Evaluation of the Effects of Ink Penetration in Ink Jet Printing: Experiments and Simulation

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In an ink jet printing system consisting of dye-based liquid inks and office copy paper (plain paper), ink penetration has profound effects on color rendition. In this report we present methodologies for evaluating these effects by means of experimental data analysis and simulations. On the experimental side, color coordinates of patches printed on two types of substrates, one with ink penetration and another without, have been compared. It is observed that ink penetration has a significant effect on the chroma and hue of the printed colors. On the simulation side, pure effects of ink penetration are studied because ink penetration can be switched on or off at will in the simulation. It is found that ink penetration increases the reflectivity in the absorption band of the ink, while it reduces the reflectivity in the transparent region of the spectrum. This explains the experimental observation that saturation of color is reduced and the hue of the color is changed upon ink penetration. Additionally, advantages and disadvantages of the evaluation methods have been discussed.

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Introduction

In ink jet printing, absorption of ink constituents by a substrate, or ink penetration, is significant over a range of timescales, from the first stages of ink transfer and ink drying by absorption, through to long term stability.[1–3] The underlying phenomena of ink penetration is formation of a layer of an ink-substrate mixture. In a combination of dye-based liquid ink with plain paper, such as office copy paper, it leads to an ink-paper mixture whose optical properties are significantly different from those of the inks.[4] This in turn results in a dramatic but negative impact on color reproduction.

Studies have so far concentrated mainly on understanding the mechanisms of ink penetration, and developing materials for paper coating. Reported studies on the optical and chromatic effects of ink penetration are few, even though such studies have recently been intensified.[5–7] Very recently, we conducted systematic and extensive studies on ink penetration by combining theoretical simulation with spectral reflectance measurements.[4] These studies stretch from theoretical development by extending the Kubelka-Munk theory to inhomogeneous ink distributions,[8,9] to the modeling and simulation of light scattering (optical dot gain) and ink penetration in ink jet tone reproduction.[10–12] Besides, characterization of ink properties and ink applications (the amount of ink printed) of an ink jet system[13] that is directly related to the determination of depth of ink penetration[14] was also conducted. This presentation aims at evaluating the effects of ink penetration from experimental and simulation perspectives.

Evaluation with Experimental Data

To evaluate the effects of ink penetration experimentally is not a trivial task. Intuitively and also ideally, one would directly compare two prints on the same type of substrate, one has ink penetration, and the other not. To accomplish such a comparison one needs to be able to manipulate (switch on and off) ink penetration at will, which is experimentally impossible. One alternative that is usually applied is to print the same color on different types of substrates, such as plain paper and photo quality paper for prints, respectively. In order to distinguish from the term of ink absorption by coating materials of the high grad paper, the term of ink penetration refers to ink absorption owing to fiber porosity of paper.

Here are some details about the experiments. In order to minimize the impact of the substrates, two types of paper that have the similar “color” were used. They were HP Photo Paper (175 g/m^2) and MultiCopy paper (80 g/m^2) produced by StoraEnso. As is seen from Table I, they are little different in color (ΔE = 1.32). The color patches were created by using HP970Cxi ink jet which used dye-based inks to create primary and secondary colors. Light to mid tone gray was generated by mixing the primary colors, while black pigment was added in when a dark gray (the commanded ink percentage greater than 60%) was printed. The printer’s driving program provided by the vendor was used. The same print mode (for plain paper) in the printer driver was

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Supplemental Material—Figure 4 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.

TABLE I. Color differences (ΔE) between the photo gloss paper and the office copy paper before and after printing (solid patches only).

color	paper white	cyan	magenta	yellow
ΔE	1.32	12.37	19.30	23.67
color	black	red	green	blue
ΔE	13.44	24.92	22.59	20.75

used in generating the test patches on both types of the substrates. The reflection spectra and color coordinate of these color patches were then measured after drying, using a spectrophotometer (Spectrolino).

