Print Color Reproduction for a Wide Gamut Source

Yousun Bang, Minki Cho, Yun-Tae Kim, Se-Eun Kim, and Heui-Keun Choh; Display and Image Processing Lab, Samsung Advanced Institute of Technology; Yongin, Gyeonggi-Do, South Korea

Abstract

Increasing number of imaging systems and devices recently support various kind of wide gamut color spaces such as Adobe RGB color space. Adobe RGB 1998 is generally used to produce more vivid colors in digital photography. Various gamut mapping techniques has been developed by many researchers to enhance printer colors. However, little literature has focused on the study of printer color mapping for a wide gamut source space. In this paper we propose a novel experimental methodology of print color correction for the wide gamut input. We compare gamut boundaries and primaries of the reference gamut sRGB and the wide gamut Adobe RGB, and then extract key factors for print color correction. While we employ a gamut mapping method from the reference gamut to the printer gamut, we transform input colors by controlling global lightness, shifting hues, and performing saturation enhancement. Based on psychophysical experiments, we find optimal values of correction factors. We apply our method in two different printers: an electrophotographic laser printer and a dye sublimation photo printer. Comparison test results show the higher preference scores in both cases. This suggests that for a given wide gamut input we can substantially match print colors with the source.

Introduction

Many imaging devices, such as digital cameras, scanners, and monitors, recently support various kinds of color spaces. sRGB, Adobe RGB, Apple RGB, and ColorMatch RGB are representative RGB color spaces that are frequently used in multimedia applications[1,2]. Each color reproduction system has its own color gamut, and thus the range of all producible colors is different depending on the imaging system. Images usually look more vivid and colorful in a wide gamut space because more colors can be represented. Adobe RGB (1998) is widely used to produce more vivid colors in digital photography; and it has wider color gamut than sRGB shown as in Fig. 1.

Due to significant discrepancies in the color gamuts of capturing devices, monitors, and printers, gamut mapping has always been an important issue. Various gamut mapping methods have been so far studied by many researchers[3,4,5]. Gamut clipping, gamut compression, and their combination methods have been developed. However, most gamut mapping algorithms have mainly focused how to convert input colors of a given source gamut into the colors of a printer gamut. Let us assume that we have a particular gamut mapping strategy from the reference source gamut into the printer gamut. When the source color space is changed to a wider one, the printer output colors by the old gamut mapping method would not be able to match with the new source colors.

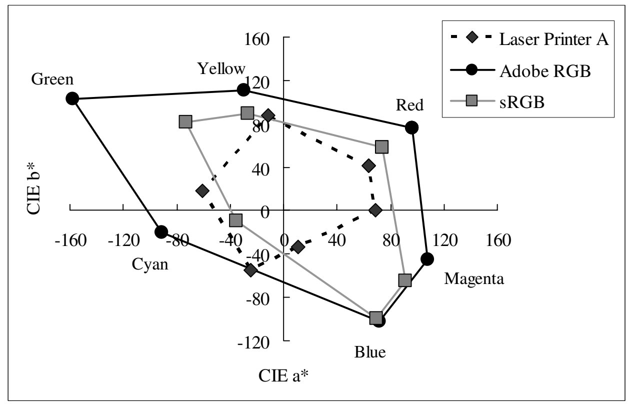

Figure 1. *Gamut analysis of Adobe RGB, sRGB, and Printer A in CIE L*a*b* space.*

In this paper, we propose an experimental methodology to reproduce printer color which is perceptually matched with a new wide gamut color. While the following four are given: *a reference source gamut*, *a wide source gamut*, *a printer gamut*, and *a reference gamut mapping method* from the reference source gamut to the printer gamut, the goal of our research is to develop a color correction technique from the wide source gamut to the printer gamut. Our approach to this problem is to analyze two color gamuts of the reference source gamut and the wide source gamut and to extract key factors of color correction. To obtain consistent print color with the wide source color, we also optimize correction parameters by conducting psychophysical experiments.

The rest of the paper is organized as follows. In the next section, we describe our proposed method for print color correction. Then we present the procedures for our psychophysical color matching experiments. Finally we discuss our experimental results and draw some conclusions.

A Proposed Method

Figure 2 shows the main block diagram of our approach. We control global lightness, and perform hue correction and saturation enhancement based on wide gamut analysis and psychophysical matching experiments. We utilize the reference gamut mapping from the reference source gamut to the printer gamut.

