Evaluation of Smoothness in Color Gradation on Multiprimary Display

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Abstract

Multiprimary displays, which are developed recently, enable to reproduce expanded color gamut using more than three primary colors. To reproduce an image using the multiprimary display, a color conversion algorithm is needed to generate multiprimary control signals from colorimetric tristimulus values. Several color conversion algorithms have been proposed, which give a unique set of multiprimary control signals to reproduce a specified color. When a smooth gradation is displayed, however, we sometimes perceive a contour-like artifact, which is called "pseudo contour." The pseudo contour affects the image quality of multiprimary displays especially when smooth tonal change is reproduced. The pseudo contour is caused by the device profile error and the difference of the color matching functions of actual observers from the standard observer, but its appearance depends on the color conversion algorithms. Therefore, we propose a method to predict the appearance of the pseudo contour and evaluate the color conversion algorithms proposed before. The experimental results demonstrate that the predicted appearance of the pseudo contour is in good agreement with the visual observation.

1. Introduction

In these years, development of multiprimary displays is progressing at Akasaka Natural Vision Research Center, NICT and other places.[1-5] Multiprimary displays, which uses more than three primary colors, can reproduce highly saturated colors i.e., the color gamut are significantly expanded. It is also expected to be used for spectral color reproduction so as to suppress the observer metamerism.

When the multiprimary displays are employed for the reproduction of expanded color gamut, color conversion is required from the given colorimetric tristimulus values to multiprimary control signals. For multiprimary displays, there is a degree of freedom in the color conversion, and the conversion from the tristimulus values to multiprimary control signals is not unique. For the multiprimary color conversion, several color conversion algorithms have been proposed.[6-8]

Matrix switching method[6] (MS) has been proposed to implement the color conversion with efficient calculation, where the polyhedron of color gamut is divided into some square pyramids and the multiprimary control signals are calculated by the linear transformation in each pyramid. Linear interpolation on equi-luminance plane method[7] (LIQUID) has also been developed, in which the control signals are calculated by the linear interpolation on equi-luminance plane in XYZ color space. Metameric black method[8] (MB) has been proposed to keep the continuity of multiprimary signals, in order to reduce a pseudo contour mentioned below. In this method, control signals are determined by using a gravity point of metameric black space. Spherical average method[9] (SA) has been also developed, where control signals keep continuity for any tonal change in all directions. These four algorithms have been implemented for six-primary displays.[10]

On the other hand, it has been pointed out that we perceive a contour-like artifact when a color gradation is displayed on multiprimary displays.[8,10] We call it "pseudo contour". The pseudo contour is caused by the device profile error and the difference of the color matching functions of actual observers from the standard observer, and the appearance of pseudo contours depend on color conversion algorithms. Therefore, in order to evaluate the color conversion algorithms, the appearance of pseudo contours need to be considered. Similar problem has been dealt with in the field of color printer using four primary inks.[11]

In this article, we propose a method to evaluate a pseudo contour quantitatively and evaluate the color conversion algorithms proposed before. The proposed method predicts and visualizes the appearance of the pseudo contour, and the experimental results demonstrate that the predicted appearance of the pseudo contour is in good agreement with the visual observation.

2. Multiprimary Display

Multiprimary displays reproduce expanded color gamut much larger than conventional three-primary color display. Six-primary displays have been implemented using two LCD (liquid crystal display)[1] and DLP (digital light processing) projectors.[3] A trial model of four-primary flat-panel LCD[4] was demonstrated by the combination of color filter and time-sequential illumination of LEDs (light emitting diodes). Multiprimary projection displays were also implemented by modifying the rotating filter wheel.[5] The system configuration of the six-primary color projection display using two modified projectors is shown in Fig. 1.

