Feedback for Printer Color Calibration

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Abstract

A feedback method is proposed for improving the color accuracy of printer calibration. Calibration of color printers involves data transformation between the device-dependent color space (e.g., CMYK) and the device-independent color space (e.g., CIE Lab). Although the goal of printer calibration is to get an accurate inverse transform T^{-1}(Lab) = CMYK, the forward transform T(CMYK) = Lab, also known as the printer model, is often derived first. Once both T and T^{-1} are optimized, a cascade, consisting of the inverse transform T^{-1} followed by the forward transform T, can be used to simulate the real printer and estimate the color output $L_1a_1b_1$ for a desired input Lab. The accuracy of calibration can be evaluated by calculating the difference ΔLab = $L_1a_1b_1$ – Lab. Since it is reasonable to assume that the difference ΔLab is most likely due to the inaccuracy of the inverse transform T^{-1}, a negative feedback of ΔLab to the original input Lab would give us an improved result of color calibration. Examples of applying the feedback idea to printer calibration with a halftone-algorithm independent printer model, the two-by-two printer model, are presented.

Introduction

Printer color calibration involves color transformations between two color spaces. Usually, one space is a device-dependent color space, such as the CMYK space, and the other space is a device-independent color space, such as the CIE Lab space. The printer itself conducts a forward color transform, i.e., for a given set of CMYK values, the printer produces an output with certain CIE Lab values. The purpose of printer calibration is to find an inverse transform, or a printer profile, which provides the corresponding CMYK values for desired Lab values. For deriving the inverse transform, data are collected through printer characterization, which represents the forward color transform. The printer characterization can be straight printing and measuring or the combination of measuring and interpolation. Alternatively, the printer characterization can be obtained through printer modeling. Using a printer model to simulate the real forward transform by the printer not only reduces the cost and time associated with massive color measurement, but also possibly provides higher accuracy than direct printing and measuring. Another advantage of using a printer model is the possibility to conduct halftone-algorithm-independent color calibration.[1,2] In this paper, we will describe a method which further explores the advantages of using a printer model in color calibration. We propose to apply a negative feedback obtained from the printer model, the forward transform, to the inverse transform for improving the overall accuracy of calibration.

Negative Feedback

Let's use a vector $\mathbf{r} = [C\ M\ Y\ K]^T$ to represent the device-dependent CMYK space and a vector $\mathbf{x} = [L\ a\ b]^T$ to represent the device-independent CIE Lab space. The forward and inverse color transforms T and T^{-1} are defined by the following equations,

$$\mathbf{x} = T(\mathbf{r}) \text{ and } \mathbf{r} = T^{-1}(x) \tag{1}$$

respectively.

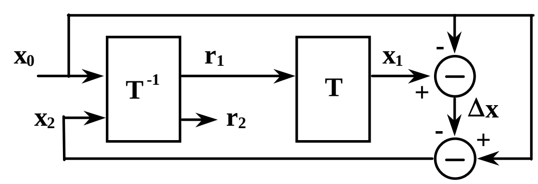

Figure 1. A feedback method for printer color calibration, where T and T^{-1} are the forward and the inverse transform, respectively.

As shown in Fig. 1, a derived inverse transform T^{-1} represents the result of a normal calibration procedure. The initial input $\mathbf{x}_0$ represents the desired Lab values and $\mathbf{r}_1$ is the CMYK output of the normal calibration. To evaluate the accuracy of calibration, a printer model, the forward transform T, is applied to $\mathbf{r}_1$ for an estimated color appearance $\mathbf{x}_1$. If both the forward and the inverse transforms are absolutely accurate, $\mathbf{x}_1$ is identical to $\mathbf{x}_0$, i.e.,

$$X_1\ T\,(T^{-1}(x_0)) = U(x_0) = x0. \tag{2}$$

where the cascade $T(T^{-1}())$ is equivalent to an identity function **U**(). Although in real applications above statement is not true, it is reasonable to expect that $\mathbf{x}_1$ is close to $\mathbf{x}_0$, and $\Delta\mathbf{x}_1$, the increment of $\mathbf{x}_1$, is also close to $\Delta\mathbf{x}_0$. A one-dimensional illustration of above relation is shown in Fig. 2.

