Applying Non-linear Compression to the Three-dimensional Gamut Mapping

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Abstract

Gamut mapping is a technique to transform out-of-gamut colors to the inside of the output device's gamut. It is essential to develop effective mapping algorithms to realize WYSIWYG (What You See Is What You Get) color reproduction.[1] We had previously found that three-dimensional gamut mapping is superior to the two-dimensional mapping, when we applied Mahalanobis distance as a color difference equation, such as BFD color difference formula,[2,3] However, in our previous experiments, a clipping method was used that maps all out-of-gamut colors to the surface of the gamut, and no change was made to colors inside the gamut. Since this method could possibly cause loss of gradation in an image, we had investigated non-linear compression for the three-dimensional gamut mapping in this study. The results of visual experiments indicated that preferred compression method depends on image contents. If the saturated colors that are out-of-gamut contain high frequency, a certain degree of compression was needed. On the other hand, if those colors only have gradual change with low frequency, clipping method was more preferred.

1. Introduction

A number of recent color management systems (CMS's) on the market have realized device independent color environment, i.e., consistent colors across different devices. However, current CMS's involve some technical problems,[4,5] one of which is the gamut difference between devices. Among the variety of devices, the gamut difference is most noticeable between a CRT monitor and a hardcopy printer. For a typical printer, the gamut volume in CIELAB color space is only 50 to 80% of that of a typical CRT monitor.[6] For this reason, it is impossible for the printer to reproduce all the colors on the monitor. Consequently, out-of-gamut colors of the monitor have to be mapped to the inside of the printer gamut while minimizing a change in image appearance. The purpose of gamut mapping is to preserve the appearance of an image as much as possible when the image is reproduced by a different device or in a different medium.

There are mainly two considerations in gamut mapping:

a) Mapping direction - where out-of-gamut colors are mapped
b) Mapping method - how the colors are mapped in a given direction

The first involves deciding the direction in color space to which out-of-gamut colors are to be mapped, and could further be categorized into mapping directions in one-dimensional, two-dimensional, and three-dimensional space. The human visual system perceives three attributes of color, i.e., lightness (L*), chroma (C*), and hue (h). Gamut mapping is usually performed in a color space that represents these attributes. It is desirable that gamut mapping be performed in a perceptually uniform color space, and the mapping direction is usually decided in such a color space.

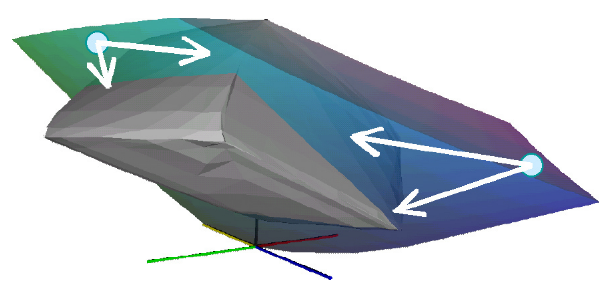


Figure 1. Mapping Directions

Once the mapping direction has been defined, how the colors are mapped in a given direction should be considered, next. This second consideration in gamut mapping: mapping methods, can further be broken down into three categories: 2-1) clipping method, 2-2) linear compression method, and 2-3) non-linear compression method as shown in figure 2.In this study, we had applied knee function as non-linear compression to the three-dimensional gamut mapping.

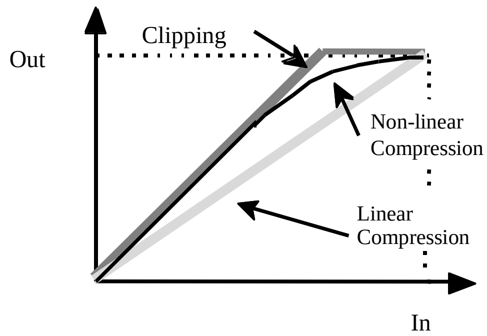


Figure 2. Mapping Methods

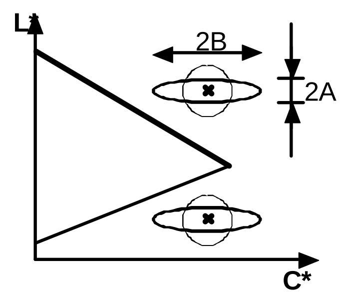
2. Mapping Direction

It was believed that one-dimensional chroma mapping while keeping lightness and hue constant was the preferred technique. However, when mapping saturated blue or yellow color, this technique causes an objectionable decrease of saturation. This is due to the large difference between the gamut boundaries in the chroma direction in these regions. To overcome these problems, a number of two-dimensional mapping techniques have been proposed.[7-9] For two-dimensional mapping, mapping lightness and chroma while keeping hue constant is generally preferred. However, we have found that mapping in the lightness direction reduces the image contrast and mapping in the chroma direction reduces the image vividness. This lead us to think that three-dimensional mapping technique including hue might be more effective than two-dimensional mapping in constant-hue plane.

