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Parametric Gamut Mapping Algorithms Using Variable Anchor Points

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In this article, a new gamut-mapping algorithm (GMA) that utilizes variable anchor points (center of gravity on the lightness axis) is proposed. The proposed algorithm increases lightness range, which is reduced from conventional gamut mapping toward an anchor point. In this process, this algorithm utilizes multiple anchor points with constant slopes to both reduce a sudden color change on the gamut boundary of the printer and to maintain a uniform color change during the mapping process. Accordingly, the proposed algorithm can reproduce high quality images with low-cost color devices.

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Introduction

Some practical output systems are only capable of producing a limited range of colors. The range of producible colors on a device is referred to as its gamut. Often, an image will contain colors that are outwith the gamut of the target output device. In such a case, the image colors must be mapped within the gamut, which requires the use of a gamut-mapping algorithm (GMA).[1–4] Conventional GMAs can be divided into three groups; successive, simultaneous, and parametric GMAs.[5] A successive GMA maps the perceptual attributes (hue, saturation, and lightness) separately.[6–8] A simultaneous GMA maps the colors so that all of their attributes are changed simultaneously. A parametric GMA changes the color behavior based on either the shape of the original and reproduction gamuts at a particular hue angle or some other user-defined parameter.[9]

The successive and simultaneous GMAs have benefit of simple processing but can't use colors covering overall gamut of each device. Accordingly, the parametric GMAs may use colors covering overall gamut because these algorithms perform the color mapping based on either the shape of the original and reproduction gamuts. In the conventional parametric GMAs,[5] lightness mapping is performed in advance to include the lightness range of the original image into the reproduction gamut. In this process, lightness range is reduced according to range difference of two media. Then, parametric GMA using an anchor point (a center of gravity on the lightness axis) is performed to decrease the lightness of the bright region of an original image while increasing the lightness of the dark region to include original colors into the reproduction gamut. From these results, the lightness range is also reduced, so the contrast is decreased. In this process, if the anchor point is not the center of the L^* axis of two media, the parametric GMA that utilizes an anchor point shows different color change in bright region and dark region. If the L^* value difference of maximum chroma of the two media is larger, the difference of the color change is increased. In addition, the input colors mapped towards an anchor point in same region show also different color change, because the conventional GMA maps input colors along the lines with different slope. Accordingly, these algorithms produce sudden color change on boundary between the mapping regions.

To solve these problems, the parametric mapping that utilizes variable anchor points is proposed to compensate the reduction of lightness contrast. For this method, the position of anchor point is varied to be less steep in bright and dark part than conventional GMAs using an anchor point. In this process, if the slope toward the anchor point is different, the parametric GMA shows different color change in bright and dark region. Therefore, a separate mapping method that utilizes variable anchor points with constant slope is used. The separate mapping method maps input color along the lines with constant slope, so the mapped colors produce an approximately uniform color change in the regions. To separate mapping regions, the proposed method classifies regions according to the lightness of the monitor and printer gamuts. To reduce sudden color change on boundary between the regions using the different mapping methods, similar mapping methods are used in the all regions. Based on these regions, the colors of the bright and dark regions in an input image are then mapped along the lines of constant slope. In the case of a middle region, mapping is performed towards an anchor point.

