Optical Dot Gain and Color Halftoning with Three Different Printing Strategies: Independent, Dot-on-Dot and Dot-off-Dot

Sasan Gooran*

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Abstract: Since most of printing devices use a limited number of colored inks, color images are separated into these colors before being halftoned. Usually the printing devices use the four colors Cyan, Magenta, Yellow and Black. The most straight forward way of halftoning a color image is to halftone its color separations independently. It has been shown in literature that halftoning the color separations dependently and using dot-off-dot printing as much as possible results in smoother halftone patterns and hence improves the print quality. It has also been shown that using the dot-off-dot printing strategy for cyan and magenta channels reduces the amount of consumed inks.

In this paper we are going to investigate and compare different aspects of three printing strategies, namely independent, dot-on-dot and dot-off-dot, in detail. Firstly, we will illustrate how these three printing strategies fill the color gamut of the investigated Desk-jet printer and offset print. Secondly, the three strategies are compared with each other in terms of consumed inks. The comparisons are firstly made using Murray-Davies model which assumes the optical dot gain to be negligible. The same comparisons are then made using the Yule-Nielsen model for optical dot gain. The impact of the optical dot gain on the resulting colors is obviously dependent not only on the utilized halftoning method but also on the printing strategy being used. The effect of optical dot gain on these three printing strategies is also investigated and illustrated in this paper.

* Department of Science and Technology, LiU Norrköping, Linköping University, Sweden

Introduction

It has been shown in literature that halftoning the cyan and magenta color separations dependently by using dot-off-dot printing as much as possible and halftoning the yellow channel independent of the two others not only results in smoother halftone patterns but also reduces the total amount of consumed inks (Gooran, 2004). There has also been shown that although a yellow dot is far less visible than cyan and magenta dots on a white paper it will have a great impact on the homogeneousness of the print when printed on a blue dot. Therefore, the print quality is further improved if yellow dots are prevented from being placed on top of blue dots (Gooran, 2006). Using different printing strategies, or correspondingly halftoning the color separations with different strategies, can result in different colors despite of using the same amount of inks. The optical dot gain has also different impacts on these different printing strategies. In this paper we are going to compare different aspects of these three different strategies used to print cyan and magenta. Firstly we investigate how these strategies fill the color gamut. Secondly the amount of inks being used for these strategies is also discussed. All these comparisons are made both in absence and presence of optical dot gain for a Desk-jet printer and an offset print.

In our investigations we have measured the spectrum, CIEXYZ and CIELab values for the paper substrate, full-tone Cyan, Magenta and Blue using a spectrophotometer (Gretag Macbeth™ Spectrolino).

Different Printing Strategies

In the present paper we are investigating the following three printing strategies; namely, independent, dot-on-dot and dot-off-dot. When the colored dots are printed independently we use Demichel's equations to approximate the coverage of different colors (Yule, 1967). As discussed in (Gooran, 2004), by using an appropriate halftoning method the dot placement in each color channel could be controlled with respect to the other channels. It is also discussed how you can avoid different colored dots being placed on top of each other as much as possible, i.e. dot-off-dot printing strategy. It is also possible to place different colored dots on top of each other as much as possible, i.e. dot-on-dot printing strategies. The fractional area covered by each colored ink varies dependent on the printing strategy being used. Let us give an example. Assume a color image with 60% and 70% coverage in its cyan and magenta color channels being halftoned using these three strategies. When the separations are halftoned independently, some of the magenta dots might be placed on top of cyan dots and some not. The fractional coverage for each color can be approximated using probability calculations, i.e. Demichel's equations. In our example, the probability to only have cyan is 0.6*(1-0.7)=0.18. The coverage for magenta, blue and the non-printed area (paper) is 0.28, 0.42 and 0.12, respectively. When dot-on-dot printing is used then, in our example, there won't be any cyan left because magenta (70%) covers a bigger area than cyan (60%). The coverage for cyan, magenta, blue and paper is therefore, 0, 0.1, 0.6 and 0.3, respectively. When dot-off-dot is used, in our example, we cannot prevent all colored dots from being placed on top of each other because the total coverage for cyan and magenta is more than 100%. If we, however, utilize dot-off-dot as much as possible we will have 30% blue (Gooran, 2004). The coverage for cyan, magenta, blue and paper is therefore 0.3, 0.4, 0.3 and 0, respectively. Now when the coverage for each color using different strategies is known the color of a surface can be approximated by an appropriate model, which is discussed in the following section.

