Color-based maximal GCR for electrophotography

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Abstract

The underline idea of gray component replacement (GCR) is to replace a mixture of primary colors (cyan, magenta, and yellow) by black. The conventional algorithms of GCR are mainly based on the concept of equal-tone-value-reduction or mixing equal amount (tone value) of primary colors generating gray, which in turn can be represented by the same amount of black. As the inks used are usually non-ideal, such a replacement can result in significant color deviation. In practice, only partial GCR is applied. We proposed an algorithm of maximal GCR based on color matching, i.e. the black is introduced in a way that preserves the color (before and after GCR). In the algorithm, the primary with the smallest tonal value is completely removed while the other two are reduced and the black is added according to the color matching calculations. The algorithm is verified by color-matching computations, for a large number of target colors. It shows that all the target colors can be matched with negligible color deviations (ΔE smaller than unity). Measurements of test prints of 90 colors which cover broad range of C,M,Y compositions, demonstrate an average color deviation ΔE=2.56 that is slightly bigger than the so called just noticeable difference (JND) and significantly smaller than that of the conventional GCR, ΔE=9.75.

Introduction

Mixing three primary inks can generate up to eight different colors that can be subdivided into four chromatic groups, namely (i) paper white; (ii) primary colors: cyan (C), magenta (M), and yellow (Y); (iii) secondary colors: red (R), green (G), and blue (B); and (iv) "black" (the component resulted from overlapping the primaries). With ideal primary inks, one can obtain gray or black by mixing C with equal amounts of M and Y. With practical inks, however, a mixture of full tone primary colors usually produces dark brown, due to non-ideal characteristics of spectral absorption of the primaries. In other words, a gray tone can not be produced by mixing equal amounts of primary inks. To achieve a proper gray tone reproduction, black ink (K) is usually introduced in addition to the primaries. Therefore, an ordinary printer consists of, at least, four inks: C, M, Y, and K.

As the introduction of the black ink is to achieve proper gray tone reproduction, it is therefore natural to replace (either partially or fully) the mixture of three primaries by black ink, avoiding unnecessary consumption of the primary inks. The amount of black ink used in print depends not only on the gray-tone of the print but also on the algorithm of gray component replacement (GCR) adapted in printing. When gray is solely generated by the black ink, it is called maximal GCR. In the conventional maximal GCR algorithm, the black plate is set to be the same as the primary with the lowest tone value, while the tone value of this primary is set to zero. Correspondingly, the other two primaries are reduced by the equal amount [1]. In the algorithm, it is implicitly assumed that the print of equal amounts of the primaries is chromatically equivalent to that printed with black ink of the same tonal value. As the inks are far from ideal, chromatic deviations is obvious when the conventional maximal GCR is employed in print. Such a maximal GCR method is, therefore, inapplicable and only a partial GCR has been employed in practice [2, 3].

The goal of the present work is to develop a maximal GCR method that keeps the prints, before and after GCR, chromatically identical or at least with a negligible color difference.

Color matching computation

The key of the method is to match the color of the print with GCR to the original color represented only by primaries. This is mathematically achieved by minimizing the color difference between the prints, defined as

$$\Delta E_{Lab} = \sqrt{(L_1^*-L_2^*)^2 + (a_1^*-a_2^*)^2 + (b_1^*-b_2^*)^2} \qquad (1)$$

where (L_1^*, a_1^*, b_1^*) and (L_2^*, a_2^*, b_2^*) denote the CIELAB color coordinates before and after the GCR, respectively.

In the calculations, Demichel's and Neugebauer's equations have been employed to calculate the area percentages of colored areas and the CIEXYZ tri-stimuli of the prints. For simplicity without losing the generality, the method is illustrated, using the following example. Assume that a color is originally represented by three primaries of tonal values (ink percentages) $c=0.2$, $m=0.4$ and $y=0.6$. Mixing the three primaries can produce up to eight color areas. The coverage of these areas equals, according to Demichel's equations,

$$\begin{aligned}
a_p &= (1-c)(1-m)(1-y) = 0.192 \\
a_c &= c(1-m)(1-y) = 0.048 \\
a_m &= (1-c)m(1-y) = 0.128 \\
a_y &= (1-c)(1-m)y = 0.288 \\
a_r &= (1-c)my = 0.192 \\
a_g &= c(1-m)y = 0.072 \\
a_b &= cm(1-y) = 0.032 \\
a_k &= cmy = 0.048
\end{aligned} \qquad (2)$$

In the equations, a_i stands for the coverage of color areas with the indices i= [p, c, m, y, r, g, b, k] denoting for Paper, Cyan, Magenta, Yellow, Red, Green, Blue and Black, respectively.