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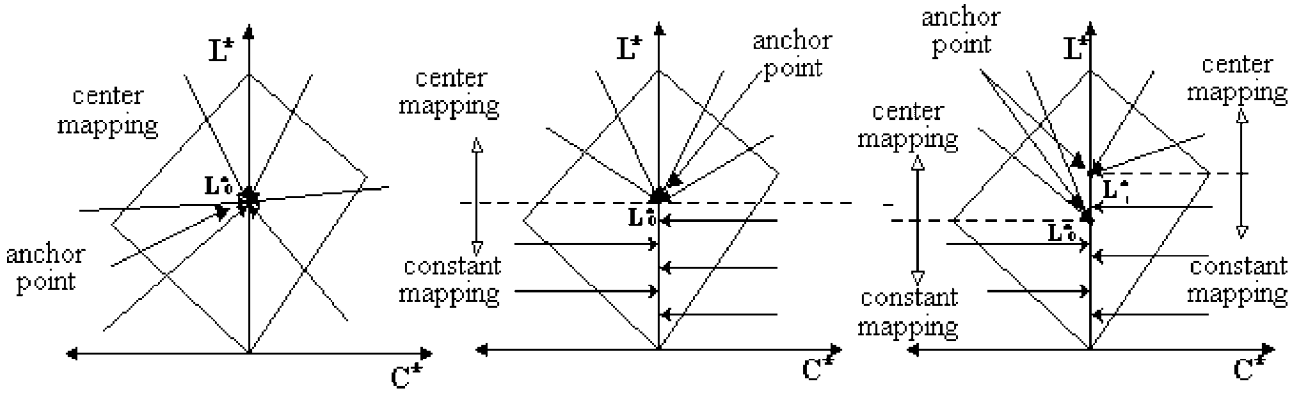
Color plates 9 and 10 are printed in color in the color plate section of this issue, pages 88 and 89.



(a) (b) (c)

Figure 1. Combined gamut mapping algorithms; (a) lightness and chroma mapping toward the central point on the L* axis; (b) two mapping methods on every hue; (c) an anchor point is set according to the lightness value of the maximum chroma on each hue.

Consequently, separate mapping utilizing variable anchor points with constant slope can reproduce a continuous tone color and reduce mapping errors.

Conventional Gamut Mapping Algorithms

Gamut mapping algorithms usually apply to three components hue, lightness and chroma. In lightness mapping and chroma mapping, linear compression or clipping method can be used to include the range of the original image into the reproduction gamut. Therefore, conventional GMAs can be divided into three groups; successive, simultaneous, and parametric GMAs.[5] A successive GMA maps the perceptual attributes (hue, saturation, and lightness) separately,[6–8] i.e., in most cases the algorithm has two stages: the mapping of lightness and the mapping of chroma. All the algorithms in this group first map lightness so that the minima and maxima of the two gamuts are mapped onto each other. A simultaneous GMA maps the colors so that all of their attributes are changed simultaneously. These algorithms map colors by moving colors towards a particular point in color space (a center of gravity). Generally, these algorithms do not have initial lightness compression, and all successive and simultaneous algorithms preserve hue.

These successive and simultaneous GMAs have benefit of simple processing but can't use colors covering overall gamut of each device. Therefore, a parametric GMA changes the color behavior based on either the shape of the original and reproduction gamuts at a particular hue angle or some other user-defined parameter.[9,10] To give smoother transitions between adjacent regions for color appearance, a number of combined mapping methods have been developed. These methods map lightness and chroma at the same time. Some of these methods are represented in Fig. 1.

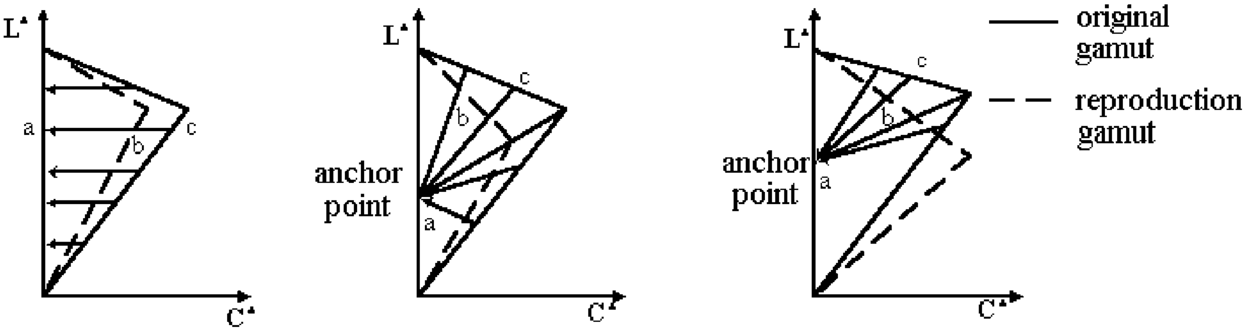
Figure 1(a) maps lightness and chroma toward the central point on the L* axis of the reproduction gamut. One defect of this method is that after mapping the overall range of the lightness is reduced because the lightness in the bright part is reduced and the lightness in the dark park is increased. Fig. 1(b) uses two mapping methods on every hue. If the lightness value of the color to be mapped is higher than that of the central point in the reproduction gamut, mapping toward the central point is used. In the opposite case linear mapping on the constant hue along the lines of constant lightness is used. Fig. 1(c) uses a similar method to Fig. 1(b) for each hue.

