Spectral Based Color Reproduction Compatible with sRGB System under Mixed Illumination Conditions for E-Commerce

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Abstract

A standard color space, sRGB, has been widely used for reproducing the accurate color in the internet system. However, this color is accurate only under the sRGB reference viewing environment. In practice, the customers viewing environments are not always standard conditions. It is known that the multispectral color reproduction can be used to obtain highly accurate colors which are independent of device and viewing conditions. However, since the recent color reproduction system is based on conventional RGB or CMYK imaging technology, it is a huge task to change resources and devices in the market to be those in the multispectral technology. In our previous research, the spectral turn technique was proposed to achieve the spectral based color reproduction in the E-commerce with a high compatibility to the sRGB system. However the haploscopic method, used to compare colors on monitor and an object, was not compatible with the exact viewing conditions in real life. In this paper we propose more practical spectral turn technique using the revised mixed chromatic adaptation model, S-LMS(2001) applied with simultaneous binocular (SMB) matching method for more correct color appearance matching between softcopy and hardcopy under the practical viewing conditions.

Introduction

The recent advancements in broadband technology became possible to buy products from the Internet from home or office conveniently. Color is the one of the most important factors in making the purchasing decision when the customer purchases the products by browsing the pictures of those products displayed on the monitor. The product purchased through the E-commerce system will be physically sent to the customer’s office or home. After that the customer can compare the color of the product’s image displayed on the monitor to the delivered product. In this case the comparison or matching the color will occur in the customer’s environment. Therefore the accurate color reproduction under the customer’s light source in his/her environment is very important in the E-commerce system.

In the recent imaging technology, device independent color reproduction based on ICC-profile[1] or RGB-color space[2] are widely used for the color reproduction. However, the accurate color reproduction is only guaranteed in the decided standard environment. This is not practical for the general customer. Viewing condition independent color reproduction based on color appearance model is expected to reproduce the color under different viewing conditions. In this reproduction, however, the reproduced appearance of color is that of color under taken illuminants. The color of the object under the customer's viewing condition cannot be reproduced by this technique.

It is known that the multispectral color reproduction is used to obtain highly accurate device independent and viewing condition independent colors. Therefore, the color reproduction techniques based on an estimation of reflectance spectra were proposed to reproduce correct color under an arbitrary environment.[3-10] However, they are not used practically in the E-commerce, since almost all of the resources and devices traded in the recent market are based on the conventional RGB or CMYK imaging technology. It is difficult to change them into those of the multi-spectral imaging technology.

Spectral turn method[11] was proposed as the spectral based color reproduction technique, which is compatible with sRGB-system for E-commerce. In the spectral turn method the values of sRGB is inversely transformed into the spectral reflectance. The process of chromatic adaptation is also inversely processed in the method. A chromatic adaptation in RLAB model is used in the previous experiments. Therefore, the haploscopic matching method was used in the experiment for comparing the color of the images displayed on the monitor with the original objects. However in practice when the customer compares the color of the purchased product with the color of the image of product, which is displayed on the monitor, they used both of their eyes simultaneously for matching the color. This is similar to the simultaneous binocular matching method (SMB) method in the experimental level. Therefore the haploscopic matching method and RLAB chromatic adaptation model used in the previous experiment was impractical for the E-commerce.

In this paper, the spectral turn method applied with the revised mixed chromatic adaptation model: S-LMS (2001)[15] is proposed to achieve more accurate color appearance and more practically match the color using the SMB matching method for the usual office conditions. The revised S-LMS model is used for the color comparison under the mixed illumination condition. Under this condition the human visual system partially adapts to the monitor's white point and to the ambient light (mixed adaptation), since the observer's eyes are not fixed to the monitor all the time, but they also look to the surrounding area. Therefore we need to apply mixed adaptation to the chromatic adaptation transformation in the spectral turn method to improve the prediction of color appearance of CRT monitor viewed under mixed illumination.

In the next section we will briefly introduce the previously proposed spectral turn method and the previous experiments. After that the new spectral turn method applied with the revised S-LMS model, experiment using SMB matching method, results and conclusion will be described respectively.