Knowing the coverage of the color areas, one can then compute the CIEXYZ tri-stimulus values by employing the Neugebauer's equations. In this example the CIEXYZ color coordinates of the print before GCR, (X, Y, Z), are calculated as follows,

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = a_p \begin{pmatrix} X_p \\ Y_p \\ Z_p \end{pmatrix} + a_c \begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} + a_m \begin{pmatrix} X_m \\ Y_m \\ Z_m \end{pmatrix} + a_y \begin{pmatrix} X_y \\ Y_y \\ Z_y \end{pmatrix} + a_r \begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix} + a_g \begin{pmatrix} X_g \\ Y_g \\ Z_g \end{pmatrix} + a_b \begin{pmatrix} X_b \\ Y_b \\ Z_b \end{pmatrix} + a_k \begin{pmatrix} X_k \\ Y_k \\ Z_k \end{pmatrix} \quad (3)$$

where (X_i, Y_i, Z_i) denote for the tri-stimuli of the color areas. The CIELAB coordinates of the print without the GCR, (L^*, a^*, b^*), are then calculated from the CIEXYZ values.

The key of the color-based maximal GCR is to reproduce the color, (*X, Y, Z*) or (L^*, a^*, b^*), with a negligible color deviation, by applying two of the three primary colors and black. It is done first by setting the color with the smallest tonal value to zero. In the example, it is the ink cyan. The tonal values of the other primaries and black are determined by reversely employing the Demichel's and Neugebauer equations, i.e., from the known tri-stimuli to find the tonal values, *m', y,'* and *k* (three equations for three unknowns). To avoid any confusion, the tonal values of the primaries are denoted with primes after the GCR. In the present study, the tonal values after the GCR, *m',y,'* and *k* are obtained by minimizing the color difference of the prints before and after employing the GCR.

As the Demichel's equations are based on probability calculations, they can naturally be applied to cases when the primaries are halftoned and printed independently, because the ink dots are placed randomly. In the case of deterministic ink-placements, Eq. 2 should be replaced by mathematical expressions that reflect the relationships between the primary tonal values and the coverage of the colored areas. To correctly compute the color of the print, the coverage of the color areas (in Eqs. 2 and 3), a_i, has to be the effective coverage, i.e. contributions from both physical and optical dot gain have to be properly taken into account. It is, therefore, necessary to find the relationships between the nominal tonal values of the primaries and black ink and, the effective coverage. These relationships can be given either by a physical model for dot gain [4, 5] or very often by dot gain curves obtained from measuring test patches. In the following section we will explore the approach based on dot-gain curves.

Determination of Dot Gain

In order to find the dot gain curves of the primaries and the black, we printed sixteen halftoned patches (for each primary and black) of nominal ink coverage, [c,m,y,k]=0, 2, 5, 8, 10, 20, 30, 40, 50, 60, 70, 80, 90, 92, 95, and 100%, respectively. The patches were printed by a laser printer with a print resolution of 300 dpi, using ordinary office papers as substrates. In order to compute the CIEXYZ color coordinates of a halftone by Eq. (3), print solids of secondary colors and gray generated by mixing the three primaries were printed on a separate paper sheet.

