Evaluating Wide Gamut Color Capture of Multispectral Cameras

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Abstract

Systems for wide-gamut display are being attracted attention, but conventional color cameras cannot capture color signals in the expanded color gamut. This paper presents a method for evaluating the capability of capturing wide color gamut, and the evaluation results of six-band camera systems comparing with a three-band system. The numerical evaluations show that six-band systems realize a wide color gamut with little loss of signal to noise ratio, and with good color accuracy. In addition, a subjective evaluation demonstrates the capability of six-band systems to acquire deep and vivid colors without loss of naturalness.

Introduction

The recent advancements in wide-gamut displays are promising, and wide-gamut color spaces, for example, Adobe RGB, and xvYCC (IEC 61966-2-4) have been standardized to exploit the expanded color gamut. It is also expected for image capturing systems to acquire wide gamut color signals. However, conventional color cameras can capture the color within the triangle bounded by RGB primary colors on a chromaticity diagram, and saturated colors are shifted inside the RGB gamut. To compensate the limitation of capturing systems, the saturation of acquired colors are sometimes emphasized for displaying, which apt to give an observer an unnatural or artificial impression.

Multispectral imaging technology has been investigated for capturing colors with high accuracy, and its effectiveness has been verified by various research groups [1-8]. It has been demonstrated that wider color range can be acquired by multispectral cameras [8], but quantitative evaluation has not been done. In this paper, the gamut of captured color by multispectral cameras is evaluated, and it is shown that multispectral cameras are suitable to capture a wide color gamut.

While the color gamut of display systems is a classical feature that represents one of the display capabilities, the gamut of image capturing systems is a relatively new concept. Recently, there have been several researches that deal with the color gamut of input systems [9-11]. However, the conceptual problems inherent to determining the gamut of input systems have not been fully solved, and we have not arrived at a common recognition on the gamut of input systems. In addition, there have yet been discussions on the concept itself that input systems are evaluated by the size of the gamut [12, 13].

The purpose of this paper is to evaluate the capability of capturing wide color gamut of image capturing systems. For this purpose, the size of the gamut can be one of the important measures. However, it is not enough, as discussed in [12, 13]. For example, a system that has a large color gamut can not necessarily capture the saturated colors accurately. In addition, by pursuing a wide color gamut, the system may have to suffer from the degradation of the colorimetric accuracy or signal to noise ratio (SNR). Then, in this paper, we first discuss how to evaluate image capturing systems from the viewpoint of wide gamut color capture, and introduce several viewpoints required for the evaluation. In the succeeding sections, the results of objective and subjective evaluations based on the discussions for six-band and three-band imaging systems are reported.

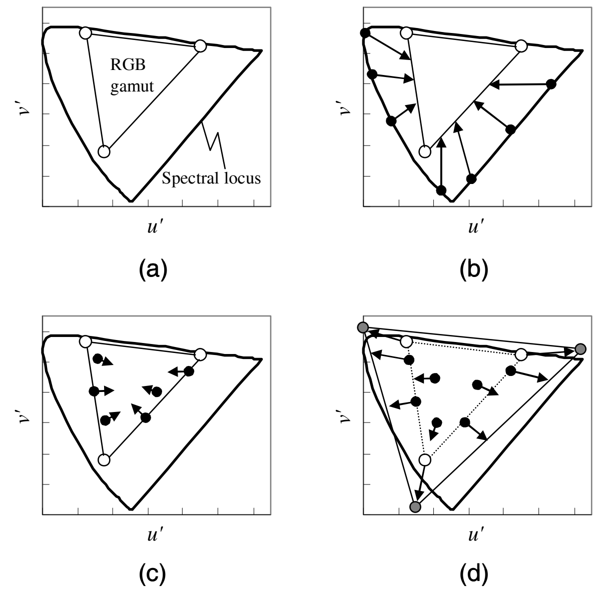


***Figure 1**. Conceptual diagrams for typical problems of RGB-compliant camera for wide gamut color capture; (a) spectral locus and analysis gamut of RGB on CIE 1976 u'v' chromaticity diagram, (b) colors with high saturations are shifted into gamut inside, (c) colors inside gamut are also shifted inward, and (d) when saturation emphasis is applied, colors are shifted outward and signal to noise ratio is reduced.*

