A Psychophysical Evaluation of a Gamut Expansion Algorithm Based on Chroma Mapping

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Abstract

Recently, wide-gamut monitors and printers have begun to appear in the market. However, there are no appropriate tools for evaluating color reproduction in such image output devices. This report describes a method to create the image data for evaluation of the wide-gamut devices. The method expands the gamut of the source image in a manner that a color in the image is mapped into a color with higher chroma and the same hue and lightness, by using a chroma mapping function. The method was applied to sRGB images such as XYZ-SCID images to make the test images for evaluating wide-gamut output devices. In order to find the optimal chroma mapping function, a psychophysical experiment was performed, where the test images made with three types of mapping functions were visually evaluated. Results show that observers judged the test images expanded with nonlinear functions were the best quality.

Introduction

Rapidly developing digital cameras and the spread of them into industrial fields such as the graphic arts industry have allowed wide color gamut image data to circulate. With increasing wide gamut image data, wide gamut monitors and printers have begun to appear in the market. However, there are no appropriate tools to evaluate such image output devices. If there exists standard image data that are designed to evaluate the wide gamut output devices, one can recognize the characteristics of the devices by using the image data. The standard image data, XYZ-SCID or CMYK-SCID, have been used for evaluation of conventional image output devices such as sRGB monitors and CMYK printers, but cannot be applicable to the wide-gamut image output devices.

There are two methods to prepare the wide-gamut image data available for evaluating the devices. One is to create wide-gamut image data by using an image input device and an image retouching software. However, this takes much effort and time. The other is to expand the gamut of standardized image data so that they can have larger gamut. This has an advantage in that the quality of the gamut-expanded images can be guaranteed to some extent, as well as we do not need to create completely new image data from the start.

In this study, the latter method was adopted. A gamut expansion algorithm was applied to RGB images, whose colors are reproducible on typical monitors, to obtain images with high chroma.

Gamut Expansion Algorithm

Adobe RGB color space was adopted as the color space for representing colors in the wide-gamut images, because the Adobe RGB color space has larger gamut than sRGB color space. Some sRGB images represented as XYZ tristimulus values are used as source images to make the wide-gamut images by gamut expansion. The gamut expansion algorithm employed in this study is defined in four steps.

1. Convert XYZ values to CIELCh values representing Lightness, chroma, and hue values.
2. Perform the color gamut expansion with chroma mapping functions at each lightness level.
3. Convert CIELCh values of the mapped colors to XYZ values.
4. Convert XYZ values to RGB values.

Step 1. Convert XYZ to CIELCh

Let the source and destination gamuts can be expressed in a constant hue plane as shown in Fig. 1. Let $X_0Y_0Z_0$ denote the XYZ tristimulus values of a source image. The values $X_0Y_0Z_0$ are transformed into CIELAB values, L^*_0, a^*_0, and b^*_0. Then hue angle h_0 and chroma C^*_0 are calculated from the following equation with the values a^*_0 and b^*_0.

$$C = \sqrt{(a_0^*)^2 + (b_0^*)^2} \qquad (1)$$

$$h_0 = \tan^{-1}(b_0^* / a_0^*) \qquad (2)$$

Step 2. Perform Gamut Expansion

The gamut expansion is performed at each lightness level such that the chroma C^*_0 of source image is transformed to the chroma C^*_1 in the destination gamut by using a chroma mapping function. Let the maximum value of C^*_0 be C^*_{0m}, and let C^*_0 be normalized with C^*_{0m} and be represented as C^*_N. Then, the C^*_1 of the source image can be expressed as follows,

$$C_1^* = k(C_N^*) \cdot C_{0m}^* \ for\ 0 \le C_N^* \le 1 \qquad (3)$$

where $k(C^*_N)$ is the chroma mapping function. The three types of functions in Fig. 2 were used for chroma mapping and were compared each other.