In the paper we consider two source gamuts: the reference source gamut *sRGB color space* and the wide source gamut *Adobe RGB color space*. Figure 1 shows three color gamuts of sRGB, Adobe RGB, and a color laser printer, *Printer A*, in CIE a*b* coordinates. As seen in the figure, Adobe RGB gamut encompasses both sRGB gamut and the gamut of Printer A, and Adobe RGB has the greater color range than sRGB in most hue angles including green-cyan area. Using colorimeters[1], we measure lightness, chroma, and hue of primary colors in two monitors[2], each of which is calibrated with sRGB color space and Adobe RGB space, respectively. We then compare their primary characterization. Table 1 and 2 show lightness, chroma, and hue values of Adobe RGB and sRGB with CIE L*c*h* coordinates. Adding other color of dots to magenta and yellow substantially reduces the visible preference; and thus for representing pure magenta and pure yellow of CMYK printer we use toner Magenta and toner Yellow. Except Magenta and Yellow, from the tables we note that Green primaries of Adobe and sRGB produce the largest hue difference, and Green and Cyan primaries produce the largest chroma difference. We incorporate this analysis to reproduce print color for the wide gamut Adobe RGB color space.

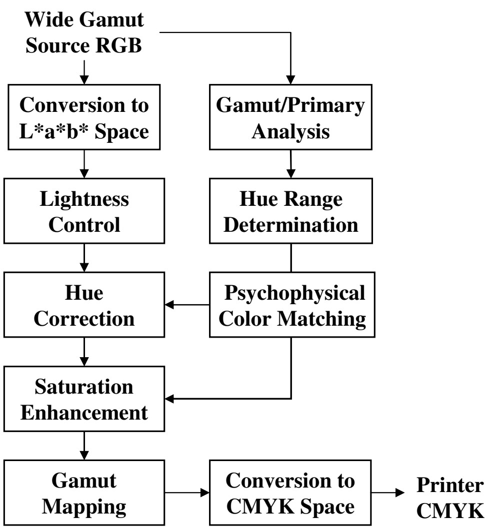

Figure 2. *Our approach to print color reproduction for a wide gamut source.*

Table 1: Primary analysis of Adobe RGB space

Adobe RGB	CIE L*	CIE c*	CIE h*
Red	66.4	122.6	38.5
Yellow	98.3	115.3	104.9
Green	84.6	188.2	144.9
Cyan	87.5	93.1	192.4
Blue	38.9	124.7	304.9
Magenta	73.6	116.8	337.5

[1]Minolta Color Analyzer CA100, CA200

[2]Barco Monitor, EIZO ColorEdge CG220

Table 2: Primary analysis for sRGB space

sRGB	CIE L*	CIE c*	CIE h*
Red	46.9	93.9	38.3
Yellow	98.4	93.4	106.6
Green	91.6	110.0	131.9
Cyan	93.9	36.8	195.5
Blue	37.1	121.3	305.1
Magenta	57.6	111.8	324.5

To control a global lightness we perform a sigmoidal lightness compression with Gaussian mean 55 and sigma 45. Since Adobe RGB images show more contrast than sRGB images, we increase contrast by controlling sigma. From the analysis of gamut boundaries and primaries, we then select key parameters for hue correction and saturation enhancement to match with Adobe RGB color. The followings are the factors chosen: Green hue shift angle, Cyan hue shift angle, Green-Cyan saturation level, and skin color parameters. When we try to match print colors with the wide gamut source color, the output print colors usually have higher chroma. But skin color should be less saturated because high chromatic skin reduces user preference.

To correct hue components, we shift hue angles using the nonlinear method as in Eq. (1) and (2).

$$h_{temp} = \frac{(h_{in} - h_{Adb,L})h_{prtr,H} - (h_{in} - h_{Adb,H})h_{prtr,L}}{h_{Adb,H} - h_{Adb,L}} \quad (1)$$

$$h_{out} = hue_{in} + (hue_{temp} - hue_{in})\frac{w_{c,\theta}}{w_{maxc,\theta}} \quad (2)$$

Here, h_{in}, h_{temp}, and h_{out} are input hue angle in CIE L*a*b*, temporary hue angle after linearized hue shifting, and the output hue angle after applying 2D weighting Lookup table (LUT). $h_{Adb,L}$, $h_{Adb,H}$, $h_{prtr,L}$, and $h_{prtr,H}$ are lower bound hue and high bound hue of Adobe RGB and printer color. In Eq. (2), $w_{c,\theta}$ is 2D weighting LUT value with chroma c and angle θ, and $w_{maxc,\theta}$ is LUT value with the maximum chroma c. The weighting lookup table is used for modifying nonlinear characteristics of blue area.