Evaluation Methods

Evaluation Viewpoints

Figure 1 shows conceptual diagrams that represent typical problems of RGB-compliant camera system for wide gamut color capture. A spectral locus and the RGB gamut bounded by primaries (for example, ITU-R BT.709) on CIE 1976 u'v' chromaticity diagram are shown in (a). Any colors outside of the RGB gamut cannot be obtained by this camera system because image signals are not allowed to be negative. Figures 1 (b)-(d) correspond to the problems listed below, where black circles indicate the positions of original colors and the end of the arrows indicate the positions of the colors obtained by the camera system.

- Colors outside the RGB gamut are shifted to the gamut inside as shown in (b).
- Obtained colors are not accurate even if the color exists within the RGB gamut. The colors adjacent to gamut boundaries are often shifted inward largely as show in (c).
- When applying some signal processing for the purpose of the enhancement of color saturation, the apparent gamut widens as shown in (d), where the triangle bounded by the gray circles is the widened gamut. Commercial digital video or still cameras often adopt such enhancement. However, the operations for enhancement (i) lose the colorimetric accuracy, (ii) sometimes give an unnatural or artificial impression, and (iii) generally causes the degradation of SNR of output images.

Therefore, the evaluation of the capability of capturing gamut should include at least following three viewpoints: the size of the color gamut, color acquisition accuracy inside the gamut, and the SNR of captured images. In this paper, objective and subjective evaluations are performed considering these three viewpoints.

Target Systems

The target of the evaluation is color image capturing systems, which consist of a capturing device and a color conversion processing that produces tristimulus values in the CIE color space from device outputs.

Two kinds of six-band cameras, referred as L6 [7] and C6, are used in the evaluation. Both cameras have been built with two commercial HDTV camera modules and spectral trimming filters. The spectral sensitivities of the cameras are shown in Fig.2. The cutoff wavelength of the filters is designed to optimize the color reproduction accuracy. While L6 camera consists of narrow six bands, C6 camera consists of wide three bands and narrow three bands considering the SNR characteristics of reproduced images. The sensitivity of the wider three bands of C6 camera is equivalent to that of the original HDTV camera. Then, the set of the wider three bands of C6 is regarded as the sensitivity of a three-band camera and referred to as C3.

In the evaluation, the color conversion processing is performed by linear matrix transformation for simplicity. The conversion matrices based on a Wiener estimation theory are mainly used, because it has been shown to give the best colorimetric accuracy in many cases. The Wiener estimation matrix is generated from the spectral sensitivity of a camera and the illumination spectrum. In addition, the correlation matrix of spectral reflectance functions and a noise covariance matrix are required, where the details are explained in the section of evaluation.

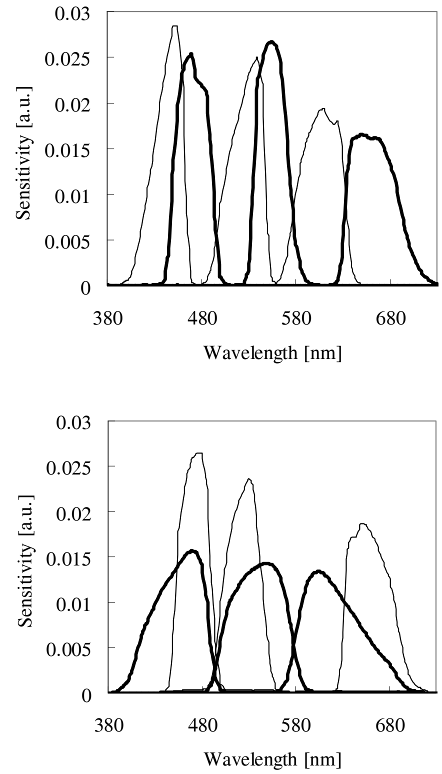


***Figure 2**. Spectral sensitivities of six-band cameras: L6 (top) and C6 (bottom). Wider three bands of C6 are regarded as sensitivity of three-band camera referred to as C3.*

