Feature Article

Gamut Mapping Algorithm Using Lightness Mapping and Multiple Anchor Points for Linear Tone and Maximum Chroma Reproduction

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This article proposes a new gamut-mapping algorithm (GMA) that utilizes both lightness mapping and multiple anchor points. The proposed lightness mapping minimizes the lightness difference of the maximum chroma between two gamuts and produces the linear tone in bright and dark regions. In the chroma mapping, a separate mapping method that utilizes multiple anchor points with constant slopes plus a fixed anchor point is proposed to maintain the maximum chroma and produce a uniform tonal dynamic range. As a result, the proposed algorithm is able to reproduce high quality images using low-cost color devices.

Journal of Imaging Science and Technology 45: 209–223 (2001)

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 outside the gamut of the target output device. In such a case, the image colors must be mapped within the reproduction 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]

Successive and simultaneous GMAs have the benefit of simple processing, however, they cannot use colors covering the overall gamut of each device. In contrast, parametric GMAs can use colors covering the overall gamut of a device because these algorithms perform color mapping based on the shape of either the original or the reproduction gamut. In conventional parametric GMAs,[5] an initial lightness mapping is performed to include the lightness range of the original image into the reproduction gamut. In this process, the lightness range of the original gamut is larger than that of the reproduction's. In addition, most of the lightness values of the original's maximum chroma at each hue angle are larger than those of the reproduction's. Therefore, if the lightness values of the maximum chroma in the two gamuts are not located at the center of the lightness axis of the two media, the parametric GMA will produce a different color change in the bright and dark regions.

In this condition, if linear compression or soft-clipping compression is applied to the lightness mapping, the lightness value difference between the two gamuts is increased. As the lightness value difference is increased, so the difference in the color change is also increased and it becomes difficult to maintain the maximum chroma in the gamut mapping process.[11]

Thereafter, if a parametric GMA using an anchor point (a center of gravity on the lightness axis) is applied to the original image, the lightness of the bright regions will decrease while the lightness of the dark regions will increase to include the original colors in the reproduction gamut. As a result, the lightness range is also reduced along with the contrast. Furthermore, if the anchor point is not located at the center of the lightness axis of the two media, the parametric GMA utilizing the anchor point will produce a different color change in the bright and dark regions. As the lightness value difference of the maximum chroma of the two media increases, so the difference in the color change will also increase. In addition, the input colors mapped towards an anchor point in the same region will also exhibit a different color change, because the conventional GMA maps the input colors along lines with different slopes. As a result, these algorithms produce sudden color changes on the boundaries between mapping regions.

Accordingly, to solve these problems, a lightness mapping is proposed that minimizes the lightness difference of the maximum chroma between two gamuts and produces the linear tone in bright and dark regions. In this process, a lightness mapping is used that is based on both the shape of the original and the reproduction gamuts at a particular hue angle. Initially, the reproduction gamut

Original manuscript received July 7, 2000

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is changed to maintain a linear tonal distribution of the color samples within a range covering the overall lightness of each device. To apply this process, a nonlinear function considering a hardware characteristic is applied. The hardware characteristic considered is the printer's dot gain. The printed dots are larger than the minimal covering size, as if "ink spreading" has occurred. As the result, the lightness produced by the printer is complicated and dependent on neighboring dots. Therefore, the lightness is nonlinearly increased as the number of marked dots per pixel increases. Consequently, a nonlinear function is applied to maintain a linear tonal distribution of the color samples within a range covering the overall lightness.

Lightness mapping is then applied to include the lightness range of the monitor gamut into the printer gamut and to minimize the lightness difference in the maximum chroma. In this article, human vision characteristics are applied. Generally, human vision in non-UCS (uniform color spaces) is more sensitive to color changes in dark and middle regions than to those in bright regions. Therefore, bright regions are more compressed than dark and middle regions. In this process, the sample patches selected in non-UCS are redistributed uniformly in UCS. The process is continued recursively until the lightness difference between the monitor and the printer gamut is minimized.

Next, a parametric-type GMA is proposed to maintain the maximum chroma and produce a uniform tonal dynamic range. Accordingly, the proposed method maps the chroma based on a constant hue and lightness when the lightness values of the maximum chroma in the two gamuts are similar. In this process, if the tonal dynamic range in the bright and dark regions is different plus the lightness values of the maximum chroma in the two gamuts are also different, the parametric GMA will produce a different color change in the bright and dark regions.

Therefore, a mapping method based on variable anchor points is used when the tonal dynamic range between bright and dark region is narrow. This mapping method maps the input colors along lines with a constant slope in each region, as a result, the mapped colors can produce an approximately uniform color change in the region and widen tonal dynamic range. In this process, in order to maintain the maximum chroma, the slope for the variable anchor point is set based on the lightness value of the maximum chroma. In contrast, if the tonal dynamic range is wide, a mapping method based on an anchor point is used. This mapping method maps the input colors towards an anchor point, thereby creating a smooth transition between bright and dark regions plus a reduced tonal dynamic range. To separate the mapping regions, the regions are divided according to the cusp of the maximum chroma of the two media. As a result, the separate mapping method can reproduce continuous tone colors and maintain the maximum chroma.

Gamut Mapping Algorithm

Lightness Mapping

Generally, the white shift between two gamuts can be determined using the measured tristimulus values. The objective of lightness mapping is to make the CIEL*a*b* values of two whites equal, however, the lightness of the blacks between two gamuts is also often different. Therefore, lightness mapping (or lightness scaling) is performed to include the lightness range of the input image into the printer gamut. The majority of algorithms proposed so far use the linear compression of lightness, which can be done either in L^* (as specified by CIE) or Bartleson and Breneman's lightness or darkness, with the former being more popular. As an option, lightness can be compressed using a soft clipping function,[6] similar to the one shown in Fig. 1. This function has the characteristic leaving the majority of the range unaltered (as its tangent is the $y = x$ function), thereby creating a smooth transition to the gamut boundaries at the extremes of the range. It is also similar to tonal reproduction curves used traditionally in graphic arts and is intrinsically image dependent. A further modification of this technique, suitable only for lightness mapping, is to keep the central part of the lightness range unaltered and only compress the extremes.

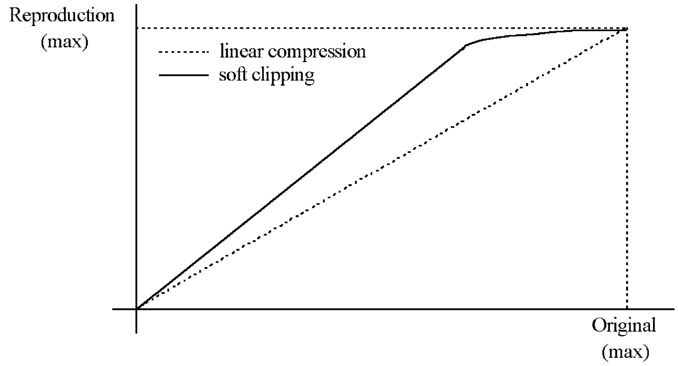


Figure 1. Soft clipping function used for lightness.

For example, to adjust the lightness between two gamuts, as shown in Fig. 2(a), lightness mapping maps the lightness linearly so that the minima and maxima of the two gamuts are mapped onto each other. This process can be expressed as

$$
\begin{aligned}
L^*_{lp} &= \frac{(L^*_p - L^*_{o\,\min}) \times (L^*_{r\,\max} - L^*_{r\,\min})}{(L^*_{o\,\max} - L^*_{o\,\min})} + L^*_{r\,\min}\,, \\
a^*_{lp} &= a^*_p, \\
b^*_{lp} &= b^*_p,
\end{aligned} \tag{1}
$$

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

In Eq. 1 and Fig. 2, the lightness mapping produces a reduction in the lightness range.

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 the 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: light-

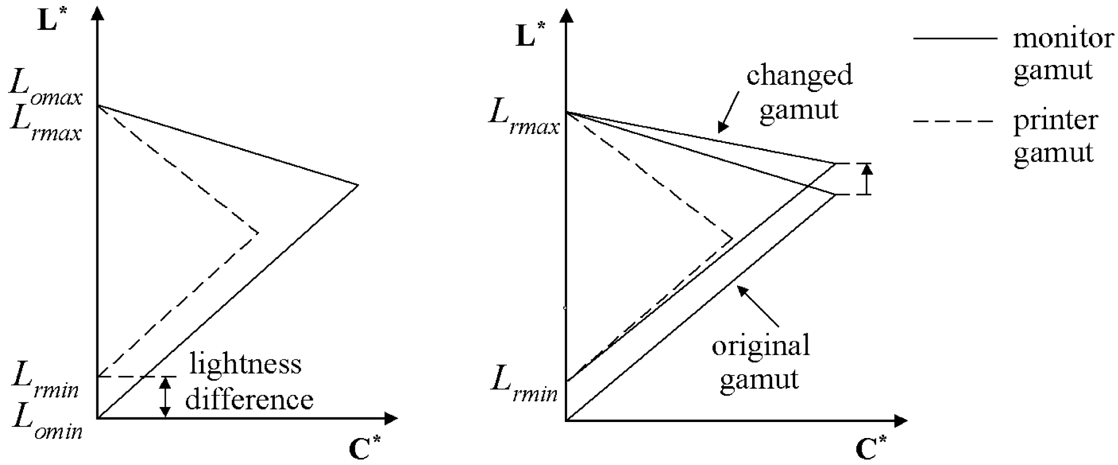


Figure 2. Lightness mapping: (a) before lightness mapping; and (b) after lightness mapping.

