Chromatic Variation and Color Gamut Reduction due to Ink Penetration

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Abstract: Ink penetration is known to have an important impact on image reproduction. The rendering of images is impossible without taking the effect into consideration. Based on our newly developed approach for ink penetration the color rendering for multi-chromatic (halftone) images have been simulated with consideration of optical gain. Simulations including and excluding ink penetration show that these effects result in remarkable color variation (hue shift and saturation reduction) on the color image rendering. Color gamut reduction resulting from these effects is also shown.

Introduction

The color rendering of a print depends on the optical properties of the materials used in printing, such as inks and substrates. It also depends on how the inks are distributed. In the case of non ink penetration, the print consists of two types media layers (inks and paper) which behave very differently. Generally speaking the inks have strong spectral absorption but little scattering power and the paper acts just the opposite (i.e. little absorption but strong scattering power). Correspondingly in modeling and simulations, the printed ink layer can be treated as a kind of filter (absorbing only) on a scattering only substrate. And the printed color depends on geometric distributions of the inks on the substrate surface (dot shape, resolution and halftone algorithm etc.). However in the case of having ink penetration, there exists an intermediate media layer, i.e. the ink penetrated paper. Because of ink penetration, the ink distribution over the substrate surface is changed (compare to the case of non-ink penetration) which naturally alters the

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color of the print. On the other hand, the ink penetrated paper is of both scattering and spectral absorption which contributes to the color rendering as well. Finally, the presence of the intermediate layer is the key for complexity of the simulation.

The ink penetration is an ordinary phenomenon in every day prints, such as newspaper. It is also common for ink jet print when uncoated paper is used, such as copy papers. The ink penetration has two folds of impact on the printed color. It causes remarkable shift on rendered color on one hand and it reduces the volume of reproducible colors (or color gamut) on the other. In the other words, it causes hue shift and saturation reduction. To prevent paper from ink penetration, one or few post-processes are added in paper making industry. One representative of such processes is called paper coating where kind of chemicals is coated onto the paper surfaces. Indeed such a post process can significantly improve the properties of the paper surfaces. Nevertheless, it makes the paper much more expensive and in turn it makes the price of the print much higher. Therefore to understand how these effects affect the color rendering are of great importance not only scientifically but also economically.

The ink penetration is a complex process. It is related with the rheologic properties of the inks and the surface characters of the papers and their bilateral interaction. The bilateral interaction is further related with the micro structure of paper's fiber which is completely irregular in distribution and orientation. All of these make the ink penetration a challenge problem for measuring and simulation. Although it has been a well aware phenomenon, only a few reports concerning the mechanism of ink penetration and simulation were published (Pauler,1987 Bristow,1987, Yang and Kruse,2000, Arney and Alber, 1998). Moreover it was assumed in the simulations that the ink penetration was independent of the tonal values (ink coverage) or only ink penetration for full tone ink plate was studied. Evidently these models are far from close to the reality especially for light tone printing in high resolution (correspondingly small and well separated ink dots). Therefore more investigation is needed in order to give a better description for the ink penetration.

Very recently, we showed that for a full tone ink plate ink penetration can optically be described as introducing an extra ink layer which forms a sandwich type structure (Yang and Kruse,2001). The transmittance value of the extra ink layer is equal to the square root of the ratio between reflectance of the ink penetrated paper to that of the clean paper. With this approach one can avoid difficulties in direct dealing with a complex media system which has strong scattering and absorption. We further proposed a model which describes ink penetration for a halftone image (Yang and Kruse,2001). Good agreement of simulations with the experimental data has confirmed the validity of the model and has revealed strong dependence of ink penetration on the ink coverage (tonal values). In present paper, we will further explore our study about the effects of ink penetration on color rendering, such as color shift and color gamut reduction.

Method for Computing Color Gamut and Chromatic Derivation

The *CIEXYZ* tristimuli can be computed according to their definitions, provided the spectral reflectance values of the images, $R(\lambda)$, is known. For example, X can be expressed as

$$X = \int S(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \tag{1}$$

The quantity $R(\lambda)$ depends on the properties of the inks and the paper, and the ink-paper interaction. Very recently we have proposed a model to compute $R(\lambda)$, in which the dependence of ink penetration of the ink coverage was considered. In addition, optical gain which results from light scattering inside the substrate was also included in the model. Simulations by applying this model were in good agreements with the measurements (Yang and Kruse, 2001). In Eq. (1), $S(\lambda)$ *is* assumed as *D65* light source (2^O).