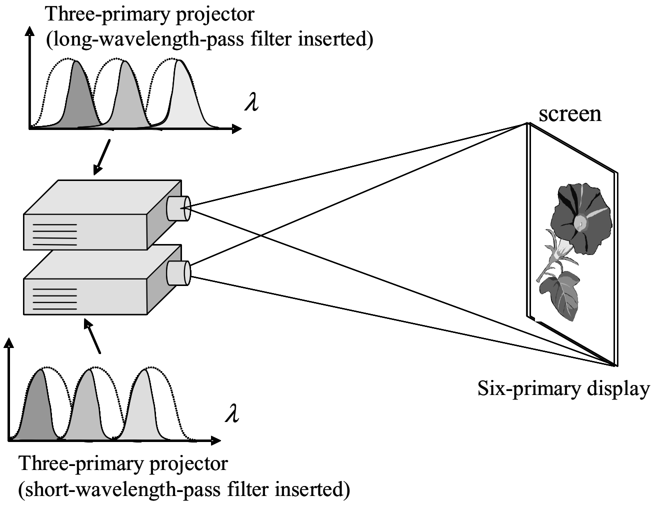


Figure 1. The system configuration of the six-primary display

The red, green, blue (RGB) lights of the three-primary projectors are trimmed by the narrow-band color filters, and each projector reproduces different three-primary colors. Two projected pictures are overlaid on the screen, and six-primary display is realized. Multiprimary displays are based on the model of the additive mixture of the primaries, described as follows; N is the number of primary colors and $S_i(\lambda)(i=1,\ldots,N)$ is the spectral intensity of the full-emitted i-th primary light. Then the spectral intensity of the displayed light $S'(\lambda)$ is represented by

$$S'(\lambda)=\sum_{i=1}^{N}a_i S_i(\lambda)+b(\lambda), \tag{1}$$

where a_i $(i=1,\ldots,N)$ $(0 \le a_i \le 1)$ is the control signal of the i-th primary and $b(\lambda)$ is the spectral intensity of the background light. Then the tristimulus values XYZ of the reproduced light C' is calculated as

$$\mathbf{C}'=\begin{pmatrix}X\\Y\\Z\end{pmatrix}=\sum_{i=1}^{N}a_i\begin{pmatrix}\int S_i(\lambda)\bar{x}(\lambda)d\lambda\\ \int S_i(\lambda)\bar{y}(\lambda)d\lambda\\ \int S_i(\lambda)\bar{z}(\lambda)d\lambda\end{pmatrix}+\begin{pmatrix}\int b(\lambda)\bar{x}(\lambda)d\lambda\\ \int b(\lambda)\bar{y}(\lambda)d\lambda\\ \int b(\lambda)\bar{z}(\lambda)d\lambda\end{pmatrix}=\sum_{i=1}^{N}a_i\mathbf{P}_i+\mathbf{b} \tag{2}$$

where $\bar{x}(\lambda),\bar{y}(\lambda),\bar{z}(\lambda)$ are XYZ color matching functions, $\mathbf{P}_i=(X_{P_i},Y_{P_i},Z_{P_i})^{\mathrm{T}}$ is the tristimulus values of the i-th primary and $\mathbf{b}=(X_{\mathrm{b}},Y_{\mathrm{b}},Z_{\mathrm{b}})^{\mathrm{T}}$ is the tristimulus values of the background light. The range of **C**' given by $(0 \le a_i \le 1)$ is the color gamut of the N-primary display,where it forms a convex polyhedron in XYZ color space.

For the colorimetric color reproduction, the multiprimary control signals a_i in eq. (2) have to be computed from the colorimetric tristimulus values (X, Y, Z). It is the inverse of eq. (2), called multiprimary color conversion, involves the degree of freedom, since N parameters are determined from tristimulus values. Different methods for the multiprimary color conversion from tristimulus values to multiprimary control signals have been proposed until now. These methods give different control signals for the multiprimary display, but the colorimetric tristimulus values are identical due to the metamerism. Namely, any difference could not be observed in the different color conversion methods, if the color reproduction process were perfect. However, errors essentially exist in the characterization of the display device and the color matching functions of actual observers in eq. (2). The influence of such error is mainly observed as a pseudo contour in the region where the color is smoothly changing.