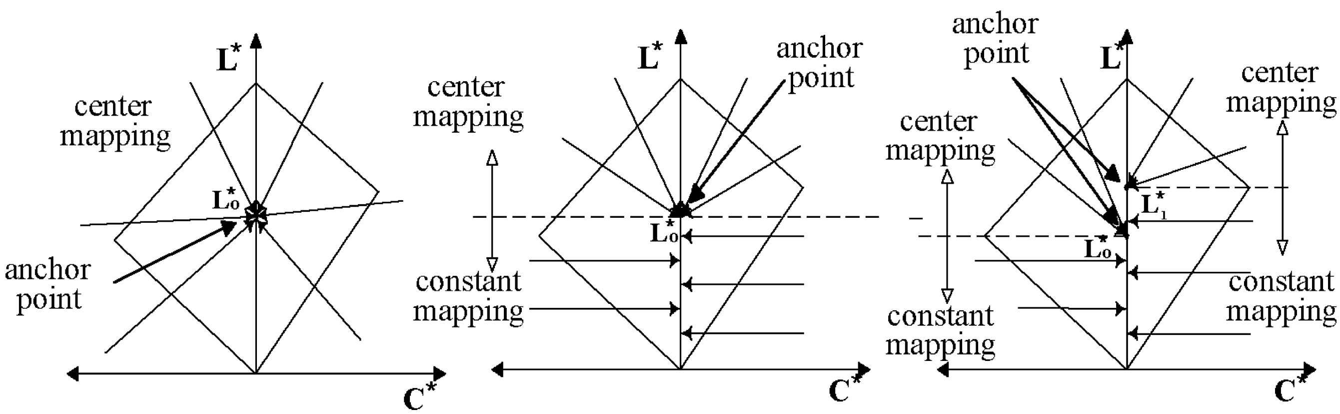


Figure 3. Combined gamut mapping algorithms; (a) lightness and chroma mapping toward central point on L* axis; (b) two mapping methods on every hue; (c) anchor point is set according to lightness value of maximum chroma on each hue.

ness mapping and chroma mapping. All the algorithms in this group map the lightness first 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 them towards a particular point in color space (a center of gravity). Generally, these algorithms do not include initial lightness compression, and all successive and simultaneous algorithms preserve the hue.

These successive and simultaneous GMAs have the benefit of simple processing. However, they cannot use colors covering the 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] A number of combined mapping methods have been developed to produce smoother transitions between adjacent regions to improve the color appearance. These methods map lightness and chroma at the same time. Some of these methods are represented in Fig. 3.

Figure 3(a) maps the lightness and chroma toward the central point on the L^* axis of the reproduction gamut. One drawback to 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. Figure 3(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. Figure 3(c) uses a similar method to Fig. 3(b) for each hue.

The difference between Figs. 3(b) and 3(c) in 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. Figures 3(b) and 3(c) may have a higher contrast than 3(a) after mapping. However, in all these methods the maximum chroma in the original image cannot 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. 4. This method performs different mapping according to the inclusion relation between the gamuts. The example in Fig. 4(a) is used

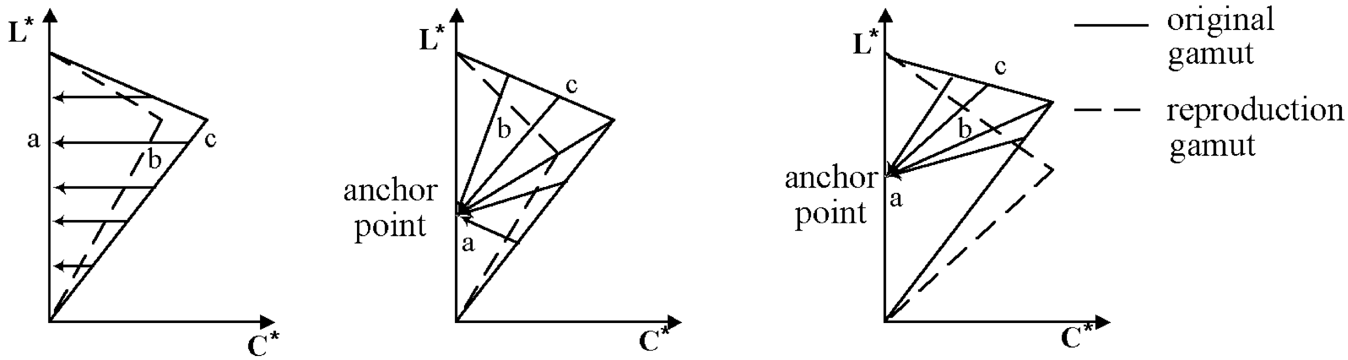


Figure 4. Johnson's GMA: (a) Original gamut is entirely included in reproduction gamut and lightness values of maximum chroma in two gamuts are similar; (b) Original gamut includes reproduction gamut, and lightness values of maximum chroma in two gamuts are different; (c) Original gamut only partially includes reproduction gamut.

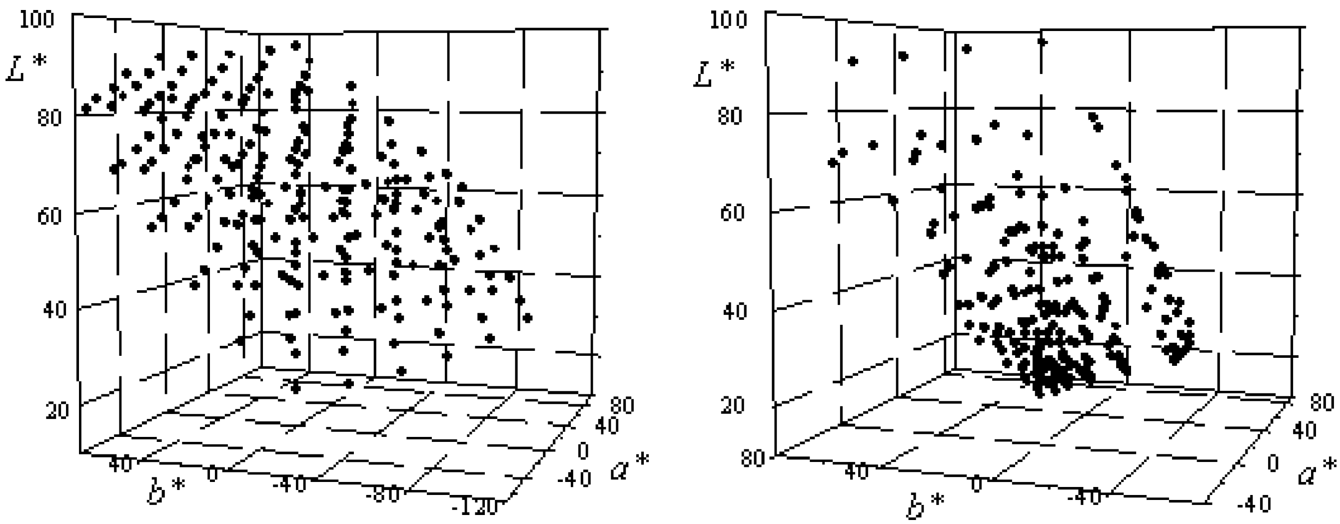


Figure 5. Shapes of two gamuts. (a) Monitor gamut: maximum lightness is 93.45 and minimum lightness is 17.35; and (b) Printer gamut: maximum lightness is 93.45 and minimum lightness is 22.56.

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. Figure 4(a) maps the chroma on a constant hue and lightness. Figure 4(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. 4(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. Figure 4(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 mid-point of the lightness axis of the reproduction gamut.

Proposed Gamut Mapping Algorithm

Proposed Lightness Mapping

The majority of algorithms proposed so far use the linear or nonlinear compression of lightness, which can be done either in L^* or in Bartleson and Breneman's lightness or darkness, with the former being more popular. This function has the characteristic of leaving the majority of the range unaltered. As an option, the lightness can be compressed using a soft clipping function, similar to the one shown in Fig. 1. This function is also similar to the tonal reproduction curves used traditionally in graphic arts, and is intrinsically image dependent. To adjust the lightness between two gamuts, this process heightens the lightness of the original gamut at different rates.

These processes have the advantage of simple processing, however, they cannot consider the shape covering the overall gamut of each device. Therefore, lightness mapping based on the shape of either the original or the reproduction gamut at a particular hue angle is needed. As shown in Fig. 5, the gamut shapes of each device are different. In addition, the line that links the cusps, as shown in Fig. 5, creates the gamut boundary. Therefore, to process lightness mapping, knowledge of the lightness of the cusp at each hue angle is required. Figure 6 shows the lightness of the cusps at each hue angle, plus the average lightness of the monitor cusps and the printer cusps is 68.1 and 47.8, respectively.