The difference between Fig. 1(b) and (c) is the position of each anchor point for each hue. An anchor point is set according to the lightness value of the maximum chroma on each hue and the mapping is performed toward this point. This kind of method includes the intent to distinguish between darkness and brightness for each hue. Fig. 1 (b) and (c) may have a higher contrast than Fig. 1(a) after mapping. However, in all these methods the maximum chroma in the original image can not be mapped to the maximum chroma in the reproduction gamut. This is due to the fact that the anchor point is set according to the middle point of the lightness axis or the lightness value of the maximum chroma in the reproduction gamut.

The method developed by Johnson[5] considers the mapping between the maximum chroma in both gamuts as described in Fig. 2. This method performs different mapping according to the relation of the inclusion between gamuts. The example in Fig. 2(a) is used when the original gamut is entirely included in the reproduction gamut and when the lightness values of the maximum chroma in the two gamuts are similar. Fig. 2(a) maps the chroma on the constant hue and lightness. Fig. 2(b) is used in the case where the original gamut includes the reproduction gamut and the lightness values of the maximum chroma in two gamuts are different. In Fig. 2(b), the colors in the original gamut are mapped toward the anchor point. This anchor point is where the lightness axis and the extending line between the maximum chroma points of the two gamuts meet. Fig. 2(c) is used where the original gamut only partially includes the reproduction gamut. Then the colors in the original gamut are mapped toward an anchor point at the midpoint of the lightness axis of the reproduction gamut.

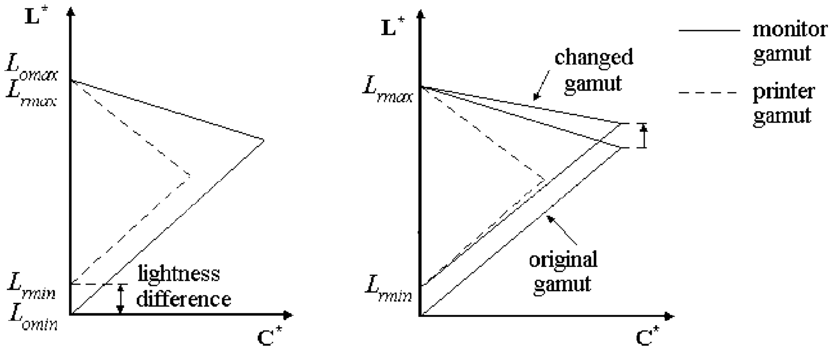
Proposed Gamut Mapping Algorithm Using Variable Anchor Points

In the mapping method developed by Johnson,[5] linear lightness mapping is performed in advance to include the lightness range of the original image into the reproduction gamut. Here, the lightness of the original gamut is changed. Additional gamut mapping toward the anchor point also reduces the resultant lightness of the original image in the reproduction gamut. Therefore, the contrast is decreased. In this process to maintain the maximum chroma in both gamuts as described in Fig. 2, the method maps along the lines going towards the point on the L* axis which is created by the line



(a) (b) (c)

Figure 2. Johnson's GMA: (a) The original gamut is entirely included in the reproduction gamut and the lightness values of the maximum chroma in the two gamuts are similar. (b) The original gamut includes the reproduction gamut and the lightness values of the maximum chroma in two gamuts are different. (c) The original gamut only partially includes the reproduction gamut.



