UDC 681.32:778.6

High-accuracy Color Reproduction (Color Management Systems)

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(Manuscript received June 7, 1999)

Gamut mapping is a key technology which realizes good matching between original, displayed, and printed colors. We examined the application of gamut mapping algorithms to device profiles to achieve color transformation in color management systems (CMSs). As a new performance evaluation method, we focused on errors that occur during this transformation. To obtain a mapping method suitable for implementation, we developed a new gamut mapping algorithm called "Chroma Proportional Clipping (CPC)." This algorithm preserves chroma and tone while reducing interpolation errors. The reproduction of chroma and tone was evaluated subjectively, and the reduction of errors was evaluated based on color differences. Compared with three conventional algorithms, CPC was given the best mean score in subjective evaluations of color matching. Also, CPC has a relatively small reduction of errors of 14.2 CIELAB units.

1. Introduction

Recent developments in computers and peripheral devices have made full-color image processing practical and easy. However, the differences between original, displayed, and printed colors is a growing problem. To solve this problem, color management systems (CMSs) which use device-independent color systems (CIELAB,1) etc.) to correct a device's color characteristics are being developed. CMSs contain device profiles and a color matching module (CMM) and correct color signals so that original, displayed, and printed colors match. The device profile describes the color characteristics of a certain device, and the CMM is software which corrects the color signals according to these profiles.

The device profile for a color printer usually consists of a look-up table (LUT). An LUT gives the relationship between device-independent colors and device-specific color signals such as CIELAB and CMYK signals. The LUT of, for example, a CIELAB uniform color space contains the CMYK values of 17 × 17 × 17 grid points. The CMM provides a color-corrected signal by converting between a device-specific signal and the signal for a device-independent color according to an LUT. The format of a profile is defined by the International Color Consortium (ICC).2) This definition applies only to data file formats, and the LUT data in the profile has to be generated by the user or a vender of that device. This means that color matching performance largely depends on the profile performance.

One of the most difficult problems with color matching is gamut mapping. Displays have larger gamuts than printers, and their shapes are very different. Printing a displayed image while maintaining the appearance requires effective gamut mapping; that is, the gamut mapping should preserve the chroma and tone as much as possible. The color matching performance cannot be evaluated numerically; instead, it must be evaluated subjectively by the human eye.

Usually, gamut mapping algorithms are used to construct an LUT, but are not used in the procedure for transforming color signals. This is because, if the LUT has already been processed by the algorithm, the gamut mapping procedure and color transformation can be performed simultaneously just by interpolating the LUT and therefore transformation of color signals can proceed at high speed.

An LUT must give the relationships between device-independent colors and device-specific color signals for the entire color region, including out-of-gamut colors, even though device-specific color signals for out-of-gamut colors cannot be determined exactly. To determine device-specific color signals for out-of-gamut colors, the gamut mapping algorithm first maps the out-of-gamut colors to in-gamut colors. Then, the device-specific color signals for the corresponding in-gamut colors are recorded as the appropriate device-specific color signals for the respective out-of-gamut colors. The results of the gamut mapping algorithm are in this way incorporated into the LUT.

Gamut mapping is performed before the LUT is interpolated to transform color signals. Therefore, it is important that the gamut mapping algorithm provides results that can be interpolated with the minimum generation of color differences.

We cleared up a problem that occurs when a gamut mapping algorithm processes an LUT and used a new numerical evaluation method in addition to the conventional subjective evaluation. The new method enables us to determine whether a gamut mapping algorithm is suitable for device profiles.

In this paper, we describe our new gamut mapping algorithm for color printers. First, we introduce the CMS structure and the ICC profile. Then, we describe an algorithm we developed which is suitable for implementation and has a good color matching performance. Finally, we give an evaluation of the new algorithm.

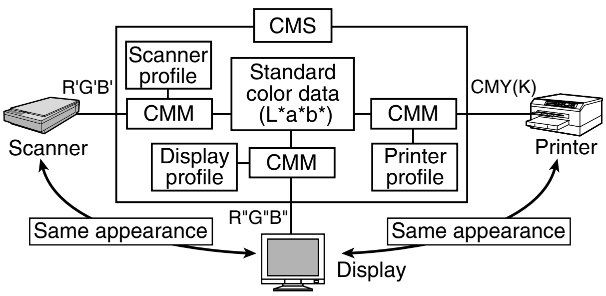
2. Color management systems (CMS)

2.1 CMS

Figure 1 shows the structure of the CMS.[2) The CMS contains device profiles and a color matching module (CMM). The device profiles describe the color characteristics of a certain device, and the CMM corrects the color signals according to these profiles. For example, to correctly display an image output by the scanner, the scanner's output data (RGB) is converted to standard color data (CIELAB, CIEXYZ, etc.) using the CMM and the profile of the scanner's color characteristics. Then, the standard data is converted to RGB data for the display using the CMM and the profile of the display's color characteristics. A similar procedure is used to print correct colors. By using these CMM procedures, the original, displayed, and printed colors can be matched. Nowadays, the CMS is a standard function of PCs (Windows and Macintosh) and the number of CMS applications is increasing.