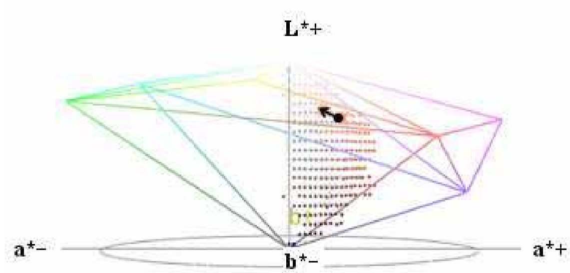

Figure 3. *Skin color correction for the wide gamut source.*

We control gamut compression ratio to enhance saturation in Green-Cyan area[6]. Enhancement of saturation increases the vividness of images. We want to match the level of visible vividness of hard-copy prints with that of soft-copy Adobe RGB images. To do this, we conduct psychophysical color matching experiments. We will describe the details in the next section. For skin color area, we transform colors to make less saturated and more bright. We applies the method similar to the correction method described as in Ref.[7]. Figure 3 shows the skin color area that we used.

Psychophysical Experiments

We fix other parameters, and find optimal values for the following three factors based on psychophysics: (1) Green hue angle, (2) Cyan-Blue hue angle, (3) Green-Cyan saturation level. We conducted color matching experiment for this purpose. We prepareed printed hard-copies with different parameter values, and let subject compare the color quality of the print-out and that of the original image displayed on the Adobe RGB monitor.

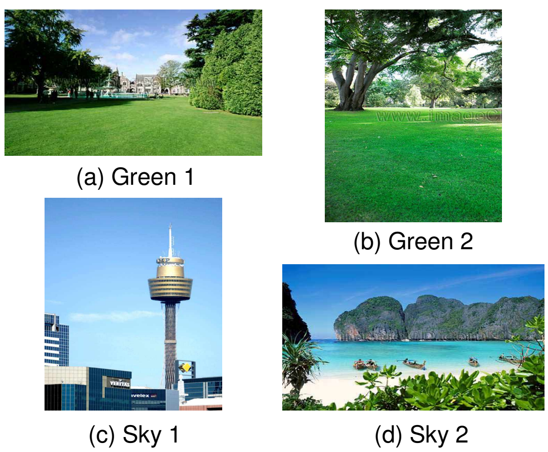

Figure 4. *Sample Images which were used for psychophysical experiments.*

By preliminary experiments, we selected 151, 157, and 165 degrees for Green hue angle, 270, 277, 280 degrees for Cyan-Blue hue, and 0.05, 0.15, and 0.25 enhancement level for Green-Cyan saturation. We carefully selected four

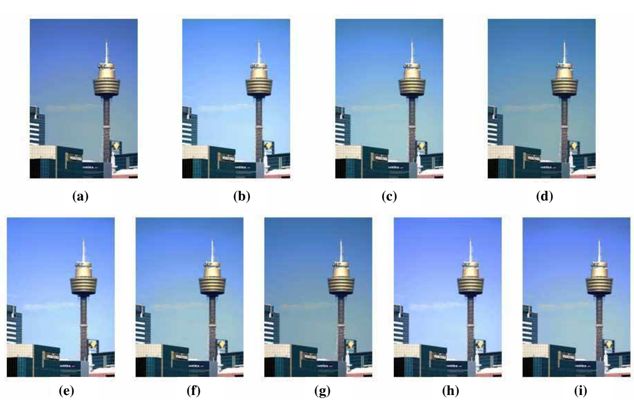

Figure 5. *Test images for Sky 1 used in our psychophysical experiments.*

Adobe RGB images as in Fig 4: two green images and two sky images. 10 observers participated in this experiments, and the experiments were performed in a dark room with the 30cm viewing distance. The monitor was calibrated to Adobe RGB, and Adobe RGB images were displayed on the monitor. In the viewing booth with D65 illumination, the hard-copy prints were compared with the monitor screen.

For each image content, we created test prints with different parameter values. We assumed that Green hue angle and cyan-blue hue angle do not affect each other. Thus, for each of Grass and Sky images we generated ICC profiles with 3 different hue angles and 3 saturation levels. And we applied the ICC profiles to the Adobe images, and saved them as BMP test images. Fig 5 shows 9 test images for Sky 1 with three cyan-blue hue angles and three saturation levels. We printed 9 test images to obtain test prints for color matching experiments.

Figure 6 shows the result of psychophysical color matching experiments. We obtained test image 8 and 9 for the best match of Green Grass, and test image 8 for Sky. The corresponding values were 165 degree for Green, and 280 degree for Cyan-Blue, and 0.15 saturation level. We used these values for print color correction.

