

Conversion between CMYK spaces preserving black separation

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Abstract

This paper describes a method for developing a transform between two device CMYK spaces in a way that preserves information about the black separation. An important application of such a transform exists in desktop color printers for proofing of electronic files prepared for offset printing.

Our method uses a novel printer inversion approach based on constrained optimization. An error function defines the gamut mapping method and black separation behavior. The constraints limit the feasible solution region to the device gamut and prevent exceeding the maximum total area coverage. Colorant values corresponding to in-gamut colors are found with precision limited only by the accuracy of the device model. Out-of-gamut colors are mapped to colors within the boundary of the device gamut. An important property of our method is that areas in the input image using only black ink will be reproduced with the maximum possible black amount for a requested color.

We present an application of this method to the creation of multidimensional lookup tables that can be packaged as ICC device link profiles.

Keywords: color conversion, gamut mapping, constrained optimization

1. Introduction

A typical problem for color printers is how to reproduce the appearance of colors using a given set of colorants. A specific combination of the amounts of each of the colorants constitutes a specification of color in a device-dependent space such as CMYK or RGB. However, this way of describing color is inherently non-portable between different printer models and different media. Therefore in recent years color management systems based on device-independent color spaces such as CIEXYZ and CIELAB have been gaining widespread use.

Graphic designers require precise control over the final amounts of the inks to be used by the offset press and therefore they usually work in the CMYK color space. Therefore the graphic arts community in America followed another way of making the color specification portable by standardizing the CMYK printing conditions through the Specifications Web Offset Publications (SWOP). This provides each CMYK colorant combination with an unambiguous interpretation in terms of the CIELAB color space and allows sharing of separated files between different printers.

In practice most electronic files prepared in the US using CMYK color specification are intended for SWOP printing conditions. Therefore desktop printers should have the capability to handle these files using some form of SWOP emulation.

This paper describes a novel method for the creation of mappings between CMYK color spaces based on the concept of constrained optimization [1]. An error function defines the gamut mapping method and black separation behavior. The constraints limit the feasible solution region to the device gamut and prevent exceeding the maximum total area coverage. Colorant values corresponding to in-gamut colors are found with precision limited only by the accuracy of the device model. Out-of-gamut colors are mapped to colors within the boundary of the device gamut.

2. Description of the method

The first step in our method is the creation of a continuous model f of a printer which for each value CMYK in the colorant space CMYK calculates a corresponding value Lab in the CIELAB color space:

$$\text{Lab} = \mathsf{f}(\text{CMYK}, \boldsymbol{w}_{\mathsf{f}})$$

Vector $\boldsymbol{w}_{\mathsf{f}}$ represents model parameters. A diagram of the model creation step is shown in Figure 1a.

It is well documented that the CIELAB space is not perceptually uniform and that to prevent hue shifts gamut mapping needs to be performed in a uniform color space such as MLAB [2]. We achieve that by converting the CIELAB measurement data to MLAB and creating a printer model with MLAB outputs. This allows us to use the error difference formulas based on the assumption of perceptual uniformity.

Our goal is the generation of a mapping from the emulated device colorant space CMYK$'$ to the printer colorant

