Evaluation of Effects of Ink Penetration in Experimental and Simulation Perspectives

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Abstract

In an ink-jet printing system consisting of dye-based liquid inks and office copy paper, ink penetration has profound effects on color rendition. In this report we presented methodologies for evaluation of these effects by means of experimental data analysis and simulations. Comparisons between prints with and without ink penetration were made in terms of spectral reflectance values and color representations. They showed dramatic impacts of ink penetration on lightness, color saturation, hue, and color gamut. Advantages and disadvantages of evaluation methods were also discussed.

Introduction

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 a formation of a layer of ink-substrate mixture. In the case of dye-based liquid ink and 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 yet negative impact on the color reproduction.

Studies have so far mainly concentrated 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 about ink penetration by combining theoretical simulation with spectral reflectance measurements.[4] The studies stretch from characterization of inks and ink application, in an ink-jet printing system, determination of depth of ink penetration, to evaluation for the impact of ink penetration, from both experiment and simulation perspectives. This presentation reports briefly a part of the studies.

Evaluation with Experimental Data

To experimentally evaluate the effects of ink penetration is not a trivial task. Ideally, one would directly compare two prints on the same type of substrate, one has ink penetration, another not. To accomplish such a comparison one needs to be able to *switch on* and *off* ink penetration at will, which is experimentally impossible. One alternative that is usually applied is to print the same colors on different types of substrates, such as plain paper for print having ink penetration and photo quality paper for not having ink penetration. To distinguish ink absorption by coating materials of the high grad paper, the term ink penetration refers to ink absorption by fibre porosity of paper.

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 at least should be bore in mind when the evaluation is made. First, different substrates have different optical properties (spectral reflectance, point spread function etc.) which will affect the color of 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, results in different physical dot gain, when halftone images are printed. To some extent, color differences resulting purely from the different substrate colors may be minimized by choosing the substrates of having similar color under certain illumination condition (metamerism). Despite these potential effects, the chromatic effect of ink penetration can still be evaluated, at least qualitatively, by such a parallel comparison, 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. The commanded ink percentages for each color range from 0 to 100% at a step of 5%. The tristimulus values in these charts were measured by employing a spectrophotometer.

Table 1. 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

Color differences between the substrates, and the solid prints on the substrates, have been collected in Table 1. As 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 dramatically increase to ΔE=12.3-25, depending on the printed colors. As only solid printed patches are compared, the color differences arise mainly from ink penetration.

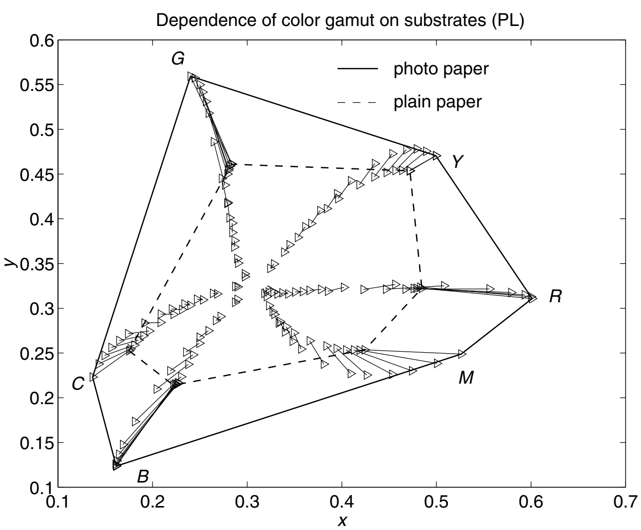

Figure 1. Chromaticity diagrams of prints on office copy-paper and on photo gloss paper drawn from the experimental data. The pairwise points (noted by triangles) corresponding to the same (commanded) dot percentage but different substrates are connected by ▷ - ▷. The 2D color gamuts of prints on the 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.

Two-Dimensional Representations of Chromatic Effects

The chromaticity diagram for halftone patches on different substrates has been plotted in Fig. 1. To explicitly illustrate the color differences between prints on photo gloss paper and those on plain paper, colors (noted by triangles) corresponding to patches of the same commanded ink percentage but on different substrates are connected by solid lines in pair in the figure. Moreover, areas possibly covered by prints on the photo gloss paper as well as on the copy paper are marked with solid and dashed lines, respectively. As these areas represent for the possible colors that can be produced by printing on these substrates, the figure shows that the photo gloss paper has significantly greater capacity in representing colors than that of the plain paper.