Linear Function

The mapping function is a linear function with a slope of more than one as follows,

$$k(C_N^*) = C_N^* \times (C_{1m}^* / C_{0m}^*) \qquad (4)$$

where C^*_{1m} is the maximum chroma value of C^*_1 for the destination gamut.
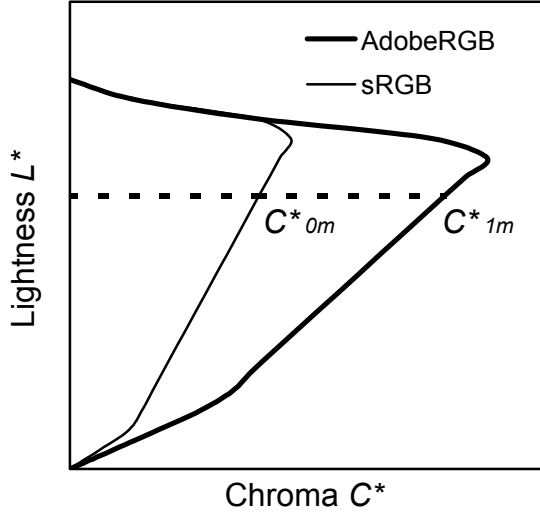
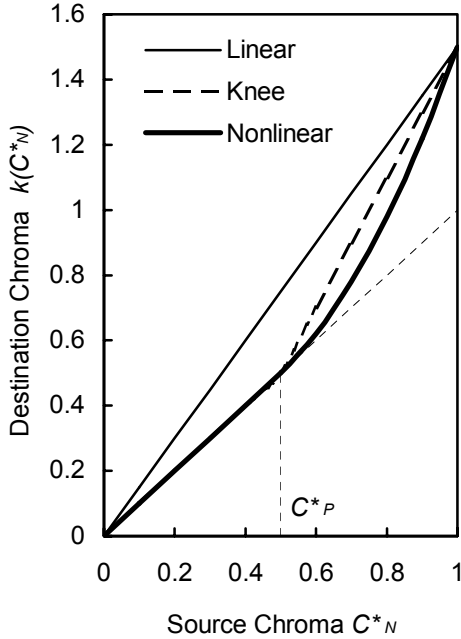Figure 1. Gamut boundaries in the L*-C* plane.

Figure 2. Three types of chroma mapping functions.

Knee Function

This function consists of two linear functions, the first of which has a slope of one and the second expands the remaining range to the maximum chroma in the destination gamut. These two linear functions are joined at the knee point with $C^*_N = C^*_P$. In this study, a value of C^*_P was 0.5.

$$k(C^*_N) = C^*_N \ for \ 0 \le C^*_N \le C^*_P \tag{5}$$

$$k(C^*_N) = C^*_N + \frac{C^*_N - C^*_P}{1 - C^*_P} \times (C^*_{1m}/C^*_{0m} - 1) $$

$$for \ C^*_P < C^*_N \le 1 \tag{6}$$

Nonlinear Function

This function increases linearly to $C^*_N = C^*_P$ and then exponentially to $C^*_N = 1$.

$$k(C^*_N) = C^*_N \ for \ 0 \le C^*_N \le C^*_P \tag{7}$$

$$k(C^*_N) = C^*_N + (\frac{C^*_N - C^*_P}{1 - C^*_P})^\gamma \times (C^*_{1m}/C^*_{0m} - 1)$$

$$for \ C^*_P < C^*_N \le 1 \tag{8}$$

where γ is a constant representing the degree of nonlinearity.

Step 3. Convert CIELch to XYZ

The CIELch values of the expanded image are transformed into XYZ values by CIELAB to XYZ color space conversion.