Approximating Tristimulus Values

When the optical dot gain is negligible we use the Murray-Davies equation to find the total reflectance of a surface (Murray, 1936),

$$R_{tot} = \sum_i a_i R_i \,, \qquad \text{Eq. 1}$$

where R_{tot} is the total reflectance of a surface, a_i the fractional area of the surface covered by color i (in this case, paper, cyan, magenta or blue) with $\sum_i a_i = 1$ and R_i is the reflectance of the same color. Since we only use cyan and magenta then the summation in Equation 1 has four terms, i.e. paper, cyan, magenta and blue. Since there is a linear relationship between the reflectance and the CIEXYZ values then Equation 1 can easily be extended to Neugebauer's equations (Neugebauer, 1931),

$$\begin{pmatrix} X_{tot} \\ Y_{tot} \\ Z_{tot} \end{pmatrix} = \sum_i a_i \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \qquad \text{Eq. 2}$$

where X_{tot}, Y_{tot} and Z_{tot} denote the CIEXYZ tristimulus values of the surface, a_i denotes the fractional area covered by a color (or paper) with $\sum_i a_i = 1$ and X_i, Y_i and Z_i are the tristimulus values of the same color.

When the optical dot gain is not negligible Equation 1 is not valid any more and we use the Yule and Nielsen's modified version of Murray-Davies model to approximate the total reflectance and the tristimulus values of a surface (Yule & Nielsen), see Equation 3.

$$R_{tot} = (\sum_i a_i R_i^{1/n})^n \qquad \text{Eq. 3}$$

where the parameters are as defined in Equation 1. The factor n is a fitting factor and its real physical meaning is not clear. Since a_i represents the real physical coverage after print then the factor n is a number between 1 and 2 and depends on the paper used. Although the total reflectance in Equation 3, unlike in Equation 1, is not a linear combination of R_i:s the Yule-Nielsen model is still used to express the relationship between CIEXYZ values, which is called the modified Neugebauer's equations, see Equation 4.

$$\begin{pmatrix} X_{tot} \\ Y_{tot} \\ Z_{tot} \end{pmatrix} = \left(\sum_i a_i \begin{pmatrix} X_i^{1/n} \\ Y_i^{1/n} \\ Z_i^{1/n} \end{pmatrix} \right)^n \qquad \text{Eq. 4}$$

Color Gamut

As mentioned earlier in this paper we compare the three printing strategies for a Desk-Jet printer and an offset print using cyan and magenta. Figure 1 illustrates the color gamut for the Desk-Jet printer, using uncoated office paper, and offset print using both coated and uncoated paper. Observe that we plotted the gamut when only cyan and magenta are used.

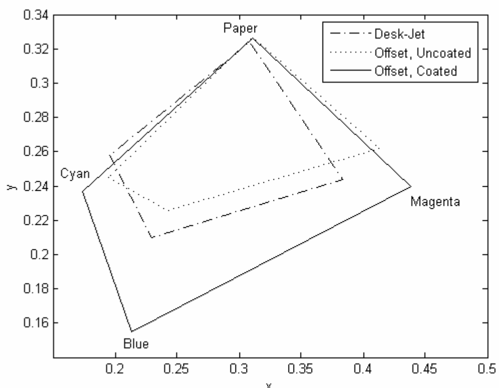


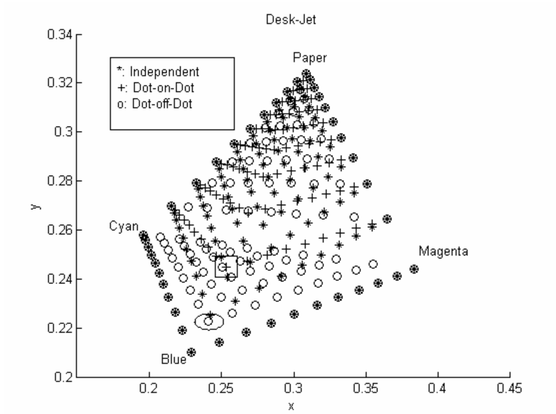
Figure 1: Color gamuts for Desk-Jet using uncoated office paper and offset using both uncoated and coated paper.