2.2 ICC profile

The ICC is a consortium which was established by FORGA (a German graphic arts research institute) and other industrial companies in 1993. Many companies from various fields, for example, PCs, printing, photography, peripheral devices, and imaging software, have joined the ICC. Fujitsu Laboratories has been a member since



CMS : Color management system
CMM : Color matching module

Figure 1
CMS structure.

1997. The number of members as of August 1999 is 74.

The ICC established a profile format specification which represents the color characteristics of color imaging devices.2) This specification is available at the ICC Web site (http://www.color.org/profiles.html). The ICC profile has become the de facto standard for PC CMSs.

Figure 2 shows the structure of the ICC profile. The profile contains a format header and tags which represent the profile size, data color space, manufacturer, LUT, and so on. The LUT describes the relations between the input/output signals and the colors measured in the input/output image. For example, a printer profile describes the relations between the input signals and the colors measured in the output print.

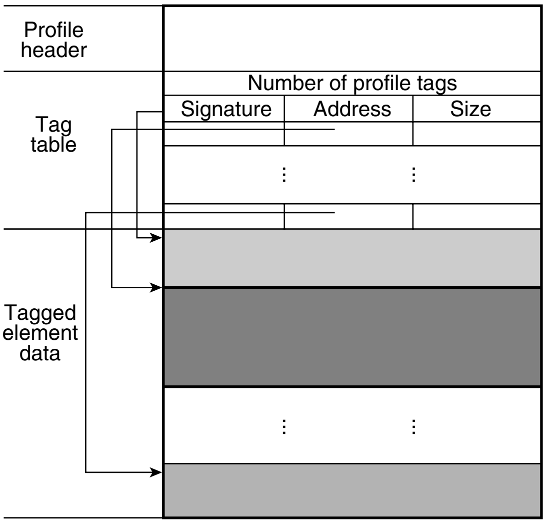


Figure 2
ICC profile.

3. Gamut mapping

Displays have bigger gamuts than printers, and the gamuts of these two devices have very different shapes. **Figure 3** shows example gamuts of a CRT display and an electrophotographic printer. As can be seen, with these gamuts, there are some colors which can be displayed but not printed. To print a displayed image while maintaining the appearance requires a gamut mapping which can preserve the chroma and tone. This is the most difficult problem and involves the most important technology for creating a printer profile.

There are three gamut mapping intents2) for various kinds of original images.

1) Perceptual
All out-of-gamut colors are compressed to fill the printer gamut. Gray balance should be preserved but colorimetric accuracy might not be preserved.

2) Saturation
The saturation of the pixels in the image is preserved. Accuracy in tone and lightness might be lowered.

3) Colorimetric
In-gamut colors are not moved, and out-of gamut colors are mapped to the closest color.

Generally, perceptual intent is applied for natural images such as portraits and scenery, saturation intent is used for business graphics, and colorimetric intent is used for company logos (because the correct color is important). There is no definitive method for any of these intents. Perceptual intent is the one used most often when it is important to reproduce the natural color balance and graduation of images, and many methods have been studied and proposed.

We developed a new gamut mapping algorithm which solves the overlooked problem of how to implement a gamut mapping to an ICC profile and preserves chroma and tone.

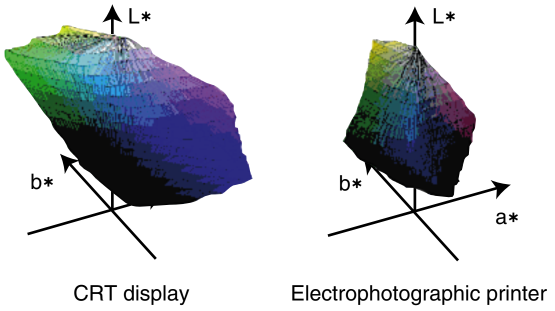


Figure 3
Gamuts of a display and printer.