The *CIEXYZ* tristimuli, X, Y and Z, can be further transformed into $CIEL^*a^*b^*$ color space where color gamut and color differences are usually evaluated.

$$\begin{bmatrix} L^* \\ a^* \\ b^* \end{bmatrix} = \begin{bmatrix} g(Y/Y_0) \\ 500(f(X/X_0) - f(Y/Y_0)) \\ 200(f(Y/Y_0) - f(Z/Z_0)) \end{bmatrix} \tag{2}$$

where

$$g(x) = \begin{cases} 116x^{1/3} - 16 & x > 0,008856 \\ 903,3x & x < 0,008856 \end{cases} \tag{3}$$

and

$$f(x) = \begin{cases} x^{1/3} & x > 0,008856 \\ 7,787x + \frac{16}{116} & x < 0,008856 \end{cases} \tag{4}$$

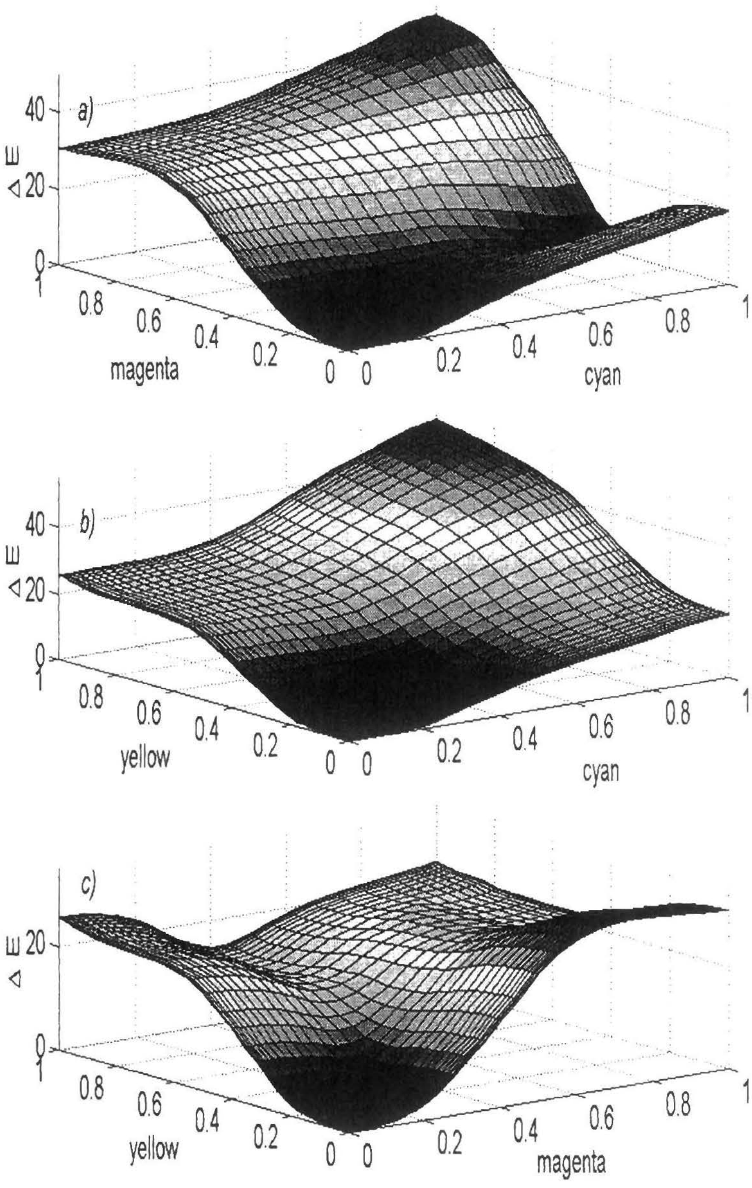

Figure 1: Color differences between images with and without ink penetration. a) cyan and magenta; b) cyan and yellow; c) magenta and yellow.

In turn the color difference resulting from ink penetration can be computed as

$$DE = \sqrt{((L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2)} \quad (5)$$

where (L^*, a^*, b^*) and (L_0^*, a_0^*, b_0^*) represent the color coordinates of the images with and without ink penetration.

Results and Discussions

The simulations have been made to simulate the effects of ink penetration on color rendering, i.e. the images were *printed* on two types of substrate, one has ink penetration and another has not. In the following, we will discuss the effects from the most important perspectives about color rendering, namely color shift and color gamut reduction.

A. Color Shift due to Ink Penetration

To characterize the difference in color, ΔE is usually used which is computed according to Eq. (5). For clarity of the demonstration, images printed with different combinations for two of the three primary inks have been simulated. Simulation for more inks is just straight forward. In the simulation, the ink dots were assumed to be round in shape and one ink dot was placed on top of the other (dot on dot). The chromatic deviation resulting from ink penetration, ΔE with respect to the ink coverages of different ink combinations, is shown in Fig. 1. At the first glance, the variation of ΔE with respect to different ink combinations are remarkably different. However, there exist a common feature in all the panels. i.e. ΔE increases along the diagonal line from *null* ink coverages to *full* ink converges (say from *cyan=magenta=0* to *cyan=magenta=1*). It means that the color difference due to the ink penetration increases with respect to the increase of the tonal values. But there exist some exceptions in the figures, for example, ΔE forms a valley in the vicinity of cyan~100% and magenta~40% (see Fig. 1a) which counters to the general trend. To understand this it is necessary to look at the differences for the components, ΔL^*,Δa^* and Δb^*.

