An adaptively spatial color gamut mapping algorithm

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To improve the accuracy of color image reproduction from displays to printers, an adaptively spatial color gamut mapping algorithm (ASCGMA) is proposed. In this algorithm, the compression degree of out-of-reproduction-gamut color is not only related to the position of the color in CIELCH color space, but also depending on the neighborhood of the color to be mapped. The psychophysical experiment of pair comparison is carried out to evaluate and compare this new algorithm with the HPMINDE and SGCK gamut mapping algorithms recommended by the International Commission on Illumination (CIE). The experimental results indicate that the proposed algorithm outperforms the algorithms of HPMINDE and SGCK except for the very dark images.

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When a color image is reproduced from one digital device to another, the color appearance of the reproduction image will disagree with the original one if there are colors in the image being out of the reproduction device gamut, which usually occurs in the image reproduction from computer displays to printers[1]. Herewith, gamut mapping is an important issue in image reproduction, and has been one of the most active directions of color management research. A number of gamut mapping algorithms have been developed in these years, for which Morovič has made a survey[2]. As a whole, the color gamut mapping algorithms can be classified into three categories. The first category is the "device-to-device" gamut mapping algorithm, which is a function of the input and output gamuts[3]. The majority of well-known gamut mapping algorithms fall in this category. The second category is the "image-to-device" gamut mapping algorithm, which is the function of the image statistics[4−6]. Both the first and second categories belong to the "point-to-point" type gamut mapping algorithms, which do not consider the neighbor relationships in the images. Accordingly, the spatial gamut mapping algorithms, classified into the third category, were brought on recently[7−12]. For such gamut mapping algorithms, the mapped color is not only dependent upon the output gamut, but also upon the colors of the neighbor points in the original image.

There is not yet a standard gamut mapping algorithm though a plethora of algorithms have been developed. Up to now, the International Commission on Illumination (CIE) has only recommended two algorithms, the hue-angle preserving minimum ΔE^*_{ab} clipping (HPMINDE) and chroma-dependent sigmoid lightness mapping and cusp knee scaling (SGCK) algorithms[13]. The HPMINDE algorithm is the simplest gamut mapping algorithm, which maps the out-of-reproduction-gamut colors to the boundary of the reproduction gamut with minimum color difference, while the colors in the reproduction gamut are preserved. This algorithm can maximally preserve the chroma of the original colors, but it can cause unacceptable artifacts as most of the out-of-gamut colors may be mapped to the same point. The SGCK algorithm is a combination of GCUSP (chroma-dependent lightness compression and linear compression to cusp)[2] and SLMCKS (sigmoid lightness mapping and cusp knee scaling) algorithms[14]. The lightness range of the original device gamut is firstly scaled to the lightness range of the reproduction gamut through the chroma-dependent sigmoid function, then the lightness and chroma of the lightness scaled color is mapped to the reproduction gamut simultaneously while preserving the hue, where the lightness of anchor point is set as the lightness of the cusp on the reproduction gamut boundary, and the knee line is set as 90% of the reproduction gamut boundary in reference to the anchor point. For the SGCK algorithm, there are three main shortcomings though it performs well[15] and is recommend by CIE. Firstly, the lightness of anchor point is set as the lightness of the cusp on the reproduction gamut boundary, which indeed can make the best use of the reproduction gamut. But if the lightness of the cusp on the reproduction gamut boundary is very low or high, there will be too much compression for the out-of-gamut colors. Secondly, the knee line is heuristically set as 90% of the reproduction gamut boundary. The main advantage of this setting is that the process speed is very fast, but if most of the image colors are out of the 90% of reproduction gamut, these colors will be compressed to the remaining 10% of the reproduction gamut, which results in the loss of image details, and so the artifacts will appear even worse. Thirdly, the SGCK algorithm does not take the neighborhood pixels color into account, which also causes spatial information loss. Most of the existing spatial gamut mapping algorithms decompose the original image into several spatial frequency bands, then apply different gamut mapping strategies for the individual spatial frequency bands, finally the processed bands are summed together with different weights to derive the mapped color[10,11]. This kind of algorithms could indeed keep the spatial relationship of the original image in the reproduction one. However, as the dealing strategies are different among the individual spatial frequency bands, an effective merging of the processed bands is not an easy work[11], which will affect the mapping quality of the algorithms. In addition, the mapping speed tends to be slow as different bands need to be dealt with separately.