3.1 Conventional methods and problems

Among the perceptual gamut mapping algorithms, clipping generally shows good performance.3) In clipping, all out-of-gamut colors are clipped onto the boundary of the destination (printer) gamut. In-gamut colors remain unchanged. The conventional clipping algorithms are as follows.

1) Minimized color differences
   Out-of-gamut colors are mapped to the closest color (**Figure 4**).4)
2) LCLIP
   Out-of-gamut colors are clipped to the boundary to maintain the same tone and lightness (**Figure 5**).5)
3) Chord clipping
   Out-of-gamut colors are moved to the points on the lightness axis that have the colors' lightnesses while providing the highest chromaticity at the given tone (**Figure 6**).6)

All of these algorithms to some degree have the following two problems.

1) A loss of detail occurs in some regions, and the chroma and lightness are reduced for some colors.
2) In-gamut colors near the boundary of the printer gamut change after being transformed by LUT interpolation.

The algorithm for minimizing the color difference (see Figure 4) maps the colors near point C to the same color. In this case, the detailed information of these colors is lost. Also, LCLIP algorithms greatly reduce the chroma of some colors – Chord clipping is relatively good with respect to this problem. We can measure the changes of the second problem as a new way of evaluating a gamut mapping.

Figure 7 shows an example of a change in an in-gamut color near the boundary of the printer gamut. The LUT records device color signals,

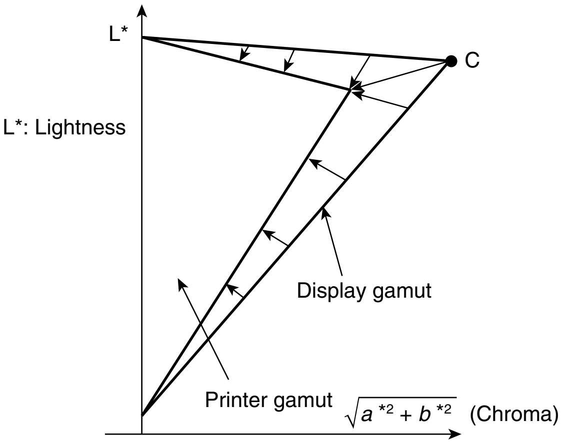


Figure 4
Minimized color difference.

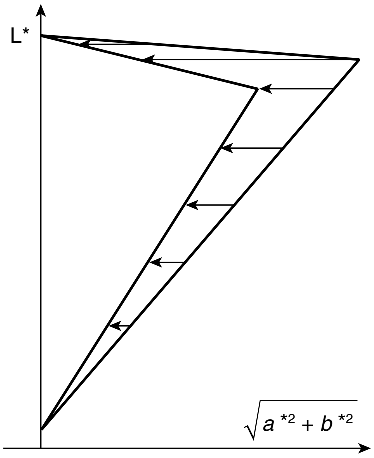


Figure 5
LCLIP.

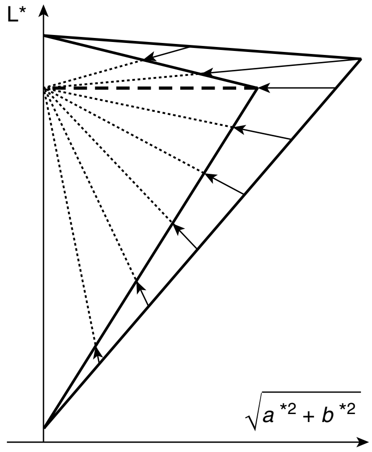


Figure 6
Chord clipping.

for example, the CMYK value of color “x,” which is the result of gamut mapping the grid point color “o.” Therefore, the device-specific color signal of color “+” is interpolated using the device-specific color signals of the colors “x” and “o,” not only by using the device-specific color signal of color “o.” The result of this interpolation is a signal that corresponds to the color “*.” Consequently, the result after interpolation is inferior to the result of the original algorithm. The degree of change depends on the difference between the colors “o” and “x.” This unexpected change might reduce the chroma of vivid colors, especially yellow.

3.2 Proposed solution

To minimize these unexpected reductions in chroma, the changes in the out-of-gamut colors near the boundary should be small. To minimize these changes, out-of-gamut colors should be mapped to the closest color. This is the approach taken by the algorithm for minimizing the color difference. However, this approach alone would cause the detailed information of some colors to be lost.

