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Color control of the multi-color printing device^{*}

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Abstract: Conventional color-printing systems often use inks of three hues, such as CMY, CMYK and CMYKLCm, but in order to obtain more realistic color reproductions, the ink set of more than three hues has been adopted by some color-printing systems. It is difficult, however, to model the composed color with the multiple inks when the number of the output ink hues exceeds three due to the none-unique mapping between the color spaces of the CIE Lab and the multi-color printing device. In this paper, we propose a fine color-printing method for multi-color printing device with the ink set of more than three hues. The proposed approach has good color expression ability and provides fine control of the printed color. By dividing the output color space into several subspaces, our method allows one-to-one mapping between the standard color space and the multi-color output color space. It has been proved effective when applied to the digital inkjet printer—Mutoh8000.

Key words: Multi-color printing device, Color gamut, Color space, Digital inkjet printer

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INTRODUCTION

During the development of printing technology, digital printing has played an important role. Now various kinds of multi-color digital inkjet printers are available. Compared with the conventional digital inkjet printer, the multi-color digital inkjet printer has larger color gamut and can faithfully produce more colors.

The conventional color printing devices normally use three or four inks, e.g., CMY, CMYK. Although some adopt more than four inks, e.g., CMYKLCm, the number of output ink hues provided by these printing devices is no more than four and the color gamut remains unchanged. In fact by adding some light inks with the same hues of existing inks can only make the output image delicate without expanding the color gamut. There are some other ways to expand the printing device color gamut.

Cholewo (2000) adopted lightness scaling to replace black with which he accomplished the conversion between CMY and CMYK. This method expands the printer's gamut and achieves better printing results. Qiao and Zeng (2002) employed 3D-Lut to generate black to enhance the printer's color reproduction ability. However all methods mentioned above can only partially expand the printing device color gamut. To enlarge the device's gamut remarkably, additional inks must be added (Mahy and de Bear, 1997).

Compared with the conventional printing device, the CMS (Color Management System) (Specification ICC.1, 2001) of the multi-color printing device is more complex. Conventional printing devices are equipped with three ink hues and their output color parameter spaces are three-dimensional. So the mapping between the standard color space and the color space of the conventional device is one-to-one. However the parameter space of the multi-color printing device is no longer three-dimensional and the conversion between it and the color space of CIE Lab becomes complex.

In this paper, we present a new algorithm which

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can effectively control the color producing of the multi-color printing device. We first extract the color gamut characteristics of the multi-color printing device by dividing the printer color space into several subspaces and establishing local mapping between each subspace and a local region in the CIE Lab color space based on sampling and function fitting. At last, we create the ICC profile of the device and experiment on the digital inkjet printer Mutoh8000.

ICC (Specification ICC.1, 2001) is the abbreviation of International Color Consortium, a formal, non-profit organization and it also prescribes a color management criterion. The ICC color device profile format provides information about a color device which can communicate to a color management system. The ICC profile includes: (1) a color processing model which converts device color data into and out of a reference profile connection space (PCS) and (2) a description of the device's color environment. CIE Lab color system is adopted as the PCS.

EXTRACT COLOR GAMUT

Output color space of the conventional printers

For clearance, we will not call some conventional printing devices with more than three inks as multi-color printing device because the number of their ink hues is only three. Besides the cyan (C), magenta (M), yellow (Y) inks, the additional inks provided by these printers are often black (K) or some light inks, e.g., light cyan (Lc), light magenta (Lm).

Theoretically, the black color can be synthesized by cyan (C), magenta (M) and yellow (Y) inks. But in practice the synthesized black color is not satisfactory. The black ink is therefore employed to replace the composition of C, M and Y inks to achieve a better effect. In short, the color space of CMYK or CMYKLcLm is three-dimensional.

Color space of multi-color printing devices

When the inks of new hues are added to the printing device, its color parameter space is no longer three-dimensional but n -dimensional, and a conceptual figure of color space mapping between it and the standard color space of CIE Lab is shown as Fig.1.