In consideration of the weaknesses of HPMINDE, SGCK, and the existing spatial gamut mapping algorithms, a new adaptively spatial color gamut mapping algorithm (ASCGMA) is proposed in this letter. CIE specified that the new developed algorithm should be obligatorily compared with the HPMINDE and SGCK algorithms, then other algorithms could be indirectly compared with the new algorithm through the references of HPMINDE and SGCK[13]. So the ASCGMA, HPMINDE, and SGCK algorithms are applied, respectively, to the gamut mapping from the most popular liquid crystal display (LCD) to printer as an instance, whose results are evaluated through the psychophysical experiment of pair comparison, and the advantages and drawbacks of the three algorithms are discussed in detail. In addition, the new algorithm is also compared with the typical spatial gamut mapping algorithms through the reference of SGCK.

As mentioned above, the lightness of anchor point should not be just set as the lightness of the cusp on the reproduction gamut boundary to avoid the over compression for the colors out of the 90% of the reproduction gamut. So the anchor point can be adaptively set with the consideration of making the best use of the reproduction gamut and the magnitude of the shift of out-of-gamut colors. To achieve this purpose, the lightness of anchor point in ASCGMA is set as the weight sum of the lightness of the cusp and the half lightness of the reproduction gamut, as shown by

$$\begin{cases} L_{\text{anchor}} = \alpha L_{\text{cusp}} + (1-\alpha)(L_{\min} + L_{\max})/2 \\ C_{\text{anchor}} = 0 \end{cases}, \quad (1)$$

where L_{anchor}, L_{cusp}, $L_{\min}$, and $L_{\max}$ denote, respectively, the lightness of the anchor point, the lightness of the cusp on the constant hue gamut boundary, the minimum and maximum lightnesses of the reproduction gamut; α is the weighting variable, which can be adaptively set according to the image color statistics and the shape of the reproduction gamut; C_{anchor} indicates the chroma of the anchor point. To equally emphasis the importance of L_{cusp} and $(L_{\min} + L_{\max})/2$, α is set as 0.5.

Since the "device-to-device" type mapping cannot make the best use of the reproduction gamut, and the "image-to-device" type mapping always loses the spatial details of the image, the proposed ASCGMA adopts the spatial gamut mapping approach to avoid these problems. In addition, ASCGMA is also different from the existing typical spatial gamut mapping algorithms. It directly compresses the out-of-gamut colors toward the anchor point of the reproduction gamut, and the degree of compression depends on the neighbor colors to retain the spatial details among the neighbor points.

First of all, the neighborhood for each color to be mapped in the image should be determined before mapping. For simplicity, the color in the image to be mapped is denoted as target color P_{t}. As the color choice in the neighborhood affects the compression magnitude of the target color, besides the colors in the neighborhood must be close to the target color in the geometry pixel space, the colors in the neighborhood should also be constrained by the color differences between the neighbor colors and the target color, and by the relative position of the target color to the reproduction gamut boundary and the positions of the neighbor colors in the CIELCH color space as well. The neighborhood for each color to be mapped could be determined as follows.

1) The Euclid distance in the geometry pixel space between the color P_{i} in the image and the target color P_{t} should be less than a distance threshold d_{th} as

$$d_{(P_{\text{i}},P_{\text{t}})} = \sqrt{(x_{\text{i}} - x_{\text{t}})^2 + (y_{\text{i}} - y_{\text{t}})^2} < d_{\text{th}}, \quad (2)$$

where $(x_{\text{i}}, y_{\text{i}})$ and $(x_{\text{t}}, y_{\text{t}})$ denote the coordinates of color P_{i} in the image and the target color P_{t} to be mapped, respectively. In this way, only the nearby colors in the geometry pixel space are involved into the neighborhood.

2) The color difference[16] between P_{i} and P_{t} should be less than a color-difference threshold $\Delta E_{ab,\text{th}}$ to only involve the similar colors into the neighborhood. Most of the gamut mapping algorithms have indicated that the preservation of hue is more important than lightness and chroma[2], so the color-difference restriction can be calculated with the weighted CIELAB color difference as

$$\Delta E_{ab,(P_{\text{i}},P_{\text{t}})} = \sqrt{(L_{\text{i}} - L_{\text{t}})^2 + (C_{\text{i}} - C_{\text{t}})^2 + \beta(2\sqrt{C_{\text{i}}C_{\text{t}}}\sin((H_{\text{i}} - H_{\text{t}})/2))^2} < \Delta E_{ab,\text{th}}, \quad (3)$$

where $(L_{\text{i}}, C_{\text{i}}, H_{\text{i}})$ and $(L_{\text{t}}, C_{\text{t}}, H_{\text{t}})$ denote the color coordinates of P_{i} and P_{t}, respectively, and β is the weighting variable to emphasize the importance of hue.