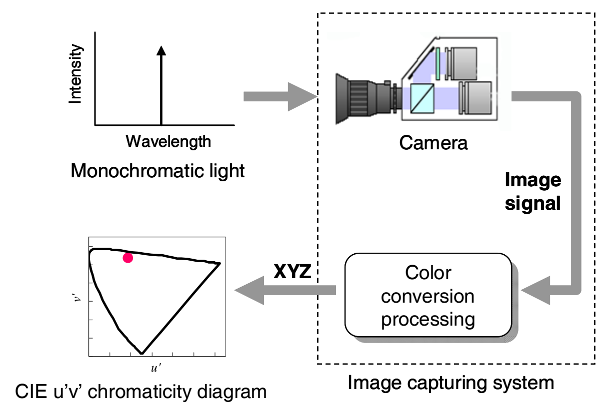


***Figure 3**. Flow of calculating analysis gamut*

Analysis Gamut

While there have been several concepts, definitions, or calculation methods for input gamut [9-11], this paper adopts the concept presented in [9] as “capture color analysis gamut”, which is simply referred to as “analysis gamut” in this paper. Analysis gamut indicates the boundary of the gamut of possible scene colors that can be estimated by the input system, and it is calculated as described below.

A schematic diagram of the flow of calculating an analysis gamut is shown in Fig. 3. Assuming that a monochromatic light enters an image capturing system, the estimated CIE XYZ tristimulus values by the image capturing system are calculated. Here, the estimated XYZ values depend on the spectral sensitivity of the capturing devices (camera or scanner) and also the color conversion matrix that converts from device outputs to XYZ values. Then, the chromaticity coordinates of the estimated XYZ values are plotted for every wavelength in the visible range. Since arbitrary spectral distribution is regarded as a combination of monochromatic lights with positive weights, the plot indicates the boundary of the colors that can be captured by this input system.