As can be seen the impact of paper quality on color gamut and hence the print quality is very evident. The color gamuts are plotted using the chromaticity values x and y for paper, full-tone cyan, magenta and blue. The chromaticity values are defined as,

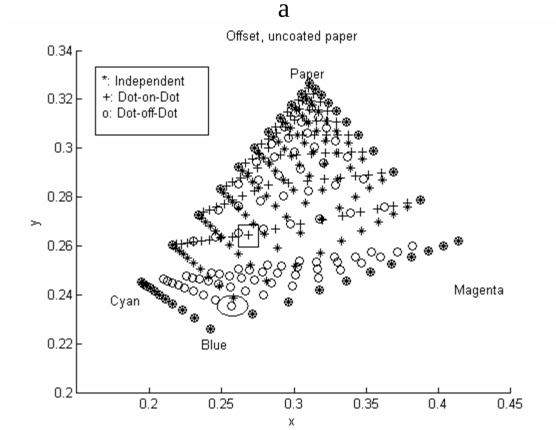
$$x = \frac{X}{X+Y+Z} \qquad \text{Eq. 5}$$
$$y = \frac{Y}{X+Y+Z}$$

where X, Y and Z are the tristimulus values discussed before.

Since we are just going to compare different printing strategies, from now on we only illustrate the gamut for the desk-jet and offset using uncoated paper. In order to illustrate how the color gamut is filled by different strategies we varied the coverage of cyan and magenta from 0% to 100% with a step of 10%.



a



b

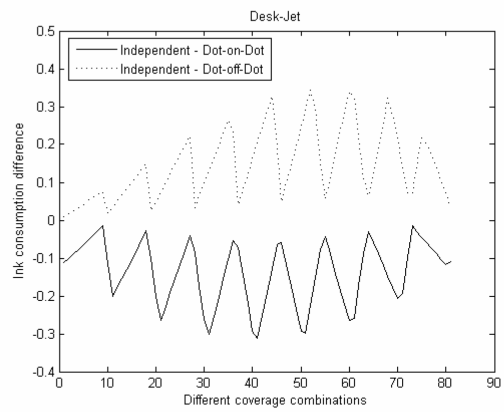
Figure 2: The color gamuts are filled differently when different printing strategies are used. The optical dot gain is assumed to be negligible. a) Desk-Jet, b) Offset, uncoated paper.

For each pair (of the total 121 pairs) of cyan and magenta coverage we calculated the coverage for paper (no print), cyan, magenta and blue for all three printing strategies as discussed earlier in this paper. Then we approximated the total color as described in the previous section. Figures 2a and b show how the color gamut is filled for these three strategies using Desk-Jet and Offset, respectively, when optical dot gain is ignored. As can be seen in both figures, especially in Figure 2b, the resulting colors for dot-on-dot printing (illustrated with +) have their concentration close to paper while those for dot-off-dot (illustrated with o) are mostly concentrated in areas close to blue. Independent printing strategy fills the color gamut more homogenously. This is not actually so surprising. If we look at the example with 90% cyan and 90% magenta, then using dot-on-dot will mean 90% blue and 10% paper. The resulting coordinates are marked with a rectangle in Figures 2a and b. This is the closest dot-on-dot can get to blue in our simulations, apart from the cases where one of the colors (or both) has 100% coverage. The same coverage using dot-off-dot printing means 80% blue, 10% cyan and 10% magenta. The resulting coordinates are marked with an ellipse in Figures 2a and b, which are much closer to blue than the corresponding coordinates for dot-on-dot.

We have also investigated how the gamut is filled when the optical dot gain is not negligible and noticed that it differs considerably only for dot-on-dot printing, which will be discussed later on in this paper.