However, only a few algorithms on gamut mapping in a three-dimensional space have been studied.[2,3,10-12] We had investigated a three-dimensional gamut mapping technique which maps all out-of-gamut colors by minimizing the weighted color difference for metric lightness, chroma, and hue in CIELAB color space.[2] The weighted color difference equation used was:

$$\Delta E_{wt} = \sqrt{\left(\frac{\Delta L^*}{K_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{K_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{K_H}\right)^2} \qquad (1)$$

K_L, K_C, and K_H are the weighting coefficients for lightness, chroma, and hue respectively. Based on a psychophysical experiment, we found that the most accurate reproductions were obtained when the (Kl:Kc:Kh) coefficients were set to (1:2:1) or (1:2:2). This indicates that larger changes are acceptable in chroma than in hue and that the smallest change is tolerated in lightness. We concluded that images mapped with $K_C \bullet K_H \bullet K_L$ gave the best matching results. This relation of these coefficients had the same tendency as the relation of the weighting functions in the CIE 1994 color difference formula,[13] which implies that lightness information is most important, and chroma could be compressed most. However, we noticed a large hue shift in blue region when gamut mapping was performed in CIELAB color space. This is caused by the curvature of the blue hue loci in CIELAB.[14,15] Mapping direction in three-dimensional space could be controlled using Mahalanobis distance as a distance function to the gamut boundary. Therefore, we investigated three-dimensional gamut mapping using various color difference formulae and color spaces.[3] The color difference formulae used in the experiments were ΔE^*_{ab}, ΔE^*_{uv}, ΔE_{94}, ΔE_{CMC}, ΔE_{BFD}, and ΔE_{wt}. The color spaces used in the experiments were CIELAB, CIELUV, CIECAM97s, IPT, and NC-IIIC[3]. In terms of the color difference formulae in CIELAB color space, gamut mapping using weighted color difference formulae such as ΔE_{94}, ΔE_{CMC}, and ΔE_{wt} were found to be more effective than normal Euclidean distance. For mapping images containing a large portion of blue colors, ΔE_{BFD} and ΔE^*_{uv} were found to be more effective. With respect to color spaces, gamut mapping performed in the CIELUV color space was superior to any other color spaces for the blue region. We concluded that ΔE_{BFD} in CIELAB and ΔE_{94} in CIELUV are the most useful combination if we are to apply same gamut mapping universally.



$$\Delta D = \sqrt{\left(\frac{\Delta L^*}{A}\right)^2 + \left(\frac{\Delta C^*}{B}\right)^2} \qquad (\Delta H^* = 0)$$

Figure 3. Mahalanobis Distance used for Color Difference Equation (in two dimensional space)

However, in our experiments, a clipping method was used that maps all out-of-gamut colors to the surface of the gamut, and no change was made to colors inside the gamut. Some of the past studies[16-18] in two-dimensional gamut mapping indicate that compression method is superior to clipping for some images. Therefore, in this study, we applied compression method in a three-dimensional gamut mapping.

3. Mapping Method

The clipping method maps all out-of-gamut colors to the surface of the reproduction gamut, and no change is made to colors inside the gamut. This method can sometimes cause loss of gradation in an image because some of the colors are mapped to the same point, but it maintains most of the image saturation. The linear compression method linearly maps all colors of the original gamut into the reproduction gamut. This method maintains the gradations in its image, but it decreases image saturation. The non-linear compression method maps all the colors of the original gamut into the reproduction gamut using a non-linear function. This method can minimize the loss of detail that occurs with clipping, while retaining the advantage of reproducing accurately most of the common gamut colors. It is generally thought that if the amount of out-of-gamut colors is small, the preferred technique is the clipping method, and if the amount of out-of-gamut colors is large, the preferred technique is linear or non-linear compression.[17] This implies that the appropriate compression method depends on the image contents.