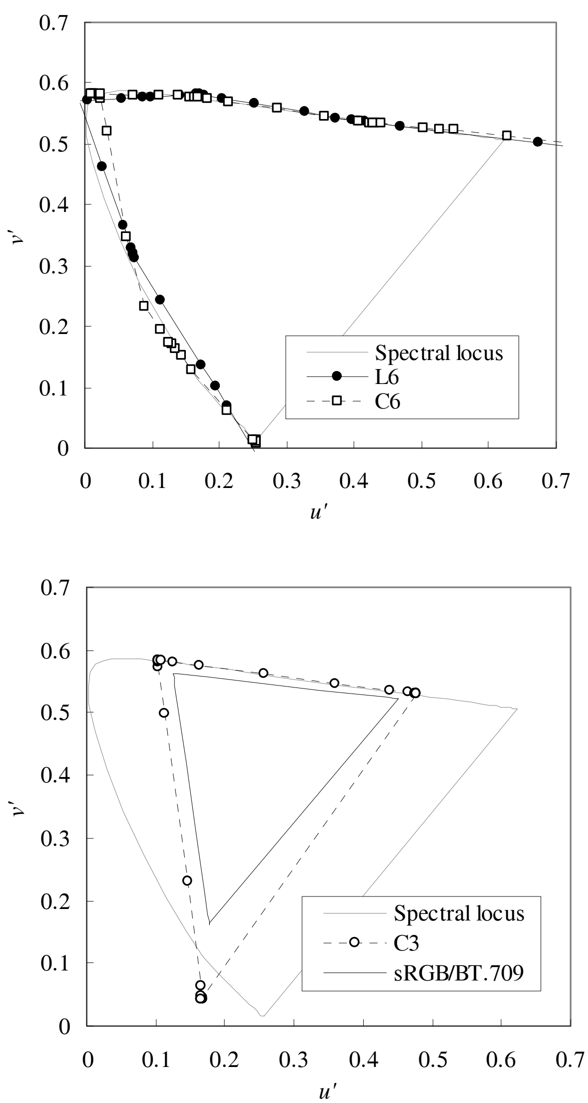


***Figure 4**. Analysis gamuts of six-band (top) and three-band (bottom) image capturing systems.*

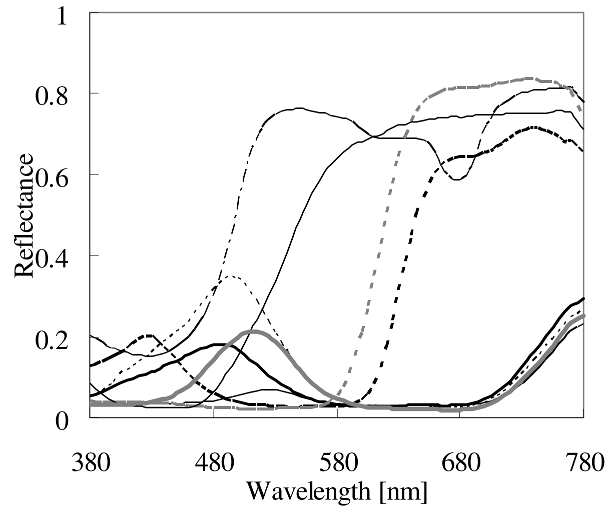


***Figure 5**. Spectral reflectance functions of eight patches of NV color chart.*

While originally a CIE xy chromaticity diagram is used in [9], a CIE u'v' uniform chromaticity diagram is used in this paper for qualifying the area size of analysis gamut and compare them among different systems.

In the evaluation of analysis gamut, Wiener estimation matrices are used as color conversion matrices, where the illumination is assumed to be D65 for both recording and reproduction. The correlation matrix of spectral reflectance functions is made based on an assumption that a spectral reflectance function can be modeled by a 1st-order Markov sequence with a correlation coefficient of 0.9995. The noise covariance is a zero matrix, assuming noise free. A Wiener estimation matrix derived under these conditions is referred to as "Wiener-MR-NF".

Figure 4 shows the analysis gamuts of L6, C6 and C3. Although the gamut of C3 is wider than sRGB gamut, C3 spans the limited area, which means that C3 cannot acquire the colors with high saturations. On the other hand, the analysis gamuts of the six-band cameras are near to the spectral locus, the shapes are slightly different though. As a result, it is verified that six-band imaging systems have much wider analysis gamut compared to a typical three-band camera system.

Colorimetric Accuracy

Colorimetric accuracies of above camera systems are experimentally evaluated to investigate how the colors around the boundary of color gamut of three-band camera system are estimated. Two kinds of color charts are used in the evaluation; Macbeth ColorChecker and NV (natural vision) color chart. The NV color chart consists of eight color patches which are located near the gamut boundary of conventional three-primary displays. The spectral reflectance functions of eight color patches are shown in Fig. 5. These two color charts are captured by C6 camera under D65 illuminant (SERIC), and the accuracy of the estimated colors from the captured image signals is evaluated from all of the six-band images (C6) and from the wider three-band images (C3). The color is estimated by Wiener estimation, where the correlation matrix of spectral reflectance functions is made based on the 24 spectral reflectance functions of Macbeth ColorChecker, and a noise covariance is made based on the observation. A Wiener estimation matrix derived under this condition is referred to as "Wiener-MB-MN" below.