Ideally, gamut mapping should both reproduce the tone and reduce the changes in the out-of-gamut colors near the boundary. Of course, the chroma should be preserved as well.

To fulfill these requirements, we propose a new gamut algorithm called “Chroma Proportional Clipping (CPC).” CPC basically maps colors as shown in **Figure 8**. Out-of-gamut colors are mapped onto a line drawn between the point in the printer gamut which has the highest chroma and the point on the lightness axis which has the same lightness as that point. The out-of-gamut colors are mapped in proportion to the ratio of their chromas and the highest chroma of the source (display) gamut. This prevents unexpected reductions in chroma because the mapping direction of the out-of-gamut colors is orthogonal relative to the boundary of the printer gamut.

However, there are two problems with this algorithm. The first problem is that there is a high loss in the lightness of some colors. The algorithm maps the peak point (highest chroma) in the source gamut to the peak point in the printer gamut. Colors such as green, where the lightness difference between the peak points of the display and printer gamuts is large, will loose a great amount of lightness.

We solved this problem by adjusting the mapping direction according to the lightness difference between the peak points. When the difference is relatively large, the direction is shifted more toward the lightness axis.

The second problem is that the details of high-chroma colors are distorted. This is caused by the shift of the mapping target points. We solved this problem by mapping high-chroma colors towards the same point.

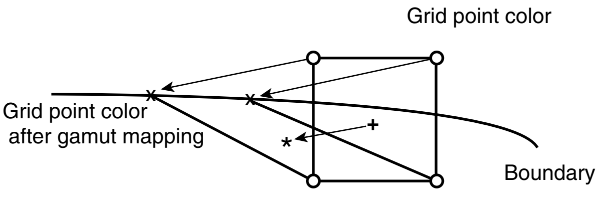


Figure 7
Unexpected change of in-gamut color.

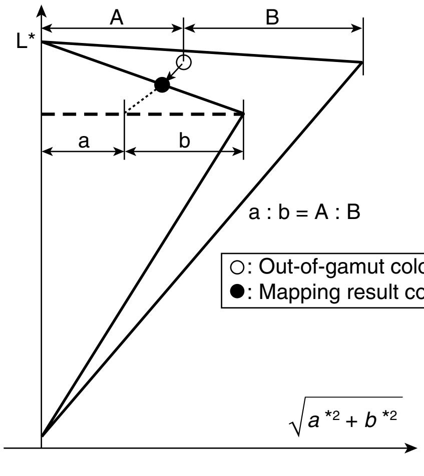


Figure 8
Basic concept of CPC algorithm.

The CPC algorithm, which incorporates the solution to the above two problems, is shown in **Figure 9**. *Cs* denotes an out-of-gamut color of a printer, and *Cd* denotes the color mapped by the CPC.

1) At a tone of *Cs*, line *L1* is created between color *C1*, which has the highest chroma in the printer gamut, and color *C2* on the lightness axis, which has the same lightness as *C1*. The point on line *L1* which has the highest chroma of the display gamut is defined as *C3*.
2) A line *L2* is created that is parallel to the lightness axis and goes through color *C3*. A line *L3* is created that is parallel to the lightness axis and goes through color *C4*, which is the color with the highest chroma in the display gamut.
3) A line *L4* is created that is parallel to line *L1* and goes through color *Cs*. The point where *L2* and *L4* intersect is defined as point *C5*. The point where *L3* and *L4* intersect is defined as point *C6*. The point where *L4* and the lightness axis intersect is defined as point *C7*.
4) A point *C8* on line *L1* is defined with the following algorithm. In this algorithm, L^*_{C1} and L^*_{C4} denote the L^* values of *C1* and *C4*, respectively.
   if $L^*_{C1} - L^*_{C4} < 60$
   then $|C2C8| : (60-(L^*_{C1}-L^*_{C4})) = |C2C1| : 60$
   else
   $C8 = C2$ (1)
5) A point *C9* on line *L1* is defined with the following algorithm.
   if $|C7Cs| < |C7C5|$
   then $|C7Cs| : |CsC6| = |C2C9| : |C9C8|$
   else
   $|C7C5| : |C5C6| = |C2C9| : |C9C8|$ (2)
6) Color *Cs* is shifted towards point *C9* and clipped to the boundary of the printer gamut.