3. Perception of a Pseudo Contour

This section explains why pseudo contours arise in multiprimary displays. Let us consider that the reproduced image contains a smooth tonal change. For simplicity, we consider X from tristimulus values for this explanation. Supposing X_k and X_{k+1} are X values of the neighboring pixels located at k and k+1 in one-dimensional smooth color gradation. If the color changes smoothly, the difference between X_k and X_{k+1}

$$\begin{aligned}\Delta X &= X_k - X_{k+1}\\ &=\sum_{i=1}^{N}a_i^k\int S_i(\lambda)\bar{x}(\lambda)d\lambda-\sum_{i=1}^{N}a_i^{k+1}\int S_i(\lambda)\bar{x}(\lambda)d\lambda\\ &=\sum_{i=1}^{N}\left(a_i^k-a_i^{k+1}\right)\int S_i(\lambda)\bar{x}(\lambda)d\lambda\end{aligned} \tag{3}$$

is small and almost constant, where a_i^k are the primary control signals to display X_k.

Although the colorimetric reproduction is independent upon the conversion methods, we have to consider the error in $\bar{x}(\lambda)$ and $S_i(\lambda)$. It is pointed out that the color matching function depends on observers and the difference from the CIE standard observer cannot be ignored.[12] In addition, the characterization error of multiprimary display causes the error in $S_i(\lambda)$. Here, let us suppose the color matching function of a real observer and the actual spectral intensity of the full-emitted *i*-th primary light are expressed as

$$\begin{aligned} \bar{x}^{real}(\lambda) &= \bar{x}(\lambda) + \Delta\bar{x}(\lambda) \\ S_i^{real}(\lambda) &= S_i(\lambda) + \Delta S_i(\lambda) \end{aligned}, \qquad (4)$$

where $\Delta\bar{x}(\lambda)$ is the deviation from the standard observer and $\Delta S_i(\lambda)$ is the error in the a spectral intensity. In this case, the actual stimulus value becomes

$$\begin{aligned} X_k^{real} &= \sum_{i=1}^{N} a_i^k \int \left(S_i(\lambda) + \Delta S_i(\lambda)\right)\left(\bar{x}(\lambda) + \Delta\bar{x}(\lambda)\right) d\lambda \\ &= X_j + \sum_{i=1}^{N} a_i^k \int S_i(\lambda)\Delta\bar{x}(\lambda) d\lambda + \sum_{i=1}^{N} a_i^k \int \Delta S_i(\lambda)\bar{x}(\lambda) d\lambda \\ &\quad + \sum_{i=1}^{N} a_i^k \int \Delta S_i(\lambda)\Delta\bar{x}(\lambda) d\lambda \end{aligned} \qquad (5)$$

Then the difference between the neighboring pixels is

$$\begin{aligned} & X_k^{real} - X_{k+1}^{real} \\ &= \Delta X + \sum_{i=1}^{N} \left(a_i^k - a_i^{k+1}\right) \left\{ \int S_i(\lambda)\Delta\bar{x}(\lambda) d\lambda + \Delta S_i(\lambda)\bar{x}(\lambda) d\lambda + \Delta S_i(\lambda)\Delta\bar{x}(\lambda) d\lambda \right\} \end{aligned} \qquad (6)$$

If $\Delta\bar{x}(\lambda)$ and $\Delta S_i(\lambda)$ are zero, the second term in the last line of Eq. (6) becomes zero and the difference between stimuli of the neighboring pixels is equivalent to the original difference ΔX. Otherwise, the second term has certain values and its amount is proportional to $a_j^k - a_j^{k+1}$. Depending on the method for multiprimary color conversion, it could be happened that primary control signals jump up/down to the different level. In this case, the difference between the control signal, $a_j^k - a_j^{k+1}$, becomes large at this point and the second term of eq. (6) becomes large. Then perceived color does not vary smoothly as expected even when smooth color gradation is displayed.