Table 1 shows the average and maximum ΔE^*_{ab} . While the difference between C6 and C3 for Macbeth ColorChecker is relatively small, it is significant for NV color chart. Figure 6 shows the original and the estimated colors of NV color chart on the u'v' plane. We can see that the estimated colors by C3 are shifted to the inward direction even when the original colors are inside the analysis gamut of C3. On the other hand, the estimated colors by C6 preserve the saturation. This result confirms that six-band cameras can acquire the colors with the saturation preserved better than a typical three-band camera system.

SNR

In the previous sections, the evaluations for the six-band and three-band systems have been done assuming a specified color conversion matrix (Wiener-MR-NF or Wiener-MB-MN). It should be noted that the results depend on the color conversion matrix used in the evaluation. For example, it is well known that if we select a SNR-preference matrix, colorimetric accuracy will be reduced instead of the improvement of the SNR of output images. Similarly, if we manipulate the elements so as to expand the color gamut, the analysis gamut can be widened, but it is expected that the degradation of the SNR may occurs. As in the above examples, selection of the matrix affects the SNR as well as the colorimetric accuracy and gamut.

This section focuses the quantitative evaluation method to see how the noise propagates by a color conversion matrix. To do this, $\Delta PSNR$ is defined as the difference between the PSNR (peak signal to noise ratio) of camera output and the PSNR of RGB color image, which is the system output as shown in Fig. 7, where the system output is assumed to be linear RGB images with the BT.709 primaries in either case of a three-band or six-band camera.

The way to calculate $\Delta PSNR$ is explained below. Let us assume that PSNR of camera outputs of every color band is constant, and represented by

$$PSNR_{in} = 10\log_{10}\frac{p^2}{\sigma^2}[\mathrm{dB}], \quad (1)$$

where p is the peak value of the camera output (255 in the case of 8bit) and σ^2 is the noise variance. Next, the PSNR of RGB signals can be estimated as follows. A set of RGB image signals are obtained by a 3-by-K color conversion matrix,

$$\mathbf{M} = \begin{pmatrix} m_{R1} & \cdots & m_{RK} \\ m_{G1} & \cdots & m_{GK} \\ m_{B1} & \cdots & m_{BK} \end{pmatrix}, \quad (2)$$

where K is the number of the color bands of the camera. Using the matrix $\mathbf{M}$, The peak value of RGB outputs can be calculated by

$$\begin{pmatrix} p_R \\ p_G \\ p_B \end{pmatrix} = \mathbf{M}\begin{pmatrix} p \\ \vdots \\ p \end{pmatrix} \quad (3)$$

and the covariance matrix of the noise on RGB outputs is estimated by

$$\mathbf{C} = \mathbf{M}\begin{pmatrix} \sigma^2 & & 0 \\ & \ddots & \\ 0 & & \sigma^2 \end{pmatrix}\mathbf{M}^T = \sigma^2\mathbf{M}\mathbf{M}^T \quad (4)$$

where the diagonal elements of the matrix $\mathbf{C}$ is the noise variance of RGB outputs. Thus we have the PSNR of RGB signla as

$$PSNR_{i\_out} = 10\log_{10}\frac{\left(p\sum_{k=1}^{K} m_{ik}\right)^2}{\sigma^2\sum_{k=1}^{K} m_{ik}^2}[\mathrm{dB}] \quad i = R, G, B. \quad (5)$$

Finally, $\Delta PSNR$ is obtained for each channel by

Table 1. Experimental results of colorimetric accuracy.