(a) (b)

Figure 3. Lightness mapping; (a) before lightness mapping and (b) after lightness mapping.

going through the two cusps as shown in Fig. 2(b). If the anchor point is not the center of the L* axis of two media, the GMA that utilizes an anchor point shows different color change in bright region and dark region. If the L* value difference of the two cusps is larger, the difference of the color change is increased. Accordingly, these algorithms produce sudden color change on boundary between both the mapping regions and the mapping methods according to shapes of the monitor and printer gamuts. In the case of the parametric GMA using clipping method, the sudden color change is not only shown on the boundary between the mapping methods but also shown on the boundary of the inside and outside of the printer gamut. Therefore, continuous tone colors cannot be reproduced precisely.

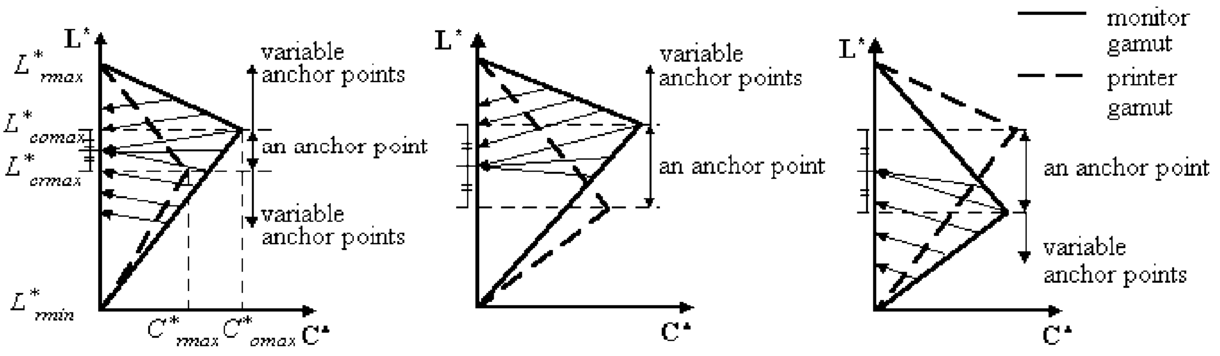
To solve these problems, a GMA that utilizes variable anchor points is proposed to compensate the reduction of lightness range. The proposed algorithm is performed in CIE L*a*b* color space to separate easily lightness and chroma.[9,10] To use colors covering overall gamut of each device, a parametric GMA is used in this article. The gamuts are obtained through the measurements of color samples, that have colors covering the majority of color space of each device. Using these measured-tristimulus values, the white shift between the two gamuts is evaluated. The objective of the process is to make the CIE L*a*b* values of the two whites equal, yet the lightness of the blacks between the two gamuts is different as shown in Fig. 3(a). Therefore, the lightness mapping (or lightness scaling) is performed to include the lightness range of input image into printer gamut. To adjust the lightness between two gamuts, the lightness mapping maps lightness linearly so that the minima and maxima of the two gamuts are mapped onto each other. The process is expressed as

$$\begin{aligned} L^*_{Ip} &= \frac{(L^*_p - L^*_{omin}) \times (L^*_{rmax} - L^*_{rmin})}{\left(L^*_{omax} - L^*_{ominx}\right)} + L^*_{rmin} \\ a^*_{Ip} &= a^*_p \qquad (1) \\ b^*_{Ip} &= b^*_p, \end{aligned}$$

where L^*_{Ip}, a^*_{Ip} and b^*_{Ip} are the result of lightness mapping, L^*_{omax} is maximum lightness of the monitor gamut, L^*_{omin} is minimum lightness of the monitor gamut, L^*_{rmax} is maximum lightness of the printer gamut, and L^*_{rmin} is minimum lightness of the printer gamut.

In Eq. 1, lightness mapping produces reduction of the lightness range. As shown in Fig. 1 and Fig. 2, gamut mapping toward an anchor point also inclines to reduce the lightness range of the mapped image.