In fact, all the multiprimary color conversion methods mentioned in section 1 are designed such that the continuity of control signals are preserved in the tristimulus space. However, depending on the conversion methods, the slope of the control signal occasionally changes. The human vision has the impulse response for luminosity as shown in Fig. 2[13]; this shows the characteristic of a vision system emphasizes the edge of color tonal change. By the convolution of the function of Fig. 2 to the reproduced image, if the slope of gradation is changed, the border is emphasized. Such a border may be perceived like a contour.

In the proposed method, non-smooth change of a color is detected by using secondary differentiation, and quantitative evaluation of a pseudo contours is performed based on the value of secondary differentiation. This approach is equivalent to modeling the characteristic of a vision system by the secondary differentiation.

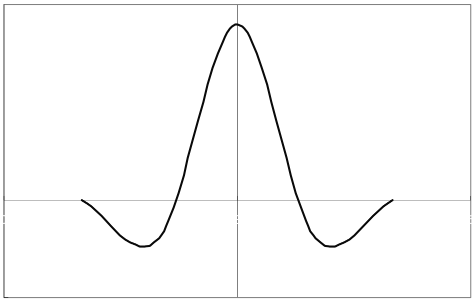


Figure 2. Impulse response for luminosity

4. Proposed Method

In this section we explain a method to evaluate the smoothness of reproduced color gradation. The method predicts the appearance of pseudo contour, and it enables to compare the performances of different color conversion algorithms using the estimated amount of pseudo contours. The flow of the proposed method is shown in Fig. 3.

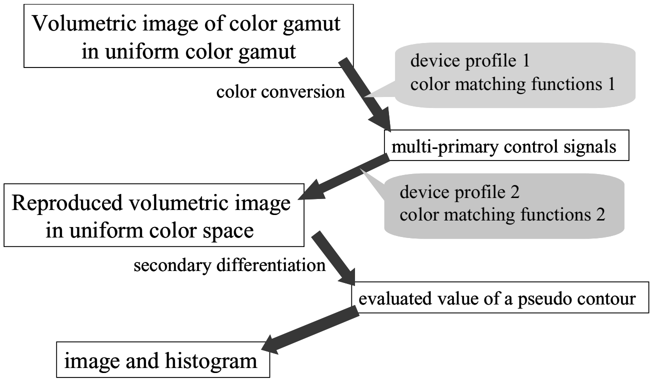


Figure 3. Flow of the proposed method

In the proposed method, in order to predict the appearance of pseudo contours over the whole color gamut contains, the three-dimensional image is used where the color smoothly changes in each direction. The image is generated by sampling at a fixed small interval in the color gamut of multiprimary display defined in CIE L*a*b* color space. The colorimetric values of each point of the image are converted into multiprimary signals with the profile of a specified device and the color matching functions. Next, it is converted into the colorimetric values again with the profile of a different device and a different set of color matching functions in order to simulate the actual color reproduction. If the control signals change non-smoothly, the calculated colorimetric values may also change non-smoothly. Then, non-smooth change of the color is detected by using secondary differentiation, and the pseudo contours can be unveiled. As the color change is linear in the original virtual picture, secondary differentiation yields nothing if error does not exist. It detects the location where the slope of color gradation is changed.

