Mechanisms involved in the optical interaction between ink and substrate for Home&Office inkjet printing

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Abstract
It is known that colour reproduction of inkjet comprises a range of mechanisms. It was possible to understand and explain some of these mechanisms by evaluating print tests with standard optical measurement and by calculations using algorithms of the Kubelka Munk and Murray Davies theories. The combined interaction of the substrate, the ink penetration, the optical properties of the inks and the dot size were clarified. Large colour gamut is governed by low ink penetration, low light scattering of the substrate and small dot size. The non-ideal property of process inks and the continuous tone character of colour reproduction of the studied desktop inkjets explained the observed convex shape of the colour gamut. For plain paper, dye-based and pigment-based inks were shown to follow different mechanisms, with lower penetration of the pigment-based ink. Colour gamut could be increased by a surface treatment that further reduced the penetration, but this treatment worked only for the pigment-based inks. Internal sizing of plain paper had only a very small influence on colour gamut for dye-based ink, even though the ink penetration was reduced.

Keywords: Paper, Inkjet, Colour Gamut, Simulation, Kubelka Munk, Murray Davies

1. Introduction

Traditional printing technologies like offset usually use CMYK as process colours. Standardised methods are established to control the print process and evaluate the influence of the substrate. The reproduction is often made with well known halftone algorithms where the ink level is constant for each halftone dot and the tone values are controlled by varying the size of the dots. Print quality is normally evaluated by carrying out test printing in print shops where trained staff runs the machines. The practical and theoretical knowledge to evaluate traditional print is well established.
The test printing and evaluation of small digital print units such as home & office inkjet or xerographical printers is often made by paper manufacturers themselves. A thorough print quality evaluation requires extensive, partly new, knowledge in graphic technology topics. The home&office inkjet printers prefer RGB as colour input data, which must be considered when creating test charts. Inkjet evaluation such as line raggedness, line bleeding, mottling and print density in full tone and halftone are all dependent on how the coloured test patches are printed. A colour correction is normally active to give appealing print results. This colour correction must be turned off to obtain pure process colours but then the colour images may not be well reproduced. Printing the test charts and images must therefore be performed with different settings making it difficult to compare print quality to the values of the test charts.

In inkjet printing there is a possibility to vary both the ink level and the dot size. There is also the freedom to place the ink on the substrate independently of any screen pattern (Wan, 2003). This makes reproduction very flexible. Users can select between a large number of settings for both photo printing and plain paper printing. Typical for home&office inkjet printers is thus the very broad print quality interval from exceptionally high quality photo prints to ordinary printouts on plain paper. Moreover, vendors use different types of water based inks. Two main groups denoted the pigmented and the dye-based inks have been established. Lately a new technology for surface treatment of paper has entered the market. This technique fixates the colorants closer to the surface, resulting in an increase in colour gamut for plain paper printing.
For a papermaker there is a need for easy to use methods for evaluating and simulating colour reproduction in order to understand the optical interaction between ink and paper. The aim of this report is:

(i) To show how standard optical measurements can be used to evaluate colour reproduction on inkjet printers.
(ii) To indicate how optical simulations (using basic theories) together with test printing and measurements are a help in understanding the optical interaction between ink and paper
(iii) To clarify different aspects of ink penetration by comparing two approaches for the enhancement of colour gamut for inkjet printing on plain paper: a) internal sizing for dye based inks and b) surface treatment for pigmented inks.

2. Previous work

Theories concerning the impact of ink penetration on optical properties have been a subject of research for many years (Lar, 1976). A mathematical framework of print-through and ink penetration was presented at Iarigai 1987 (Bri, 1987). Measurements using this theory have given valuable information about the optical interaction between ink and paper for offset prints on plain paper (Pau, 1986). It has also been possible to simulate the effect of ink penetration by using Kubelka Munk theory (Pau, 1987 and Yan, 2005). The Kubelka Munk theory gives fairly good correlation with measured data when simulating the colours of inkjet prints (Eng, 1986 and Kan, 1991). By applying the simulation of ink penetration for all wavelength it has been possible to simulate how colour gamut is influenced by different ink penetrations (Pau, 2002a and Pau, 2002b).