In this article, to have higher contrast, the slope of the line going towards anchor point is varied to be less steep in bright and dark region than conventional GMAs using an anchor point. In this process, if the slope toward the anchor point is different, the parametric GMA shows different color change in bright and dark region. If linear mapping along the lines of constant lightness is used, chroma characteristic of the gamut is not considered. Therefore, a separate mapping method that



(a) (b) (c)

Figure 4. Gamut mapping using multiple anchor points of constant slope: (a) The printer gamut is entirely included in the monitor gamut. (b) The monitor gamut only partially includes the printer gamut and the lightness value of maximum chroma of the monitor gamut is larger than the one of the printer gamut. (c) The monitor gamut only partially includes the printer gamut and the lightness value of maximum chroma of the printer gamut is larger than the one of the monitor gamut.

utilizes variable anchor points is used to produce an approximately uniform color change in all lightness range. The position of the anchor point is varied to have constant slope according to position of the input color. Then, the separate mapping method maps input color along the lines with constant slope in each region, so the mapped colors produce an approximately uniform color change in the regions. And to reduce sudden color change on boundary between the mapping methods, similar mapping methods are used in the all regions. To separate mapping regions as shown in Fig. 4, the regions are divided according to the cusp of maximum chroma of the two media. Based on these regions, the colors of the bright and dark regions in an input image are mapped into the printer gamut by clipping their chroma component along the lines of a constant slope. For this method, the slope toward the anchor point is constant in the each region as shown in Fig. 4. In the case of a middle region, mapping towards an anchor point is performed for smooth transition between bright regions and dark region.

In case that the printer gamut is included in the monitor gamut, we can express the anchor point as shown in Eq. 2,

where L^*_{comax} is the lightness of maximum chroma of the monitor gamut, L^*_{crmax} is the lightness of maximum chroma of the printer gamut, L^*_{Ip} and C^*_{Ip} are the result of lightness mapping of the input image, and C^*_{omax} is the maximum chroma of the monitor gamut. In the case of middle region, mapping toward an anchor point is proposed. The anchor point is set according to the center lightness of two maximum chroma points as

$$\begin{aligned} L^*_a &= L^*_{comax} - \frac{(L^*_{comax} - L^*_{crmax})/2}{C^*_{omax}} \times C^*_{omax} \\ a^*_a &= 0 \\ b^*_a &= 0 \end{aligned} \quad . \tag{3}$$

Then, the colors outside the printer gamut are clipped toward an anchor point. If the lightness values of the maximum chroma in the two gamuts are similar, this method is identical with the Johnson's method as shown in Fig. 2(a). In case that the printer gamut is partially included in the monitor gamut as in Fig. 4(b) and (c), the gamut mapping is only accomplished in the included region. The anchor point is expressed as shown in Eq. 4,

$$\begin{aligned} L^*_a &= \begin{cases} L^*_{Ip} - \dfrac{(L^*_{comax} - L^*_{crmax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} \ge L^*_{crmax}\ and\ L^*_{Ip} \ge L^*_{comax} \\ L^*_{Ip} + \dfrac{(L^*_{co\max} - L^*_{crmax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} \ge L^*_{crmax}\ and\ L^*_{Ip} < L^*_{crmax} \\ L^*_{Ip} - \dfrac{(L^*_{crmax} - L^*_{comax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} < L^*_{crmax}\ and\ L^*_{Ip} \ge L^*_{crmax} \\ L^*_{Ip} + \dfrac{(L^*_{crmax} - L^*_{comax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} < L^*_{crmax}\ and\ L^*_{Ip} < L^*_{comax} \end{cases} \\ a^*_a &= 0 \\ b^*_a &= 0 \end{aligned} \tag{2}$$

$$L^*_a = \begin{cases} L^*_{Ip} - \dfrac{(L^*_{comax} - L^*_{crmax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} \geq L^*_{crmax}\ and\ L^*_{Ip} \geq L^*_{comax} \\ L^*_{Ip} + \dfrac{(L^*_{crmax} - L^*_{comax})/2}{C^*_{omax}} \times C^*_{Ip}, & if\ L^*_{comax} < L^*_{crmax}\ and\ L^*_{Ip} < L^*_{comax} \end{cases} .$$
$$a^*_a = 0 \qquad (4)$$
$$b^*_a = 0$$