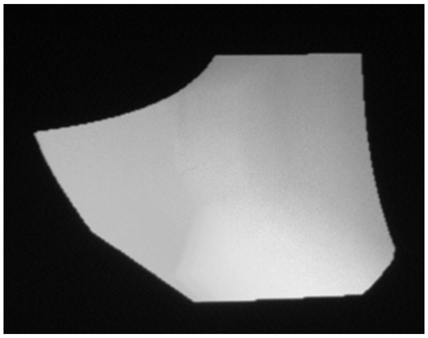
The secondary differentiation is performed as follows; First, the average of the distances between one point and the neighboring six points are calculated as the results of first differentiation, which means the rate of color change at the point. Next, the average of the differences between one first differentiation value and the neighboring six differentiation values is calculated as the secondary differentiation value, which means the variation of the rate of color change at the point. Then, this secondary differentiation value can be regarded as the evaluated value that expresses the possibility of the pseudo contour.

To implement the proposed method, we use some sets of device profiles and color matching functions. In this article, at the time of the conversion to six-primary control signals from colorimetric values, we use the device characteristics of an actual six-primary display and CIE 1931 2-deg color matching functions. At the time of the conversion to colorimetric values from six-primary control signals, three combinations are used. (1) the device profile of an actual six-primary display and CIE 1964 10-deg observer. (2) the same device profile and CIE 1989 standard deviate observer, which simulates the observer metamerism. (3) the device profile including 5% error and CIE 1931 2-deg, which simulates the error of device profile. In (3), each primary has -5%, 0% and 5% error independently, we use the average value of 729 (=3^6) results.

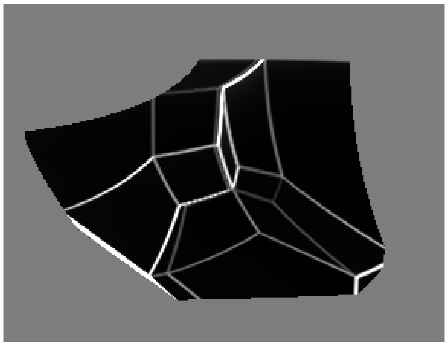
As a result, although the difference was seen, it brought a similar result. Therefore it can be said that only of above conditions is reasonable to be used for the calculation of the evaluated values and the evaluation of the color conversion algorithms. Consequently, we actualized general prediction for the appearance of pseudo contour by adding these three kinds of evaluated value.

Finally, the evaluated value acquired for every sampling point is expressed as a histogram and an image. The horizontal axis of a histogram is the evaluated value, and a vertical axis is the number of the corresponding pixels. An image is formed to represents the evaluated values as a sectional view of a color space.

The validity of the evaluated value is checked by subjective evaluation experiment. The sectional view of CIE L*a*b* color space, which is a two-dimensional gradation, is reproduced on the screen of six-primary display and subjects point out the contours perceived in the gradation. We have prepared the evaluation image as Figs. 6-8, and compare the patterns and the results from the subjects. Figure 4 is comparison of the evaluated image and sectional image which is displayed on the screen and shot by the digital still camera (DSC). The image shot by the DSC is equivalent to the case of very large difference of the color matching functions of actual observers from the standard observer, because the spectral sensitivity of the DSC is different from the color matching functions of standard observer. From Fig. 4, the pattern of the contours can be seen in the evaluated image as white curving lines. The pattern of the contours pointed out by the subjects was in agreement with the pattern of an evaluation image in general, and it was confirmed that the evaluated value can predict the position of pseudo contours. However, the correlation was low between the intensity perceived by the subjects and the evaluated value. Moreover, all lines indicated in the evaluated image have not been perceived by subjects as pseudo contours. The reason of the disagreement is that the profile and the color matching functions used in the experiment are different from the actual one, and the characteristic of a vision system is different from the secondary differentiation. The evaluated image is considered as the possible appearance of the pseudo contour pattern. A future examination is required in order to perform more precise quantitative evaluation.