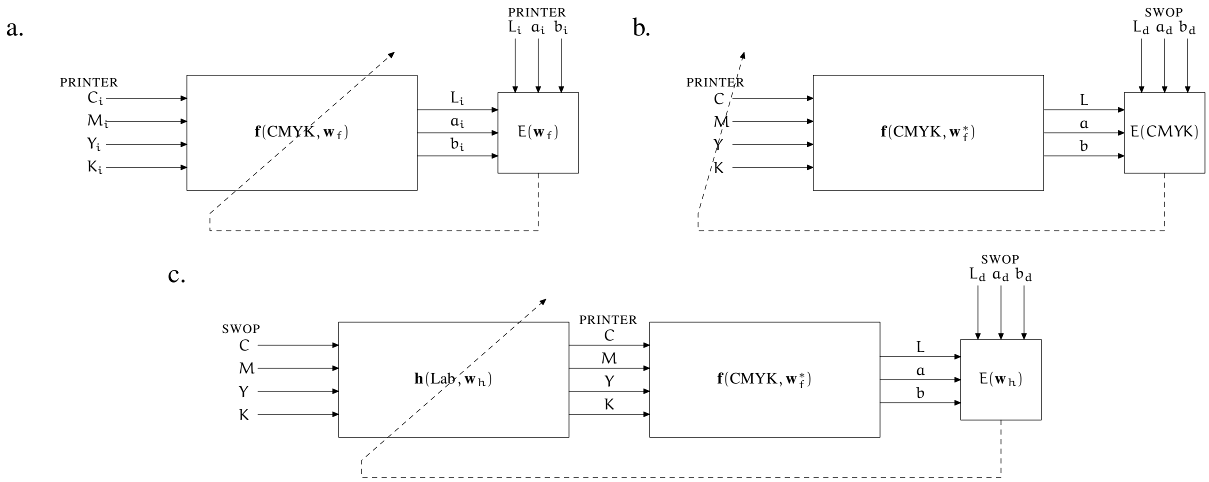

Figure 1: *Block diagrams of a. printer model adaptation; b. determination of a single color value; and c. creation of a* CMYK *to* CMYK *mapping. The dashed arrow represents the process of adapting the model parameters (w_f or w_h) or colorant values (*CMYK*) in order to minimize an error function* $E(\cdot)$.

space CMYK. One method of obtaining the solutions is to create a continuous model h which can then be queried for specific color values. A model h is a vector function

$$\mathrm{CMYK} = h(\mathrm{CMYK}', w_h)$$

where w_h is a vector of parameters. These parameters are found by minimizing the error function E subject to constraints in the colorant space:

$$w_h^* = \arg\min_{w_h} \sum_i E(f(h(\mathrm{CMYK}'_{di}, w_h), w_f^*), \mathrm{Lab}_{di}).$$

The calibrated CMYK spaces (such as SWOP) are usually defined by a table of standardized measurements relating a particular CMYK$'$ colorant combination CMYK'_{di} to an expected CIELAB color Lab_{di}. These color pairs can be used directly as a training set provided that they represent the desired mapping with sufficient accuracy. Otherwise, additional pairs can be interpolated between the data points provided by the standard.

A block diagram of the optimization process is shown in Figure 1c. The resulting function $h(\mathrm{CMYK}', w_h^*)$ is then sampled to create a multi-dimensional lookup table.

In this paper we describe an alternative method of finding the inverse mapping by computing the colorant values for each color point individually. A block diagram of this approach is shown in Figure 1b. In this case the desired printer colorant values CMYK_i^* are found for a particular color Lab_i by means of minimizing a cost function E related to the accuracy of color reproduction and gamut mapping with constraints reflecting the device gamut and printing process limitations:

$$\mathrm{CMYK}_i^* = \arg\min_{\mathrm{CMYK}} E(f(\mathrm{CMYK}, w_f^*), \mathrm{Lab}_{di}).$$

2.1. Color difference error function

A simple form of a color difference function is the distance between two colors in the Cartesian CIELAB color space. However, gamut mapping is performed more conveniently in the perceptual coordinates of the CIELCH space. These cylindrical coordinates are lightness (L^*), chroma (C^*), and hue (h^*). The error formula we use in this color space is similar to the ΔE_{94} CIE color difference equation:

$$E_{\mathrm{LCH}}(\mathrm{LCh}, \mathrm{LCh}_d) = \frac{S_L}{2}(L^* - L_d^*)^2 + \frac{S_C}{2}(C^* - C_d^*)^2 + \frac{S_h}{2}(h^* - h_d^*)^2.$$

Here the values of the S coefficients are not determined by the value of chroma coordinate but are chosen to obtain the desired weighting of each coordinate. These weights can vary depending on the desired color LCh_d.

By setting $S_L = S_h = 1$ and $S_C = 0.1$ we can obtain a three-dimensional out-of-gamut mapping that resembles chroma clipping. Making $S_C > S_h \geq S_L$ results in a mapping that attempts to preserve chroma at the cost of accuracy in hue and lightness, which can be used for creation of lookup tables for the ICC saturation rendering intent. Experiments performed by Katoh and Ito [3] on gamut mapping of computer generated images show that most observers prefer mappings performed with $S_L \geq S_h \geq S_C$. The weights S are related to the coefficients K used by Katoh: $S_L = 2/K_L^2$, $S_C = 2/K_C^2$, and $S_h = 2/K_H^2$.

The specific values of coefficients S do not significantly influence in-gamut color mapping because for them $E_{LCH} \approx 0$ is attainable. However, even in this case they can come back into play if unrealistic values of K_d (see Section 2.4) are requested.