Parallel Comparison for Prints on Two Types of Substrates

When different substrates are used for printing, it seems to be reasonable to compare the color of the test patches in parallel, i.e., to compare patches of the same (commanded) ink percentage but on different substrates. Nevertheless, two things should be considered when the evaluation is made. First, different substrates have different optical properties (spectral reflectance or color, point spread function of light, etc.) which will affect color rendition for the prints and optical dot gain characteristics. Secondly, they have different surface and bulk properties that will influence the ink distribution on the substrates. This will, for example, result in different physical dot gain when halftone images are printed on different types of substrates. To some extent, color differences resulting purely from the different substrate colors may be minimized by choosing the substrates having similar color under certain illumination conditions (metamerism). Despite these potential complications, chromatic effect of ink penetration can still be evaluated, at least qualitatively, by such a parallel comparison, this is because ink penetration has, by far, much stronger impact on the printed colors when dye-based inks are printed on ordinary office copy paper.

In the present study, plain paper (StoraEnso, 80 g/m^2) and photo gloss paper (Hewlett Packard, 175 g/m^2) were chosen as the substrates. Their tristimulus values (CIEXYZ) are (84.03, 88.78, 94.75) and (86.49, 91.16, 96.10), respectively. Their color difference equals to ΔE = 1.32, which is therefore hardly noticeable, even though they are evidently different in gloss. Test patches of primary and secondary colors were created by printing on these substrates. For each color, the commanded ink percentages range from 0 to 100% in steps of 5%. The tristimulus values of these charts were measured employing a spectrophotometer.

Color differences between the substrates, and the solid prints on the substrates, have been collected in Table I. As is shown, the color difference between the photo gloss paper and the plain paper before printing is hardly noticeable (ΔE = 1.32). However after printing with full tone colors, their color differences increase dramatically to ΔE = 12.3 – 25, depending on the printed colors. Since only solid printed patches are compared, the color differences arise mainly from ink penetration. Neither physical nor optical dot gain which is closely related with the substrates, contributes to these differences.

Evaluation Based on Experimental Data

The chromaticity diagram for halftone patches on different substrates has been plotted in Fig. 1. Color corresponding to a certain ink coverage is denoted by a triangle. To explicitly illustrate color differences between

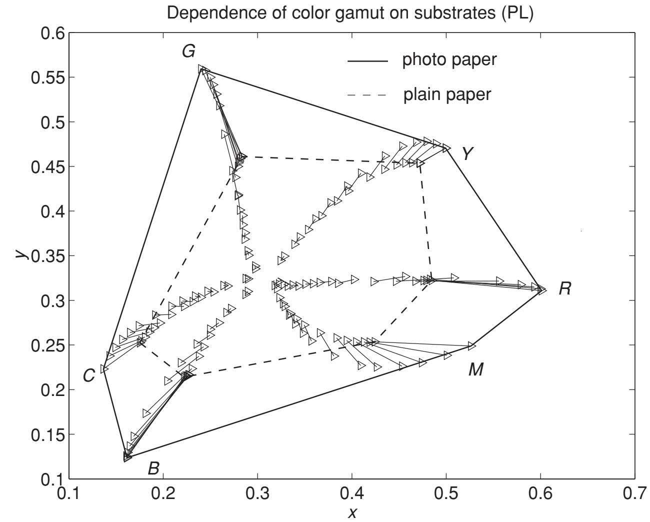

Figure 1. Chromaticity diagrams of prints on office copy paper and on photo gloss paper drawn from the experimental data. The pairwise points (noted by triangles) corresponding to the same (commanded) dot percentage but different substrates, are connected by Δ – Δ. The 2D color gamuts of prints on the plain paper and photo gloss paper are marked by dashed line and solid line, respectively. C, M, Y, R, G, and B mean cyan, magenta, etc.

prints on photo gloss paper and those on plain paper, colors of the same ink percentage but on different substrates are pair-wise connected by solid lines. Moreover, areas of the diagram that can possibly be covered by prints on the photo gloss paper and on the copy paper are marked with solid and dashed lines, respectively. As these areas represent the possible colors that can be produced by printing on these substrates, the figure implies that the photo gloss paper has significantly greater capacity in representing colors than does the plain paper.

Chromatic effects of ink penetration can be further examined in terms of chroma and hue of the colors. Figure 2 is a two-dimensional representation in the CIELAB color space. The colors corresponding to the same ink and substrate but different ink percentages have been joined up with solid lines and dashed lines, respectively, for prints on the photo gloss paper and on the copy paper. Observations from the figure may be summarized as follows:

- chroma increases with respect to increasing ink coverage,
- prints on different substrates appear similar in the light tone but differ significantly in both chroma and hue, in mid to dark tone colors,
- prints on the photo gloss paper produce colors of significantly greater chroma.