Ink Consumption

Let us start to describe our approach for comparing the ink consumption for the printing strategies by an example. Assume that cyan and magenta dots with 60% and 70% coverage respectively are printed independently. The resulting color approximated using Demichel's and Neugebauer's equations is (X, Y, Z)=(30.18, 28.33, 49.69), or (L, a, b)=(60.18, 12.72, -22.63) for Desk-Jet. Now we seek for the cyan and magenta coverage when printed using dot-on-dot results in the same color, i.e. results in a color that has a minimized color difference ΔE_{Lab} to (L, a, b)=(60.18, 12.72, -22.63). Least squares method gives 69.8% and 82.7% for cyan and magenta, respectively, which result in (X, Y, Z)=(28.89, 27.16, 46.79) or (L, a, b)=(59.12, 12.38, -21.40) for dot-on-dot printing. ΔE_{Lab} is only 1.66 for this example. In order to match the same color using dot-off-dot the coverage for cyan and magenta is 44.6% and 51.0%, respectively. It can be noticed that the total amount of ink is 130%, 152.5% and 95.6% for independent, dot-on-dot and dot-off-dot printing, respectively. This means that dot-on-dot needs more and dot-off-dot needs less ink than independent to reproduce the same color. For a general study of ink consumption for the printing strategies the cyan and magenta coverage was varied from 10% to 90% with a step of 10%, i.e. eighty one different combinations. The reason we ignored 0% and 100% is that when the coverage for at least one of the colors is 0% or 100% all three strategies result in the same color. For each combination we calculated the resulting color for independent printing strategy. Then by using least squares method to minimize the ΔE_{Lab} color difference we found the coverages for cyan and magenta for dot-on-dot and dot-off-dot. The solid lines in Figures 3a and b show the total ink consumption using independent printing minus the total ink consumption using dot-on-dot printing for Desk-Jet and offset, respectively. The dotted lines show the same difference between independent and dot-off-dot printing. As can be noticed the former difference is always negative and the latter one is always positive. This confirms that the conclusion we draw in the example above is also valid for all other coverage. That is dot-on-dot printing needs more and dot-off-dot printing needs less ink compared to independent printing to reproduce the same color. In average dot-on-dot printing needs 13.7% more ink and dot-off-dot printing needs 14.6% less ink than independent printing for Desk-Jet.



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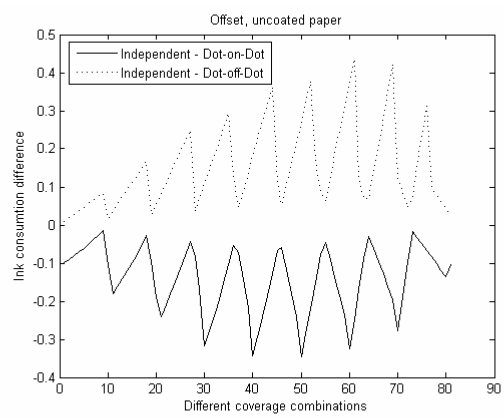


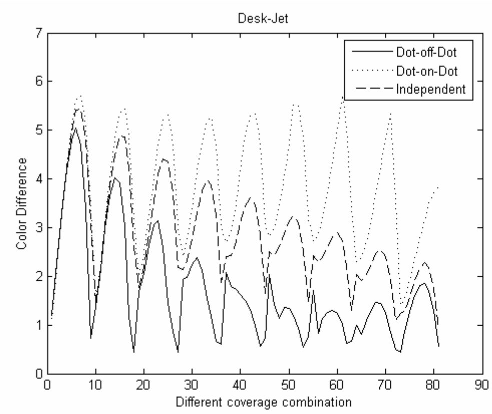
b

Figure 3: The total ink consumption for independent printing minus that for dot-on-dot and dot-off-dot printing. a) Desk-Jet, b) Offset, uncoated paper.

For offset the same numbers are 13.9% and 15.1% for uncoated paper and 14.1% and 15.5% for coated paper. In the simulations presented here the optical dot gain was ignored. Its impact is discussed in the following section.

Optical Dot Gain

As discussed earlier it was observed that the effect of optical dot gain was much more evident on dot-on-dot printing when we studied how the color gamut was filled. In order to study the optical dot gain's impact on the printing strategies we again vary the coverage for cyan and magenta from 10% to 90% with a step of 10%. For each pair of coverage we calculate the ΔE_{Lab} color difference between the resulting colors with no optical dot gain and with optical dot gain represented by Yule-Nielsen model with n=1.5 for all three strategies.



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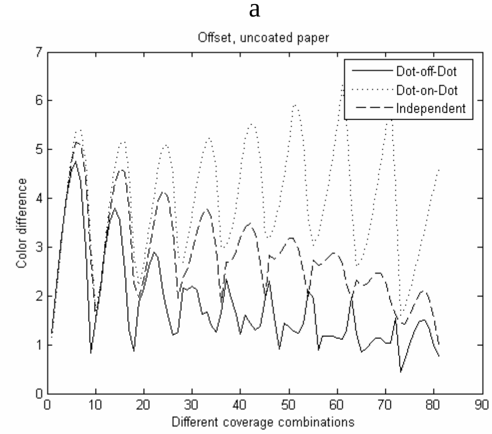

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Figure 4: the ΔE_{Lab} color difference between the resulting colors with no optical dot gain and with optical dot gain represented by Yule-Nielsen model with n=1.5 a) Desk-Jet, b) Offset, uncoated paper.