To conduct a negative feedback, the difference between the output of the cascade $\mathbf{x}_1$ and the desired Lab values $\mathbf{x}_0$ is calculated by

$$\Delta\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_0. \tag{3}$$

The modified input, given by

$$\mathbf{x}_2 = \mathbf{x}_0 - \Delta\mathbf{x}, \tag{4}$$

is applied to the inverse transform and a more accurate result is expected.

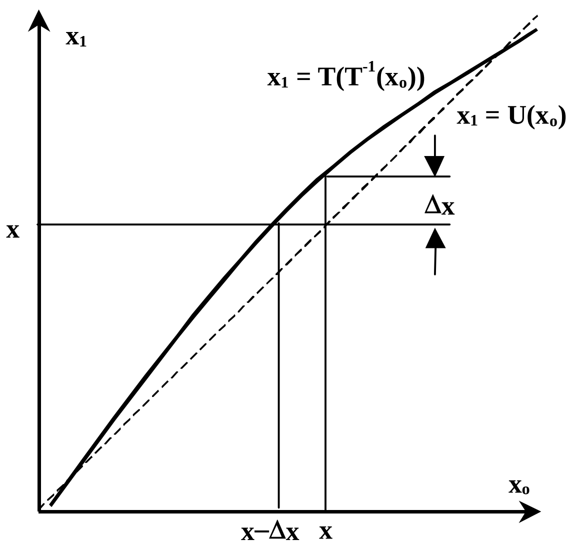

Figure 2. A one-dimensional illustration for the negative feedback. If the function $\mathrm{T}(\mathrm{T}^{-1}(\mathbf{x}))$ *is close to an identity function* $\mathrm{U}(\mathbf{x})$*, a negative feedback to the input* $\mathbf{x}_0$ *would correct most of the output difference* $\Delta\mathbf{x}$ *between* $\mathrm{T}(\mathrm{T}^{-1}(\mathbf{x}))$ *and* $\mathrm{U}(\mathbf{x})$.

One may notice that the discussion above about the feedback method is based on the overall accuracy of the cascade, which is evaluated in the CIE Lab space $\mathbf{x}$. However, the required output space of color calibration is the CMYK space $\mathbf{r}$. The improvement of the overall accuracy does not guarantee that the feedback output $\mathbf{r}_2$, is necessarily better than $\mathbf{r}_1$, the one without feedback. Since the inverse transforms T^{-1} might be in any shape, theoretically, the feedback method would not always result in an improvement, even if we had a perfect forward transform T. Fortunately, most color transforms in printer calibration are continuous and relatively smooth within the gamut. Also, the forward transform is usually more accurate than the inverse transform. If we have a good printer model, we can expect an improved accuracy of color calibration by employing the feedback compensation.

Printer Models

There are many different printer models used for color calibration. Since most color printers are binary printers, it is necessary to convert continuous-tone CMYK images into binary CMYK images through halftoning. Accordingly, we may divide different printer models into two categories: the halftone-algorithm dependent models and the halftone-algorithm independent models. Examples of the halftone-algorithm dependent printer models include the well-known Neugebauer printer model,[3] its modifications[4,5] and the cellular printer model by Balasubramanian.[6] A halftone-algorithm independent printer model predicts the color appearance based on CMYK binary patterns, therefore, one printer model can be used for calibrating multiple halftone screens or halftone algorithms in a color printer. A brief description of a halftone-algorithm independent printer model, the two-by-two printer model[1,2] is given in Appendix of this paper. A major advantage of this printer model is that it is truly measurement based. A 2x2 printer model is fully specified by measuring a set of color patches without any additional interpolation or rendering. So, the 2x2 printer modeling may provide the required high accuracy for color calibration.