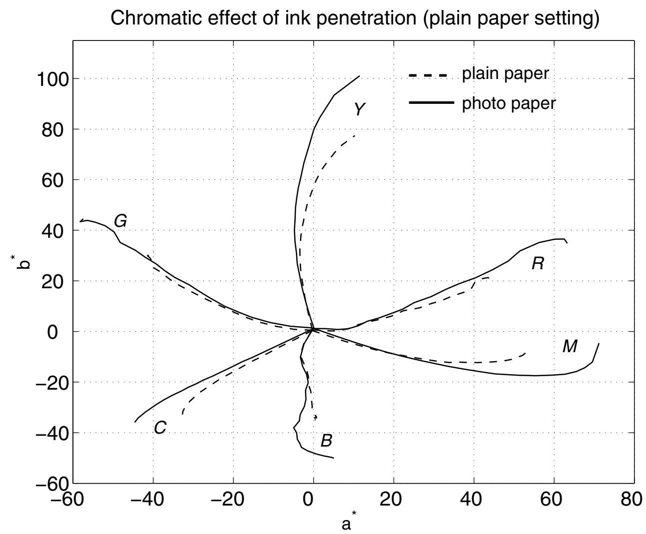

*Figure 2. Color gamut (2D) in L*a*b* coordinate system. The images were printed on different substrates, plain and photo glossy papers, but with the same substrate setting (plain paper) in the printer driving program.*

Chromatic effects of ink penetration can be further examined in terms of chroma and hue of the colors. Figure 2 is a 2-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:

- 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 following. First as the ink coverage increases, the white light reflected from the non-printed substrate decreases and the chroma increases. Second, because the two substrates have almost the same color, curves corresponding to these substrates overlap each other when the ink coverage is small.

However, the curves gradually separate when the ink coverage increases, because of increasing ink penetration. Finally, ink penetration forms an ink-porous mixture which has strong scattering-power and leads to the reflected light being less saturated in color.

Evaluation with Simulations

Although there is no direct experimentally possible comparison, it can be achieved with help of simulations. Since one can *switch on* or *off* ink penetration 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, the sole effect of ink penetration can be studied.

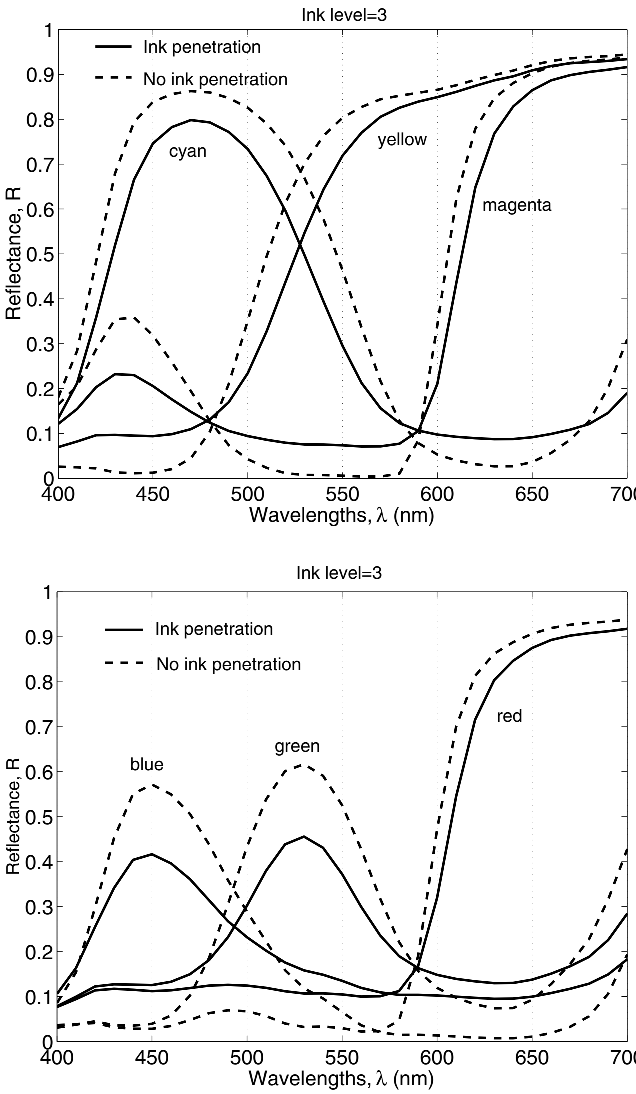

Figure 3. Comparison (simulations) of colors printed on office copy-paper with and without ink penetration.