Step 4. Convert XYZ to RGB

The XYZ values calculated in step3 are finally transformed into Adobe RGB color space with a reference white of D65. This transformation is performed by using the following 3x3 matrix,

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} 2.04159 & -0.56501 & -0.34473 \\ -0.96924 & 1.87597 & 0.04156 \\ 0.01344 & -0.11836 & 1.01518 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{9}$$

where r, g, and b are RGB tristimulus values in Adobe RGB color space. Taking into account the monitor gamma, the rgb values are converted to monitor device values because the rgb values are proportional to luminance.

$$V' = 1.099 \times V^{0.45} - 0.099 \ for \ 0.018 \le V \le 1.0 \tag{10}$$

$$V' = 4.50 \times V \ for \ 0.0 \le V < 0.018 \tag{11}$$

where $V = r$ or g or b and $V' = R$ or G or B. Finally V' is converted to 8bit digital counts.

$$V_{8bit} = 255 \times V' \tag{12}$$

Experiment

A psychophysical experiment was performed to determine an optimum chroma mapping function for gamut expansion. As the source images to be tested, "Flower", "Japanese goods", and "Threads" were selected from XYZ/sRGB-SCID[1] as shown in Fig. 3. These pictorial images contain a wide variety of objects in saturated colors and with rich gradation, which are suitable for evaluating color reproduction in image output devices. Three types of gamut-expanded images were generated by applying gamut expansion algorithm to each source image with three different chroma mapp.ing functions. Three combinations of two different gamut-expanded images were evaluated in paired-comparison

method. The two gamut-expanded images were displayed side by side on a Mitsubishi RDF225WG 22-inch CRT monitor that supports Adobe RGB color space. Five observers, all students of Tokyo Polytechnic University, took part in the experiment. Each observer was instructed to view a pair of images on the monitor, and to choose an answer from a list: "Left image is better", "Right image is better", and "Can't tell" for each image characteristics: brightness, contrast, chromaticness, etc. The viewing distance was about 40 cm and the experiments were performed in a dark room.

Results and Discussion

For each image, the 3 x 3 matrices of comparison results for each observer were averaged over five observers, being transformed into Z-scores. Case 5 of Thurstone's model was used for the data analysis. The Z-scores obtained for "Threads" are plotted in Fig. 4. For chromaticness, brightness, and contrast, the linear mapping shows the highest score, but the lowest score for almost all the other characteristics. The results for all the test images are summarized in Table1. For any test images, the nonlinear mapping function had the best score and the linear mapping function was the worst. A similar result is reported in the study[2] on gamut compression. Figure 5 the comparison of image gamut boundaries in a*b* plane between the source image and the image expanded using the linear mapping function. It is indicated that the gamut-expanded version of "Threads" image contains many higher chroma colors that exceeds the sRGB gamut. Thus the gamut-expanded image is able to be used for evaluating color reproduction in image output devices.

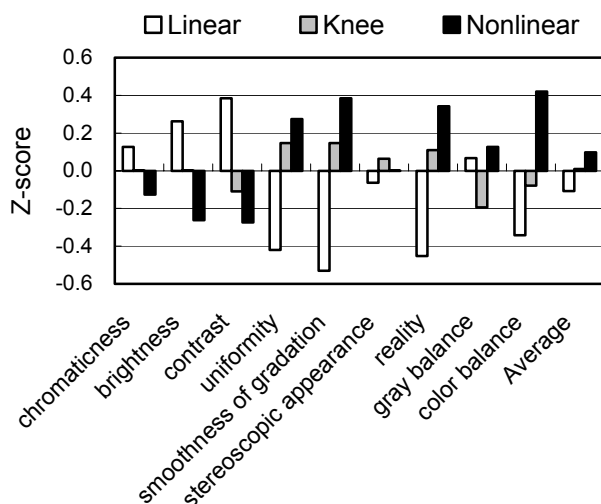Figure 3. Test images: Flowers, Japanese goods, Threads (from left to right)

Figure 4. Z-scores obtained for "Threads"