In Fig. 6, the lightness of the monitor's cusps at each hue angle is mostly larger than that of the printer's.

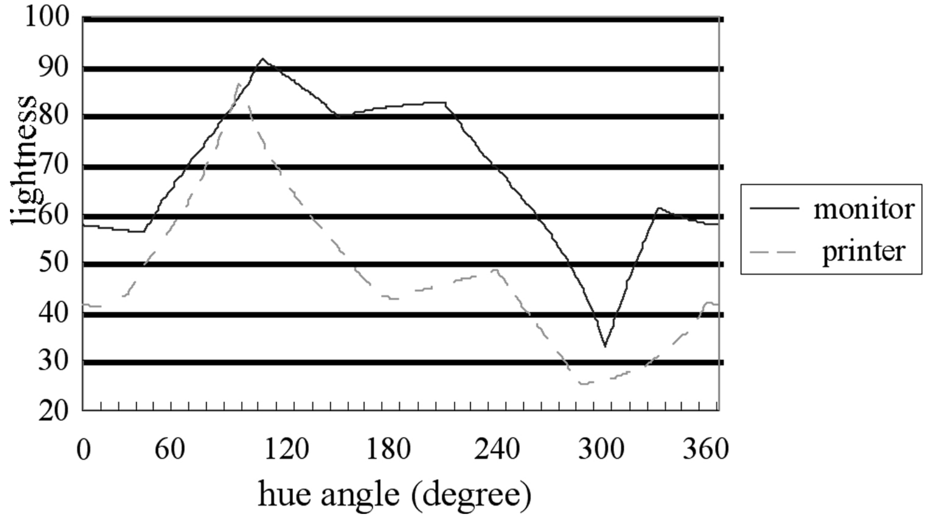


Figure 6. Lightness of cusps at each hue angle without intensity mapping.

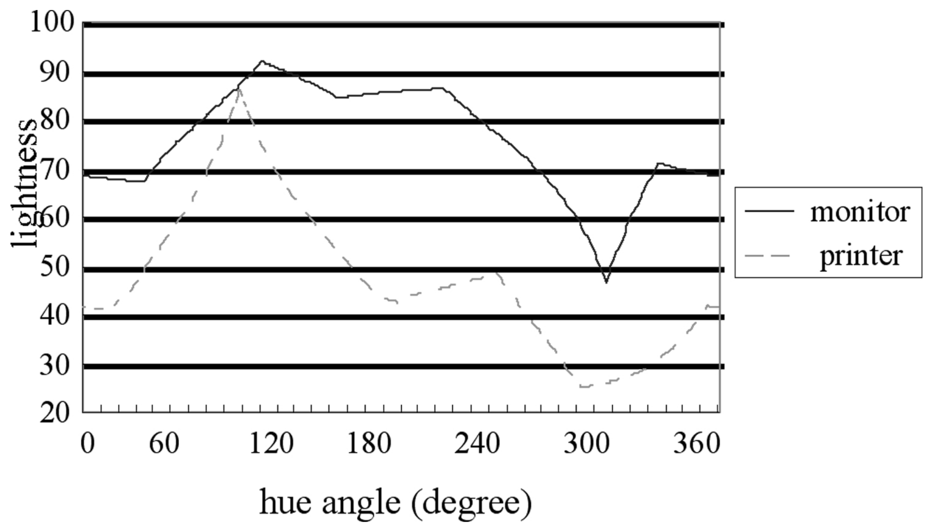


Figure 7. Lightness mapping using linear compression.

Therefore, in chroma mapping this condition produces different color changes in bright and dark regions. In this case, if linear compression or soft clipping compression is applied to lightness mapping, the difference in the average lightness is increased and the different color changes in bright and dark regions are also increased. Fig. 7 is the result of using the linear compression of Eq. 1, where the average lightness of the monitor and printer cusps is 75.8 and 47.8, respectively.

To solve these problems, a lightness mapping is proposed that minimizes the lightness difference of the cusps at each hue angle and produces the linear tone in bright and dark regions. In this process, a lightness mapping is used that is based on the shape of either the original or the reproduction gamut at a particular hue angle. The proposed algorithm is performed in CIEL*a*b* color space to facilitate the separation of lightness and chroma.[9,10] Initially, the reproduction gamut is changed to maintain a linear tonal distribution of the color samples within a range covering the overall lightness of each device.

To apply this process, a nonlinear function considering a hardware characteristic is applied. The hardware characteristic considered is illustrated in Fig. 8. The dots are larger than the minimal covering size, as if "ink spreading" has occurred. As a result, the lightness produced by the printer is complicated and dependent on neighboring dots. In the figure, α, β, and γ are the ratios of the areas of the shaded regions and they can be expressed in terms of the ratio ρ of the actual dot radius to the ideal dot radius as follows

$$\alpha = \frac{1}{4}\sqrt{2\rho^2 - 1} + \frac{\rho^2}{2}\sin^{-1}\left(\frac{1}{\sqrt{2}\rho}\right) - \frac{1}{2} \qquad (2)$$

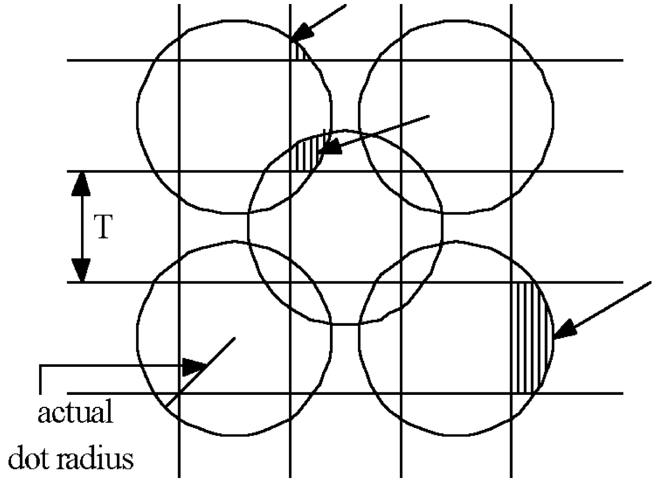


Figure 8. Circular dot overlap printer model.

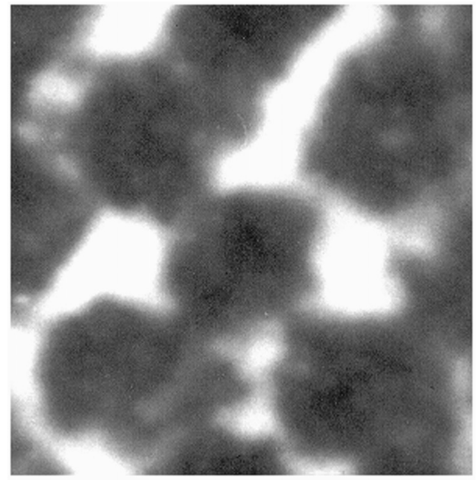


Figure 9. Actual cyan dots pictured by Olympus PM-10AK3.

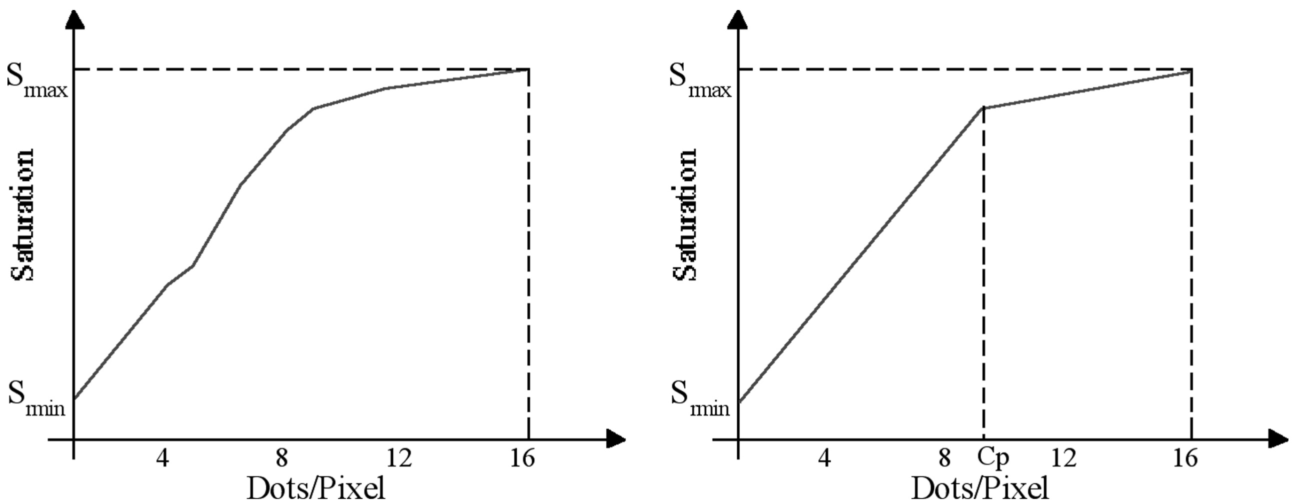


Figure 10. Saturation change curve with respect to amount of primary inks.

$$\beta = \frac{\pi\rho^2}{8} - \frac{\rho^2}{2}\sin^{-1}\left(\frac{1}{\sqrt{2}\rho}\right) - \frac{1}{4}\sqrt{2\rho^2 - 1} + \frac{1}{4} \quad (3)$$

$$\gamma = \frac{\rho^2}{2}\sin^{-1}\left(\sqrt{\frac{\rho^2 - 1}{\rho^2}}\right) - \frac{1}{2}\sqrt{\rho^2 - 1} - \beta \quad (4)$$

Figures 8 and 9 show the circular dot model and the actual cyan dots, respectively. Figure 9 was taken by an Olympus PM-10AK3 and scanned by an HP scanner. As shown in Fig. 9, the actual dots exhibit dot spreading on the paper. This distortion produces an unwanted color image because each primary ink has its own ink spreading rate, ρ. Therefore, the reproduced lightness is proportional to the marked area. The marked area in the printing is changed according to the marking position. If the difference in the marking area is not considered, the lightness of the printed image will not be equal to the image displayed on the monitor. Therefore, the corresponding saturation will increase as the number of marked dots per pixel increases.