ΔE^*_{ab}	Macbeth ColorChecker		NV color chart	
	Ave.	Max.	Ave.	Max.
C6	1.39	3.24	1.59	3.26
C3	2.66	11.00	7.02	13.94

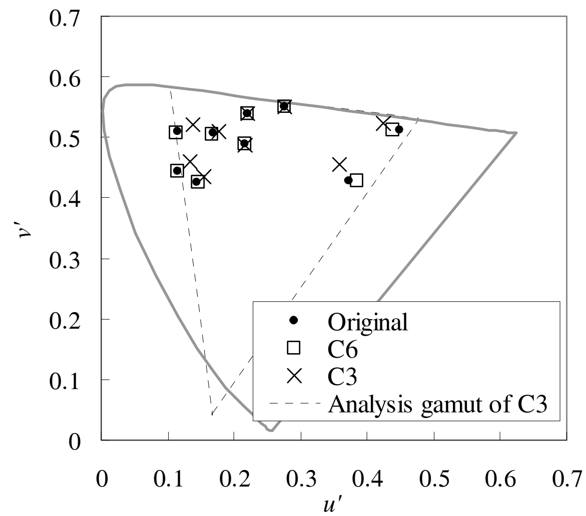


***Figure 6**. Experimental results of color estimation for NV color chart.*

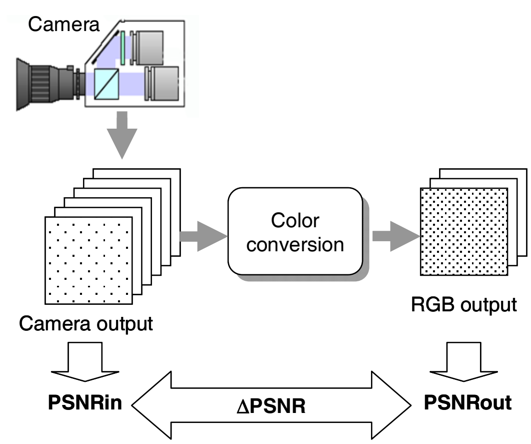


***Figure 7**. Concept of ΔPSNR for evaluating color conversion matrix.*

$$\Delta PSNR_i = PSNR_{i\_out} - PSNR_{in} = 10\log_{10}\frac{\left(\sum_{k=1}^{K} m_{ik}\right)^2}{\sum_{k=1}^{K} m_{ik}^2}[\mathrm{dB}] \quad i = R, G, B. \quad (6)$$

It should be noted that when the number of the color bands K increases by N times, $\Delta PSNR$ is increased by $10\log_{10}N$ [dB]. Therefore, the $\Delta PSNR$ of six-band imaging systems is inherently $10\log_{10}2 \approx 3$dB higher than that of three-band imaging systems.

Evaluations are performed for the L6 and C3 cameras with changing the matrix **M**. We select a reference matrix $\overline{\mathbf{M}}$ as a product of the matrix of Wiener-MR-NF and the transformation matrix from XYZ to BT.709 RGB. The other matrices are derived by manipulating the elements of $\overline{\mathbf{M}}$ by

$$\tilde{m}_{ik} = w\left(\overline{m}_{ik} - \langle \overline{m}_i \rangle\right) + \langle \overline{m}_i \rangle , \tag{7}$$

where $\overline{m}_{ik}$ is the element of the reference matrix, w is a coefficient for the manipulation, and

$$\langle \overline{m}_{ik} \rangle = \frac{1}{K}\sum_{k=1}^{K} \overline{m}_{ik} . \tag{8}$$

It is expected that w of larger than 1.0 has an effect to expand the color gamut and vice versa.