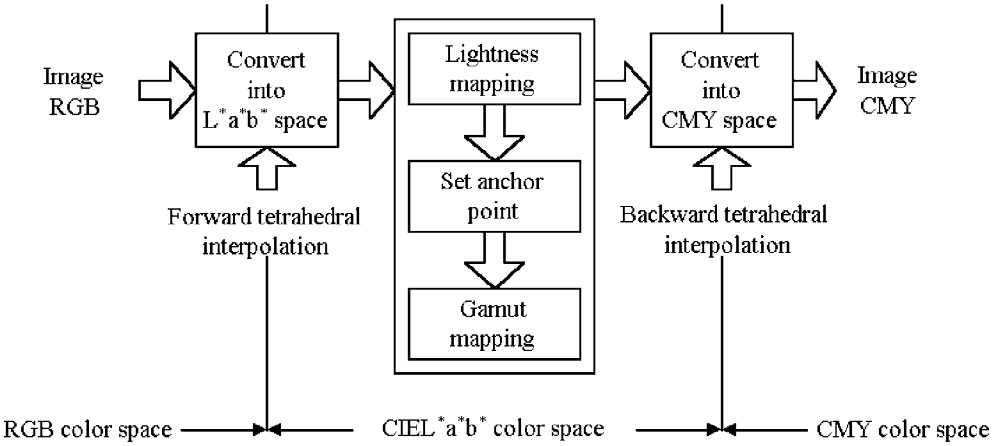


Figure 5. The total procedure of the proposed algorithm.

Mapping methods according to the gamut shapes are almost identical as shown in Fig. 4. So, the result of separate mapping produces approximately uniform color change in the all regions and maps into the printer gamut. Consequently, separate mapping utilizing variable anchor points with a constant slope can reproduce a continuous tone image in the boundary region of a printer gamut and reduce mapping errors.

To print gamut-mapped image, color space conversion is necessary. In this article, the interpolation from CIEL*a*b* color space to CMY is defined as backward interpolation. Figure 5 represents the total procedure of the gamut mapping method. The color image of the RGB format is converted into the CIEL*a*b* color space by forward interpolation. The color space conversion is performed using tetrahedral interpolation that can perform with less multiplication, an easier coefficient calculation for weighted-averages and a better accuracy in the interpolation. In CIEL*a*b* color space, lightness mapping, anchor point setting, and gamut mapping are performed in sequence. Then the gamut-mapped image is reconverted into CMY color space using backward tetrahedral interpolation.

Experimental Result

Two images were chosen for testing the proposed algorithms. A fresh image was obtained from internet-site and a color chart image was generated from a computer graphic. The original for all images was taken to be their appearance on the calibrated Samsung SyncMaster-700p monitor used throughout the experiment. To print the gamut-mapped images, all images were reproduced on a LG Art-jet ink-jet printer.

In other to know the gamut of each device, 6 × 6 × 6 color samples were generated in RGB space for the monitor and printed in CMY space for the printer. Then, the color samples were measured by spectrophotometer in CIEL*a*b* color space. To measure sample colors displayed on the monitor and printed on the printer, Minolta CA-100 and Minolta CM-3600d were used respectively. By the device gamuts obtained from the color samples, the gamut mapping was performed. The block diagram is shown in Fig. 6.