As shown in Fig. 10, the saturation is abruptly increased in the low and mid range and slowly increased in high range. Therefore, the nonlinear function must be adjusted in proportion to the saturation increment. In this article, a simplified function is used for the fast processing. The changed printer gamut is shown in Fig. 11 and the average lightness of the printer cusps is 55.8, as shown in Fig. 12. As the result, the uniformity of the gamut samples as shown Fig. 11 is increased and the average lightness of the printer cusps is located nearly at the center of the lightness axis.

Thereafter, lightness mapping is applied to include the lightness range of the monitor gamut in the printer gamut and minimize the lightness difference between the cusps at each hue angle. In this article, human vision characteristic is applied. Human vision is more sensitive to color changes in dark and middle regions than to those in bright regions. Therefore, bright regions can be more compressed than dark and middle regions. This process is continued recursively until the lightness difference between the monitor and the printer cusps is minimized. This process can be expressed as

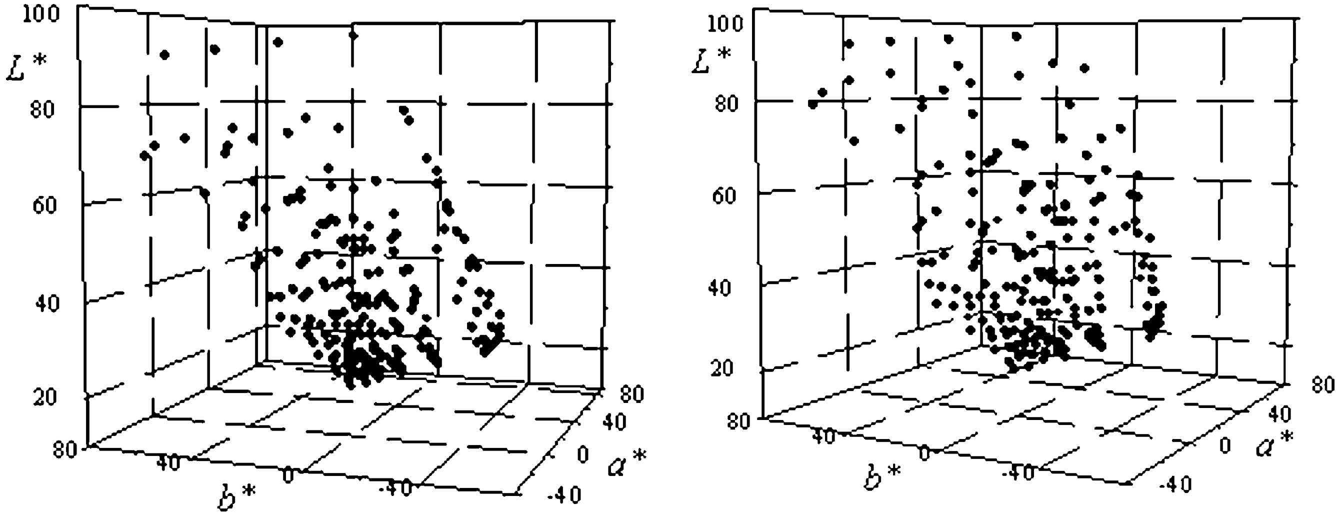


Figure 11. Shapes of the printer gamut: (a) with no lightness change; (b) with lightness change.

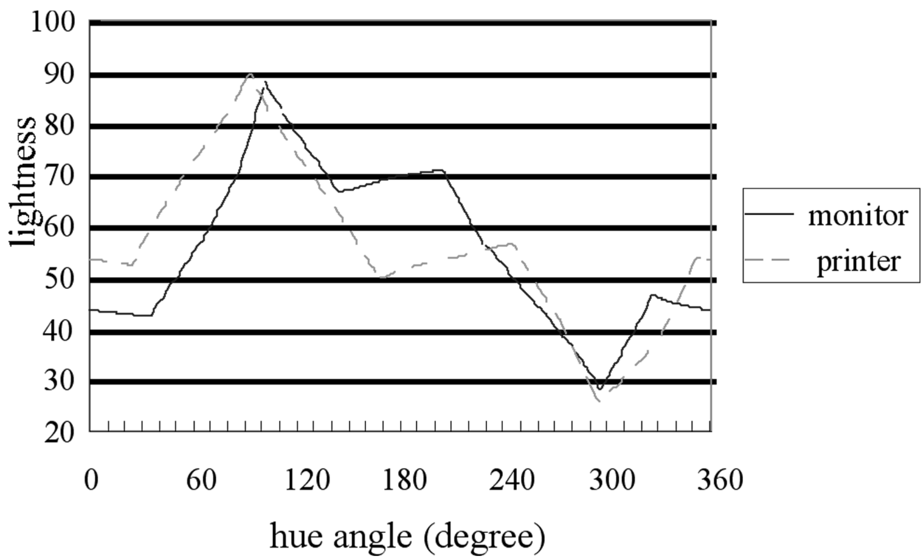


Figure 12. Lightness mapping using proposed method.

$$L'_m = K \frac{\ln\left(1-\mu_m\left(L_{m-m_{\min}}\right)\right)}{\ln\left(1-\mu_m\right)} + p_{\min} \qquad (5)$$

where L_m is the original lightness of the monitor gamut, L'_m is the changed lightness of the monitor gamut, p_{min} is the minimum lightness of the printer gamut, $m_{\min}$ is the minimum lightness of the monitor gamut, and K_m and μ_m are constant to minimize the lightness difference between the two gamuts. In this process, K_m and μ_m are changed until the mean-square-error (MSE) of the lightness difference of the cusps at each hue angle is minimized. As a result, the average lightness of the monitor cusps is 56.7, as shown in Fig. 12. Therefore, the proposed method can reduce the lightness difference between the printer and monitor cusps and produce uniform color changes in bright and dark regions. Based on this result, the maximum chroma of the monitor gamut can easily be reproduced in chroma mapping.

Chroma Mapping for Maximum Chroma Reproduction

In the mapping method developed by Johnson,[5] an initial linear lightness mapping is performed to include the lightness range of the original image into the reproduction gamut. In this case, the lightness of the original gamut is changed. The additional gamut mapping toward an anchor point also reduces the resultant lightness of the original image in the reproduction gamut. Therefore, the contrast is often decreased.

To maintain the maximum chroma in both gamuts, as described in Fig. 4, this method maps along the lines going towards a point on the L^* axis, which is created by the line that links the two cusps, as shown in Fig. 4(b). If the anchor point is not at the center of the L^* axis of the two media, a GMA that utilizes such an anchor point will then produce different color changes in bright and dark regions. As the L^* value difference between the two cusps increases, the difference in the color change will be more dramatic. Accordingly, these algo-

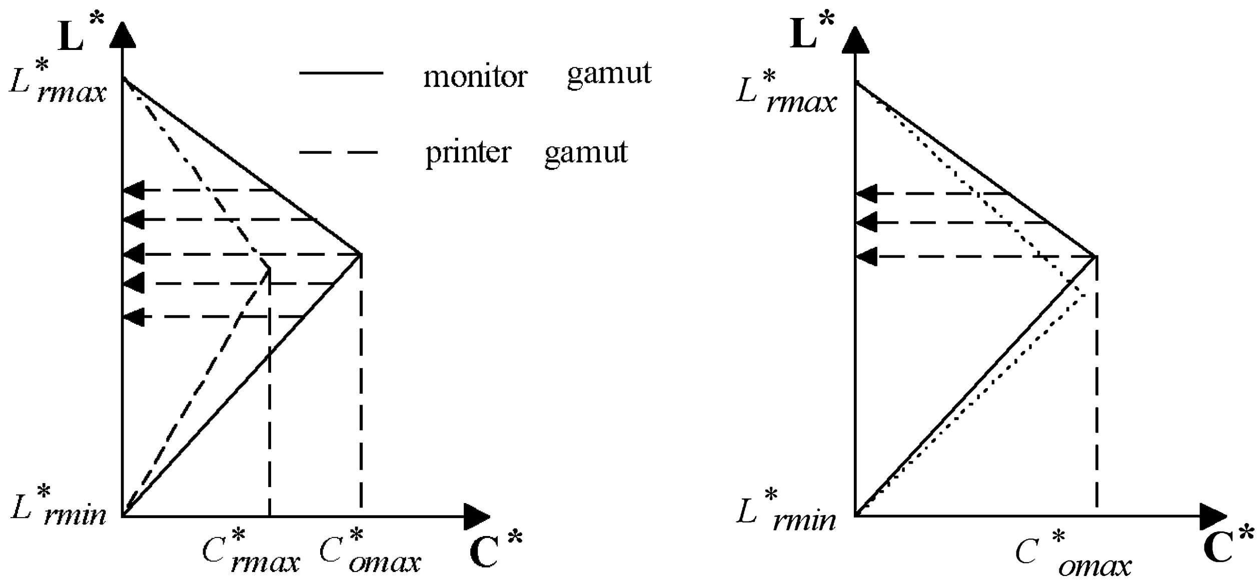


Figure 13. Gamut mapping based on constant hue and lightness: (a) Printer gamut is entirely included in monitor gamut; (b) Monitor gamut only partially includes printer gamut.