Halftoning is described by the Murray Davies equation saying that the reflectance is directly related to the surface area covered by ink (Mur, 1936). The Neugebauer equations are the extension to four colour reproduction (Neu, 1937). The optical dot gain was introduced by Yule Nelson (Yul, 1951) and it has been thoroughly investigated by introducing a point spread function of the light (Gus, 1997). Gustafsson showed that a large dot gain can increase colour gamut. Attempts to include more and more detail in the simulation of colour reproduction have been accomplished over the last 50 years. The Clapper Yule equation (Cla, 1955) is an algorithm that simulates halftoning, taking into account optical dot gain and surface reflection. Hersch and Emmel have also introduced ink spreading and fluorescence in their models (Eme, 2002 and Eme, 2003). The new models are more accurate but the disadvantage is the complexity and the need for many unknown constants that must be established. This is a drawback when simulating digital print units since new inks and new colour reproduction methods are introduced which results in a range of new constants to be determined.

It is well known that photo-gloss papers give extremely high colour gamut and very appealing print. The main drawback with plain paper is the low colour strength. It has been shown however, that also moderate increases in colour gamut are important for the perception of print quality (Nor, 2006).

3. Methods

3.1 Simulation

In this work the effect of ink penetration is simulated by using the Kubelka Munk theory. Light scattering and light absorption of the paper and the ink are the bases for the simulation. It is assumed that the ink penetrates into the paper in a linear fashion with increasing ink weight. The ink is further assumed to be homogenously distributed in the ink/paper layer. A barrier is simulated by constraining the penetration to a certain maximum penetration. The light scattering and light absorption of the ink/paper layer is calculated using the additively blending rule (Pau, 1986).
The simulation is extended to colour by including the process inks: cyan, magenta and yellow (CMY). The basis for calculation is then the spectral light scattering and light absorption of the process inks CMY ($s_{ink}(\lambda)$, $k_{ink}(\lambda)$) and spectral $s$ and $k$ of the paper ($s_{paper}(\lambda)$, $k_{paper}(\lambda)$). Secondary colours are simulated by calculating the spectral $s$ and $k$ of the two primary colours added together assuming additivity. It is then also assumed that ink weight and ink penetration are doubled. The colours between primary and secondary colours are calculated assuming linear additivity in light absorption of the inks. By adding the one or two remaining process inks the dark colours (lower part of colour gamut) are simulated ending with 300 % ink coverage i.e. equal parts of the process inks cyan, magenta and yellow (Pau, 2002).

The denotation Simulated Halftoning is in this work, a combination of the Kubelka Munk theory and Murray Davies equation. The Kubelka Munk theory is used to calculate the full tones for different hues taking into account the ink penetration. The Murray Davies equation is thereafter used to simulate halftoning from 0 to 100 % in 25 steps, see figure 1 and 2.

Light absorption of the ink was determined by the variable Rg method (Pau, 1995). Full tones were printed on overhead film and the ink weight was determined by balancing before and after printing. The reflectance was measured for black and white background. Light scattering of the substrate was however assumed not to be influenced by the ink in the simulations presented in this work. Cyan and magenta of the process inks had typical unwanted absorption for the shorter wavelengths (Kan, 1999). To study the effect of this unwanted absorption (the non ideal property) a set of ideal ink with very low light absorption in two third of spectrum and high absorption of the rest of spectrum was included in the simulations.

![Figure 1 and 2. Schematic figure of halftone and continuous tone reproduction (left). The ink weight of the dots are 2.0 g/m². Schematic figure indicating how colours of the gamut are simulated by either continuous tone (ink weight) or half tone (tone steps) reproduction. The RGB shows how magenta was described in the RGB test chart.](image)

### 3.2 Measurements

The ink penetration was established by using the method described by Bristow (Bri, 1987). The ink penetration depth is the ratio of the grammage in which the ink has penetrated to the total grammage of the substrate. The ink penetration (normally expressed in percent) can be calculated based on the reflectance values of equation 1:
\[
W / W_p = \frac{\ln \left( \frac{1 - R_{Ro} R_{R}}{1 - R_{Ro} R_{Ro}} \right) \left( 1 - R_{Ro} R_{Ro} \right) \left( 1 - R_{Ro} / R_{Ro} \right)}{\ln \left( \frac{1 - R_{Ro} R_{Ro} \Omega}{1 - R_{Ro} / R_{Ro}} \right) \left( 1 - R_{Ro} / R_{Ro} \right)}
\]

where
- \( R_{o} \) = Reflectance factor of one sheet over black background
- \( R_{oo} \) = Reflectance factor of an opaque pad
- \( R_{P} \) = Reflectance factor of printed paper backed with \( R_{oo} \)
- \( R_{Q} \) = Reflectance factor of back side of printed paper backed with \( R_{oo} \).