Spectral Turn Method

The spectral turn technique compatible with the conventional RGB or CMYK imaging technology was proposed to achieve a highly accurate color reproduction for E-commerce.[11] In this technique, the process of the camera system is assumed to be based on the sRGB system and the spectral based technique is applied into the conventional system.

Figure 1 shows the process of spectral based processing for sRGB system. The sRGB system is assumed to be designed to reproduce the appearance of color under the taken illuminant on the sRGB display under the standard sRGB viewing conditions. Based on the process of the spectral based color reproduction, the process in the camera is assumed as the process surrounded by broken lines in Figure 1. From the camera, the sRGB values were transformed to tristimulus values, $\mathbf{x} = [X, Y, Z]^t$ with the consideration of the chromatic adaptation and color appearance transformation.

Then, to match the color under illuminant #2, it is necessary to process the color inversely into the spectral reflectance. The estimation of the spectral reflectance, $r(\lambda)$, can be obtained by using the following equation

$$r = (TL_1)^{-}x \qquad (1)$$

where L_1 is the diagonal matrix with spectral radiance of illuminant #1, T is the matrix of color matching function. After this we return the spectral reflectance values to the sRGB values after the exchange of the illuminants.

In the previously proposed spectral turn method, the taken image is reproduced on sRGB display under sRGB environment, and confirmed that the color is reproduced correctly on sRGB display by simultaneous haploscopic (SMH) matching method. Then the processed image assumed to be taken under the observer's illumination was reproduced by using spectral turn technique for matching the color to the original object placed under the observer's illuminant. The single state chromatic adaptation model of RLAB model, which was developed for matching the color under single illuminant condition,[3] was used. To precisely match between the color of softcopy images on the self-luminous display and the object under the observer's ambient illuminant by using this model, the observer's eyes should not be adapted to the monitor and the ambient light in the same time. Therefore the haploscopic method was used in the previous method. Figure 2 shows the simultaneous haploscopic matching method used in the previous spectral turn experiment.

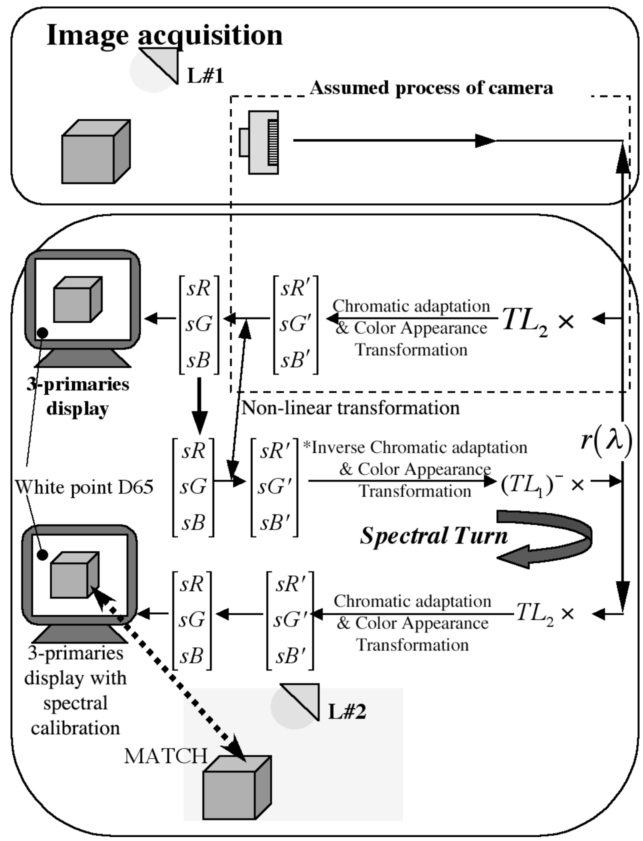

Figure 1. The process of spectral based processing for sRGB system.

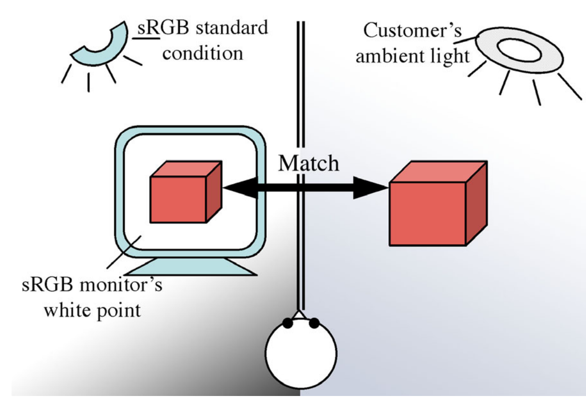

Figure 2. Haploscopic matching method used in the previous experiment for the spectral turn technique applied with the single chromatic adaptation model in RLAB model.