2.2. Physical gamut constraint

This constraint reflects the fact that one cannot request less than 0 percent or more than 100 percent of each of the colorants:

$$0 \le C, M, Y, K \le 1$$

and defines the surface of the gamut in the colorant space.

2.3. Total area coverage constraint

Most printing processes have technological limitations that reduce the maximum total area coverage (TAC), i.e., the total amount of colorants printed at any point. For inkjet printers excessive amounts of ink may cause soaking and wrinkling of the paper. Electrophotographic printers may exhibit poor fusing when the toner layer is too thick. The SWOP web offset printing standard explicitly sets the TAC limit at 300%. Therefore an additional constraint is imposed which limits the effective gamut of a printer to colors that can be produced without exceeding the TAC:

$$C + M + Y + K \le \text{TAC}.$$

2.4. Black preference error function

Printers using more than three colorants have additional degrees of freedom to represent a specified color. For example it is possible to render most colors strictly inside the CMYK printer gamut using infinitely many colorant combinations. We can select the preferred level of black by means of an additional error term such as:

$$E_{\text{black}}(\text{CMYK}, K_d) = \frac{1}{2}(K - K_d)^2.$$

Hung [4] described a method for colorimetric black replacement. For each color the maximum (K_{MAX}) and minimum (K_{MIN}) amounts of black with which it can be reproduced are determined. We perform this determination for both the input and output device printing conditions. In our method K_{MAX} and K_{MIN} are found by inverting the device model by constraining the solution to have at least one of the CMY components equal to zero, and by penalizing $K > 0$, respectively. All these steps take into account the TAC constraints specific for the devices.

Then the final inversion of the output device model is performed with K_d set to a value preserving the relationship of the input black amount K_i with respect to the lower (K_{MIN}) and upper (K_{MAX}) limits:

$$K_d = K_{MIN} + \frac{K_{MAX} - K_{MIN}}{K_{iMAX} - K_{iMIN}}(K_i - K_{iMIN}). \quad (1)$$

An important property of our method is that areas in the input image using only black ink will be reproduced with the maximum possible black amount. In contrast, conversions based on ICC profiles which lose information about the black separation when the data is converted through the three-channel CIELAB space. Thus, our method has the advantage of avoiding the often cited problem in which the black text is reproduced using process colors.

3. Solving the constrained optimization problem

To minimize the error function in the presence of constraints, special optimization algorithms need to be used. For example, when only physical gamut constraints were specified we employed a bound-constrained optimization algorithm LBFGS. However, for the inverse model method (shown in Figure 1c) the colorant space constraints become very complicated: $0 \le h(\text{Lab}, w_h)_i \le 1$. Therefore we converted the constraints into additional error terms. This allows use of simpler unconstrained optimization algorithms. We use an efficient second-order optimization algorithm known as scaled conjugate gradient. Each constraint is replaced by a penalty function which is continuous in the control space.

The total error function $E(\text{CMYK})$ consists of the error terms both in the color space (color difference error E_{LCH}) and in the colorant space (such as gamut and TAC constraint penalties and black preference error) and is parameterized by the desired color value Lab_d and the desired black level K_d:

$$\begin{aligned} E(\text{CMYK}, \text{Lab}_d, K_d) &= E_{LCH}(\text{Lab}) + E_{CMYK}(\text{CMYK}) \\ &= E_{LCH}(f(\text{CMYK}, w_f^*), \text{Lab}_d) + E_{CMYK}(\text{CMYK}, K_d). \end{aligned}$$

The control space error function E_{CMYK} is constructed as a weighted sum of two constraint penalties and black preference error:

$$E_{CMYK}(\text{CMYK}) = S_{\text{gamut}} E_{\text{gamut}} + S_{\text{TAC}} E_{\text{TAC}} + S_{\text{black}} E_{\text{black}}.$$

The S coefficients determine the importance of error components, relative to each other and also relative to E_{LCH}.

The process of optimization stops when it reaches a stationary point on the error surface where, by definition, $\nabla E = 0$. Since the gamut and limit penalties can be made arbitrarily large, they can effectively trap the solution inside the gamut of the printer. This way the type of out-of-gamut mapping is determined mainly by the E_{LCH} term.