Figures 4a and b show that the color difference for both Desk-Jet and offset is biggest for dot-on-dot and smallest for dot-off-dot. This means that the colors change more because of optical dot gain when dot-on-dot printing is used. The average ΔE_{Lab} color differences for dot-on-dot, independent and dot-off-dot are 3.79, 2.81, and 1.72 for Desk-Jet. The same average values are 3.97, 2.82 and 1.80 for Offset using uncoated paper. Observe that the Yule-Nielsen factor *n* has been chosen to be 1.5. Since the papers used in Offset and Desk-Jet are not the same then this factor cannot be the same either. This factor may not be correct to characterize any of this paper. Since our goal has been to compare different printing strategies we just chose a factor to simulate optical dot gain's effect on these strategies. Regardless of what *n* we choose our simulations illustrate that dot-on-dot printing is more sensitive and dot-off-dot less sensitive to optical dot gain. This observation can also be verified instinctively. When dot-on-dot is used the coverage of paper and blue are bigger than the other two strategies. Since the paper is the brightest color and blue is the darkest one of all four the light diffusion has a greater impact on dot-on-dot.

In order to compare the ink consumption for these printing strategies in presence of optical dot gain we used the same approach as before but this time we used the modified Neugebauer's equations (Eq. 4) with n=1.5. The results show that dot-on-dot still needs more ink and dot-off-dot needs less ink than independent printing. For Desk-Jet dot-on-dot printing needs 10.80% more ink; compare it with 13.7% when optical dot gain was ignored. On the other hand, dot-off-dot printing needs 11.26% less ink than independent; compare it with 14.6% when optical dot gain was negligible. These observations are actually in line with the conclusions discussed above. The conclusion is that in the presence of optical dot gain the total ink consumption for independent minus the total ink consumption for dot-on-dot is less negative (observe that it is still negative) in the favor of dot-on-dot. On the other hand in the presence of optical dot gain the total ink consumption for independent minus the total ink consumption for dot-off-dot is less positive (observe that it is still positive) in the favor of independent printing.

Summary and Conclusions

The spectra, CIEXYZ and CIELab values for paper, full-tone cyan, magenta and blue were measured for Desk-Jet printer using office copy paper and Offset print using uncoated and coated paper. Three different printing strategies, independent, dot-on-dot and dot-off-dot, which vary in the way they print the colored dots have been compared with each other using different models to approximate the resulting color values. The three strategies fill the color gamut differently. While in dot-on-dot printing the resulting colors are mostly concentrated in the areas close to the paper coordinate, the resulting colors using dot-off-dot have their concentration around blue. With regards to the ink consumption our simulations show that dot-on-dot consumes most ink and dot-off-dot least ink of all three. The effect of optical dot gain was also simulated using Yule-Nielsen's model with n=1.5. The results show that optical dot gain has a greater impact on dot-on-dot than the other two strategies. However, even in the presence of optical dot gain the ink consumption was greatest for dot-on-dot and lowest for dot-off-dot but the two technologies differed less in ink consumption compared to the case where optical dot gain was assumed negligible.

References

Gooran S.

2004 "Dependent Color Halftoning, Better Quality with Less Ink," Journal of Imaging Science & Technology, Volume 48, Number 4, pp. 354-362.

2006 "In Dependent Color Halftoning, Yellow Matters," Journal of Imaging Science & Technology, Volume 50, Number 5, pp. 448-457.

Yule J.A.C.

1967 "Principle of color reproduction," New York: John Wiley & Sons.

Murray, A.

1936 "Monochrome reproduction in photoengraving," J. Franklin Institute (Philadelphia), 221, p. 721.

Neugebauer H.

1931 "Die theoretischen Grundlagen des Mehrfarbenuchdrucks," Z. tech. Phys. 36, pp. 75-89.

Yule J.A.C. and Nielsen W.J.

The penetration of light into paper and its effect on halftone reproduction.