Table 1: Z-Scores for the Three Mapping Functions

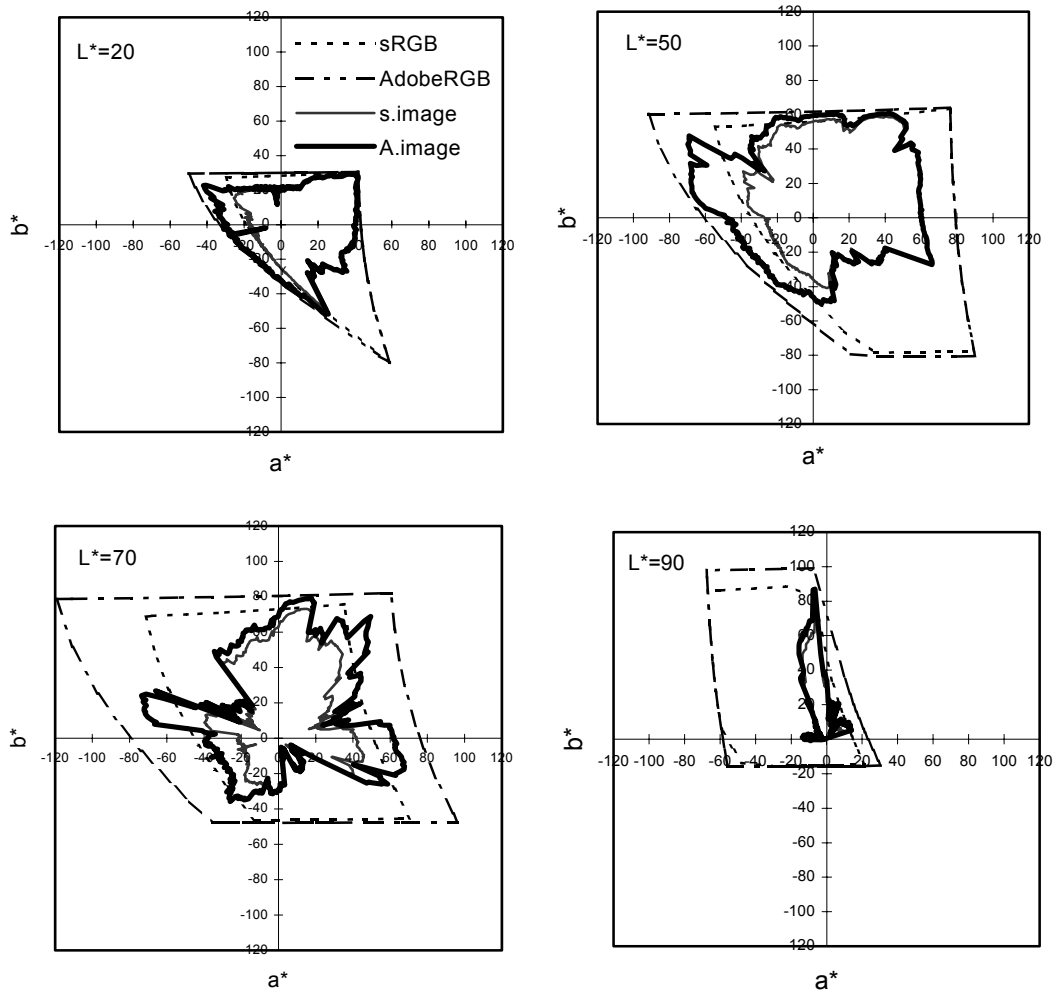|	Linear	Knee	Nonlinear
Flower	-0.13	0.06	0.08
Japanese goods	-0.05	0.08	0.40
Threads	-0.11	0.01	0.10
Average	-0.10	0.05	0.19

Figure 5. Comparison of gamut boundaries between the source and expanded images of "threads" in linear mapping. The "s.image" represents the source image and "A.image" represents the image mapped into AdobeRGB gamut.

Conclusions

A gamut expansion algorithm based on chroma mapping was applied to sRGB images to create wide-gamut images and was evaluated in a psychophysical experiment. Results showed the effectiveness of proposed method.

Acknowledgment

References

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Author Biography

Toyoshi Morioka received his BE in image engineering from Tokyo Polytechnic University in 2004. He is now a second year student in Master degree program at Tokyo Polytechnic University. His research interest includes image science and color reproduction.