Print density was calculated as \( D = \log_{10} \left( \frac{R_{oo}}{R_{print}} \right) \). A spectrophotometer, DataColour 450 was used for these measurements. The calculation of ink penetration was made at the wavelength that had lowest reflectance factor.

The colour gamut was established by measuring a colour map comprising 925 colour patches, figure 2. The measurements were made by a spectrophotometer attached to an x,y table (Spechtrolino). The spectral values were measured and CIE Lab coordinates \( D_{50/2} \) were calculated according to standard. The colour volume was calculated with a convex hull algorithm. A Convex/Concave number was calculated as a ratio of the volume of colour gamut to the body of the dodecahedron \( W,B,Y,R,M,C,G \) i.e \( L{\ast}{a}{\ast}{b}{\ast} \) of process colours, secondary colours and black and white. This gamut volume was calculated by adding volumes of tetrahedra (Ryd, 1995). The tone value (TV) was calculated as \( TV = 100 \ast (R_{oo}-R_{halftone})/(R_{oo}-R_{fulltone}) \). The colour area was calculated using Green Theorem for a closed polygon of the six colours of \( a{\ast}b{\ast} \) values of process and secondary colours.

### 3.3 Test printing

The test chart for colour gamut, see figure 2, was printed in the normal way with printer settings for the respectively substrate i.e. plain paper quality or photo quality but with colour correction turned off. The halftone patches of the process inks were controlled to be pure i.e. without any ink dots of the other process inks included in the patches. One test printing was performed with colour correction activated.

Test charts for colour gamut and ink penetration studies were printed with different ink levels (one to five drops per pixel) and small (dispersed) and large dots (condensed). Weighting before and after printing of full tones gave the ink weight for the five ink levels, table 1

<table>
<thead>
<tr>
<th>Number of drops</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ink weight g/m²</td>
<td>0,79</td>
<td>1,63</td>
<td>2,57</td>
<td>3,43</td>
<td>4,35</td>
</tr>
</tbody>
</table>

**Figure 3: Condensed and dispersed dots.**
The dispersed and condensed ink dots were placed in 133 lpi halftone screen. The condensed dot was created by focusing the dots to the centre of the raster cell and the dispersed by placing the dots evenly distributed in the cell, figure 3.

4. Results

4.1 The influence of ink weight and dot size on colour gamut

Different relationships were observed from the test printing with increasing ink weight (by ejecting 1 to 5 drops per pixel) and the two dot sizes, figure 4.

- Total colour gamut (Tot) increased with ink weight and reached a plateau at 2 g/m².
- Tetrahedra colour gamut (Tet) showed a maximum value at 2 g/m² and decreased with higher ink levels.
- Dot gain or tone value increase (TVI) increased continuously with ink weight.
- For smaller dot size, higher levels of total gamut and dot gain were achieved. The tetrahedra colour gamut (Tet.S) reached the same value as for the larger dot (Tet.L) since full tones are not affected by dot size.

The influence of the smaller dots was recorded as a more convex colour gamut, with higher lightness in the upper part of the gamut, figure 5. As inkjet can both change ink weight and dot size the total colour volume must always be measured.

![Graph](image)

Figure 4 and 5: Total Gamut, Tetrahedra gamut and TVI (circles) vs. ink weights for prints with small and large dots (left). 3-D Colour gamut for prints made with highest ink weight with small (no grid) and large dots (grid marked), (right). Test printing with dye based ink on a photo-matt paper.

4.2 The continuous tone character of inkjet

Calculating the upper colour gamut by increasing the ink weights means that a continuous tone algorithm is used in the simulation. Using properties of the ideal ink showed that colour strength then increased at almost constant lightness level in the upper part of the gamut. On the other hand the process inks generated a reduction in lightness and a colour change, figure 6. It is interesting to observe that measurements of printed inkjet showed the same shape of gamut as the simulated continuous tone colour reproduction, compare figure 7 with figure 6.
When colour reproduction was simulated with a halftoning algorithm a concave colour gamut was obtained, figure 8. Measurements of colour gamut, clarified that offset has halftone whereas inkjet has more continuous tone characteristics of colour reproduction, compare figures 8 and 9.

4.3 The influence of ink penetration and light scattering

4.3.1 Photo quality
The high colour gamut of prints made on photo-gloss paper is explained by low light scattering of the ink receiving layer at the top of the construction of this substrate, figures 10 and 11. The figures show simulated continuous tone reproduction and measured colour gamut of prints. It is of course a challenge to find ways for improving the colour gamut of plain paper printing.
4.3.2 Plain paper
The penetration of ink increased in an almost linear fashion with ink weight in plain paper, figure 12. Internal sizing of the paper reduced the penetration which was expected since hydrophobic treatment reduces the water uptake. Internal sizing also gave increased print density, figure 12. The print density was however reduced by adding the filler which is in line with the fact that increased light scattering reduces the colour strength. The normal option for a paper maker is to include filler in copy products, due to a desire to obtain low print through, but also for economic reason.