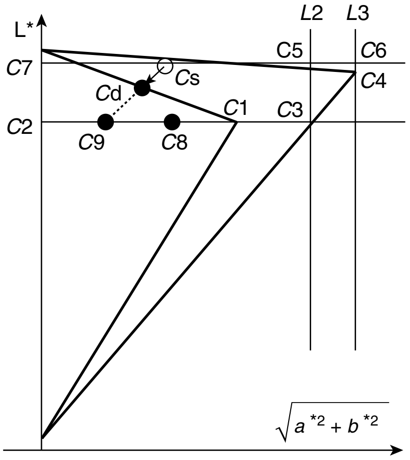


Figure 9
Overview of CPC algorithm.

Figure 10 shows the changes of grid points near the boundary of the color yellow according to each algorithm. With CPC, the changes of grid points are relatively small.

3.3 Evaluation

We evaluated the performance of the proposed CPC algorithm using two methods. First, the preservation of chroma and tone was evaluated subjectively. An image was displayed on a CRT monitor adjusted to 5000 K and printed by a color printer. To generate the print data, the original image data was converted with a CPC-processed LUT. The displayed image and printed image were placed in a D50 booth and compared according to a quality scale of 1 to 5 (**Table 1**). We used six photographic images and six people to make the comparisons. All images included very colorful objects, such as fruits, flowers, and painted objects having colors whose chroma and tone are difficult to preserve.

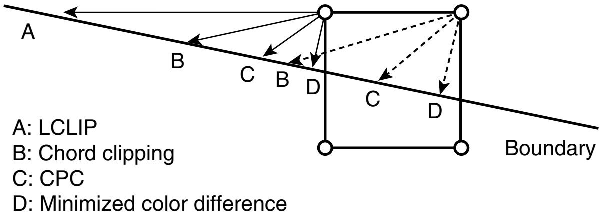


Figure 10
Changes of grid points near boundary.

Next, we evaluated the color differences that were generated by interpolation with a CPC-processed LUT. A total of 669 colors at the printer gamut boundary were examined. In this part of the evaluation, we used relative colorimetry, which is a technique adopted from the ICC specification.[2] The colorimetry (X_{rel}, Y_{rel}, Z_{rel}) was derived from the equations below. (X_{abs}, Y_{abs}, Z_{abs}) denotes the absolute colorimetry value as measured under a D50 light source for reflective objects. (X_{d50}, Y_{d50}, Z_{d50}) denotes the tristimulus value of a D50 light source. (X_{mw}, Y_{mw}, Z_{mw}) denotes the absolute colorimetry value for the media white point.

$$X_{rel} = X_{abs}\,(X_{d50}/X_{mw}) \tag{3}$$
$$Y_{rel} = Y_{abs}\,(Y_{d50}/Y_{mw}) \tag{4}$$
$$Z_{rel} = Z_{abs}\,(Z_{d50}/Z_{mw}) \tag{5}$$

Table 2 shows the results of the subjective evaluations. It clearly shows that CPC was the most effective algorithm. **Table 3** shows the maximum color differences that were obtained by interpolation. Applying CPC provides the second smallest difference in color. This result indicates that the change of in-gamut colors through interpolation is relatively small.

Figure 11 shows Fujitsu's GL-8300 color electrophotographic printer. The GL-8300 applies our new color matching technology to built-in ICC profiles. It is a high-speed (13 color pages per minute), high-quality printer and is mainly used in business fields. We have developed ICC profile creation technologies for color scanners and displays and built them into some of Fujitsu's products.

4. Conclusion

We have developed a gamut mapping algorithm called Chroma Proportional Clipping (CPC) which can preserve chroma and tone. CPC is also suitable for implementation to device profiles because the unexpected change of in-gamut colors due to LUT interpolation is small and the chroma of vivid colors can be preserved. We evaluated this algorithm using two methods and found that it had good performance. CPC was given a higher score (mean opinion score of 3.3 on a scale of 1 to 5) than three conventional clipping algorithms in subjective evaluations of color matching. An evaluation of the resulting color differences showed

Table 1
Quality scale for subjective evaluations.

5	The same
4	Slightly different
3	Different
2	Definitely different
1	Very different

Table 2
Results of subjective evaluations.

Algorithm	Result
CPC	3.3
Minimized color difference	2.8
LCLIP	2.9
Chord clipping	3.1

Table 3
Maximum color differences after interpolation.

Algorithm	Result
CPC	14.2
Minimized color difference	8.1
LCLIP	54.1
Chord clipping	31.6

Figure 11
GL-8300 color printer.

that the change of color was 14.2 CIELAB units. This change is relatively small and supports the results of the subjective evaluations. These results indicate that CPC is superior to conventional methods.

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