(a) image shot by the digital still camera



(b) evaluated image

Figure 4. Comparison of the evaluated image and the image shot by the digital camera

5. Result of Evaluation

Color conversion algorithms are evaluated by the proposed method. We examine four algorithms; MS, LIQUID, MB and SA. The results are expressed as histograms and images. For comparison, the evaluation result of Pseudo three primaries method (PTP) is also introduced only for reference though it is not the multiprimary color conversion algorithms. From the result of PTP, we can confirm the propriety of the proposed method, because PTP cannot cause pseudo contours. In this method, we use the rule in which two of the six primary control signals must take the same value so that the continuity of control signals are guaranteed. Note that the color gamut in this case is much smaller than other methods, that is almost same as the three-primary display gamut.

Figure 5 is the result expressed by the histogram, and the associated values are shown in Table1. Here, "Color gamut" means the number of pixels that have neighbor six points inside the color gamut. Comparing with PTP, other methods have much larger color gamut, showing the effect of six-primary. The horizontal axis of a histogram is an evaluated value of pseudo contours, and a vertical axis is the number of corresponding pixels. Average value means evaluated value per pixel. As for the average value, we can see that the possibility of appearing of pseudo contours is the highest in MS. LIQUID and MB, which are designed considering to improve the continuity of multiprimary signals, give better results than MS. SA gives the best result, because the continuity of multiprimary signals and their derivatives is the main objective of this method. The histogram shows LIQUID has more pixels which have high evaluated value (over 0.30) than the MB. It cannot be justified the performance of LIQUID and MB from table 1 and Fig. 5.