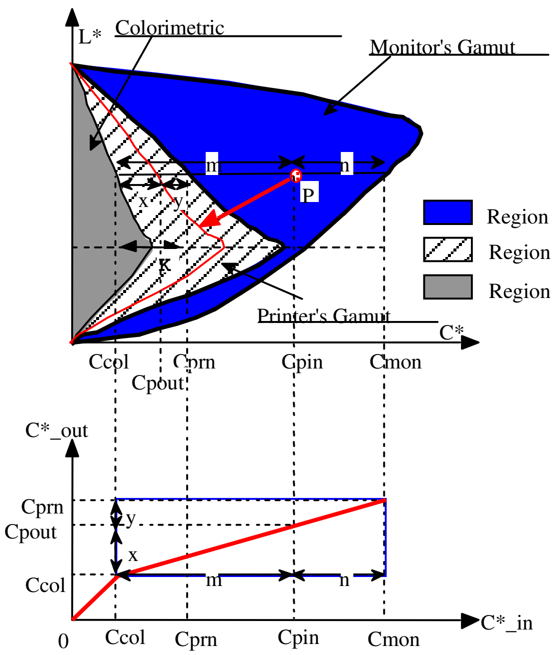


Figure 4. Non-linear Compression in Three-dimensional Gamut Mapping (Onion-peel Method)

Here, we applied non-linear compression method to the three-dimensional gamut mapping. First, a virtual gamut boundary is created proportional to output device (Printer)'s gamut. We call this method as "onion-peel" method, because peeling off its real gamut surface creates virtual gamut boundaries. For example, if the color is located at point P in figure.4, a virtual gamut is created as to satisfy a ratio (m:n = x:y), which is defined by a compression function given below. The compression function could be either linear or non-linear function. In figure 4, knee function was used for the non-linear compression. Then, a color on the virtual gamut boundary that has minimum color difference is selected as a mapped color for point P. Any kind of Mahalanobis distance could be used for a color difference formula. In this experiment, we used ΔE_{94} as a color difference equation in CIELUV color space, as our previous results indicated this combination was superior to others.

By using knee function (or similar functions that partially has 45 degree slope line), colors in region C will remain same, which means that colors won't be compressed. Therefore, region C is called as "colorimetric region." On the other hand, colors in both region A and region B will be compressed into region B. In this study, we have applied several kinds of three-dimensional gamut compression by changing area of region C, i.e., colorimetric region. This could be controlled by changing knee point of the knee function.

4. Experiments and Results

Visual experiments were performed to evaluate which of the non-linear function performed best. Experiments were performed in a dark room to eliminate color appearance differences between an original image on the CRT monitor: Sony GDM-2000TC and the images reproduced by the continuous color ink-jet printer: Iris Realist FX. Both the CRT monitor and the continuous ink jet printer were cololimetrically characterized. Observers made comparisons between an original image displayed on the CRT monitor and a pair of reproduced hardcopy images in the Macbeth SpectraLight® light-booth. The CRT and the light-booth were placed at 90 degrees from each other with respect to the observers. The successive binocular viewing technique was used for image comparison. An original image displayed on the CRT monitor had a white proximal field of 2 degrees visual field and a background was a neutral gray with 20% luminance factor. The reproduction images also had a proximal field and a background that were similar to the original image. Using a paired-comparison paradigm, every possible pair of different reproduction was presented in the light-booth and the subjects' task was to choose which of the pair looked more similar to the original image displayed on the CRT monitor. Twelve observer participated in the experiments.

Image A

Image B

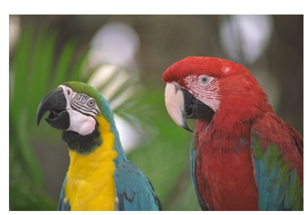


Image C

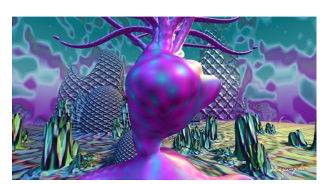


Image D (©Kawaguchi)