3) The compression of the colors in the reproduction gamut is to keep the color relationship with the nearby out-of-gamut colors, which have to be mapped into the reproduction gamut, so the colors in the neighborhood should be out of the reproduction gamut. Accordingly, the number of colors included in the neighborhood decreases with the increase of distance from the target color to the anchor point. For the particular case of the target color being in the deep reproduction gamut, there will be no color in the neighborhood, so the target color will not be modified, which could maximally preserve the color appearance of the original image in the reproduction one.

4) Only when a color's corresponding distance to the anchor point is longer than that between the target color and anchor point in the chroma-lightness plane, it will affect the compression of the target color. Hence merely those colors away from the anchor point farther than the target color are involved into the neighborhood.

Once the neighborhood for the target color has been determined, the compression magnitude of the target color could be derived through the colors in the neighborhood. However, the contribution of the colors in the neighborhood to the compression magnitude should vary with the closeness of the target color P_{t} to the color P_{i} in the neighborhood. The bilateral filter[17] is widely used to weight the importance between neighbor colors in spatial gamut mapping algorithms, and the improved bilateral filter, employed in this algorithm is described as

$$s_{(P_{\mathrm{i}},P_{\mathrm{t}})} = \mathrm{e}^{-\frac{1}{2}\left(\frac{d_{(P_{\mathrm{i}},P_{\mathrm{t}})}}{\sigma_d}\right)^2},$$
$$c_{(P_{\mathrm{i}},P_{\mathrm{t}})} = \mathrm{e}^{-\frac{1}{2}\left(\frac{\Delta E_{ab,(P_{\mathrm{i}},P_{\mathrm{t}})}}{\sigma_c}\right)^2}, \quad (4)$$

where $s_{(P_{\mathrm{i}},P_{\mathrm{t}})}$ and $c_{(P_{\mathrm{i}},P_{\mathrm{t}})}$ are the geometric and color closenesses, respectively, between the color P_{i} in the neighborhood and the target color P_{t}; $d_{(P_{\mathrm{i}},P_{\mathrm{t}})}$ and $\Delta E_{ab,(P_{\mathrm{i}},P_{\mathrm{t}})}$ denote the Euclid distance and weighting color difference as shown in Eqs. (2) and (3), respectively; σ_d and σ_c are the spread parameters of the Gaussian function, and σ_d should vary with the image size and the viewing condition. Considering the influences of different values for σ_d and σ_c investigated by many researchers[3,11,12,17], both σ_d and σ_c are heuristically adopted as 3 in this study. Once the values of σ_d and σ_c have been fixed, d_{th} and $\Delta E_{ab,\mathrm{th}}$ could be accordingly determined as to be not less than three times of σ, corresponding to the 0.997 integral area of the Gaussian distribution, in order to involve as many neighbor colors into the neighborhood as possible. However, the larger of the d_{th} or $\Delta E_{ab,\mathrm{th}}$ is, the slower the mapping speed is, since the number of colors in the neighborhood increases with the increase of d_{th} and $\Delta E_{ab,\mathrm{th}}$. In this study, both d_{th} and $\Delta E_{ab,\mathrm{th}}$ are adopted as 10 to make a compromise, and β is set as 5 in Eq. (3) by trial and error.

The neighborhood and the bilateral filter for each color to be mapped have been determined now. Then, the compression magnitude could be derived through the statistically mean offset vector of the colors in the neighborhood weighted by the bilateral filter. To compress the target color P_{t}, the mathematical framework of ASCGMA is given as

$$\mathbf{P}_{\mathrm{t,res}} = \mathbf{V}_{\mathrm{t,clip}} + w_{\mathrm{t}}\mathbf{V}_{\mathrm{t,u}} + \mathbf{P}_{\mathrm{a}}, \quad (5)$$
$$\mathbf{V}_{\mathrm{t,clip}} = \mathbf{P}_{\mathrm{t,clip}} - \mathbf{P}_{\mathrm{a}}, \quad (6)$$
$$\mathbf{V}_{\mathrm{t,u}} = \frac{\mathbf{P}_{\mathrm{t}} - \mathbf{P}_{\mathrm{a}}}{|\mathbf{P}_{\mathrm{t}} - \mathbf{P}_{\mathrm{a}}|}, \quad (7)$$