In practice, realistic color reproduction is influenced by many factors such as paper quality, ink set,

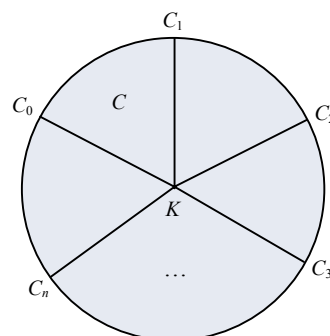


Fig.1 The color space of multi-color printing device mapped to the standard color space

the basic resolution of the printer, screening and color management. For a given offset system, however, most of these parameters are fixed, so the quality of the reproduced color can only be enhanced by optimizing the last two factors listed above.

Color management is responsible for the transformation from image color to the printing color, also referred to as the transformation between device independent to device dependent color spaces.

With the ICC-based color management platform, we must solve the one-to-many mapping problem for a multi-color printing device since there are more ink hues than the number of colorimetric coordinates. By such color printing devices, an image color can be matched with more than one combination of inks. For example, in Fig.1, the color C in the area surrounded by the colors C_0 , C_1 and K can be rendered by combining either inks corresponding to color C_0 , C_1 and K , or C_0 , C_2 and K , or C_n , C_1 and K , and so on. Although the way to print a given color is not unique, not every way is practically applicable (Tzeng and Berns, 2000; Chen *et al.*, 2003).

If the color aberration between the two ink colors C_i and C_j is large, whenever we increase or decrease any of the inks slightly, the synthesized color by mixing these two color inks and the black ink would change apparently, making fine color reproduction difficult.

Obviously to enable fine control over color printing, the two color inks for color composition must be chosen in such a way that their color aberration is the least.

Supposing a multi-color printing device has black ink and n color inks. We sort the n ink colors from C_0 to C_n . Each pair of adjacent colors C_i , C_{i+1}

and black compose a three-dimensional volume as shown in Fig.2. We adopt a divide-and-conquer strategy to establish a one-to-one mapping between the color space of the multi-color printer and that of CIE Lab.

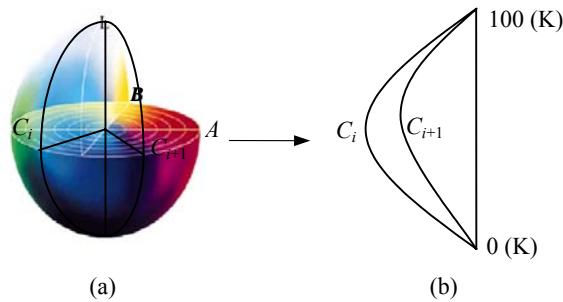


Fig.2 CIE Lab color space and a subspace of it. (a) CIE Lab color space; (b) A subspace with color C_i and C_{i+1} on its border

Sampling points

Fig.3a shows a color subspace of the multi-color printing device which is defined by C_i , C_{i+1} and black ink. It is reconstructed as a cube in Fig.3b with values on the three axes corresponding to the dosage of C_i , C_{i+1} and black inks. We call such a cube a printer's color section cube (PCSC in short). It is reasonable to assume that each PCSC can be mapped to a local region on the color space of CIE Lab according to a set of analytic equations.

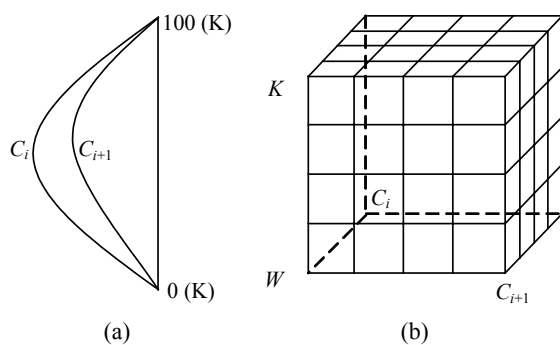


Fig.3 The division of the color space. (a) A color subspace of the multi-color printing device; (b) A printer's color section cube

To derive such mapping equations, we first divide the domain of each section cube of a printer into a number of small cubes by uniform sampling along each axis of PCSC cube as shown in Fig.4. This will

give $(n-1)^3$ small cubes and n^3 lattice points, where n is the number of the points on each axis. The coordinate of each lattice point is (C_i, C_{i+1}, K) .