Experimental Results

The feedback method for printer calibration has been tested with different printer models and different color printers. Most experimental results have shown improvement of the accuracy for color calibration. The following experiment was conducted using the 2x2 printer model with a 400-dpi CMY color printer. To characterize the 2x2 CMY printer model, a set of 1072 patches was printed and their spectral reflectance was measured. For color calibration, a data set with 8x8x8 samples uniformly distributed in the CMY space was selected. Then, 8x8x8 CMY binary patterns were obtained by halftoning constant inputs with the selected continuous-tone CMY values. A chosen set of halftone screens with line frequencies approximately equal to 141 lpi was used for halftoning. Expected Lab values from the 8x8x8 CMY binary patterns were calculated using the characterized 2x2 printer model and the definition of CIE Lab. The inverse transform, mapping the Lab space to the continuous-tone CMY space, was derived using a neural-network-based calibration method from the obtained database. In order to test the accuracy of the calibration, a set of 500 points randomly distributed in Lab space and within the printer gamut was chosen. The CMY values predicted by calibrations with and without the negative feedback were calculated. Again, the forward transform is conducted through halftoning with the selected screens and calculating with the 2x2 printer model. Two sets of testing patches, corresponding to the calibrations with and without feedback, were printed and measured in CIE Lab values. The desired Lab values were compared with the measurement results. For each set of 500 samples, the average ΔE and the maximal ΔE were calculated and listed in Table 1.

Table 1. A comparison of average ΔE and maximum ΔE between color calibrations with and without feedback for the 141-lpi screen set.

	Without Feedback	With Feedback
Average ΔE	1.9	0.9
Maximum ΔE	9.1	8.6

A similar test was conducted with the same printer but a different set of halftone screens, which have line frequencies approximately 171-lpi. The result, as shown in

Table 2, also indicates the improvement of the accuracy for color calibration.

Table 2. A comparison of average ΔE and maximum ΔE between color calibrations with and without feedback for the 171-lpi screen set.

	Without Feedback	With Feedback
Average ΔE	2.4	1.0
Maximum ΔE	9.7	9.0

Conclusion

A negative feedback method is proposed in this paper for improving the accuracy of printer color calibration. The feedback compensation idea is not limited to any particular calibration approach. In a wide sense, interpolation plus printing and measuring is also printer modeling. Also, the proposed method is not limited to particular color spaces. For example, in the experiment described above, the device-dependent space could be the binary CMY space, if the halftoning process was considered as a part of the inverse transform. Clearly, this simple feedback idea could benefit many existing calibration routines from obtaining extra accuracy for printer color calibration. It is also noticed that an iterative feedback may be applied to the system for a possible optimal enhancement. The key issue here is the proper printer modeling. More applications of this feedback method and its variations may be found once simpler, more accurate and more efficient printer models for halftoning and color calibration are discovered.

Appendix: Two-by-Two Printer Model

Neugebauer Equation and Yule-Nielsen Modification

For binary printers, the Neugebauer equation[3] predicts colors through combination of the primary printer colorants. For the following discussion, colors are specified in spectral reflectance[4] though they could be in tristimulus values XYZ as well. The predicted color output $R(\lambda)$ by a binary color printer is given by

$$R(\lambda)=\sum_{i=1}^{N} a_i R_i(\lambda), \tag{5}$$

where a_i and $R_i(\lambda)$ are the area coverage and the spectral-reflectance of each primary colorant, λ is the wavelength and N is the total number of primary colors. For a black-and-white printer, N=2, while for a CMY three-color printer, N=8.

Considering the scattering of light within the paper, Yule and Nielsen modified the Neugebauer equation[5]. Accordingly, the color output is given by the following equation

$$R(\lambda)^{1/n}=\sum_{i=1}^{N} a_i R_i(\lambda)^{1/n}, \tag{6}$$

where n is the Yule-Nielsen factor, which is often chosen as a fitting parameter.

Due to the complexity of dot overlapping, the main difficulty in applications of Neugebauer equations is how to accurately estimate the area coverage of primaries.

Two-by-Two Centering Model

In Fig. 3, the output from a binary color printer with an arbitrary binary input pattern is represented by overlapped circular dots with different colors. The two-by-two printer model[1,2] defines the output pixels using a lattice, which is offset from the nominal coordinate half-pixel horizontally and half-pixel vertically. Each output pixel defined in the new coordinate represents a 2x2-overlapping pattern within the pixel area. It is most interesting that any 2x2 pattern can be reproduced as a "solid color". In other words, a large area, or a patch, can be so printed that all pixels within the printed area have exactly the same microscopic 2x2 pattern. For example, the pixel specified by the heavy-line box in Fig. 3 shows a unique overlapping pattern, as redrawn in Fig. 4a. It is not difficult to see that all pixels in Fig. 5 have either the exact overlapping pattern Fig. 4a or its mirror images, shown as Figs. 4b, 4c and 4d. Thus, all 2x2 overlapping patterns can be measured individually and macroscopically for their color appearance.