These observations may be explained as follows. First, as the ink coverage increases, the white light reflected from the non-printed substrate decreases and at the same time contributions from the printed areas increase. Hence, the chroma increases. Second, since the color of the substrates predominates in the light tone regions and since the substrates have similar color, curves corresponding to the substrates overlap with each other when the ink coverage is small (light tone). However, the curves become gradually separated when the ink

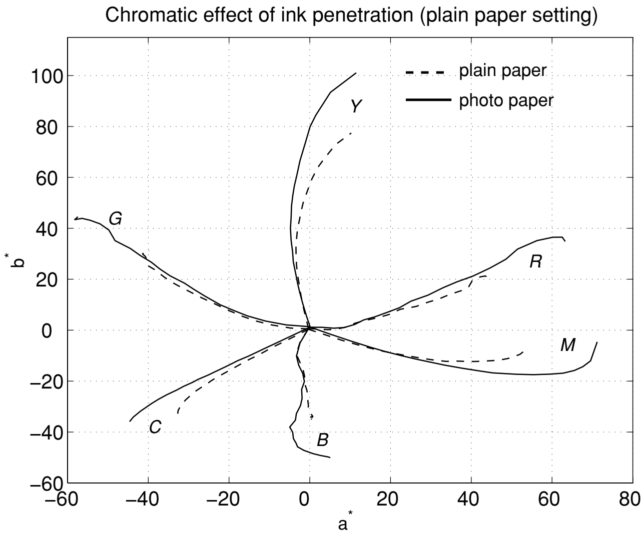

Figure 2. Color gamut (2D) in CIELAB color system. The images were printed on different substrates, plain and photo glossy papers, but with the same substrate setting (plain paper) in the printer driving program.

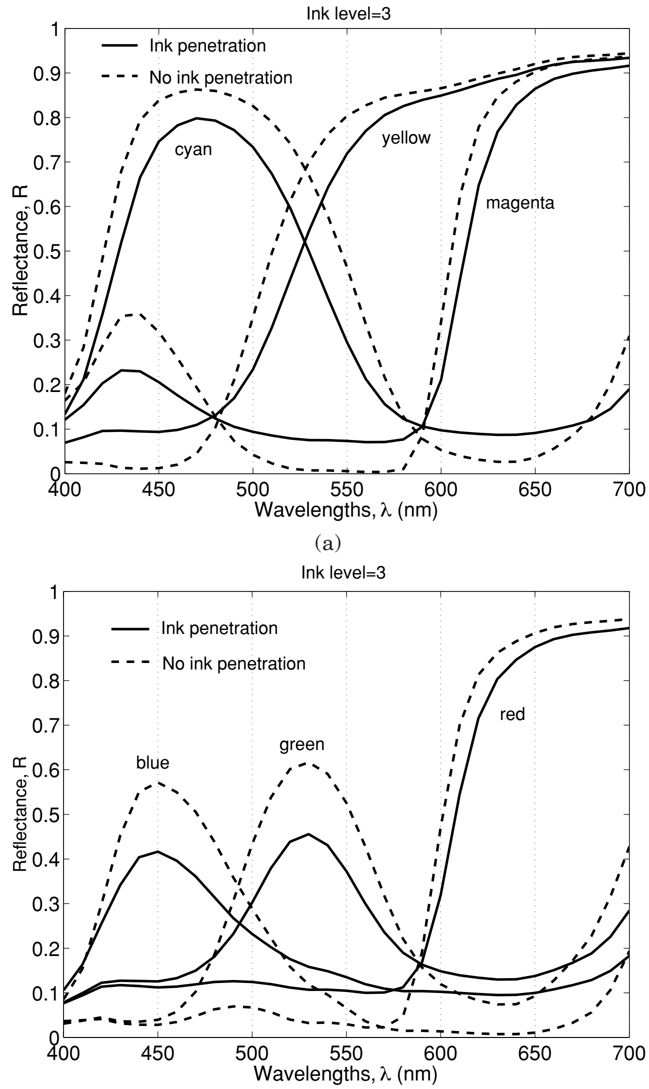

Figure 3. Comparison (simulated results) of colors printed on office copy paper with and without considering ink penetration in simulations.

coverage increases, because of different ink–paper interaction characteristics of the substrates. Finally, due to ink penetration an ink-porous mixture is formed, which has strong scattering power and leads to the reflected light being less saturated in the case of ink penetration. More discussions of this issue will be given in the following sections.