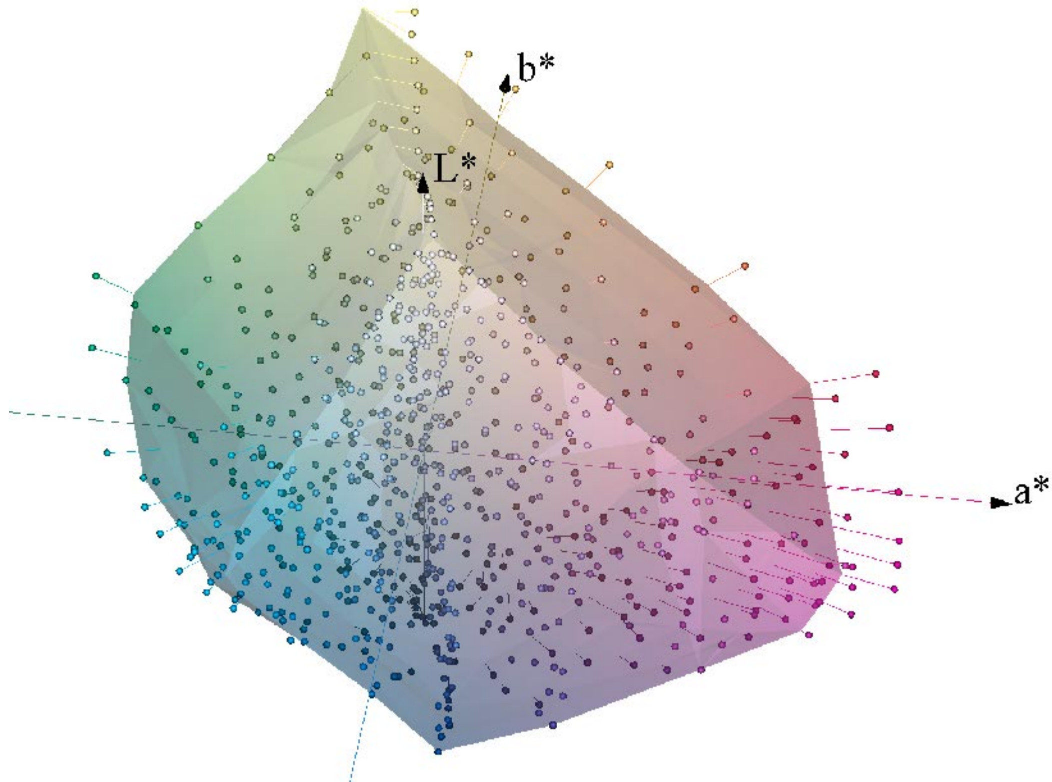

Figure 2: *Visualization of* SWOP *calibrated colorant space emulation for an example laser printer. Lines connect spheres marking the* SWOP CIELAB *points to the* CIELAB *values corresponding to* CMYK *values obtained from the mapping.*

4. Results

A visualization of a SWOP to CMYK mapping created for an example laser printer is shown in Figure 2. The out-of-gamut mapping was performed in the MLAB space to avoid hue shifts caused by the non-uniformity of CIELAB. The error lines for points located in the gamut of the target printer have zero length which means that they are mapped colorimetrically.

Depending on the degree of similarity between the black and yellow colorants of the two devices, we may opt to reproduce these pure input device colorants as pure output device colorants using one-dimensional lookup tables storing closest possible matches. The tradeoff between color accuracy and image quality (misregistration, presence of cyan or magenta dots in yellow parts of an image) has to be taken into account when making such a decision.

Figure 3 shows the comparison of separations obtained using the typical color management workflow with the results obtained using the proposed method (row (f)). To restate Equation (1), the black separation from row (f) uses the same proportion of black in relation to separations (c) and (d) as separation (e) in relation to separations (a) and (b). Relatively low (260%) TAC limit on the target printer produces visible reduction of the process color amounts in the dark areas of the image.

The proposed method allows emulation of a CMYK device on a printer with consideration to input separation settings and gamut and total area coverage limitations of the output device. The obtained interpolation table can be embedded in a printer or packaged as an ICC device link profile. The method can be extended to use nonlinear mapping between black ratios.

5. References

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Figure 3: *Separations of the* SCID *image* N1 *assuming* SWOP *colorants: a.* SWOP K_{MIN}*; b.* SWOP K_{MAX}*; c. target printer* K_{MIN}*; d. target printer* K_{MAX}*; e. original* CMYK *separations; f. target printer using proposed method. The columns two to five are* CMYK *separations and the first column is the resulting composite image.*