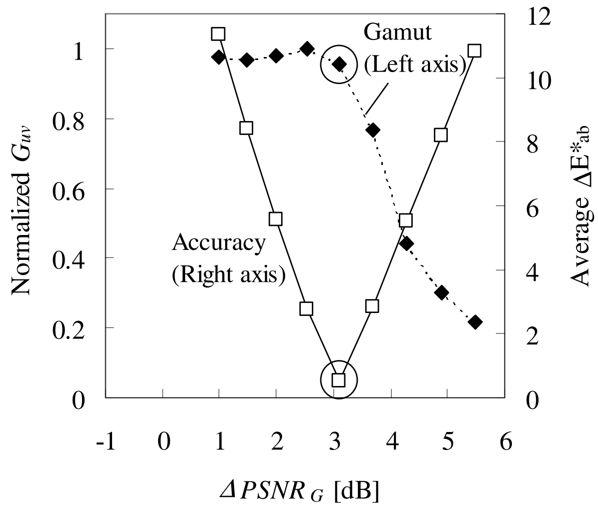
For each matrix **M** with w = 0.6, 0.7,…, 1.3, 1.4, $\Delta PSNR_i$ is calculated. At the same time, the size of the analysis gamut and the colorimetric accuracy are quantified. The size of the analysis gamut G_{uv} is calculated as the area size of the analysis gamut on CIE u'v' diagram, in which only the area included in both the analysis gamut and the spectral locus is counted. Then, G_{uv} is normalized by the area size bounded by the spectral locus. As the colorimetric accuracy, the average ΔE^*_{ab} of the estimated colors for the 24 color patches in Macbeth ColorChekcer is calculated by simulations, where D65 illumination is assumed for both recording and reproduction.

Figures 8 (a) and (b) show the normalized G_{uv} (left axis) and the average ΔE^*_{ab} (right axis) as a function of $\Delta PSNR_G$ for L6 and C3 respectively. Because $\Delta PSNR_i$ of L6 can be higher by 3dB than that of C3 due to the difference of the number of bands, the origin of the horizontal axes are shifted by 3dB. The circled plots indicate the results obtained by the reference matrix. The right-hand plots of it corresponds to the manipulated matrix with w of smaller than 1.0. The left-hand plots of it corresponds to the manipulated matrix with w of larger than 1.0. First of all, the best colorimetric accuracy is achieved by the reference matrix for both L6 and C3, and any manipulation reduces the accuracy. In terms of the gamut, we can see a tradeoff relationship between $\Delta PSNR_G$ and G_{uv} in the case of C3; expanding the color gamut causes the loss of PSNR. Although a similar tradeoff relationship can be seen in the results of L6, a sufficiently large gamut can be obtained without any manipulation of the reference matrix. As a result, a large gamut can be achieved without loss of colorimetric accuracy and SNR. From this result, it can be said that multispectral imaging has the possibility to expand the input gamut without sacrificing PSNR and colorimetric accuracy.

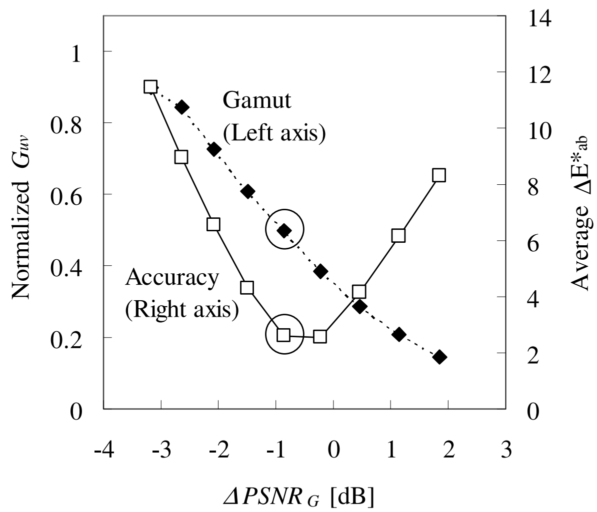
Subjective Evaluation

Two sets of objects which contain highly saturated colors are prepared, referred to as Toy and Scarf. They are captured by C6 camera, and the images are reproduced by following three methods;

- C6: the color is estimated from all of the six-band images by the matrix of Wiener-MB-MN.