In Fig. 2, we showed the calculated $\Delta L = L - L_0$, $\Delta a^* = a^* - a_0^*$ and $\Delta b^* = b^* - b_0^*$ versus ink coverages of cyan and magenta. For clarity of explanation, we first examine the differences for the primary colors, cyan and magenta, which correspond to curves at *magenta=0* (pure cyan) and *cyan=0* (pure magenta) in the sub-figures, respectively. In Fig. 2b), curves (a*-a0*) for pure cyan and magenta are identical at *cyan=magenta=0*, but they move along opposite directions as their ink coverages increase, separately (i.e. ink coverage of cyan remains zero when that of magenta increase). These mean that ink cyan appears remarkably reddish,

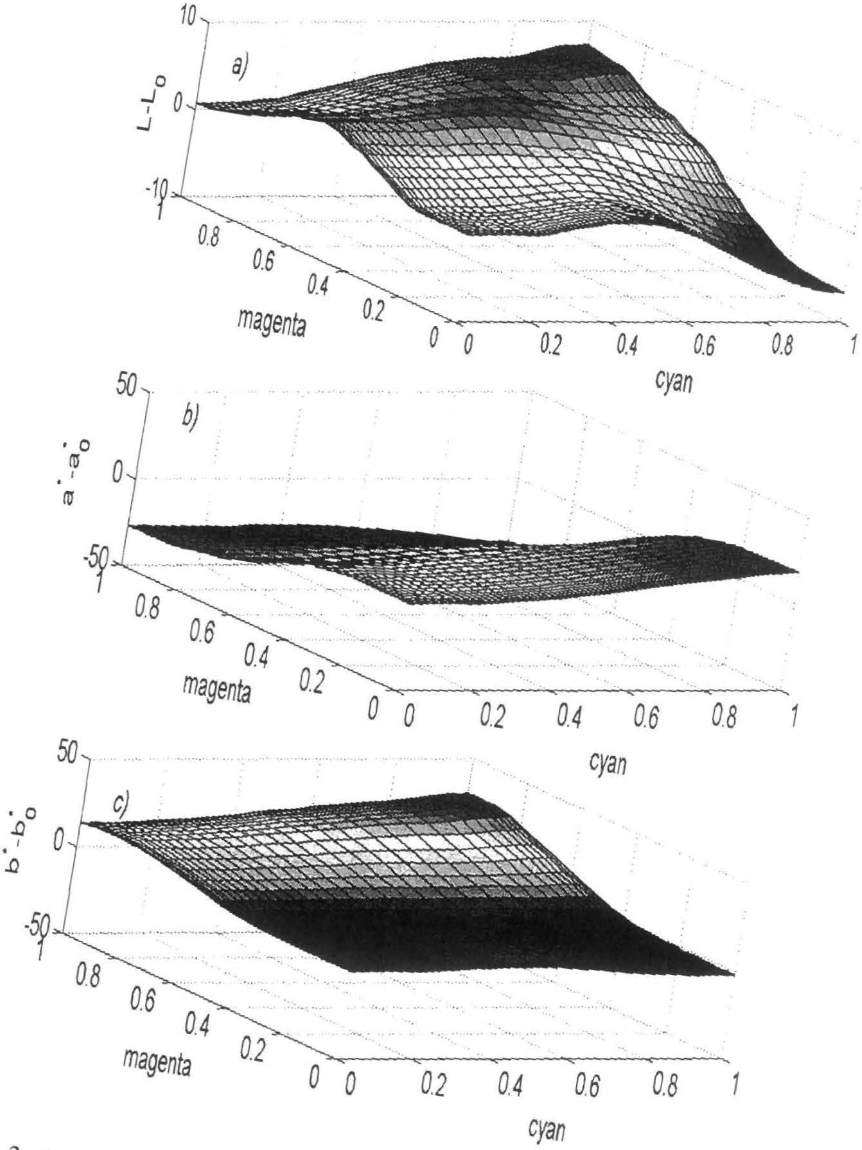

*Figure 2: Color shift for La*b* components due to ink penetration for images printed with two primary inks, cyan and magenta.*