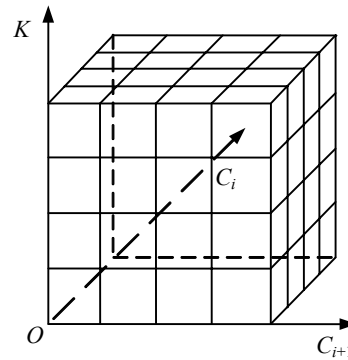


Fig.4 The division of the subspace

Then we use the multi-color printing device to print each sample point and measure its color specification using the special instrument.

Optimizing the set of sample points

The precise measurement of sample points color is important for constructing the mapping equation. Besides, if the color of sample points is not reproduced exactly, it will bring errors to the mapping equations.

Unfortunately, the printed color of a sample point is influenced by many factors. Although we sample the color section cube of the printer uniformly, the color aberrations of some adjacent sample points might be too big, while some might be too small. When the color aberration between the reproduced colors of two adjacent sample points deviates from the normal value by a threshold, the reproduced color on this sample point is insignificant. So we first check the printed color of all the sample points, then delete the invalid points and supplement the set with the new sample points before solving for the mapping equation.

1. Deleting abnormal sample points

The color model of the printing device is a color decreasing model, when the dosage of output inks increases, the lightness of the output color will be reduced. But there are occasionally some counter examples in practice due to various reasons. These abnormal sample points are called distorted points. Obviously these distorted points cannot contribute to

the establishment of the mapping equations and should be deleted.

Besides the distorted points, the point whose color aberrations with respect to its adjacent sample points are smaller than the given value should also be deleted.

Except the sample points on the border of the color space, each sample point is adjacent to 6 sample points. If the corresponding 6 aberration values are all less than the threshold, the concerned sample point is deleted.

The color aberration of two sample points can be evaluated by:

$$\Delta E_{ab}=[(\Delta K)^2+(\Delta C_i)^2+(\Delta C_{i+1})^2]^{1/2}. \quad (1)$$

2. Supplement with new sample points

After we reject the abnormal sample points, the sampling density of the color section cube of the printer will become inhomogeneous. To amend this, we select new sample points near the original sample locations such that the color aberration between the candidate points and their adjacent neighbors is adequate.

Determining the mapping equation

1. Device and destination color specification

Let each reproduced color within the color section cube in local coordinates of the printing device be (α, β, γ) and the set of sample points in the cube be

$$\pi_s = \{(x_1, y_1, z_1), (x_2, y_2, z_2), \dots, (x_8, y_8, z_8)\}.$$

Let the reproduced color of the sample points in CIE Lab (called destination space) color coordinates be

$$\pi_d = \{(L_1, a_1, b_1), (L_2, a_2, b_2), \dots, (L_8, a_8, b_8)\}.$$

2. Regression process

Converting a color specification from one color space to another necessitates finding the links of the mapping. Polynomials are the frequently used links. The polynomials regression is based on the assumption that the correlation between color spaces can be approximated by a set of simultaneous equation (Kang, 1997). Since we divide the device color space into some small cubes, the assumption referred to

above is enabled.

The general regression for a three-variable cubic function is shown in Eq.(2).

$$p_i(v) = u_{i0} + \sum_{j=1}^3 u_{ij} v_r + \sum_{j=4}^9 u_{ij} v_r v_s + \sum_{j=10}^{36} u_{ij} v_r v_s v_t \quad (r, s, t = 1, 2, \text{ or } 3). \quad (2)$$

The coefficients of Eq.(2) can be determined by

$$U = (VV^T)^{-1}(VP), \quad (3)$$

where V is a matrix of size $m \times n$, m is the number of terms in the polynomials, n is the number of sample points, as a requirement of regression $n > m$. The product of VV^T is an $m \times m$ symmetric matrix. Six-term equation with eight datasets (π_s and π_d) is used here:

$$p(L, a, b) = \alpha_1 L + \alpha_2 a + \alpha_3 b + \alpha_4 La + \alpha_5 ab + \alpha_6 bL, \quad (4)$$

where α is the vector of the coefficients and p is the vector of dependent variables. The relevant equations are:

$$\begin{cases} x = \alpha_1 L + \alpha_2 a + \alpha_3 b + \alpha_4 La + \alpha_5 Lb + \alpha_6 ab, \\ y = \beta_1 L + \beta_2 a + \beta_3 b + \beta_4 La + \beta_5 Lb + \beta_6 ab, \\ z = \gamma_1 L + \gamma_2 a + \gamma_3 b + \gamma_4 La + \gamma_5 Lb + \gamma_6 ab, \end{cases} \quad (5)$$

$$V = \begin{bmatrix} L_1 & L_2 & L_3 & \dots & L_7 & L_8 \\ a_1 & a_2 & a_3 & \dots & a_7 & a_8 \\ b_1 & b_2 & b_3 & \dots & b_7 & b_8 \\ L_1 a_1 & L_2 a_2 & L_3 a_3 & \dots & L_7 a_7 & L_8 a_8 \\ a_1 b_1 & a_2 b_2 & a_3 b_3 & \dots & a_7 b_7 & a_8 b_8 \\ b_1 L_1 & b_2 L_2 & b_3 L_3 & \dots & b_7 L_7 & b_8 L_8 \end{bmatrix}, \quad (6)$$

$$X = [x_1 \ x_2 \ x_3 \ \dots \ x_8]^T,$$

$$Y = [y_1 \ y_2 \ y_3 \ \dots \ y_8]^T,$$

$$Z = [z_1 \ z_2 \ z_3 \ \dots \ z_8]^T,$$

$$A = [\alpha_1 \ \alpha_2 \ \alpha_3 \ \dots \ \alpha_8]^T,$$

$$B = [\beta_1 \ \beta_2 \ \beta_3 \ \dots \ \beta_8]^T,$$

$$C = [\gamma_1 \ \gamma_2 \ \gamma_3 \ \dots \ \gamma_8]^T.$$

Each group of coefficients are:

$$A = (VV^T)^{-1}VX, \tag{7}$$

$$B = (VV^T)^{-1}VY, \tag{8}$$

$$C = (VV^T)^{-1}VZ. \tag{9}$$

We choose the Gaussian method elimination to invert the matrix due to its low computational cost.

EXPERIMENTS AND ANALYSIS

To verify the method proposed in this paper, we design an experiment. First we generate the ICC profile of the multi-color printing device and apply it to the digital inkjet printer, Mutoh8000 (Hardeberg and Schmitt, 1997; Bandyopadhyay, 2002; Saito and Kotera, 2002). The Mutoh8000 is equipped with 5 color inks, e.g., black (K), cyan (C), magenta (M), yellow (Y), orange (O), and green (G).

A flowchart of the experiment is shown in Fig.5.

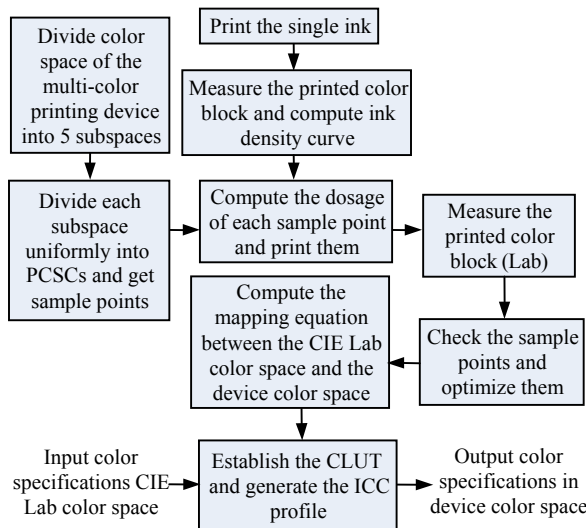


Fig.5 The experiment process to test the method

- (1) Printing each single color ink and generating its color density curve;
- (2) Dividing the printing device color space and sampling, then optimizing the sample points set;
- (3) Measuring the color value of the printed samples and establishing the mapping equation be-

tween the printer's color space and the CIE Lab color space;

(4) Creating the CLUT (color lookup table) and generating the ICC profile of the multi-color printing device.

When we used the generated ICC profile to print color images, the saturation of the printed image increased in the green and red area. The color gamut of the Mutoh8000 is larger than that of the conventional printing device (Fig.6 and Fig.7).