where $P_{\mathrm{t,res}}$ denotes the compression resultant color, P_{a} represents the anchor point, and $P_{\mathrm{t,clip}}$ is the simultaneous clip[2] gamut mapping point of P_{t}. If P_{t} is in the reproduction gamut, $P_{\mathrm{t,clip}}$ equals P_{t}, else $P_{\mathrm{t,clip}}$ is the point of interception between the vector from P_{t} to P_{a} and the reproduction gamut line boundary of hue H_{t}. $\mathbf{V}_{\mathrm{t,clip}}$ and $\mathbf{V}_{\mathrm{t,u}}$ represent, respectively, the vector from $P_{\mathrm{t,clip}}$ to P_{a} and the unit vector from P_{t} to P_{a}, and w_{t} is the weighting variant, which can be calculated through the neighboring colors as

$$w_{\mathrm{t}} = \begin{cases} \dfrac{\sum\limits_{P_{\mathrm{i}}\in A} s_{(P_{\mathrm{i}},P_{\mathrm{t}})}c_{(P_{\mathrm{i}},P_{\mathrm{t}})}(\mathbf{V}_{\mathrm{i}}-\mathbf{V}_{\mathrm{i,clip}})\cdot\mathbf{V}_{\mathrm{t,u}}}{\sum\limits_{P_{\mathrm{i}}\in A} s_{(P_{\mathrm{i}},P_{\mathrm{t}})}c_{(P_{\mathrm{i}},P_{\mathrm{t}})}}, & P_{\mathrm{t}} \in \text{gamut} \\ \dfrac{\sum\limits_{P_{\mathrm{i}}\in A} s_{(P_{\mathrm{i}},P_{\mathrm{t}})}c_{(P_{\mathrm{i}},P_{\mathrm{t}})}((\mathbf{V}_{\mathrm{i}}-\mathbf{V}_{\mathrm{i,clip}})\cdot\mathbf{V}_{\mathrm{t,u}}-|(\mathbf{V}_{\mathrm{t}}-\mathbf{V}_{\mathrm{t,clip}})|)}{\sum\limits_{P_i\in A} s_{(P_{\mathrm{i}},P_{\mathrm{t}})}c_{(P_{\mathrm{i}},P_{\mathrm{t}})}}, & P_{\mathrm{t}} \notin \text{gamut} \end{cases}, \quad (8)$$

where A represents the neighborhood, $\mathbf{V}_{\mathrm{i}}$ and $\mathbf{V}_{\mathrm{t}}$ denote the vectors from P_{i} in the neighborhood to P_{a} and from P_{t} to P_{a} in the chroma-lightness plane, respectively, $\mathbf{V}_{\mathrm{i,clip}}$ is the vector from $P_{\mathrm{i,clip}}$ to P_{a}, and "·" denotes the scalar product.

To evaluate the proposed gamut mapping algorithm ASCGMA, seven images were gamut mapped from a LCD (Eizo cg220) to an ink-jet printer (Canon S100SP) with the ASCGMA, HPMINDE, and SGCK algorithms, respectively. The seven images are illustrated in Fig. 1, in which image 1 is the obligatory test image, images 2–4 are the recommended images as specified by the CIE guidelines[13], while images 5–7 are typically selected from the Kodak Photo CD image samples. The psychophysical experiment of pair comparison was conducted to compare the performances among HPMINDE, SGCK, and ASCGMA. To eliminate the visual effect caused by the media difference between the display and printer so as to focus on the comparisons among the three algorithms, the visual assessments were implemented on the Eizo display. The original image was displayed in the middle of the screen, and two reproduced images by different gamut mapping algorithms were randomly shown on the left and right side of the original one. There were 21 combinations of compared images for the three algorithms and seven images. The order of the 21 combinations appearing to the observer was also in random to avoid the memorial effect. A panel of 10 observers took part in the psychophysical experiment, in which the observers were asked to judge which of the two reproduced images was more accurate in comparison with the original one based on the different parts of the images. Each reproduced image was evaluated twice by every observer on different days.

The mean values of the two assessments for individual images were calculated for each observer, which were then converted to z-scores following the Morovic's method[2]. The 95% confidence intervals were also calculated to verify whether the performances of HPMINDE, SGCK, and ASCGMA were significantly different from each other.

Fig. 1. Seven images for testing gamut mapping algorithms from display to printer.