The results of the previous experiment showed that most of the color was reproduced well by the spectral turn method. We concluded that the proposed spectral turn technique has a high compatibility to the conventional imaging technology and the spectral band color reproduction can be implemented. However, the haploscopic matching method applied in the previous spectral turn experiment was used only for the fixed state of single adaptation. That is impractical for general use in the usual office or home environment.

In the next section, the revised mixed chromatic adaptation model, S-LMS (2001)[16] is applied into in the spectral turn method for using more practical simultaneous binocular (SMB) matching method. Since this SMB matching method can be used to simulate the practical viewing situation when the customer uses his/her both eyes simultaneously to compare the color of digital picture on the monitor and the delivered product under the ambient light.

Spectral Turn Applied with the Mixed Chromatic Adaptation Model: (Revised S-LMS)

In the usual office or home environments there are mainly 2 kinds of illuminants that affect the customer's eyes when the product and its image are viewed or compared simultaneously. Those illuminants are the monitor or self-luminous display and the ambient light as shown in Figure 3.

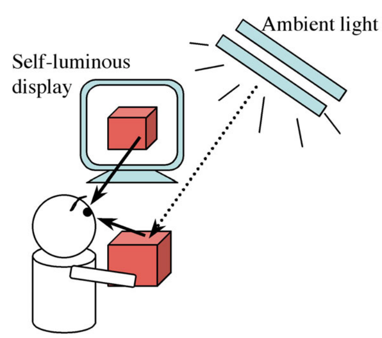

Figure 3. Human visual system adapted partially under the mixed illumination condition (as in the simultaneous binocular matching method).

This viewing condition is called mixed illumination condition. Under this condition the human eyes adapt partially to each illuminant called unfixed state of mixed chromatic adaptation.

Therefore, to achieve more accurate color appearance matching between the softcopy and the hardcopy (the image of product and the product in the E-commerce system) under the practical viewing conditions the mixed chromatic adaptation model: S-LMS (2001) is newly applied to the spectral turn method, as shown in figure 4.

The device independent sRGB values of the image taken under the illuminant $L_{\#1}$ are transformed to the tristimulus values. Then the revised S-LMS model is used inversely to calculate the tristimulus values which are used in the next spectral transformation step. The inverse matrix of color matching function, T, and the diagonal matrix with spectral radiance of illuminant #1, L_1, are used to estimate the spectral reflectance, $r(\lambda)$. After that, we transform these spectral reflectance values back to the tristimulus values corresponded to illuminant $L_{\#2}$ by using the matrix functions T and L_2. The revised S-LMS is used to transform the tristimulus values corresponded to the mixed illumination viewing condition. Finally these values are converted to the digital counts of sRGB values to display on the sRGB monitor under the observer's ambient light. The detail of the model is explained below.

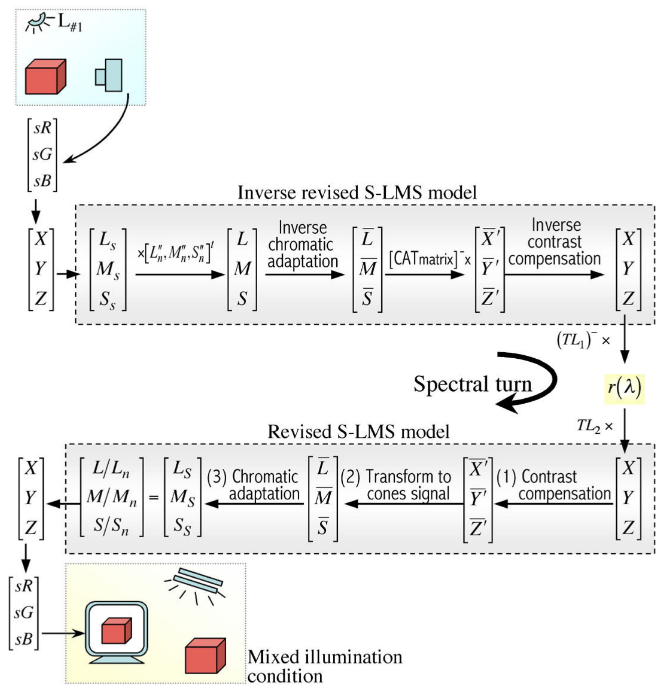

Figure 4. The spectral turn method applied with the mixed chromatic adaptation model: revised S-LMS model.