Spectral Reflectance Values

Simulations for spectral reflectance values of primary and secondary solid color patches 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 discussion, we refer to the band containing the local maximum as the *transparent* band and that containing the local minimum as the *absorption* band. In the transparent band, the print for the case of no ink penetration has greater reflection compared to that with ink penetration. In contrast, in the case of the absorption band, the print with ink penetration shows stronger reflection than that without. 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 it consists of an ink-paper mixture layer and the substrate backing in the case of having ink penetration. As is known the ink-layer (no ink penetration) has little scattering power, the reflection in the transparent band is essentially due to reflection from the substrate. Comparatively, the layer of the ink-paper mixture has a much stronger scattering power, in which a photon propagates in a 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 properties but on light distribution. More detailed discussions see Ref. [8]. This results in weaker reflection for the case 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 is of little scattering, light detected by the spectrometer, in the case of no ink penetration, is the tiny portion that survives from the absorption after twice passing through the ink layer. Nevertheless, the light may return to the air before it passes through the entire ink-paper mixture due to scattering of the paper materials which makes the ink-paper mixture more reflective.

Color Gamut

To accurately map the color gamut of an ink-jet printing system, information like 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 is beyond the scope of this study.

In the simulation, we took a simplified approach. The printer consists of 4 inks, cyan (c), magenta (m), yellow (y), and black (k). The inks are distributed randomly and the distinct colored areas described by the DeMichel equation, for example, area percentage of color cyan is given by

$$a_c = c(1 - m)(1 - y)(1 - k) \quad (1)$$

The reflectance is then computed by applying superposition

$$R = \sum a_x R_x \qquad (2)$$

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 ($x = k1,...,k9$) are approximated by reflectance of a solid black.

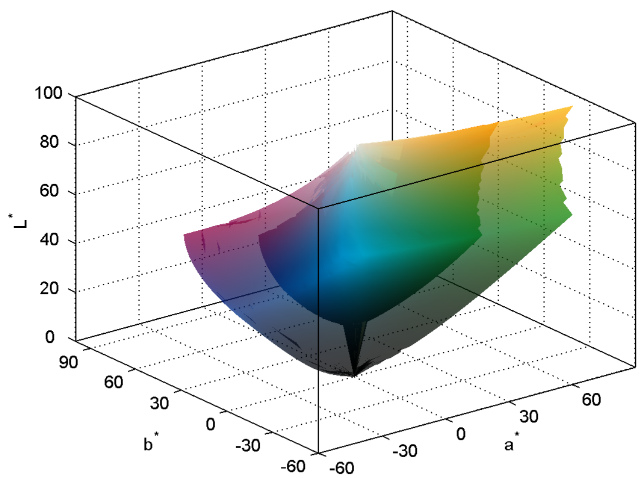

Figure 4. Simulated Color gamuts for prints, on office copy-paper, with (inner) and without (outer) considering ink penetration.

In the simulation, the commanded ink coverage of the primary inks ranges from 0 to 100% at a step 4%. Figure 4 depicts the simulated color gamut of printing with (inner volume) and without (outer volume) consideration of ink penetration, in *CIELAB* color space. As 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 status) have different color coordinates (lightness, chroma, and hue). Differences, that appear in the vicinity of solid black is a consequence of increasing amount of pigmented black in ink composition for 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 color coordinates 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 demonstrate the dramatic impact of ink penetration on the capacity of the color reproduction or the color gamut. It was shown experimentally that the color gamut of printing on high quality special paper can be up to 50% larger compared to prints on plain paper.[7]

Summary

Evaluation of optical and chromatic effects of ink penetration has been carried out, based on both 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 effect on the chroma and hue of the printed colors. Issues related to different optical and surface characteristics of the different substrates have been discussed. With help of simulation, pure effect of ink penetration can be studied. Contributions from different substrates (color, physical and optical dot gain) that exist in the experimental evaluation can be avoided. The simulations show that the color gamut of the printing system is dramatically reduced because of ink penetration.

Acknowledgement

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Biography

Li Yang received his Ph.D in Media Technology, in Linkoping University, Campus Norroping, in April 2003. He continues to work as a researcher in the Group of Media Technology. His research interests include ink-paper interaction with focus on characterization of ink penetration and ink spreading in ink-jet printing, by combining experiments with simulation, and optical dot gain. He is a member of IS&T and TAGA. More information may be found on my web page at http://www.itn.liu.se/~liyan/ or bying sending email: liyan@itn.liu.se.