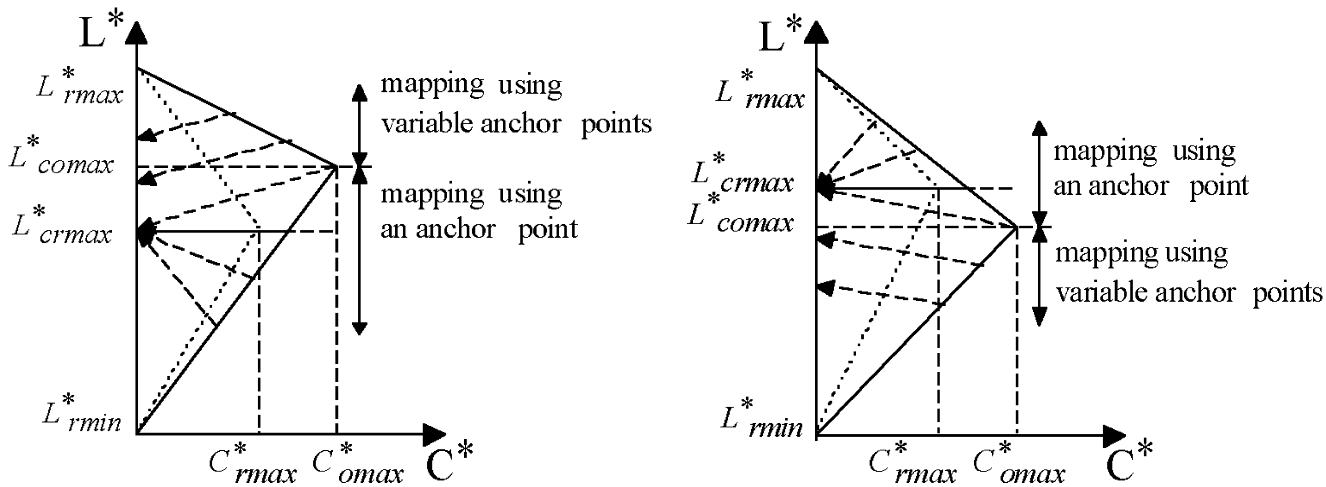


Figure 14. Gamut mapping using both variable anchor point method and fixed anchor point: printer gamut is entirely included in monitor gamut: (a) Lightness value of maximum chroma in monitor gamut is larger than that in printer gamut; (b) Lightness value of maximum chroma in printer gamut is larger than that of monitor gamut.

rithms produce sudden color changes on the boundaries between mapping regions and mapping methods based on the shapes of the monitor and printer gamuts. In the case of a parametric GMA that uses the clipping method, a sudden color change is not only produced on the boundaries between mapping methods but also on the inside and outside boundaries of the printer gamut. Therefore, continuous tone colors cannot be accurately reproduced.

To solve these problems, a GMA is proposed that utilizes variable anchor points. The proposed algorithm is performed in CIEL*a*b* color space to facilitate the separation of lightness and chroma. A parametric-type GMA is also used to enable the use of colors covering the overall gamut of each device. To maintain a maximum chroma and uniform tonal dynamic range, as shown in Fig. 13, the proposed method maps the chroma based on a constant hue and lightness when the lightness values of the maximum chroma in the two gamuts are similar. In this case, the anchor point is expressed as

$$L_a^* = L_{lp}^*,\ a_a^* = 0,\ b_a^* = 0 \tag{6}$$

where L^*_{Ip} is the lightness mapping results of the input image.

In this process, if the lightness values of the maximum chroma are not similar, the proposed GMA is unable to maintain the maximum chroma. Therefore, a separate mapping method that utilizes variable anchor points is used to produce an approximately uniform color change across the whole lightness range along with a maximum chroma reproduction. To maintain the maximum chroma, the slope of the line going towards an anchor point is varied. In this process, if the anchor point is not located at the center of the L^* axis of the two media, a conventional GMA will produce a different tonal dynamic range between the bright and dark regions. Therefore, the proposed method uses both a variable anchor point method and a fixed anchor point as shown in Figs. 14 and 15.

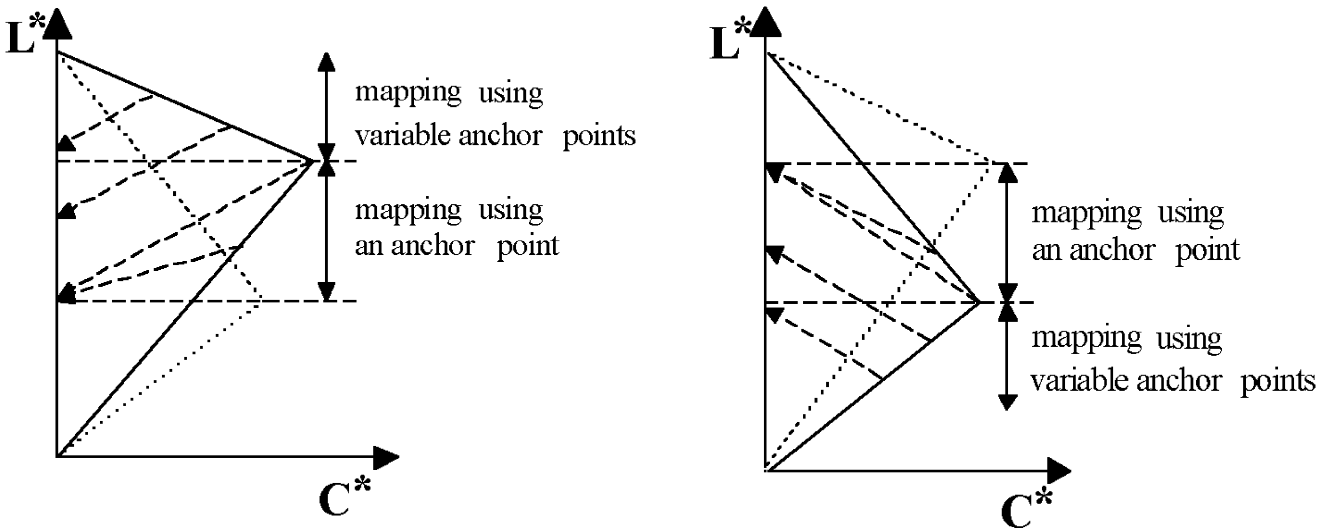


Figure 15. Gamut mapping using both variable anchor point method and fixed anchor point: monitor gamut only partially includes printer gamut. (a) Lightness value of maximum chroma in monitor gamut is larger than that of printer gamut. (b) Lightness value of maximum chroma in printer gamut is larger than that of monitor gamut.

In this process, if the tonal dynamic range is different, a parametric GMA will produce a different color change in bright and dark regions. Therefore, the mapping method based on a variable anchor points is used when the tonal dynamic range is narrow. This mapping method maps the input colors along lines with a constant slope in each region, Therefore, the mapped colors produce an approximately uniform color change in the region plus a wide tonal dynamic range. The position of the anchor point is varied to produce a constant slope relative to the position of the input color. Conversely, if the tonal dynamic range is wide, the mapping method based on a fixed anchor point is used.

Because this mapping method maps the input colors towards an anchor point, a smooth transition is created between bright and dark regions and a reduced tonal dynamic range. In the case that the lightness of the maximum chroma in the monitor gamut is larger than that in the printer gamut, the anchor point can be expressed as shown in Eq. 7, where L^*_{comax} is the lightness of the maximum chroma of the monitor gamut, L^*_{crmax} is the lightness of the maximum chroma of the printer gamut, L^*_{Ip} and C^*_{Ip} are the lightness mapping results of the input image, and C^*_{omax} is the maximum chroma of the monitor gamut.

In the case that the lightness of the maximum chroma in the printer gamut is larger than that in the monitor gamut, the anchor point can be expressed as shown in Eq. 8.