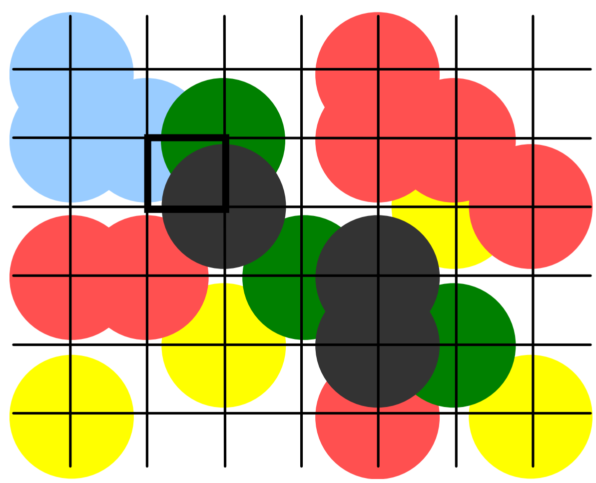

Figure 3. An arbitrary output by a binary color printer is represented as overlapped dots with different colors. The lattice, which cross the centers of printed dots, defines the output pixels, or 2x2 patterns.

The modified Neugebauer equation, given by Eq. 6, can be directly applied to the 2x2 printer model for predicting colors of any dot combinations. Hence, $R_i(\lambda)$ in Eq. 6 represents the spectral reflectance of each 2x2 pattern and N is the total number of different 2x2 patterns[1,2]. For a black-and-white binary printer, N=7, and for a CMY binary color printer, N=1072. The area coverage a_i of each 2x2 pattern is directly proportional to its occurrence m_I and can be calculated by

$$a_i = m_i \Big/ \sum_{j=1}^{N} m_j \,. \tag{7}$$

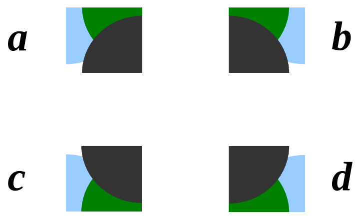

Figure 4. a: A two-by-two overlapping pattern, also shown in Fig. 3 by the heavy-line box; b, c, d: three mirror images of the 2x2 pattern shown in a.

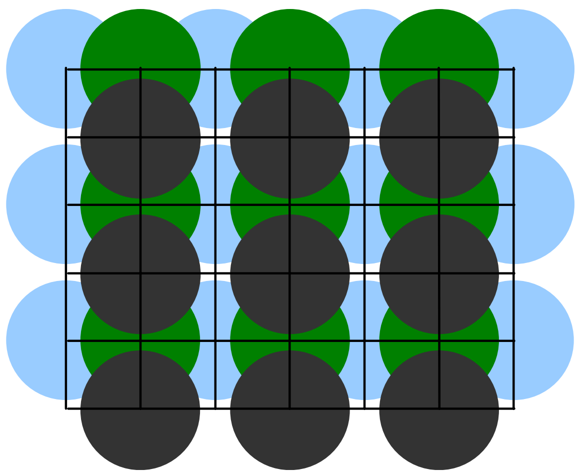

Figure 5. A color patch used to measure the color appearance of the 2x2 pattern shown in Fig. 4. All pixels of this patch have the same 2x2 pattern.

The 2x2 modeling requires that all dots should be symmetric about both x- and y-axis and not larger than the size specified by 2x2 pixels. These conditions are certainly satisfied by most binary printers, at least in the statistic sense.

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Biography

Shen-Ge Wang is currently a principal scientist with Xerox Corporation, Digital Imaging Technology Center. He received a BS degree in Instrumental Mechanics from Changchun Institute of Optics, China, in 1970 and a Ph.D. degree in Optics from University of Rochester in 1986, respectively. His research interests include digital and optical image processing, pattern recognition and color science.