There are three essential stages used in the revised S-LMS model as shown in figure 4. For the first stage, the contrast variation for the soft copy images caused by the reflection of the ambient light must be compensated. The second stage is the transformation from tristimulus values to cone signals. And the final stage is the compensation for chromatic adaptation. The following equations (2)~(7) described these three stages of the S-LMS model in detail.

(1) Compensation for Contrast Variation

$$\begin{bmatrix} \overline{X}'_{n(CRT)} \\ \overline{Y}'_{n(CRT)} \\ \overline{Z}'_{n(CRT)} \end{bmatrix} = \frac{1}{Y_{n(CRT)} + R_{bk} \cdot Y_{(Ambient)}} \cdot \left\{ \begin{bmatrix} X_{(CRT)} \\ Y_{(CRT)} \\ Z_{(CRT)} \end{bmatrix} + R_{bk} \cdot \begin{bmatrix} X_{(Ambient)} \\ Y_{(Ambient)} \\ Z_{(Ambient)} \end{bmatrix} \right\} \quad (2)$$

where "R_{bk}" is the reflectance factor of the CRT screen surface, usually it varies between 0.03 and 0.05. The subscript "$_{(CRT)}$"refers to the CRT monitor and "$_{(Ambient)}$"refers to the ambient light. $X_{(Ambient)}$, $Y_{(Ambient)}$, $Z_{(Ambient)}$ were obtained by measuring white object placed on the CRT screen. After adding this reflection, the maximum value of "$Y'_{(CRT)}$"is normalized to one. The subscript "n" indicates the maximum value and " ⁻ " indicates normalized value.

(2) Chromatic Adaptation Transformation

The chromatic adaptation transformation (CAT) matrix described in CIE's proposed revision for CIECAM97s is used to transform the tristimulus values into the human visual system's cone signals.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8562 & 0.3372 & -0.1934 \\ -0.8360 & 1.8324 & 0.0033 \\ 0.0357 & -0.0469 & 1.0112 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (3)$$

(3) Compensation for Chromatic Adaptation

There are two steps for the calculation of the adaptation white point, Incomplete Adaptation and Mixed Adaptation. For the calculation of incomplete adaptation, the equations below are used. These equations are mathematically identical to the CIE's proposal for incomplete adaptation, which means that the human visual system incompletely adapts to the CRT monitor's white point.

$$\begin{aligned} L'_{n(CRT)} &= L_{n(CRT)} / d_L \\ M'_{n(CRT)} &= M_{n(CRT)} / d_M \\ S'_{n(CRT)} &= S_{n(CRT)} / d_S \end{aligned} \quad (4)$$

$$\begin{aligned} d_L &= D + L_{n(CRT)}(1-D) \\ d_M &= D + M_{n(CRT)}(1-D) \\ d_S &= D + S_{n(CRT)}(1-D) \\ D &= F \cdot \left\{1 - 1 / \left[1 + 2\left(Y_A^{1/4}\right) + \left(Y_A^2\right)/300\right]\right\} \end{aligned} \quad (5)$$

where $L_{n(CRT)}$, $M_{n(CRT)}$ and $S_{n(CRT)}$ are the cone signals to the monitor's white point. D-factor can be calculated by using F and Y_A (cd/m^2), which are a factor degree of adaptation (1.0 for average surround) and the luminance of the adapting field (the luminance of the visual field outside of the background which can be measured by using a photometer[17]), respectively. Then, the mixed adaptation is applied.