4.4 Internal sizing and surface treatment, the effect on colour gamut for plain paper printing
Internal sizing gave only a slight increase in colour area and tetraeder colour gamut, whereas total colour gamut did not show any change for printing with dye-based inks. The surface treatment aiming at fixing the pigmented-based inks to surface significantly increased colour strength. The surface treatment increased total colour gamut, tetra colour gamut and the colour area, figures 14 and 15.
Figure 14 and 15: Colour gamut (total, tetraeder and colour area) of prints with dye-based inks on paper with and without internal sizing (left). Colour gamut of prints with pigmented inks on paper with five levels of surface treatment (right).

The surface treatment of pigmented inks not only gives higher colour strength in full tones but also increases colour gamut in the lower part of gamut, whereas the internal sizing showed a tendency to reduce colour strength in the upper part of gamut, figures 16 and 17.

Figure 16 and 17: $L^*$ vs. colour area of tones of the upper and lower part of colour gamut. Measurements of prints with dye-based inks of papers with and without internal sizing (left) and of prints with pigmented inks of papers with and without surface treatment (right).

Even though the internal sizing had no or only slightly increasing effect on colour strength it did reduce the penetration of the dye-based ink. The surface treatment reduced the ink penetration of the pigmented inks to very low levels, figures 18 and 19.

Figure 18 and 19: Penetration of dye-based inks in paper with and without internal sizing (left). Penetration of pigmented-based inks in papers with four levels of surface treatments (right). The penetration was established for process colours (CMY) and secondary colours (RGB).
4.5 The colour correction

The colour correction of inkjet printers are often based on sRGB that has low colour strength for cyan and blue colours, figure 20. Although colour gamut is reduced in the colour correction our experience so far is that gamut enhancement is largely retained even after colour correction. The result is a more colour full print, with correct colours.

![Colour area for inkjet printed on plain paper without and with colour correction.](image)

Figure 20: Colour area for inkjet printed on plain paper without and with colour correction.

5. Conclusion

A range of mechanisms have been explained. Reduced ink penetration and low light scattering in the ink substrate layer promotes high colour strength. The non ideal characteristics of the process inks limits colour gamut at high ink levels. Inkjet has the character of continuous tone colour reproduction. The convex shape of colour gamut is probably a combined consequence of small dots and the non ideal properties of the process inks. Offset prints and simulated halftone colour reproduction have a concave colour gamut shape. A special surface treatment of plain paper increased the colour gamut for tested inkjet printers using pigmented inks. The ink penetration was reduced to very low levels. This treatment enhanced the colour gamut by increasing the colour strength of the full tones and of the dark colours. The internal sizing had no influence on the colour gamut, even though ink penetration was reduced. The ink penetration was however not reduced to very low levels. It should be investigated if the surface treatments actually make the ink stay above the surface. An interesting observation was that internal sizing did reduce the dot gain twice as much as the surface treatment did. As lower dot gain gives lower colour strength this may be another explanation why internal sizing did not give any colour gamut increase. The observed higher colour gamut for the test-print with the smaller dots (dispersed dots) is probably related to the non ideal properties of the process inks. Dispersed dot printing means to distribute the ink over more dots i.e. the ink thickness of each dot decreases. Lower ink weight reduces the negative influence of the non ideal process inks. This reasoning can also be applied for optical dot gain. The light spreading gives rise to a coloured corona around the dot. In this area the light passes only in an upward direction whereas inside the dot light passes the colour twice i.e. optical dot gain can be seen as the ink weight is reduced. These explanations are supported by calculation were ideal inks gave the same colour gamut for continuous tone and halftone colour reproduction.

This work has shown that optical measurements combined with simulations can give a better understanding of the complex optical interactions of inkjet prints.

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Literature references


Larsson, L O and Trollsås P O, (1976) *Print- through as an ink/paper interaction effect in newsprint*, In The fundamentals of Paper related to its uses BPBIF 1976, 600-612


Pauler, N (2002), *Ink penetration and its influence on print density and colour gamut*. TAGA Image processing and Graphical Art Conference

Rydefalk S and Wedin M (1997) *Literature review on the Colour Gamut in the printing process*, PFT nr 32 STFI