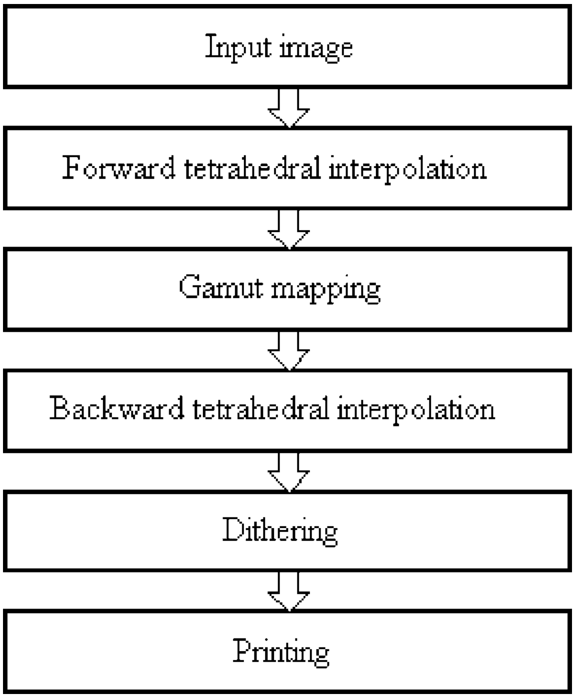


Figure 6. The block diagram for gamut mapping and dithering.

TABLE I. The Comparison of ΔE^*_{ab} between Colors Displayed on the Monitor and Colors Reproduced on the Printer

	CUSP's algorithm	Johnson's algorithm	The proposed algorithm
ΔE^*_{ab}	9.86574	13.00708	8.665285

To compare the GMAs' quality, color difference ΔE^*_{ab} was used. In this process, Macbeth color-chart was used as reference colors. To obtain color difference between the two devices, the Macbeth color-chart was displayed on the monitor and printed on the printer, then the colors were measured by spectrophotometer. From the result, ΔE^*_{ab} was calculated as follows;

$$\Delta E^*{}_{ab} = \sqrt{(L^*{}_O - L^*{}_R)^2 + (a^*{}_O - a^*{}_R)^2 + (b^*{}_O - b^*{}_R)^2} \quad (5)$$

where $L^*{}_O a^*{}_O b^*{}_O$ is CIEL*a*b* values measured on the monitor, $L^*{}_R a^*{}_R b^*{}_R$ is CIEL*a*b* values measured on the printer. Table I shows the comparison of the ΔE^*_{ab}. In the table, the proposed algorithm takes less errors than the conventional CUSP's method and Johnson's one.

In Plate 9 (p. 88) and Plate 10 (p. 89), the images were printed by error diffusion using various GMAs. In both plates, (a) is the result of CUSP's algorithm, (b) is the result of Johnson's algorithm, and (c) is the result of the proposed algorithm. In Plate 9 (a) and (b), the results show that color change in dark region is not discriminated well and colors in bright region are darkening. Plate 9 (c), using the proposed method, shows linear color increment. Plate 10(a) shows cyan component in the white region and Plate 10(b) shows blocking effect in the right upper region. Plate 10(c) doesn't show a cyan component in the white region or the blocking effect. Plate 10 (c) has higher contrast than (a) and (b), and effectively represents the chroma component. Also, black is more blackish than the conventional methods. Therefore, the image that is reproduced by our proposed algorithm has an almost equivalent visual quality with image displayed on the monitor. The results using the proposed algorithm show high quality and less color degradation than the conventional algorithms.

Conclusion

A new method for printing a full resolution color image on limited color output devices was proposed. In this article, parametric GMA using variable anchor points was proposed to increases lightness range, which is reduced from conventional gamut mapping toward an anchor point. In this process, the proposed algorithm used multiple anchor points of constant slope to reduce sudden color change on gamut boundary of the regions. Therefore, the proposed algorithm could reproduce continuous tone image and reduce mapping errors.