$$\begin{aligned} L''_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot L'_{n(CRT)} + \left(1 - R_{adp}\right) \cdot \left(\frac{Y'_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot L_{(Ambient)} \\ M''_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot M'_{n(CRT)} + \left(1 - R_{adp}\right) \cdot \left(\frac{Y'_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot M_{(Ambient)} \\ S''_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot S'_{n(CRT)} + \left(1 - R_{adp}\right) \cdot \left(\frac{Y'_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot S_{(Ambient)} \end{aligned} \quad (6)$$

$$where\, Y_{adp} = \left\{R_{adp} \cdot Y'^{1/3}_{n(CRT)} + (1 - R_{adp}) \cdot Y'^{1/3}_{n(Ambient)}\right\}^3$$

R_{adp} is the adaptation ratio to the monitor's white point , $Y_{n(CRT)}$ is the absolute luminance of the monitor's white point, and $Y_{n(Ambient)}$ is the absolute luminance of the ambient light. The weighting factors: $(Y_{n(CRT)}/Y_{adp})^{1/3}$, $(Y_{n(Ambient)}/Y_{adp})^{1/3}$ in the above equation were introduced to correspond to the absolute luminance difference.

Finally, the viewing-condition independent index: S-LMS can be expressed below.

$$\begin{aligned} L_S &= L_{(CRT)} / L''_{n(CRT)} \\ M_S &= M_{(CRT)} / M''_{n(CRT)} \\ S_S &= S_{(CRT)} / S''_{n(CRT)} \end{aligned} \quad (7)$$

Then the S-LMS data, L_s, M_s, and S_s, are transformed back to XYZ values by using the inversed CAT matrix with the output device's viewing condition parameters at the same adaptation ratio used above. These tristimulus values are converted into the digital counts for display based on the device profile that should be obtained or measured. The reproduced color on the display will match with the color of the real object under illuminant $L_{\#2}$. We may call this as spectral based corresponding color reproduction.

In addition, to apply this model with the spectral turn technique, we need to inverse the model before transform the tristimulus values to the spectral reflectance values, as shown in figure 4. The inverse S-LMS step can be achieved by calculating inversely of the revised S-LMS model explained above.

Following the whole proposed process of the spectral turn technique applied with the revised S-LMS model, we will be able to achieve more practical spectral based color reproduction compatible with sRGB system under mixed illumination conditions for E-commerce. In the next section we will describe the experiment used for this technique.

Experiment

Figure 5 shows the steps of the experiment using the spectral turn method applied with the mixed chromatic adaptation: revised S-LMS model. The object's original image was taken under the first illuminant (In this experiment, the standard daylight D65 was used). Then, the processed image was reproduced from the original image by using the proposed mixed illumination spectral turn method to be compatible with the mixed illumination condition, which is the usual user's viewing condition. To compare or match the color of the object's images and original object or product, the simultaneous binocular matching method was applied. The original images taken by the digital camera and the processed images were placed on the sRGB display simultaneously. The observers compared the color of both images with the color of the original object, and then chose the best matched image, as shown in figure 5.

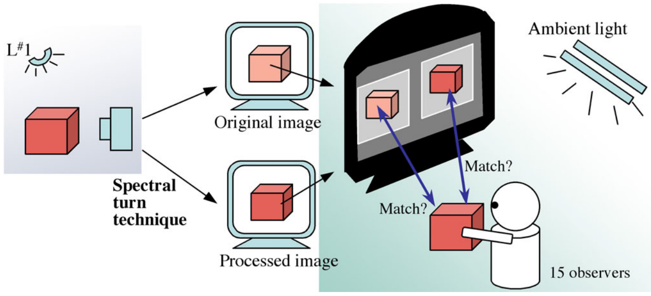

Figure 5. The experiment using the spectral turn method applied with the mixed chromatic adaptation: revised S-LMS model.

The room where the experiments were performed simulated a typical office or home environment. In the preliminary experiment we set the room to be illuminated by the standard A light source. For the original object, we used the standard Gretag-Macbeth color checker in the first step.

For the color-matching step, 15 observers participated. Before the experiments, all of the observers took a color-blind test to confirm that they had color-normal vision. The observers were given approximately five minutes to adapt to the viewing conditions of the room and they were instructed to sit approximately 50-60 cm from the screen and to identify and to match the original object to the softcopy image on the monitor. Every observer was allowed to move the original object anywhere he/she desired, but not on the screen next to the softcopy image, so that the observer had to move his/her eyes at some distances to make comparisons. Also no time restriction was placed to the observers.

