by dermatologists. Then it is confirmed that the color reproducibility is satisfactory in the clinical images, even better than pictures photographed on reversal films. In the next step, the colorimetric accuracy of reproduced image with using smaller number of bands is investigated. As a result, the color differences of immunologic disease cases, such as scleroderma and dermatomyositis, are estimated to be larger than the discriminable level of human vision when 3-band camera is used, and more than 5-bands are required for high-fidelity color reproduction.

The possibility of computerized diagnostic support using MSI is also investigated. The spectral features of abnormal part are enhanced with suppression of the color variation in normal skin. Referring the wavelength dependency of light penetration in the skin and the spectral absorbance characteristics of melanin and hemoglobin, it is considered that the melanin quantity in superficial layer is observed in the component around 470nm, the density of blood capillaries is reflected around 550nm range, and blood vessels in relatively deep region, such as vein are enhanced in the 620nm or longer component. The enhancement of 550nm component visualizes blood-rich pixels, and the lesion of inflammatory skin disease can be clearly extracted as shown in fig.12, while it is failed in RGB and 550nm only images. It will be useful for supporting diagnosis in dermatology, such as the grading of disorders or the quantitative evaluation of treatments. Moreover, in teledermatology applications, there are limitations in the observation flexibility and difficulty due to the absence of tactile information, and it would be valuable to present supplementary image with specific wavelength enhanced along with the natural color image, as the more exact determination of the skin disease condition.

(4) Medical application of video transmission system

Spectrum-based natural color reproduction system for motion picture will broaden the application fields. We conducted an experiment on the real-time video reproduction using 6-band HDTV camera and 6-primary display in dermatology application, in cooperation with Yokohama-city University. An imitated skin disease, prick test was done to the volunteer's arm, and the image was transmitted through 100Mbps network between two hospitals about 10km apart. To evaluate the reproduced color, the image was also reproduced at the same location as the image capturing, and the image on the screen was compared with the actual object by dermatologists. As the evaluations by dermatologists, the reproduced color is much more similar to the reality than the conventional HDTV, and the clarity of flare is improved as well. It is also shown that the use of motion picture with natural color facilitates the observation of wheal and flare. The system performance is almost sufficient for practical use, while the reduction of system size is expected.

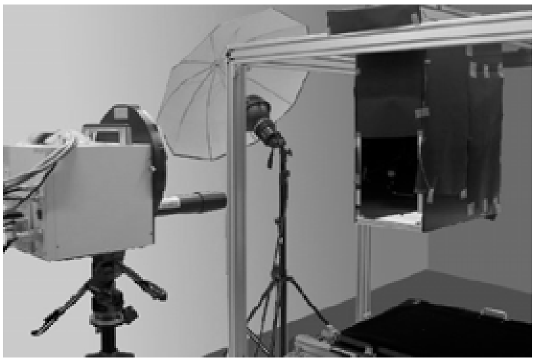


Fig.13 The setup for the MSI capturing of codices.

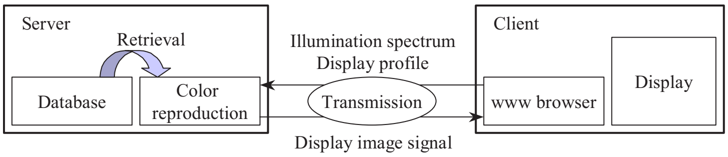


Fig.14 Electronic commerce prototype system. Image data can be retrieved from the database, and the color under the observation illuminant can be reproduced, through web-based user interface. The illumination environment and display profile are sent to the server, and the image for display is generated in the server and sent back to the client.

5.2 Digital archive and electronic museum

There have been many reports on the multispectral imaging for digital archive [41]. In NV project, the digital archives by both multispectral still-image and video are investigated. The woodprint by Shiko Munakata, a famous Japanese printmaker, was captured by the 16-band MSC, displayed on a screen, and provided to the presswork by the collaboration with Aomori Digital Archives Association. A conventional color management technique was applied in printing process, and the quality of printed replica was rated very high. Followings are the other experimental results;

(1) Digital archive of cultural heritage

An experiment on the digital archive of cultural heritage was carried out with Biblioteca Nacional de Antropologia e Historia (BNAH) and Instituto Nacional de Astrofisica, Optica y Electronica (INAOE), Mexico. 16-band MSI's of "codices," pictorial documents of Aztecan era, are captured [Fig.13] [11]. To minimize light irradiation, flush light synchronized with 16 exposures was used, where its spectral energy distribution were measured in advance. For large size objects, a high-resolution image is generated by tiling smaller images. The result of color reproduction is shown on a display and evaluated by the staffs in the BNAH. Also, the spectral information in the image will be useful for the analysis of pigments or dyes, or the selection of material for restoration.

(2) Digital archive and reproduction of natural scene

NV enables high-reality color reproduction of fantastic natural scene rarely observed. It will be valuable for educational video and multimedia contents, promotion of regional nature, virtual travel simulation. As an example, the natural color reproduction of aurora is experimentally tried in this project under the cooperation with Alaska University at Fairbanks. Since the luminance of 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 aurora, caused by the oxygen, nitrogen, nitrogen ions, are measured by spectroradiometer, and used in the spectral estimation from 3-band images. The images, 30fps motion picture in 640x480 pixels for each camera, from three cameras are tiled to obtain larger field of view. In the display, neutral density filters are attached on the multiprimary projectors to reproduce very low luminance of real aurora. By the visual evaluation, the reproduced colors, including faint green, dark red, and light pink are fairly faithful to the reality.