The CIEXYZ and CIELAB values for each color patch were measured using a spectrophotometer: Gretag SpectroLino. One of the most straightforward ways of finding the effective dot coverage is using CIE-Y values. For a monochromatic print, according to the Neugebauer model for CIE-Y, one receives,

$$Y_{mea} = a_{eff} Y_i + (1 - a_{eff}) Y_p \quad (4)$$

where Y_{mea} denotes for the measured Y value of the print, while Y_i and Y_p for the Y values of print solid (100% coverage) and that of the paper (0% coverage), respectively. Consequently, the effective dot coverage, a_{eff}, can be calculated as

$$a_{eff} = \frac{Y_{mea} - Y_p}{Y_i - Y_p} \quad (5)$$

Since there are 16 patches, and then 16 measured CIE-Y values, the relationship between the nominal and the effective dot coverage is known on these grid points. By interpolation one can obtain the relationship for an arbitrary nominal tonal value and vice versa. Due to different responses of the Y-stimulus to different color spectra, the relationship derived solely from the Y-stimulus works not equally well for all the primaries. Therefore, an improved approach was used, in which the best effective dot coverage is found to give the minimum color difference from the measured color,

$$\Delta E = \sqrt{(L^* - L^*_{mea})^2 + (a^* - a^*_{mea})^2 + (b^* - b^*_{mea})^2} \quad (6)$$

where,

$$\begin{pmatrix} L^* \\ a^* \\ b^* \end{pmatrix} = trans \begin{pmatrix} a_{eff} X_i + (1 - a_{eff}) X_p \\ a_{eff} Y_i + (1 - a_{eff}) Y_p \\ a_{eff} Z_i + (1 - a_{eff}) Z_p \end{pmatrix} \quad (7)$$

and

$$\begin{pmatrix} L^*_{mea} \\ a^*_{mea} \\ b^*_{mea} \end{pmatrix} = trans \begin{pmatrix} X_{mea} \\ Y_{mea} \\ Z_{mea} \end{pmatrix} \quad (8)$$

In these equations, *trans* is an abbreviation for the standard color transform from CIEXYZ to CIELAB color space. This gives slightly different dot gain curves than that solely using the Y stimulus and it works equally well for all the primary colors.

Results and discussion

The present method was first verified through color-matching computations, using a large number of color stimuli as "target color". According to the computations, all the colors that are originally represented by three primaries can be reproduced with our GCR method within a color difference less than ΔE=1.0. It means, at least from a theoretical point of view, the color-based maximal GCR is achievable.

The method is then evaluated using printed colors. The color generated with the GCR is measured and compared with the measurement of the corresponding color without using the GCR. The evaluation was made for 90 pairs of carefully selected halftone prints (a color map), covering a broad range of ink coverage of C, M and Y channels. Similar to the test patches used for obtaining the dot-gain curves, all the colors were generated with FM halftone algorithm and printed by a laser printer (in an office environment) with a print resolution of 300 dpi. The halftoning was conducted independently for the primaries and the black (black is only involved in the prints with the GCR). Correlations between the nominal and effective dot coverage were obtained through the dot gain curves of the primary colors and the black. The effect of dot gain was then taken into account in generating the colors. Nevertheless, it is worthy to notice that as the dot gain curves were obtained from an independent printing trial (see **Sec. Determination of Dot Gain**), they may not reflect the exact dot-gain characteristics of the printing system when the color map (used for the evaluation) are printed [6]. As a matter of fact, it is the main source that causes a remarkable difference between measured color deviation and that predicted by the color-matching computation. Later on we will come back to this point.

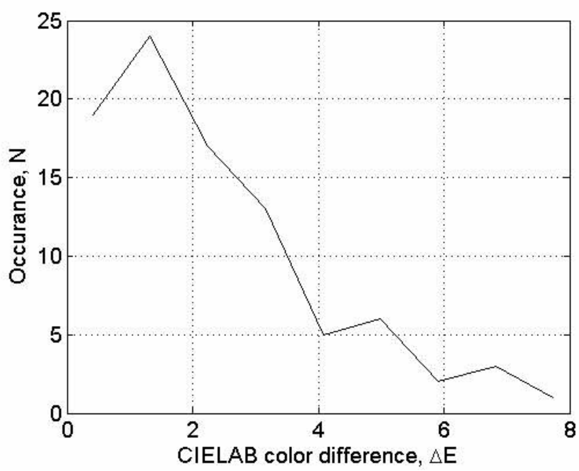

Figure 1. The number of occurrence of the measured color deviation of the pairs of prints (with and without the GCR).