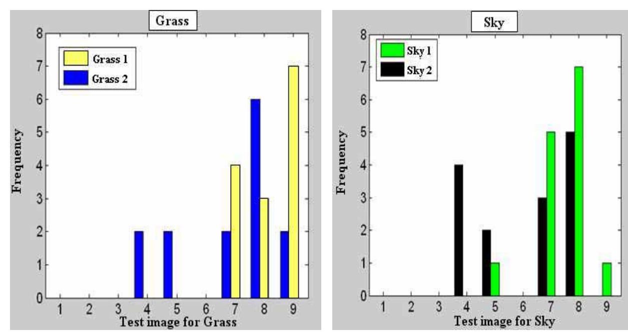

Figure 6. *The response frequency for green and sky images.*

Test Results and Discussion

We tested our algorithm using a psychophysical scaling method. We selected 7 different Adobe RGB images for color laser printer A and dye sublimation photo printer B as in Fig. 7. We test generated test prints with two different algorithms: (1) default driver mode, and (2) the proposed method. 10 observers participated these comparison tests. Each observer gave a score between 1 and 5 for the level of color matching of test prints with the digital images displayed on the Adobe RGB monitor. For each image content, we computed the average score over the observers, and obtained the total average score over the seven image contents.

From the total average score, we calculated *User Satisfaction Index* (USI). USI is defined as written in Eq. (3):

$$USI(\%) = 100\{Log(\frac{1}{N}\sum_{N} point_i)/Log(Max_{point})\}. \quad (3)$$

USI indicates how much subjects prefer hard copy prints. Usually the preference is fair if USI is greater than 68.26%, good if greater than 86.14%, and the best if it is 100%. In

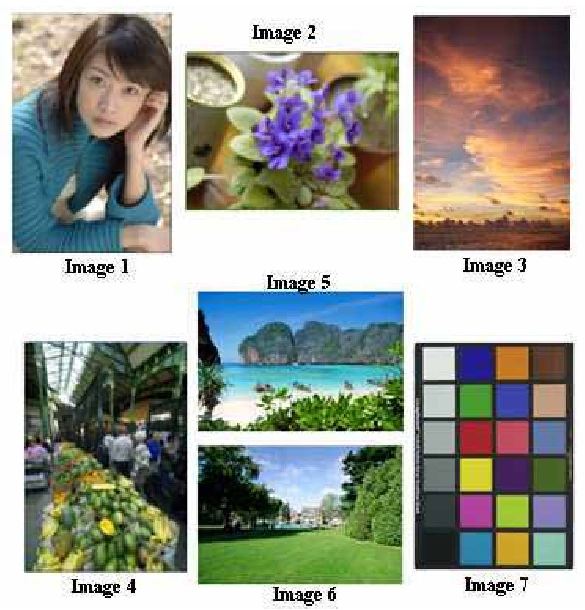

Figure 7. *Images used in the comparison test for the laser printer A.*

the table 3, the USI of the proposed method is 83.4%, which is superior than 68% of the default laser driver mode. Table 4 also shows that the USI's of the proposed method and the driver mode are 87.7% and 52.5%. For the both printer A and B, we obtained the higher USI percents in the proposed method.

Table 3: Test results for color laser printer A

Image	Old method	Proposed Method
Face	3.8	2.9
Market	2.3	4.0
Sunset	4.2	3.5
Chart	3.2	4.1
Purple Flower	2.4	4.0
Park	2.3	4.2
Island	2.7	4.1
Average Score	2.9	3.8
Average USI	68.0	83.4

Conclusions

In the paper, we developed a methodology to reproduce print color for the wide gamut source with the given reference gamut mapping from the reference source to the printer gamut. We characterized the wide gamut input color space by analyzing the color gamut and primaries. We controlled lightness, hue, and saturation based on wide gamut analysis and psychophysical experiments. Based on our psychophysical experiments, we found the optimal values for print color correction parameters. We tested our algorithm with the color laser printer and the photo printer. The test results show the higher preference scores in both cases. This suggests that for a given wide gamut input we can substantially match print colors with the source.

Table 4: Test results for photo printer B

Image	Old method	Proposed Method
Face	2.5	4.0
Sheep	1.9	3.7
Sunset	3.4	4.6
Airport	2.1	4.4
Island	2.8	4.0
Park	1.9	4.2
Grass	1.7	3.8
Average Score	2.3	4.1
Average USI	52.5	87.7

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Author Biography

Yousun Bang received her BS and MS degrees in mathematics from Ewha Womans University, Seoul, Korea, in 1994 and 1996, respectively. She received her PhD degree in the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, in 2005. She has been working in Display & Image Processing Lab at Samsung Advanced Institute of Technology since 2004. Her research interests include display and printer color management, image rendering and enhancement, and image quality.