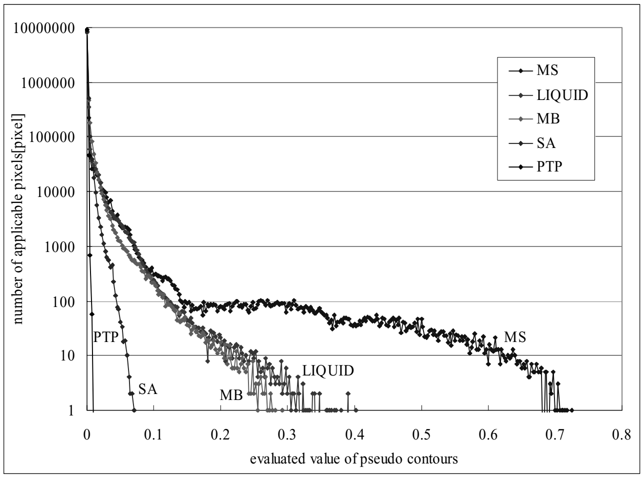


Figure 5. evaluated values expressed by the histogram

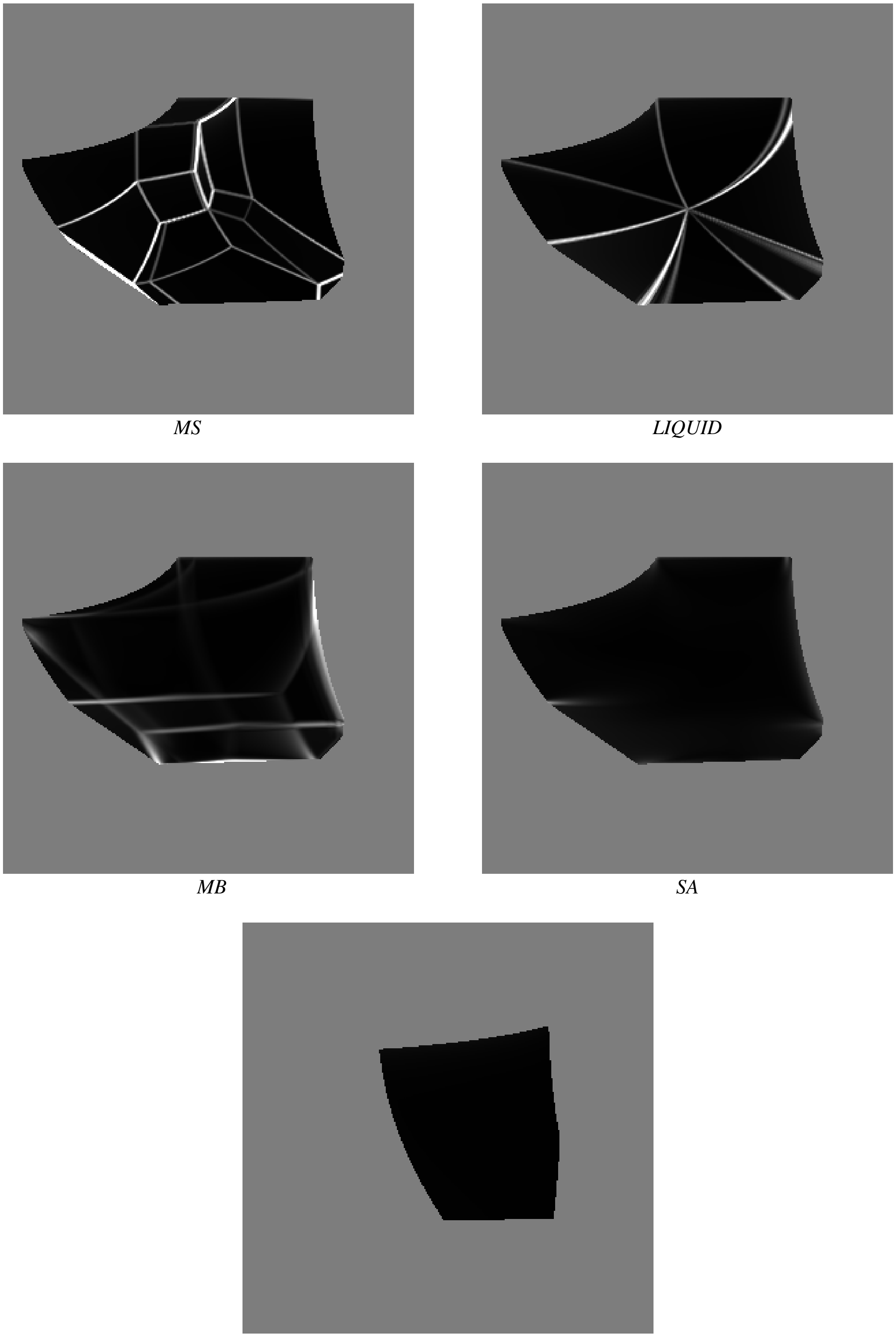
Table 1. Evaluated Values by the Secondary Differentiation

	Color gamut	Maximum	Average
MS	1,416,693	0.723895	0.007328
LIQUID	1,416,693	0.401308	0.004943
MB	1,416,693	0.292913	0.004960
SA	1,416,693	0.070687	0.002148
PTP	746,465	0.008184	0.000523

Then, the pattern of a pseudo contour is expressed by images. Some typical results are shown in Figs.6-8. These images are a*-b* plane at L*= 56, H*-L* plane at C*= 50 and C*-L* plane at H*= 165 respectively. The pixel values indicate the evaluation values; the white pixels correspond to the high evaluated values, which mean high possibility of pseudo contours. The surrounding gray domain means the outside of color gamut. In the case of MS and LIQUID, pseudo contours are perceived as they divide color space. In the case of MB, pseudo contours are perceived near the edge of color gamut. On the other side, in the case of SA and PTP, little pseudo contours are perceived.

6. Summaries

In this article, we propose a method to evaluate a pseudo contour quantitatively and evaluate the color conversion algorithms proposed before. The proposed method predicts and visualizes the appearance of the pseudo contour by using the secondary differentiation. The pseudo contour is caused by the device profile error and the difference of the color matching functions of actual observers from the standard observer. In the proposed method, those disturbances are taken into consideration. The color conversion algorithms, MS, LIQUID, MB and SA are evaluated by the proposed method, and we demonstrate that MS yields larger pseudo contours than other methods, SA gives excellent result in the sense of pseudo contours, and every method produces different pseudo contour patterns.