Each color in the Gretag-Macbeth color checker was compared to that color in both original image and processed image. The number of the observers who chose processed images was counted to calculate the processed images preferring rate (%). For example, after the observers compared the green patch in Macbeth color checker, there were 10 observers from all 15 participants who chose the processed color image to be the best matched to the original object. In this case the processed images preferring rate was 67%. We used this preferring rate to determine the results.

In the next step of experiments we used the real products (for example cloths, accessories, postcards, etc.) instead of Macbeth Color Checker for color matching under varied illuminants (around 3000K~7000K). It should be noted that to obtain the best results in the experiment, a proximal field should not be distinguished when the images are shown on the monitor (the proximal field is the immediate environment of the stimulus extending for about 2 degrees from the edge of the stimulus in all, or most, directions[18]).

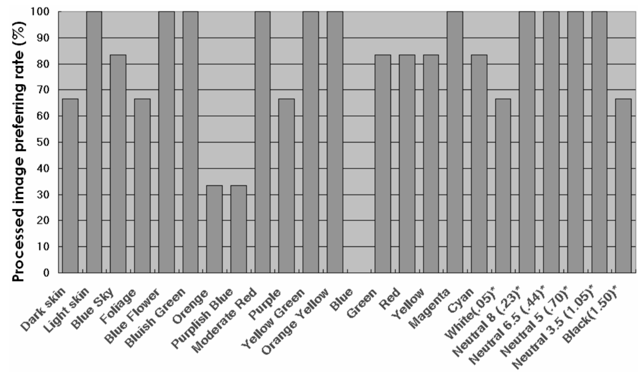

Figure 6. The graph of the processed images preferring rate (%) of each color in Macbeth Color Checker.

Results and Discussion

Figure 6 shows the results of the preliminary experiment by a bar graph of the processed images preferring rate (%) of each color in Macbeth Color Checker. This graph indicates that almost all of the processed color obtained by using the spectral turn method applied with revised S-LMS model was preferred by more than 50% of the observers. This means that the color of the processed image matched to each color of Macbeth color checker more than the original image obtained from the sRGB camera.

However, the blue, purplish blue and orange colors could not be matched well by this experiment. These errors might be either occurred from the experimental errors or the limitation for reproducing the blue color of the CRT monitor.

For the next experiments, which used the variety color objects and variety ambient lights instead of Macbeth color checker and A light source, the results indicated that almost all of the observers preferred the processed images of those products. In addition, the reproduced colors matched very well under the yellowish light sources. However, the processed images could not be matched well under the bluish illuminants (6000K~7000K).

Conclusion

The proposed spectral turn technique has a high compatibility to the conventional imaging technology and this technique can be implemented to spectral based color reproduction. The mixed chromatic adaptation revised S-LMS model (2001) applied within this spectral turn technique can be used to improve this technique for more practical use. Especially the applied revised S-LMS model could provide highly accurate color matching under warm color illuminants. However, the inadequate results from the color matching under the bluish lights need to be corrected.

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Biography

Kunlaya Cherdhirunkorn was born in Bangkok, Thailand, on 12 February 1976. She received B.S. degree in department of photographic science and printing technology from Chulalongkorn University in 1997. Now, she is the master course student in Chiba University. She is interested in multispectral imaging and color reproduction technology.

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Yoichi Miyake has been professor in the Department of Information and Image Sciences, Chiba University since 1989. He received the B.S. and M.E. in Image Science from Chiba University in 1966 and 1968, respectively. He received Ph.D. from the Tokyo Institute of Technology. During 1978 and 1979 he was an academic guest of Swiss Federal Institute of Technology. In 1997, he was a guest professor of University of Rochester. He received the Charles E. Ives award in 1991 from the IS&T. He became a fellow of IS&T in 1995. He also received Electronic Imaging Honoree of the Year in 2000 from SPIE and IS&T. He is one of the pioneers of multi-spectral imaging. He was served as president of Japanese Association of Science and Technology for Identification and the Society of Photographic Science and Technology of Japan. He is currently served as vice president of IS&T