Evaluation with Simulations

Simulation allows a direct comparison that is not possible experimentally, since one can switch on or off the ink penetration at will in the simulation. There is no need to use different types of substrates as is the case in the experimental evaluation. Therefore, the differences in optical and physical dot gain resulting from using different types of substrates are avoided. In other words, effects of ink penetration can be studied in isolation.

In the simulation, the paper is treated as a uniform media layer that becomes a two-layer system after printing. The top layer is an ink–paper mixture, while the bottom layer comprises the clean paper. In the case of no ink penetration, the ink layer is assumed to be in optical contact with the paper's surface. The reflection spectra of the ink penetration is computed by applying the extended Kubelka–Munk (K–M) theory.[9] Ink distribution in the ink–paper mixture is assumed being homogeneous in the present study. Extension to an inhomogeneous ink distribution is straightforward by applying the newly developed framework,[9] whereby treatment of the homogeneous and inhomogeneous ink penetration is unified. Detailed descriptions of the simulation can be found elsewhere.[4,14]

Spectral Reflectance Values

Simulations for spectral reflectance values for solid patches of primary and secondary colors are depicted in Fig. 3. From the figure one can clearly see the significant effect of ink penetration. Interestingly enough, the effect shows a strong wavelength dependence. For convenience of the discussion, we refer to the spectral band containing the local maximum as the transparent band and that containing the local minimum as the absorption band. In transparent bands, prints having no ink penetration show greater reflectivity. In contrast, in absorption bands, prints with ink penetration show stronger reflectivity. These observations reflect the collective contribution to light reflection from the substrate, the ink layer, and ink–paper mixture. In the case of no ink penetration, the print consists of an ink layer and a substrate backing (plain paper), while with penetration it consists of a layer of ink–paper mixture and the substrate backing. As is known the ink layer has little scattering power, the reflection in the transparent band is essentially from the substrate in the case of no ink penetration. Comparatively, the layer of the ink-paper mixture has a much stronger scattering power, and an incident photon propagates in zig-zag fashion. Consequently, the absorption power of the ink-paper mixture becomes greater than that of the pure ink layer, (in K–M theory, the absorption coefficient depends not only on the substrate properties but also on light distribution[9,15]). This results in weaker reflectivity of the print with ink penetration. In the absorption band, on the other hand, the light is dramatically attenuated by absorption when it passes through the ink layer. Because the ink scatters very little, the light detected by the spectrometer, in the case of no ink penetration, is the tiny portion that survives from the absorption after passing twice through the ink layer. However, in case of ink penetration, the light may return to the air before it passes through the entire layer of ink–paper mixture due to scattering from the paper materials. This makes the ink-paper mixture more reflective. Since the local maximum and minimum of the spectral reflection curve move in opposite direction upon the ink penetration, the color saturation is therefore reduced. This explains the experimental observation discussed above.

Color Gamut

To accurately map the color gamut of an ink jet printing system, information such as PSF (point spread function) of the substrate, ink spreading characteristics on the substrate, ink penetration of halftone dots, etc., are needed. To obtain such information requires carefully designed measurements, which are beyond the scope of this study. Instead, we will take a simplified approach in the simulation.

The printer consists of 4 inks, cyan, magenta, yellow, and black. Their dot percentages are noted as c, m, y, and k, respectively. The inks are distributed randomly and the distinct colored areas are described by the DeMichel equation, for example, the area percentage of color cyan is given by

$$a_c = c(1 - m)(1 - y)(1 - k) \tag{1}$$

The reflectance is then computed by applying superposition

$$R = \sum a_x R_x \tag{2}$$

where the subscript, x, denotes the color and, R_x, reflectance of the color. For the primary or secondary colors, R_x is approximated by reflectance of its solid print, while the remainders (tertiary colors) are approximated by reflectance of a solid black.