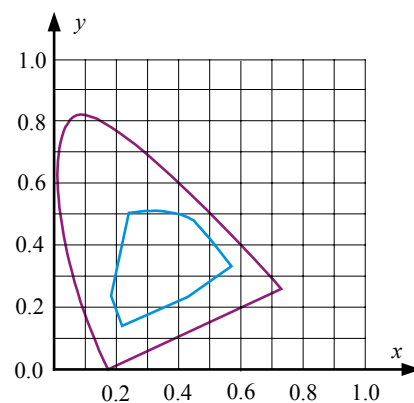


Fig.6 Gamut in the xy-chromaticity diagram of the CMYK inks

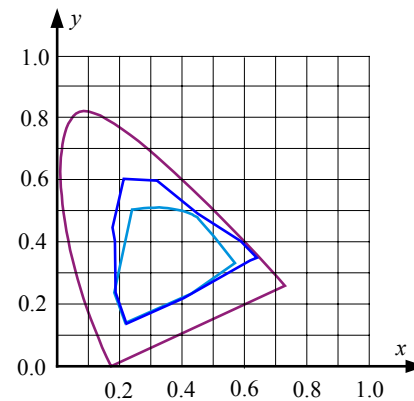


Fig.7 Gamut in the xy-chromaticity diagram of the CMYKOG inks and CMYK inks

To prove the color consistency using the ICC profile generated, we chose several sample points stochastically (shown in Fig.8) in CIE Lab color space. Then we printed them and measured their color values (shown in Fig.9). Fig.10 shows the distribution of color aberrations of each pair of colors.

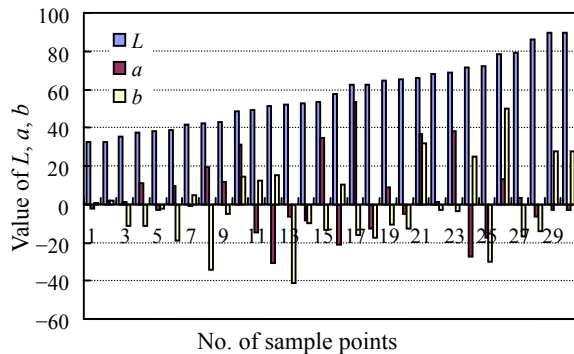


Fig.8 Schematic diagram of the selected sample points values

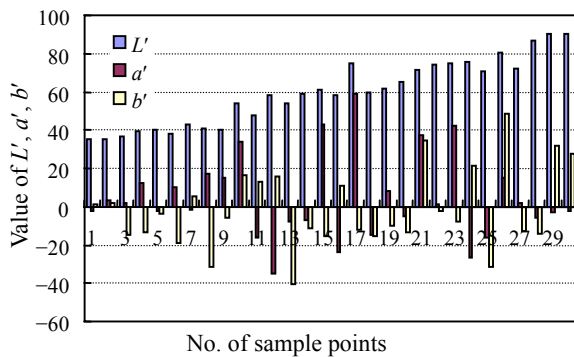


Fig.9 Schematic diagram of the color values measured

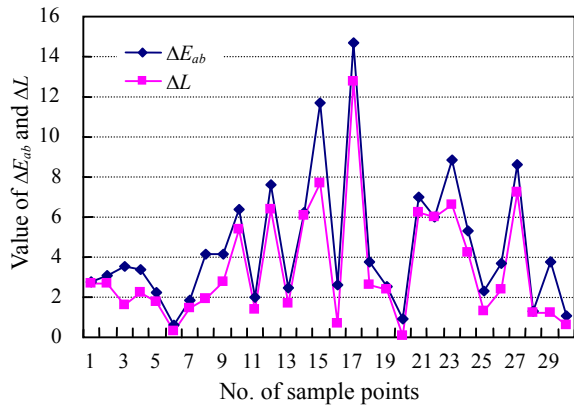


Fig.10 Distributing diagram of the aberrations

CONCLUSION

We have proposed a method for fine color control of the multi-color printing device. By applying the divide-conquer strategy and dividing the device color space into color section cubes, our method converts the *n*-to-one mapping to one-to-one mapping between the local color space of printer and the CIE Lab color space. This method is not only applicable for multi-color printing device but also for the conventional printing device.

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