Figure 5. Four Images Used for Visual Experiments

Four images were used in these experiments; image A is from the SHIPP image that has ten balls of yarn in variety of colors. Image B is a portrait image of a lady with many colorful objects. Image C has two macaws; one is cyan and yellow, and the other is red, and image D is a CG image in magenta color. The ratio of out-of-gamut colors of each image was 57, 22, 11 and 46% respectively. And the average color difference: ΔE_{94} of the out-of-gamut colors of each image was 2.30, 2.82, 1.59 and 4.42, respectively. (Note that ΔE_{94} is reduced for highly saturated colors than normal ΔE^*ab)

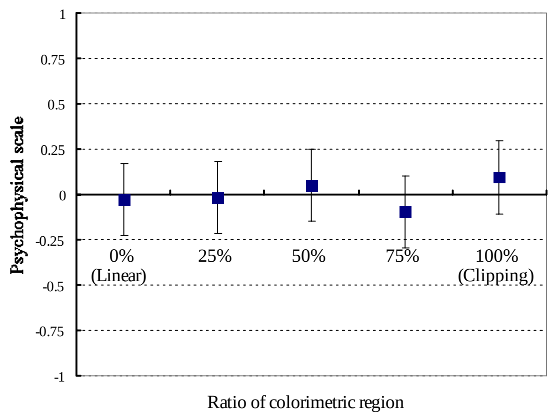


Figure 6. Results of Visual Experiments (Average of four images) – Abscissa indicates ratio of the colorimetric region and ordinate indicates psychophysical scale.

As an average of all of four images in figure 6, no statistical difference was found among the compression methods. However, if we see each image separately in figure 7, different trends were found for different images. This implies that compression method depends on image contents. First, for an image A and C, images that are compressed to a certain degree were more preferred than an image with simple-clipping method. These images include high frequency in saturated colors; shadows in balls of yarn in image A, and feather in image C. On the other hand, for a CG image (image D), that contains much of saturated colors in low frequency, clipping method was most preferred. Image B had almost no preference, statistically. These trends had almost no correlation with either "the average color difference: ΔE_{94} of the out-of-gamut colors" or "the ratio of out-of-gamut colors" explained earlier. Image D had the largest ratio of out-of-gamut colors and its average color difference was largest of all the four images used in the experiments. Yet, clipping method was most preferred. Conversely, clipping method was least preferred for image C that has the smallest ratio of out-of-gamut colors and its average color difference was smallest. Rather, experimental results indicate that compression method depends on the spatial frequency of saturated (i.e., out-of-gamut) colors.

This indicates that human visual system is less sensitive to the loss of the gradation information when the colors in high chroma are gradually changing, as in image D.

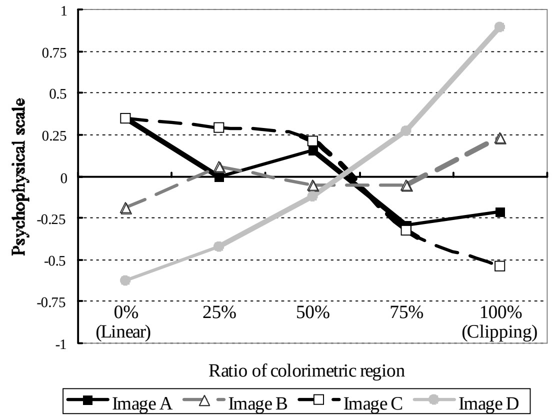


Figure 7. Results of Visual Experiments (Each of four images) – Abscissa indicates ratio of the colorimetric region and ordinate indicates psychophysical scale.

5. Discussion

Nakauchi et al. proposed that gamut mapping should be performed as to minimize human perceptual difference of the image, not just color difference of individual pixels[19]. The perceptual difference between reproduction and original: ***PD*** is defined by applying human visual system's CSF (contrast sensitivity function) to the surrounding pixels of the image and then obtaining their difference between the original and reproduction.

$$PD = \sum_{c} \sum_{fc} \left\| h_{fc}^{c} * \left[o^{c}(x,y) - r^{c}(x,y) \right] \right\|^2 \qquad (2)$$

Here h is the point-spread-function of spatial frequency channel. $o(x,y)$ and $r(x,y)$ are the 2D image planes of an original and reproduction at the point (x,y) in the image and the asterisk (*) represents convolution. Their idea is to keep gradation information in image during gamut mapping, if it could be perceived by human visual system, and their result also indicates that simple clipping was not preferred for most of the images. This technique needs to be calculated image to image basis, and its optimization iteration time might not be practical for industrial use at this moment. However, we believe it is our next challenge to incorporate CSF in gamut mapping for pictorial images.