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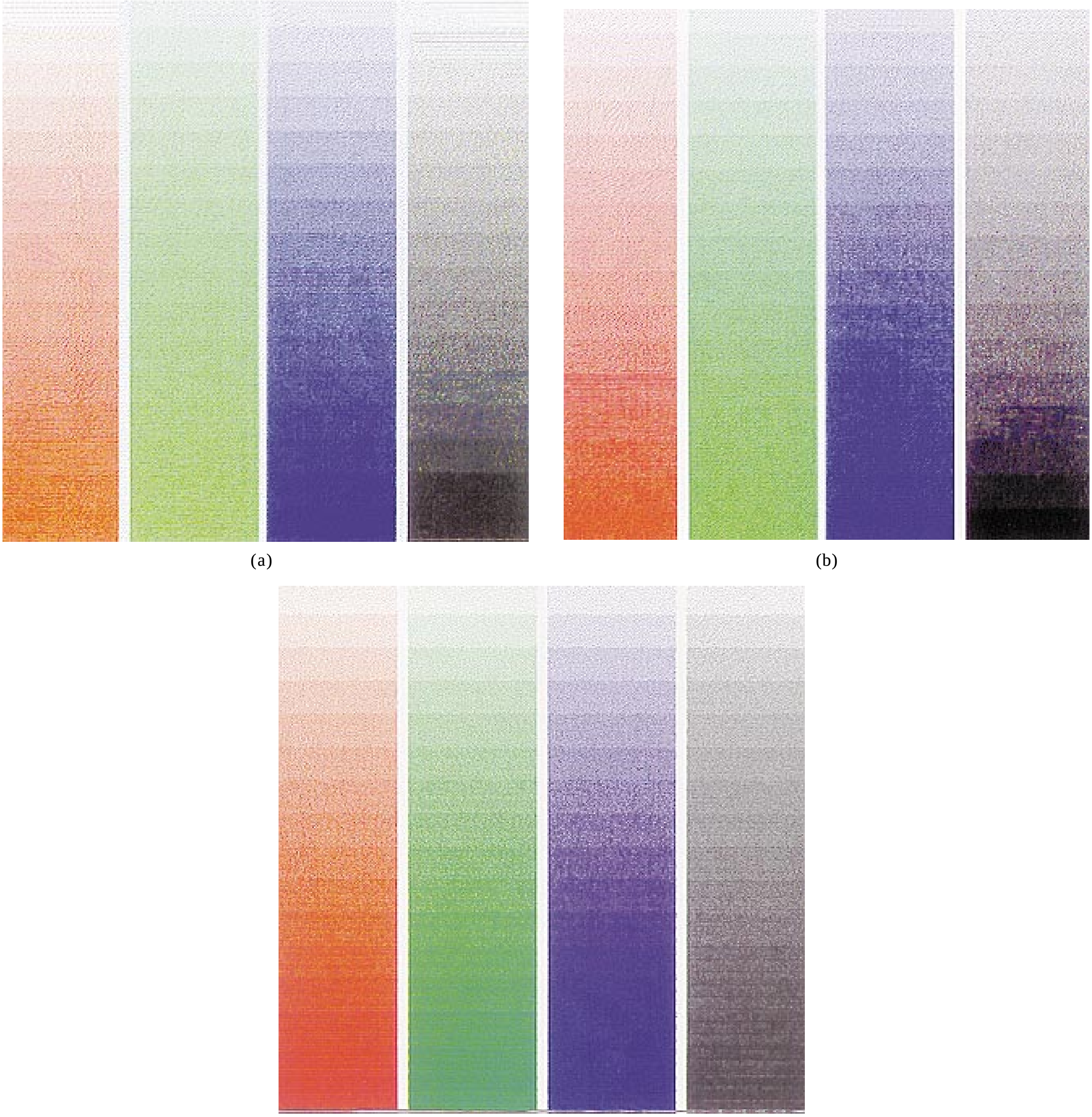
(a)

(b)

(c)

Plate 9. The graphic images printed by error diffusion using various GMAs; (a) CUSP's algorithm; (b) Johnson's algorithm, and (c) the proposed algorithm (Lee, *et al*., pp. 68–73).

(a)

(b)

(c)

Plate 10. The real images printed by error diffusion using various GMAs; (a) CUSP's algorithm; (b) Johnson's algorithm, and (c) the proposed algorithm (Lee, *et al*., pp. 68–73).