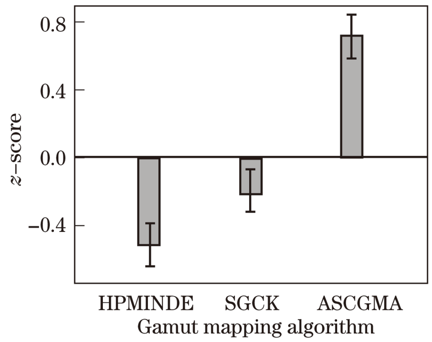

Fig. 2. z-scores of HPMINDE, SGCK, and ASCGMA for all the images and observers.

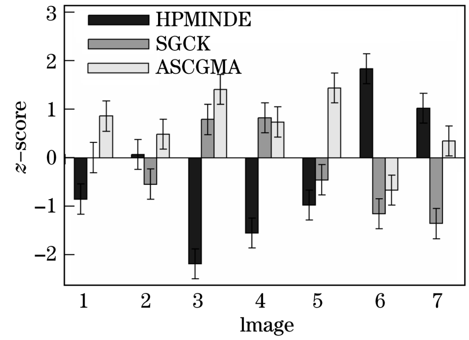

Fig. 3. z-scores of seven test images for HPMINDE, SGCK, and ASCGMA.

Table 1. Percentages of Colors with Lightness Being Less Than 50 for All Test Images, z-Scores for HPMINDE, SGCK, and ASCGMA, and Their Correlation Coefficients

Test Image	1	2	3	4	5	6	7	Correlation Coefficient
Percentage of Colors (%)	50	54	41	49	55	82	72	
z-Score of HPMINDE	–0.86	0.06	–2.19	–1.56	–0.98	1.83	1.02	0.96
z-Score of SGCK	0.00	–0.55	0.79	0.82	–0.46	–1.16	–1.36	–0.87
z-Score of ASCGMA	0.86	0.48	1.41	0.73	1.44	–0.67	0.34	–0.86

The resulted z-scores and confidence intervals for all images and all observers are depicted in Fig. 2, which shows that ASCGMA outperforms significantly the other two algorithms, followed by SGCK, and HPMINDE the poorest as a whole. It indicates that the ASCGMA algorithm can indeed improve the gamut mapping performance.

For the individual images, HPMINDE performed the best on image 6 and image 7, and a little better than SGCK on image 2, as illustrated in Fig. 3. This is because that the colors in image 2 and, especially, image 6 and image 7 are much darker than the others. Table 1 lists the percentage of colors whose lightness is less than 50 and the corresponding z-scores for each test image, together with the correlation coefficients between the percentages of low lightness colors and the z-scores for the three algorithms. As seen from Table 1, there are correlations between the percentages and the z-scores of the three algorithms; especially, a strong correlation exists between the percentages and the z-scores for HPMINDE algorithm. The fact that the principles of the individual algorithms are different is the main reason for HPMINDE performing better than SGCK and ASCGMA for the dark images. HPMINDE maps the out-of-gamut colors to the boundary of the reproduction gamut and preserves the colors in the gamut, so the mapped images can still remain dark for the original dark images. On the other hand, SGCK and ASCGMA map the out-of-gamut colors to the anchor point of the reproduction gamut, so the colors in the gamut may also be changed such that the mapped images are much lighter than the original dark images. However, HPMINDE performs the poorest for all the other images, while ASCGMA is better than or similar to SGCK for all the images. Generally, ASCGMA performs rather well for all the test images except for the very dark image 6. Dugay *et al.* have implemented two psychophysical experiments to evaluate the accuracy among HPMINDE, SGCK, and three typical spatial gamut mapping algorithms (Zolliker, Kolås, and Gatta)[15], the result indicated that SGCK performed most steadily and no worse than the three spatial algorithms. The above comparison implies, in a sense, that ASCGMA outperforms the three typical spatial gamut mapping algorithms according to the CIE guidelines[13].

In conclusion, a survey of the gamut mapping algorithms is summarized, together with the principles, advantages, and drawbacks of HPMINDE and SGCK recommended by CIE, based on which a new adaptively spatial gamut mapping algorithm is proposed. To compare the proposed algorithm and the two algorithms recommended by CIE, seven typical digital images are selected to test their gamut mapping performances from an Eizo display to a Cannon printer. The psychophysical experiment of pair comparison is carried out by a panel of 10 observes to evaluate these algorithms. The visual results indicate that, as a whole, ASCGMA performs the best, HPMINDE is the poorest, and SGCK is in between, while HPMINDE exhibits superiority for very dark images.

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