(a)



(b)

Figure 8. *Normalized gamut area G_{uv} (left axis) and average ΔE^*_{ab} of 24 Macbeth color patches (right axis) as function of $\Delta PSNR_G$ for (a) L6 and (b) C3 as changing the color conversion matrix. Circled plots correspond to the result obtained with reference color conversion matrix (Wiener-MF-NR + BT.709).*

- C3: the color is estimated from wider three-band images by the matrix of Wiener-MB-MN.
- C3-E: C3 reproduction applied by the enhancement of color saturation so as to have the approximately same saturation as that of C6 reproduction.

A wide-gamut 25.5-inch display, LCD2690WUXi (NEC), is used for displaying the images, which spans 95% of Adobe RGB gamut.

A pair comparison method is used for the subjective evaluation. The evaluation is done in a dark room, and the distance between a subject and the display is set at 6H, where H means the vertical size of the display. Two images are successively displayed with a black image between them, and a subject selects one of the two images which has (i) higher vividness, (ii) deeper colors, and (iii) more naturalness respectively. Four subjects participate in the evaluation, then, 24 responses are obtained for each pair in total.

Figure 9 shows an analysis results for Toy. The vertical axis shows scale values centered at C3's scale value; for instance, a positive value on the vividness scale means the image gives higher vivid impression to subjects than C3. The results show that while C3-E gives the highest vividness, its color deepness and naturalness are lower than those of C3 and C6. On the other hand, C6 scores a higher value on the vividness than C3, in addition, the color deepness and the naturalness are higher or equivalent to C3. This tendency can be seen also in the result of Scarf. These results show that six-band image capturing system can acquire image with wide gamut without loss of naturalness.

Discussions

In the section of SNR, the tradeoff relationship between the gamut size, colorimetric accuracy, and SNR is examined for two camera systems with different color conversion matrices. However, the characteristics of an input system depend not only on its matrix but also on the spectral sensitivity of the camera. Therefore, it can be said that the camera sensitivity itself can be evaluated from the viewpoint of the tradeoff relationship. Let us consider a XYZ camera that is a three-band camera with the sensitivity of xyz color matching functions, for instance. While the XYZ camera apparently realizes 1.0 of its normalized G_{uv} and captures colors without error, it is well known that the SNR of the XYZ camera is much worse than that of conventional RGB cameras. This is one of the examples of the tradeoff relationship described above. The evaluation for the camera sensitivity is a future work.

Conclusions

This paper first discussed the methods for evaluation of image capturing systems on the capability of wide gamut color capture. Based on the discussion, two six-band camera systems and a three-band camera system have been evaluated, and the following results have been obtained for six-band camera systems.

- The maximum possible area on a chromaticity diagram to capture colors can be near to the spectral locus.
- The saturation of the acquired colors is well preserved, even for the colors with high saturation.
- A wide gamut is realized with little loss of signal to noise ratio on output images.
- Deep and vivid colors can be acquired without loss of the naturalness of images.

The three-dimensional evaluation for the spectral sensitivity of input devices based on the three viewpoints, color acquisition accuracy, SNR, and gamut, is a future work.

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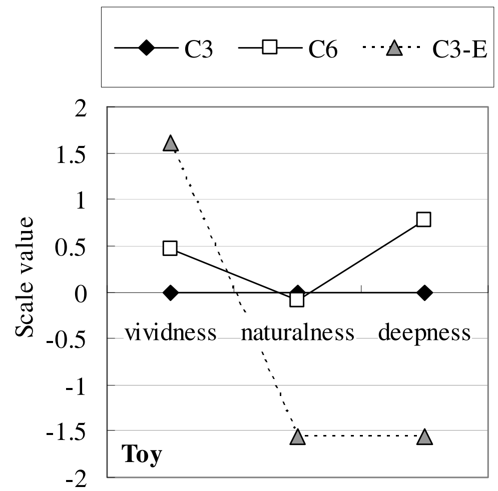

***Figure 9**. Results of subjective evaluation for Toy. Vividness of C3-E is highest, but its naturalness and deepness are lowest. C6 scores higher scores of vividness and deepness than C3 without loss of naturalness.*

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