To separate the mapping regions, as shown in Figs. 14 and 15, the regions are divided according to the cusp of the 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 toward the anchor points. In this process, to maintain the maximum chroma, the slope for the variable anchor point is set by the line as shown in Figs. 14 and 15. If the line that links the maximum chroma points of the two gamuts creates this slope, this method will produce different color changes in bright and dark regions. As the slope is steep, so the difference in the color change will also increase. Accordingly, this method produces sudden color changes on boundaries between neighboring mapping

$$\begin{aligned} L^*_a &= \begin{cases} L^*_{Ip} - \dfrac{(L^*_{co\max} - L^*_{cr\max})}{C^*_{o\max}} \times C^*_{lp}, & \text{if } L^*_{co\max} \ge L^*_{cr\max} \text{ and } L^*_{Ip} \ge L^*_{co\max} \\ L^*_{cr\max}, & \text{otherwise} \end{cases} \\ a^*_a &= 0 \\ b^*_a &= 0 \end{aligned} \tag{7}$$

$$\begin{aligned} L^*_a &= \begin{cases} L^*_{Ip} - \dfrac{(L^*_{cr\max} - L^*_{co\max})}{C^*_{o\max}} \times C^*_{lp}, & \text{if } L^*_{co\max} < L^*_{cr\max} \text{ and } L^*_{Ip} \le L^*_{cr\max} \\ L^*_{cr\max}, & \text{otherwise} \end{cases} \\ a^*_a &= 0 \\ b^*_a &= 0 \end{aligned} \tag{8}$$

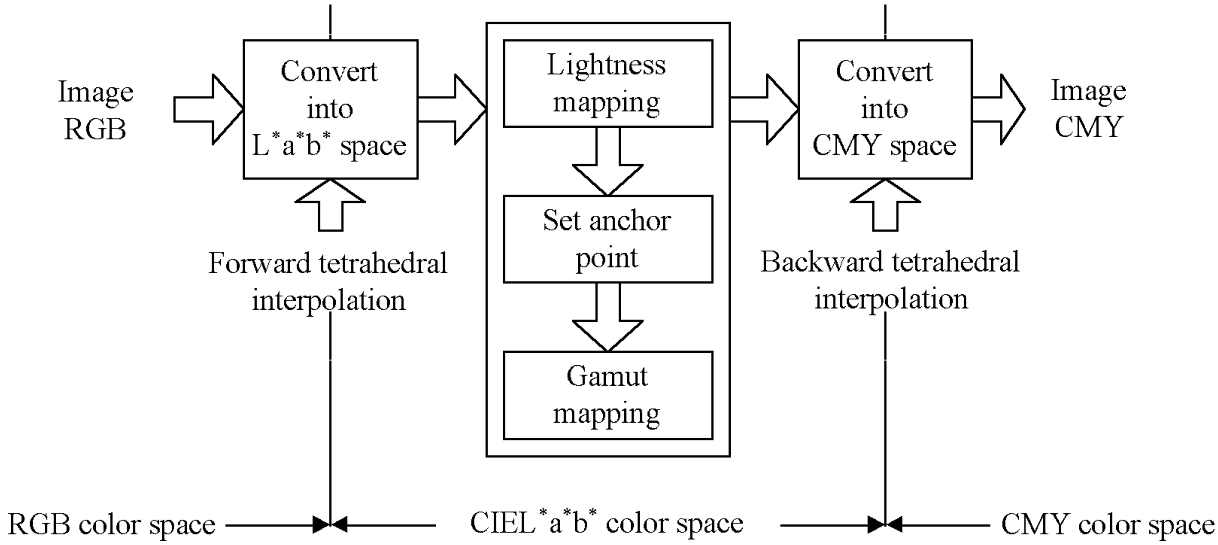


Figure 16. Total procedure of proposed algorithm.

regions. In the case of the method using a fixed anchor point, this method is performed to create a smooth transition between bright and dark regions. Thereafter, the colors outside the printer gamut are clipped toward this anchor point.

To print a 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 16 represents the total procedure of the gamut mapping method. A color image in a RGB format is converted into CIEL*a*b* color space by forward interpolation. The color space conversion is performed using tetrahedral interpolation,[12] which uses less multiplication, is an easier coefficient calculation for weighted averages, and produces a better accuracy in the interpolation. In CIEL*a*b* color space, the lightness mapping, anchor point setting, and gamut mapping are all performed in sequence. Thereafter, the gamut mapped image is reconverted into CMY color space using backward tetrahedral interpolation.

Experimental Results

In order to determine the gamut of each device, $6 \times 6 \times 6$ color samples were generated in RGB space for the monitor and printed in CMY space for the printer. The originals for all images were taken as their appearance on a calibrated Samsung SyncMaster-700p monitor used throughout the experiment. To print the gamut mapped images, all images were reproduced by error diffusion on a LG GIP-6000 ink jet printer. Then, the color samples were measured by a spectrophotometer in CIEL*a*b* color space. To measure the sample colors displayed on the monitor and printed on the printer, a Minolta CA-100 and Minolta CM-3600d were used, respectively. The measured values were stored in a 3-D LUT (lookup table). Using the device gamuts obtained from the color samples, gamut mapping was then performed. A block diagram is shown in Fig. 17.

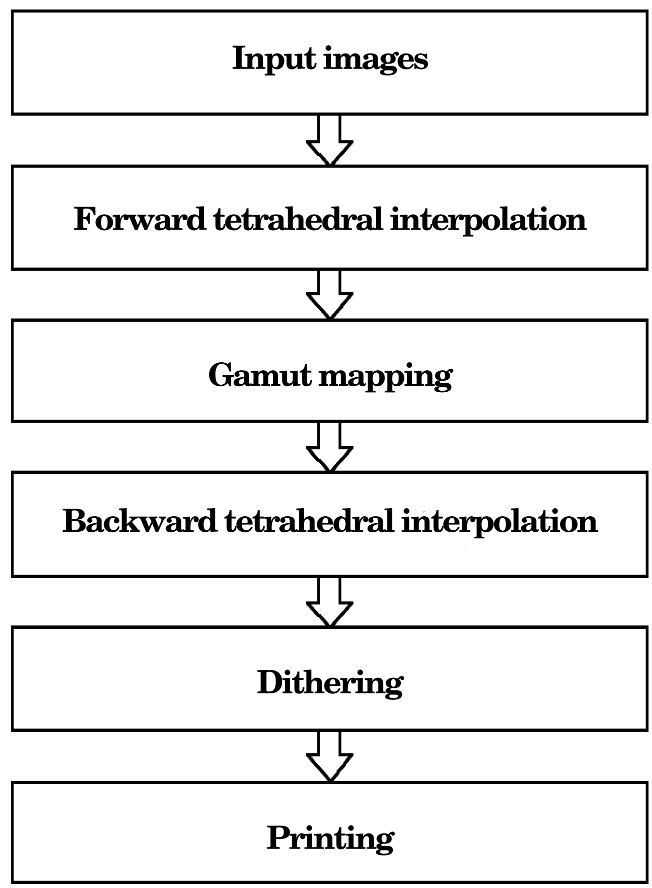
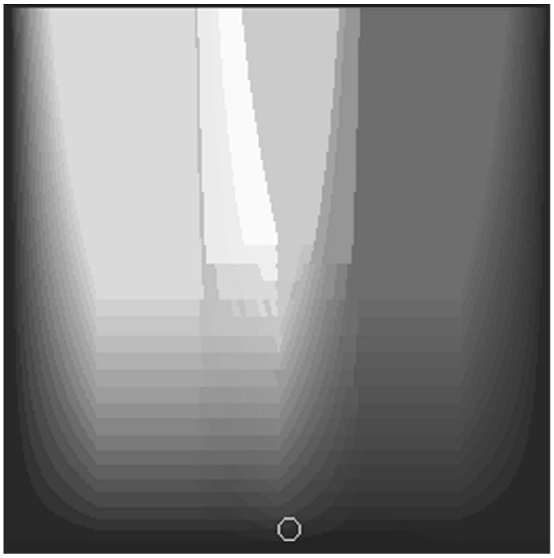
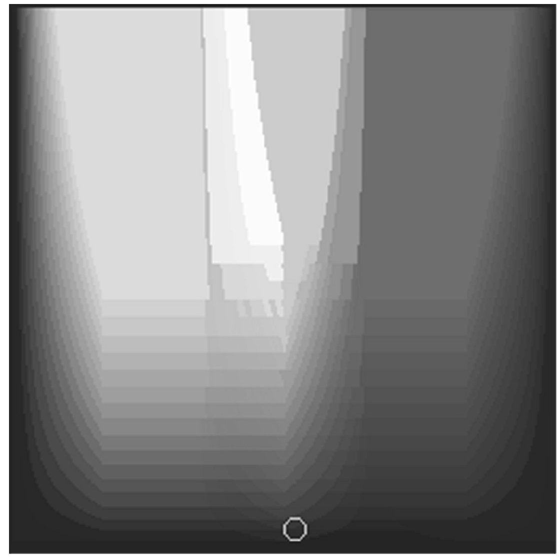


Figure 17. Block diagram for gamut mapping and dithering.