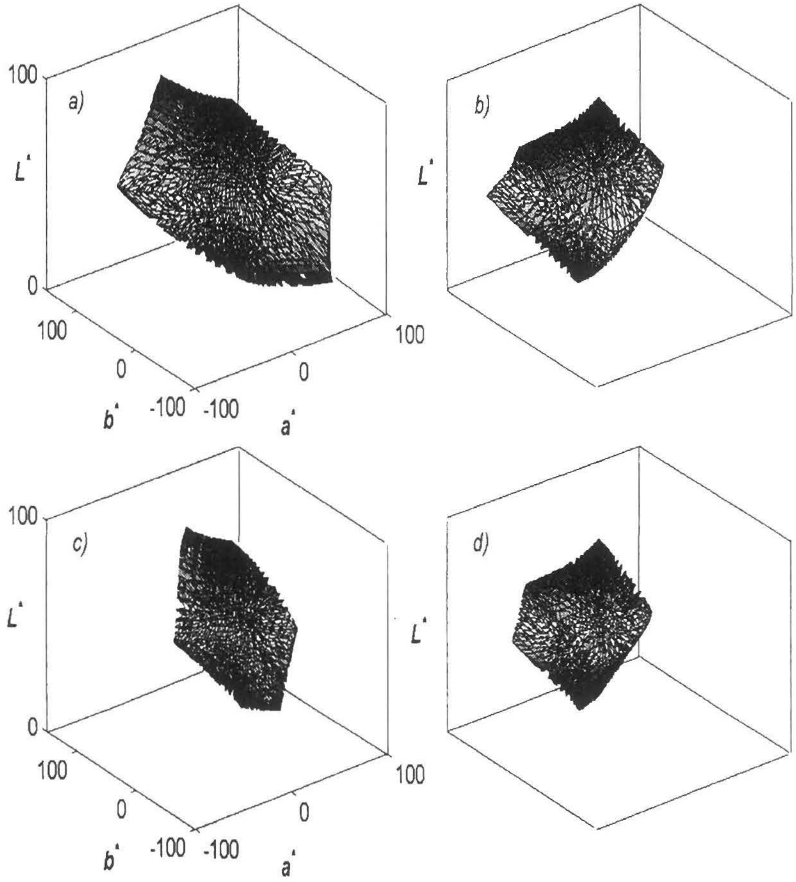

Figure 3: Simulated color gamut for images printed on different substrates; a) without ink penetration, c) with ink penetration, b) and d) are rotated from a) and c) 90^o counterclockwise around (0,0,1) axis .

for a bigger ink coverage due to ink penetration because $(a^*-a_0^*)>0$, but ink magenta becomes more greenish correspondingly (because $(a^*-a_0^*)<0$). Therefore for *cyan=1* when coverage of ink magenta increases from *0* to *1*, $(a^*-a_0^*)$ experiences a change from positive to zero and then to negative. For $(a^*-a_0^*)^2$, however, it corresponds to a minimum at the vicinity of $(a^*-a_0^*)^2 = 0$. Consequently, it results in a valley on the ΔE surface (see Eq. 5). In addition in Fig. 2c), it is shown that ink magenta becomes more yellowish due to ink penetration, but ink cyan is little influenced. Comparatively influence from ink penetration to the lightness (see Fig. 2a) of the image (L^*-L_0^*) is relatively weaker than that for other color components. In the other words, the effect of ink penetration is mainly on the hue angle and saturation, which means that the printed color can appear differently and very much unsaturated when there exists ink penetration. This agrees with experimental observation.

B. Color Gamut Reduction

Another effect of the ink penetration for color rendering is on the color gamut. The color gamut that corresponds to the volume of the reproducible color in a color space (say $L^*a^*b^*$) is a measure for the color reproducibility for certain devices and materials used for printing. Here we focus ourself on the ink-substrate interaction only, i.e. the influence of the ink penetration.

In Fig. 3 we showed the simulations of color gamut for the image printed on the non ink penetrated substrate (Fig. 3a) and on the ink penetrated substrate (Fig. 3c). Fig. 3b and Fig. 3d are the simulated color gamuts from different point of view (Fig. 3b and Fig. 3d were rotated 90° counterclockwise around (0,0,1) axis from Fig. 3a and Fig. 3c, respectively). For a easier comparison, all the sub-figures have been prepared in the same scale of coordinates. Evidently, the volume corresponds to the case of having ink penetration (Fig. 3b) is significantly smaller than that without ink penetration (Fig. 3a), or the color gamut is very much reduced due to the ink penetration into the substrate. This is also in line with experimental observations.

Conclusions

Applying our recently developed model for ink penetration, we have simulated the effects of ink penetration on the color rendering. It was found that the ink penetration can result in remarkable color difference or shift (hue) and at the same it can cause significant reduction on color's saturation. In addition, the volume for reproducible color or the color gamut is significantly reduced due to the ink penetration. The simulations provide a quantitative description about the effects of ink penetration on the color rendering which is surely important for the quality evaluation.

Acknowledgment

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