6. Conclusion

Non-linear compression was applied to three-dimensional gamut mapping. Experimental results indicate that preferred compression method depends on image contents, and these results have no correlation with neither average color difference or ratio of out-of-gamut colors. If the saturated colors that are out-of-gamut have high frequency, certain compression was needed. On the other hand, if those color changes are gradual, simple clipping was most preferred.

References

1. R. S. Berns, "Color WYSIWYG: A Combination of Device Colorimetric Characterization and Appearance Modeling", *SID 92 Digest*, 549-552, (1992)
2. N. Katoh, M. Ito, "Gamut Mapping for Computer Generated Images (II)", *Proc. IS&T/SID's Color Imaging Conf.*, **4**, 126-129, (1996)
3. M. Ito, N. Katoh, "Three-dimensional Gamut Mapping Using Various Color Difference Formulae and Color Spaces," *Proc. SPIE* **3648**, 83-95, (1999)
4. M. R. Luo, J. Morovic, "Two Unsolved Issues in Colour Management - Colour Appearance and Gamut Mapping," *Proc. 5th Intl. Conf. High Technology: Imaging Science and Technology - Evolution & Promise*, Chiba, Japan, 136-147 (1996)
5. N. Katoh, et al., "Effect of Ambient Light on Color Appearance of Softcopy Images: Mixed Chromatic Adaptation for Self-luminous Displays," *J. Elec. Imaging*, **7**, 794-806 (1998)
6. N. Katoh, T. Deguchi, "Reconsideration of CRT Monitor Characteristics," *Proc. IS&T/SID Color Imaging Conf.*, **5**, 33-40 (1997)
7. E. G. Pariser, "An Investigation of Color Gamut Reduction Techniques", *IS&T Symp. Elec. Prepress Tech. - Color Printing*, 105-107, (1991)
8. M. Ito, N. Katoh, "Gamut Compression for Computer Generated Images", *Extended Abstracts SPSTJ 70th Anniversary Symp. of Fine Imaging (in Japanese)*, 85-88, (1995)
9. J. Morovic, M. R. Luo, "Cross-media Psychophysical Evaluation of Gamut Mapping Evaluation of Gamut Mapping Algorithms", *Proc. AIC Color 97 Kyoto*, **2**, 594-597, (1997)
10. K. E. Spaulding, et al., "UltraColor: A New Gamut Mapping Strategy", *Proc. SPIE **2414***, 61-68, (1995)
11. N. Tsumura, et al., "Color Gamut Mapping Based on Mahalanobis Distance for Color Reproduction of Electronic Endoscope Image under Different Illuminant", *Proc. Color Imaging Conf.*, **5**, 158-162, (1997)
12. F. Ebner, M. D. Fairchild, "Gamut Mapping from Below: Finding Minimum Perceptual Distances for Colors Outside the Gamut Volume", *Color Res. Appl.*, **22**, 402-413, (1997)
13. CIE 116-1995, "Industrial Colour-Difference Evaluation", (1995)
14. P. C. Hung, R. S. Berns, "Determination of Constant Hue Loci for a CRT Gamut and Their Predictions Using Color Appearance Space", *Color Res. Appl.*, **20**, 385-295, (1995)
15. F. Ebner, M. D. Fairchild, "Finding Constant Hue Surfaces in Color Space", *Proc. SPIE* **3300**, 107-117, (1998)
16. R. S. Gentile, et al., "A Comparison of Techniques for Color Gamut Mismatch Compensation", *J. Imaging Tech.*, **16**, 176-181, (1990)
17. T. Hoshino, R. S. Berns, "Color Gamut Mapping Techniques for Color Hard Copy Images," *Proc. SPIE* **1909**, 152-164, (1993)
18. E. D. Montag, M. D. Fairchild, "Psychophysical Evaluation of Gamut Mapping Techniques Using Simple Rendered Images and Artificial Gamut Boundaries", *IEEE Trans. on Image Proc.*, 977-989, (1997)
19. S. Nakauchi, et al., "Color Gamut Mapping Based on a Perceptual Image Difference Measure," *Color Res. Appl.*, **24**, pp.280-291, (1999)