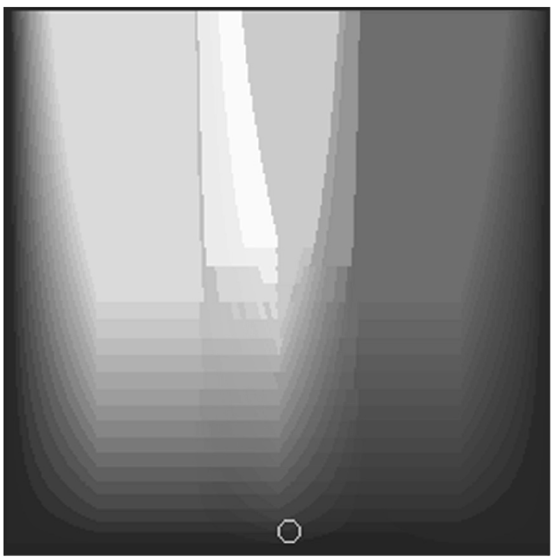
Three images were chosen to test the general performance of the proposed gamut mapping. One of the images was downloaded from the Internet and the other two were generated using a graphic tool. In Figs. 18, 19, and 20, the images were printed by error diffusion using various GMAs. In Figs 18 through 20, (a) is the result printed without gamut mapping; (b) is the result of the CUSP algorithm;[13] (c) is the result of Johnson's algorithm; (d) is the result of Lee's algorithm;[11] and (e) is the result of the proposed algorithm. In Fig. 18(a), the colors are saturated in the mid-tone region, thereby producing a non-linear tonal distribution. Figures 18(b)



(a)



(b)

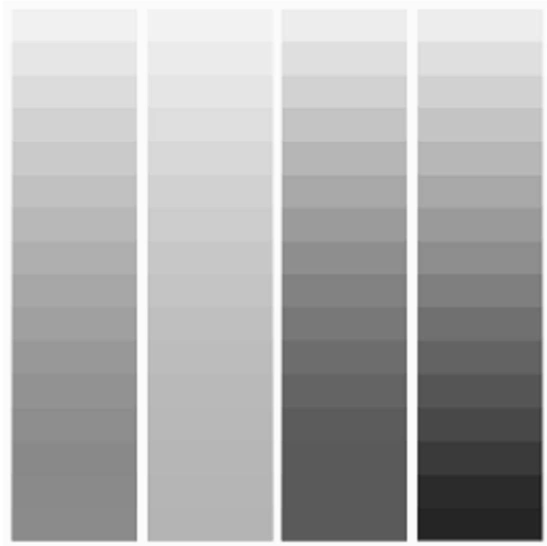


(c)

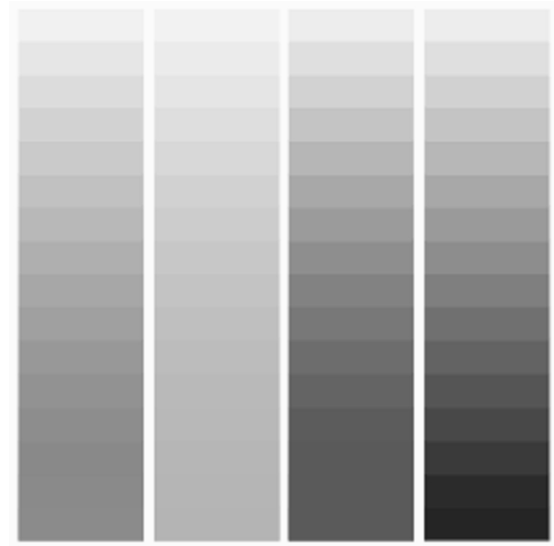
(d)

(e)

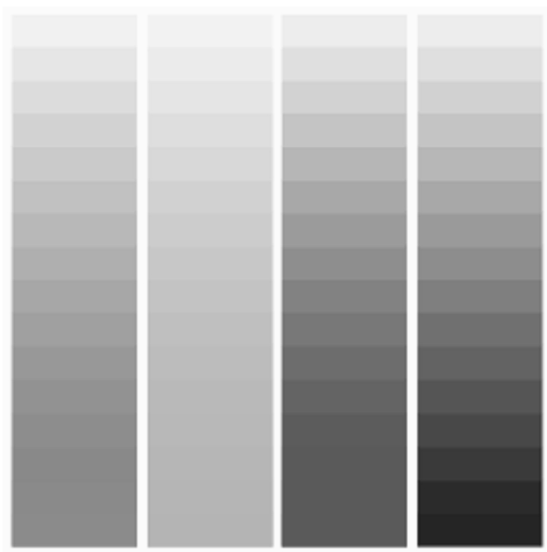
Figure 18. Color chart images printed by error diffusion using various GMAs: (a) with no GMA; (b) CUSP algorithm; (c) Johnson's algorithm; (d) Lee's algorithm; and (e) proposed algorithm. Supplemental Materials—Figures 18 through 22 can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.



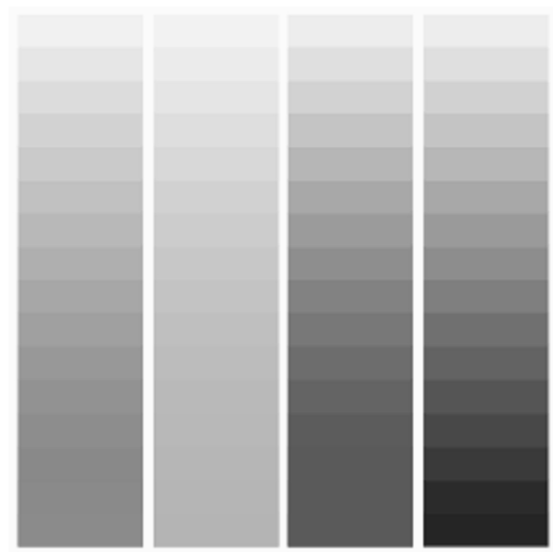
(a)



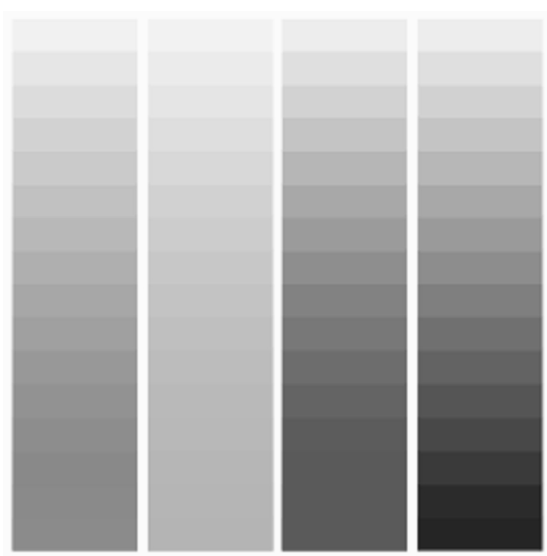
(b)



(c)

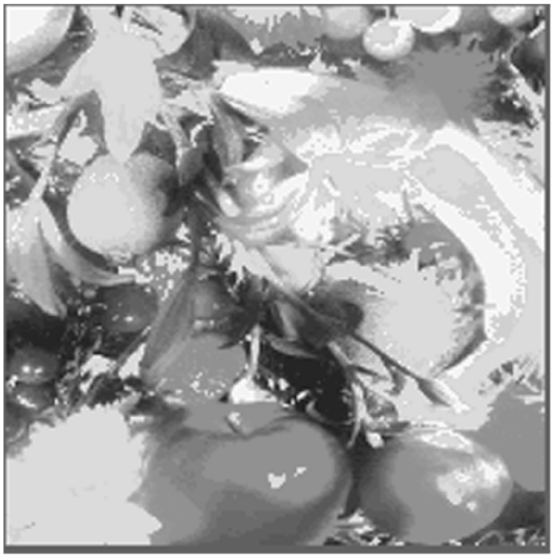


(d)

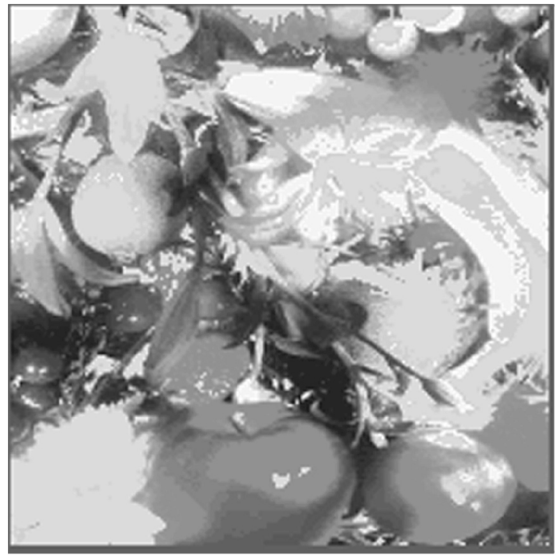


(e)

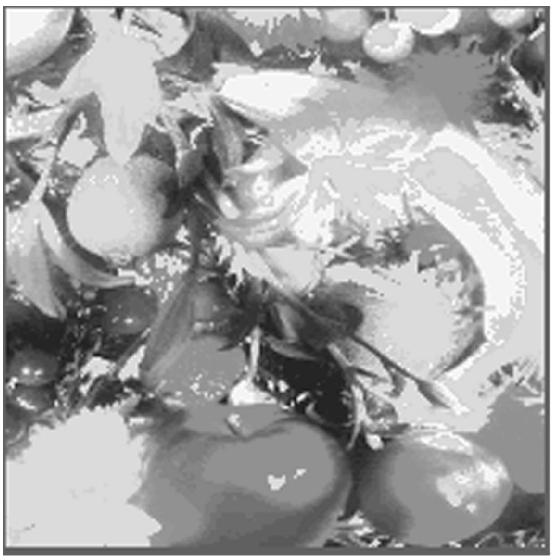
Figure 19. Color bar images printed by error diffusion using various GMAs: (a) with no GMA; (b) CUSP algorithm; (c) Johnson's algorithm; (d) Lee's algorithm; and (e) proposed algorithm. Supplemental Materials—Figures 18 through 22 can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.