MS

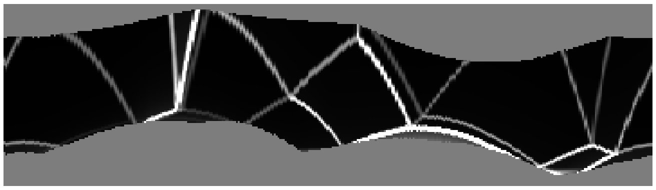
LIQUID

MB

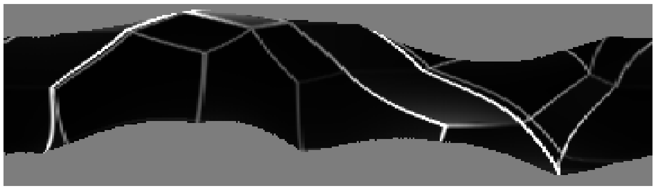
SA

PTP

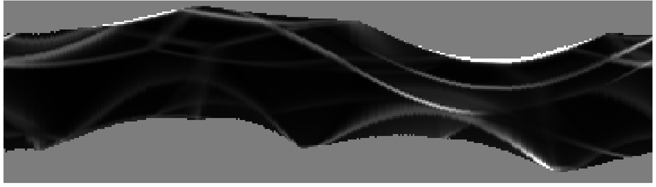
Figure 6. Pattern of pseudo contours expressed by images (a-b* plane at L*= 56)*



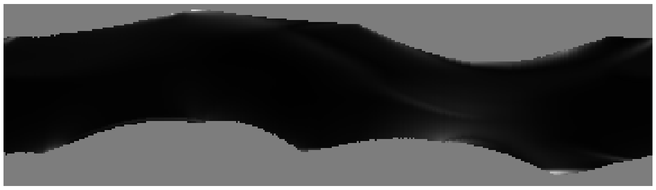
MS



LIQUID



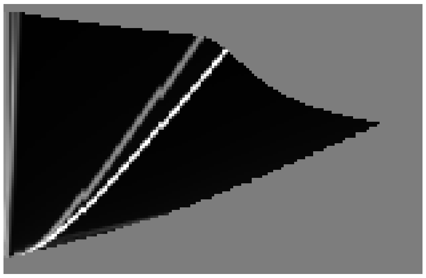
MB



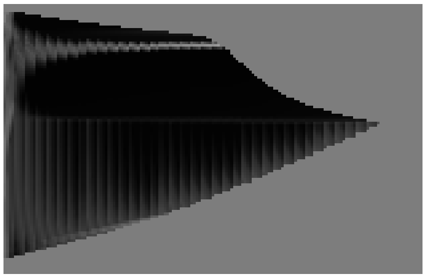
SA

PTP

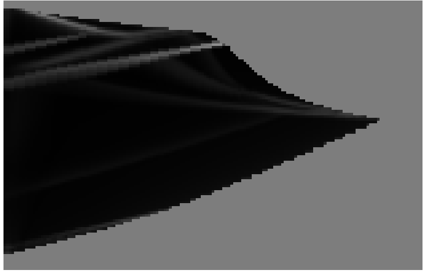
Figure 7. Pattern of pseudo contours expressed by images (H-L* plane at C*= 50)*



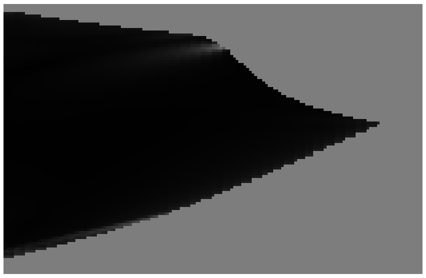
MS



LIQUID



MB



SA

PTP

Figure 8. pattern of pseudo contours expressed by images (C-L* plane at H*= 165)*

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Biography

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