The CIELAB color coordinates of the prints on the color map (with- and without the GCR) were computed from the spectral reflectance values measured with the spectrophotometer. The standard light source, D65, was used in the computation. The color difference between each pair of the prints, with- and without applying the GCR, is quantified in CIELAB ΔE values. As shown in Fig. 1, for some of the print-pairs their color differences are remarkably bigger than the computed ones (smaller than unity), with $\Delta E=7.74$ as the maximum. The averaged color difference is 2.56. Such a result is not ideal but may still be considered as acceptable, since a color difference less than 2.3 is considered negligible [7]. Figure 1 demonstrates the occurrence of the measured color differences. Clearly, for the most number of the colors (63 out of 90, or 70%), the color differences are smaller than 3, while 76 out of 90 (85%) is below $\Delta E=4$.

There are a few factors that possibly contribute to the bigger measured color differences compared with the ones predicted by the color matching computations. First of all is the stability or repeatability of the printing system. In the color-matching calculations, dot-gain curves were obtained from a separate print trial which is probably different from the real dot-gain behaviors when the color map was printed. As physical dot gain is closely related with the amount of toner transferred, variations in the processes related to the toner transfer will lead to different dot-gain curves from the ones used in color-matching computation. In consequence, the color-matching computation will not be able to exactly reflect the real situation when the color is printed. According to our experiences, many factors can affect the amount of toner transferred, as for instance, variations in printing environments (temperature and humidity), the dielectric properties of the paper (it changes from paper to paper), the amount of toner left in the system (full, nearly empty, something in between), etc. The second cause may be the simple algorithm adapted for dot gain compensation in the color matching computations. As the dot gain curves were obtained from the test patches of the primaries only, they are probably not good approximations to the dot gain behavior of the secondary colors and even worse for the gray resulting from mixing the three primaries. For example color blue generated by overlying a cyan dot on a dot of magenta may have different dot gain characteristics from both cyan and magenta. This issue is particularly important when liquid toners (like in inkjet) are used [8].

In parallel to the application of the color-based maximal GCR method, studies employing the conventional maximal GCR have also been carried out. For the same color map, the method generates an average color difference of $\Delta E=9.75$, which is about four times as that of the proposed method [6]. This is an encouraging indicator concerning the effectiveness of the present method, even though it is still a quite bit from satisfactory.

One of the potential benefits of the current algorithm is the reduced consumption of colorants. According to our calculation when halftoned with the color-based maximal GCR, the print of the standard test image: the musicians, will save up to 48% of the toner consumption [6]. The reduction in toner consumption will contribute to a shorter printing time, as it will shorten the time for processes like charging, toner transferring, and fusing, etc. For printers using liquid colorants, ink jet for example, it means less amount of ink-jetting and more importantly shorter time of drying. Further more, for conventional print technologies, like offset and flexography, employing the proposed GCR enables one to generate any color spot by printing not more than twice (printing one or two of the three primaries or black). This helps to reduce the possible miss-registration that commonly exists in the conventional print techniques. The possible negative side of the algorithm is that the black has different spectral characteristics from those of the primaries, since the color-matching is only in a metameric sense. This implies when illumination changes, the color-pair may appear remarkably different. But this problem may be overcome by selecting ink combinations with the best color constancy between illuminants as suggested by Chen et al [9].

Summary

In the present study, we explored the possibility to achieve maximal GCR while keeping the printed color (with GCR) matching the original. The tonal values of the two primaries and black are determined by color-matching computations, minimizing the color difference between the original (print without GCR) and the print with the GCR. To account for the effects of dot gain, dot-gain curves obtained from test patches of the primaries and black are used in the computation.

Color-matching computations were carried out for a large number of target color stimuli. The color differences between all the color pairs (with- and without the GCR), according to the computations, are smaller than unity ($\Delta E<1.0$). This indicates the applicability of color-based maximal GCR, from the theoretical perspective. In practice, the algorithm has been tested with a color map comprising 90 colors. The average color difference based on measurements is $\Delta E=2.56$, which is slightly higher than the just noticeable difference (JND), $\Delta E=2.3$. The discrepancy between the computed- and the measured color differences, may be caused by the (non) stability/repeatability of the printing system and changing print environments. It may also result partially from the simplified approach accounting for the dot-gain effect, in which the possible interaction between the dots of the different primaries that produce the secondary colors and gray has been neglected.

The potential benefits applying the algorithm are to reduce colorant consumption that may contribute to shortened time of printing and/or drying as well as reduced miss-registration.

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Author Biography

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