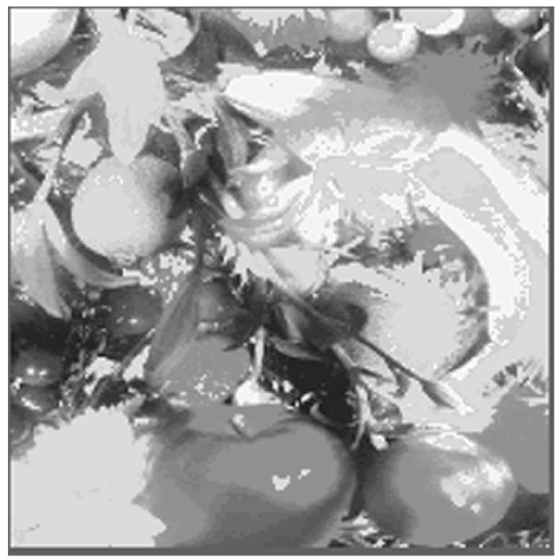
(a)



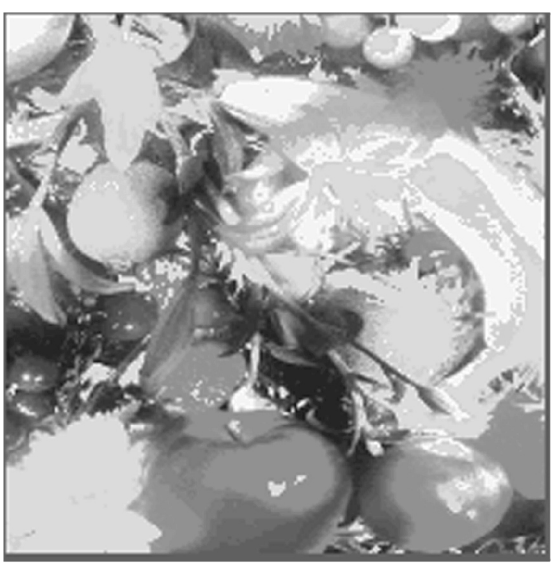
(b)



(c)



(d)



(e)

Figure 20. Fresh images printed by error diffusion using various GMAs: (a) with no GMA; (b) CUSP algorithm; (c) Johnson's algorithm; (d) Lee's algorithm; and (e) proposed algorithm. Supplemental Materials—Figures 18 through 22 can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.

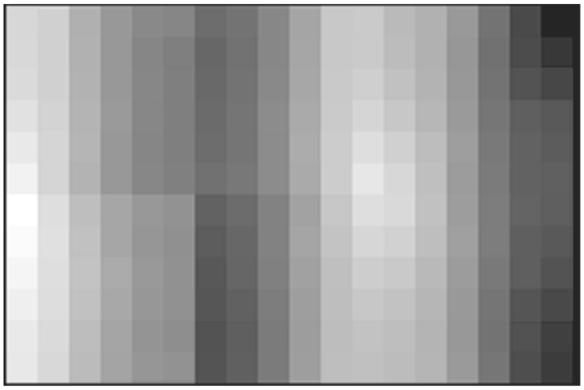


Figure 21. 216 color samples for measuring monitor and printer gamuts. Supplemental Materials—Figures 18 through 22 can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.

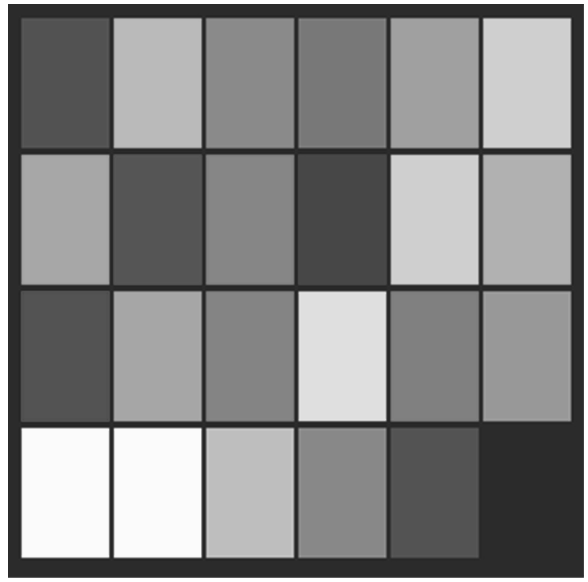


Figure 22. Macbeth color chart. Supplemental Materials—Figures 18 through 22 can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.

and 18(c) show a non-uniform color distribution and non-linear tonal increase at each hue angle. In particular, a greenish component is widely distributed in the bright regions. Figure 18(d) produces an approximately uniform color distribution in all regions, however, the maximum chroma components are reduced and the tonal dynamic ranges are different between the bright and dark regions. However, Figure 18(e) shows an approximately uniform color distribution in all regions and the maximum chroma components are also produced.

In Fig. 19(a), the colors are saturated in the mid-tone region. In Figs. 19(b) and 19(c), the results show that the color changes in the dark regions are not well discriminated and the colors in the bright blue and black regions show a greenish component. Also, in 19(b) and 19(c), the blue components are shown as violet. Figure 19(d) shows a linear color increment, however, the maximum chroma components are not reproduced. In contrast, Fig. 19(e) shows a linear color increment plus the maximum chroma components. Figure 20(b) shows a cyanic component in the white region and 20(c) shows a blocking effect in the right upper region. In Fig. 20(d), the maximum chroma components are smaller than in 20(e). However, Fig. 20(e) shows no cyanic component in the white region or blocking effect. In addition, Fig. 20(e) has a higher contrast than (b), (c), and (d), and effectively represents the chroma component. Furthermore, the black is blacker than with the conventional methods. As the results, the image reproduced by the proposed algorithm was chosen by observers to most like monitor.

The color difference (ΔE^*ab) was used to compare the quality of the GMAs. Figure 21 shows the 216 color samples measured. A Macbeth color chart, as shown in Fig. 22, was used as the color reference for this process. To obtain the color difference between the two devices, the Macbeth color chart was displayed on the monitor and then printed by dithering methods on the printer. Thereafter, the reproduced colors were measured by a spectrophotometer. From theses results, the ΔE^*ab was calculated as follows;

$$\Delta E^*_{ab} = \sqrt{\left(L^*_O - L^*_R\right)^2 + \left(a^*_O - a^*_R\right)^2 + \left(b^*_O - b^*_R\right)^2} \quad (9)$$

TABLE I. Comparison of Gamut Mapping Algorithms Using Error Diffusion

	E*ab
CUSP algorithm	9.865
Johnson's algorithm	13.007
Lee's algorithm	8.665
Proposed algorithm	7.423

where L^*_O, a^*_O, b^*_O are the CIEL*a*b* values measured on the monitor and L^*_O, a^*_O, b^*_O are the CIEL*a*b* values measured on the printer. Table I shows a comparison of the gamut mapping algorithms based on the colors displayed on the monitor and the colors reproduced on the printer using error diffusion. The two conventional methods used for the comparison were the CUSP method that uses the cusp of the two gamuts with a constant hue angle, Johnson's combined lightness and chroma mapping method, and Lee's method that uses variable anchor points. In this table, the proposed algorithm produced fewer errors than the conventional CUSP method or Johnson's and Lee's methods.

Conclusion

A new method was proposed for printing full-resolution color images on limited color output devices. A lightness mapping was proposed that minimizes the lightness difference in the maximum chroma at each hue angle and increases the linearity of the sample distribution in bright and dark regions. As a result, the reproduction gamut is changed to increase a linear tonal distribution of color samples within a range covering the overall lightness. In addition, the original gamut is changed until the lightness difference of the maximum chroma between the two gamuts is minimized.

Next, a parametric-type GMA was proposed to maintain the maximum chroma and produce a uniform tonal dynamic range. In this process, to maintain the maximum chroma, the slope for the variable anchor point is set according to the lightness value of the maximum chroma. To produce a uniform tonal dynamic range, the proposed method uses a combination of a variable anchor point method and a fixed anchor point. Consequently, the proposed algorithm can reproduce a maximum chroma with fewer mapping errors. In conclusion, the proposed techniques enable limited color output devices to display and print high quality color images.

Acknowledgment. This work was supported by grant no. 2000-1-30200-005-3 from the Basic Research Program of the Korea Science and Engineering Foundation.

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