5.3 Electronic commerce application

In the electronic commerce (EC) for BtoC such as the online-shopping with using color images, the color difference is a serious problem. In BtoB EC, exchange of samples are still sometimes required only for the evaluation or ordering of color. Visual communication technology that enables natural color reproduction will contribute the further progress in both BtoC and BtoB EC of automobiles, apparels, cosmetics, toys, and interior furnishings. A prototype of electronic catalog system for textile application was developed in NV. It is a web-based server-client system as shown in fig.14, and besides the color reproduction under observation illuminant, it offers following features; the automatic selection of color patch index corresponding to the specified image, and the retrieval of fabric image based on the histogram of color or spectral reflectance.

The display of wider color gamut is required in textile applications. From the experiment using 464 colors from SCOTDIC color book (Kensaikan International Ltd.) of cotton, it is confirmed that 100% colors are covered by 6-primary display, while 6% are out of sRGB color gamut. The advantage of the 6-primary displays becomes clearer in existence of ambient light. According to the evaluation by experts relating to color in apparel industry, the color difference between the real fabric and reproduced image is almost negligible, though the impression of surface texture is somewhat different between the display screen and real fabrics. The use of motion pictures improves such impression,

Fig.15 The multispectral BRDF/BTF measurement system.

(a) (b)

Fig. 16 (a) Photograph of a real dress, and (b) result of multispectral rendering. See pdf file for color matching.

better reproducing the angular dependency of reflection property in textile and metallic or pearl painting of automobile.

5.4 Digital prototyping - spectral BRDF measurement and rendering

Digital prototyping becomes important technology for expedition and efficiency of product development, and CG technologies enable the realistic rendering of virtual products, using BRDF (Bidirectional Reflectance Distribution Function) or BTF (Bidirectional Texture Function), but the high-fidelity color has not been achieved yet. We developed a multispectral BRDF/BTF measurement system [fig.15] and multispectral rendering technique for high-fidelity color digital prototyping. The system of fig.15 is based on a device for the BRDF measurement (OGM-3, Digital Fashion Ltd.), and Xenon light sources with filter wheel are attached to capture 16-band MSI. The spectral BRDF rendering is realized with using multispectral image; the image of each band is independently calculated. The result is reproduced on 6-primary display and compared with real object [fig.16], and high color reproducibility is confirmed [42].

5.5 Application to catalog printing

Although printing technology is not a subject of this project, the captured MSI can be employed for color print. We conducted an experiment for the application to the printing of catalogs for product promotion, in a 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 DSC's are not enough. If the in-house color proofing and adjustment can be omitted, the reduction of printing process becomes possible as well as the print quality improvement.

In the experiment, the setting were prepared assuming normal photographing situation of commercial products by a professional photographer. Nine different arrangements were tried. A 16-band MSC and RGB DSC's (Sinarback 23 by Sinar, and D1X by Nikon) were used for comparison purpose. In the multispectral image capture, three flush lamps are synchronized with shutters for 16 times exposures. At first, the images obtained from the RGB DSC's were printed by an inkjet printer, which is used in the normal color proofing. A professional print director puts instructions for color corrections on the printed samples. Color correction instructions were given at 4-5 points on average for every picture.

To process the image captured by 16-band MSC, the spectral distribution of flush lamp was measured in advance, and then the spectrum-based color reproduction is applied to obtain the image in CIEXYZ color space under standard D50 illuminant. Then it is converted to 16-bit CIE $L^*a^*b^*$ color digits, the "unsharp mask" filter is applied to adjust the sharpness to the DSC images, and RGB digits are generated by Apple ColorSync 3.0 with using 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 to any of resultant samples. The print director also commented that the printed results from 16-band MSI is even better than the proof for presentation produced from RGB DSC image after the color correction [43].

5.6 Wide gamut CG system

The expanded color gamut by the use of multiprimary display, provides a new tool, or new color for graphics expression, so we developed a CG system for coloring with multiprimary colors, named "IRODORI" (Japanese word, meaning coloring or color scheme) [44]. Through the experiences of graphic expression with using the high-chroma colors enabled by 6-primary display, we demonstrate the significance of wide-gamut graphics; (a) rendering of reality in vivid or splendid colors of actual objects, such as flowers, butterflies, marine blue, verdant green leaves, dresses and accessories, (b) the enhanced reality based on "memory color," which often shifts to higher saturation with time, (c) strong impact or fantastic impression by the color combinations which are hardly encountered, and (d) rich color tone thanks to the expansion of color range, providing the depth impression by the faint color change especially with dark colors, or the expression of gloss, metallic colors, or emissive colors.

6. Conclusion

This paper introduces the activities of natural vision project over the seven years, including the development and system integration of multispectral and multiprimary imaging for video and still-image communication, as well as the demonstration of the effectiveness of spectrum-based color reproduction [45]. NV project proposed the renovation of color imaging techniques from the observation purpose to the measurement-oriented system. It thus enables not only the high-fidelity color reproduction but also the application of image analysis based on the quantitative spectral information. Moreover, multispectral information will be also of great utility in the image editing for preferable color, and other various image processing such as object extraction or image synthesis, though those were not the main topic of this project that basically aims to natural color reproduction.

Wide gamut display becomes one of the recent topics in display industry, and the presentations of multiprimary displays can be also found from other groups. It is expected to establish the basis of multispectral or wide-gamut video contents creation, management, distribution, and utilization in near future. For the widespread use of the technology, compact and easy-handling devices, and refined system integration are the next important subject to be addressed.

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