In the simulation, the commanded ink coverage of the primary inks ranges from 0 to 100% in steps of 4%. The simulation included effects of both optical and physical dot gains. Detailed description about the simulation may be found elsewhere.[4] Figure 4 depicts the simulated color gamuts of prints with (inner volume) and without (outer volume) consideration of ink penetration, in CIELAB color space, from two different viewing angles. As is seen from the figure, the two color volumes have no points in common expect for the paper white. In other words, prints of the same ink coverage (but different ink penetration behavior) have different color coordinates (lightness, chroma, and hue) in the color space. Differences, that appear in the vicinity of solid black are a consequence of the increasing amount of pigmented black in the ink composition in the dark tone printing. It is observed that from light to mid tone, the gray is created by mixing the primary inks. However, for the dark tone gray (from about 65%), the pigmented black ink is gradually added, in increasing amounts as the tone values increase. Since pigment particles are much larger in size than the dye molecules, they do not penetrate much into the substrate (the dye compositions still do). Therefore, the simulations predict similar colors for the solid black in both cases. Consequently, a nail-type structure is formed in the vicinity of the black point. Furthermore, the evident difference between the inner and the outer volumes demonstrates the dramatic impact of the ink penetration on the capacity of the color reproduction or the color gamut of the printing system which consists of printer, inks, and paper. The simulation is in qualitative agreement with the experimental observations that the color gamut of the printing system can be up to 50% larger by printing on high quality special paper than on plain paper.[7]

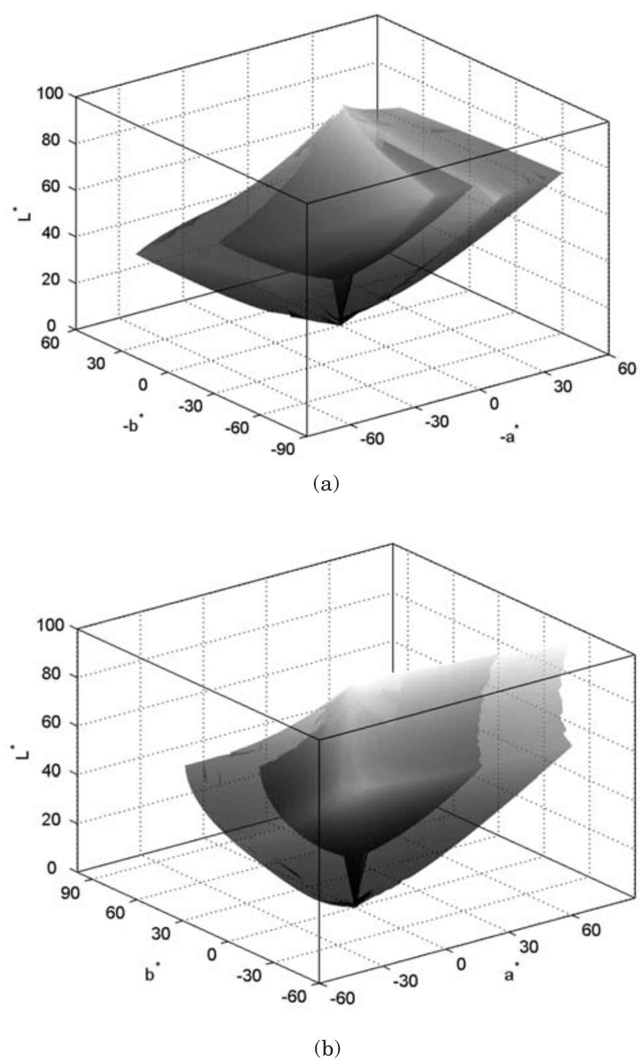

Figure 4. Simulated color gamut for prints, on office copy paper, with (inner) and without (outer) considering ink penetration. Figure (b) is obtained by rotating (a) 180° around the L* axis. *Supplemental Material—Figure 4 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

Conclusion and Summary

Evaluation of optical and chromatic effects of ink penetration has been carried out, based on experimental data analysis as well as simulations. On the experimental side, experimental color coordinates of patches printed on two types of substrates, one with ink penetration and another without, have been compared. It is observed that ink penetration has significant effects on the chroma and hue of the printed colors. Unfortunately, no pure effect of ink penetration can be evaluated experimentally, because of coexistence of other effects resulting from different optical and surface properties of the substrates. These differences lead to, for instance, different physical and optical dot gain of the prints. With the help of simulation, however, the pure effect of ink penetration can be studied, because ink penetration can be switch on or off at will in the simulation. Simulations show that ink penetration raises the reflection spectrum in the absorption band of the ink, while it reduces the reflection in the transparent band. Consequently, the saturation of color is reduced and the hue of the color is changed upon the ink penetration. These simulated results provide not only confirmation but also explanations to the experimental observations.

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