High-Resolution Analysis of Optical and Physical Dot Gain

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Abstract

The printed dots appear bigger than the dots in the original digital bitmap. This is partly because of the spreading and penetrating of the ink on and in the paper, called *physical dot gain,* and partly because of the diffusion of the light in paper, which is referred to as *optical dot gain.* Dot gain is often approximated by measurements obtained by densitometer or spectrophotometer. In this study we use a very high-resolution scanner with a resolution of 2µm/pixel and with a field of view of 2.7×2 mm, which makes it possible to clearly see the small halftone dots and their surroundings. In this camera it is also possible to illuminate the paper surface both from above and below, which means that the camera can capture both the reflected and transmitted lights. Since the transmitted light does not scatter in paper, the optical dot gain has no effect on the transmitted image. In this paper we investigate the behavior of physical and optical dot gain for print on coated paper in offset, by using the micro-scale images. We also present a method to separate optical and physical dot gain by using the reflected and the transmitted images. By comparing the reflectance and transmittance histograms it is possible to understand that there is no optical dot gain in transmitted image. We also compare our results with the result obtained by a spectrophotometer, which also measures both reflected and transmitted light. Previously the physical and optical dot gains were mostly analyzed numerically; however, in this paper we will also graphically illustrate and compare these two concepts by using micro-scale images.

Introduction

The scattering of light within paper can affect the tone characteristics of a printed halftone image. A halftone image is formed by variation in the average reflectance, which is determined by the size of the ink dots. Photon migration

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within the paper from non-inked to inked regions tends to increase the photon absorption and thus decrease the halftone reflectance—the dots are effectively larger than their physical size. This effect is known as *optical dot gain* (Hersch, 2005; Rogers, 1997). Previous research showed that the optical dot gain depends on two different factors, namely the properties of the materials such as paper and ink and the geometrical distribution of ink such as resolution, location, size, and shape (Yang, 2001; Sormaz, 2009). One of the most famous and simplest models to predict the reflectance of a halftone print is the Murray-Davies model (Murray, 1936), see Equation 1.

$$R_\lambda = aR_{\lambda,i} + (1-a)R_{\lambda,p} \qquad \text{Equation 1}$$

Where R_λ is the measured reflectance spectrum, a is the fractional dot area of the ink, $R_{\lambda,i}$ is the reflectance spectrum of the ink at full coverage, and $R_{\lambda,p}$ is the reflectance spectrum of the paper. The λ subscripts indicate the fact that all three reflectance values are a function of wavelength. Optical dot gain originates from light scattering inside the paper. In this case, the light is exchanged between different chromatic areas, and thus the dots appear bigger than its physical size. The effect of optical dot gain depends on the ratio of the lateral light scattering length within the paper to the size of the printed halftone dots (Clapper, 1953). *Physical dot gain* refers to a fact that size of the printed dots differs from the nominal ones (bigger or smaller) (Yang, 2004). According to the Murray-Davies model the effective dot area (a_{eff}) is estimated by minimizing the difference between root mean square (Δrms) of the calculated and measured spectrum, see Equation 2.

$$a_{eff,R}(a_{ref}) = \frac{R_{\lambda,meas}(a_{ref}) - R_{\lambda,p}}{R_{\lambda,i} - R_{\lambda,p}} \qquad \text{Equation 2}$$

where a_{ref} and $a_{eff,R}$ (a_{ref}) are the reference area and the effective dot area after print, respectively. Total dot gain Δa_{tot} , is given by the difference between the physical dot area, $a_{eff,R}$ (a_{ref}), and the nominal one, a_{ref}.

$$\Delta a_{tot} = a_{eff,R}(a_{ref}) - a_{ref} \qquad \text{Equation 3}$$

One of the methods to subtract the physical dot gain from total dot gain is to use transmittance spectrum (Koopipat, 2005). The transmittance spectrum is obtained from the light that is perpendicularly illuminated from underneath the paper. In this situation the light passes from the paper without any scattering. The effective physical dot area can be computed by using the transmittance spectrum instead of reflectance spectrum in Equation 2.

$$a_{eff,T}(a_{ref}) = \frac{T_{\lambda,meas}(a_{ref}) - T_{\lambda,p}}{T_{\lambda,i} - T_{\lambda,p}} \qquad \text{Equation 4}$$

The physical dot gain Δa_{phy}, will be calculated by taking the difference between the effective physical dot area $a_{eff,T}$ (a_{ref}), and the nominal one, a_{ref}.

$$\Delta a_{phy} = a_{eff,T}(a_{ref}) - a_{ref} \qquad \text{Equation 5}$$

In this paper two different approaches will be described for estimating the physical dot gain. One of them is obtained from transmittance spectrum and the other one from micro-scale images. The results of these two different approaches will be compared with each other. The models developed in the current study are derived from the Murray-Davies equation and are based on experimental measurements. For this purpose 21 patches with different coverage of gray have been printed. All the patches are halftoned by AM (150 lpi, 1200 dpi) halftoning method and printed by commercial offset press (Heidelberg) on coated paper (150 gr/cm^2) and an effort was made to keep the density of ink constant. The nominal dot area coverage of the patches are 0, 5, 10, ... 95, 100%. A spectrophotometer is used for measuring the spectrum of reflectance and transmittance. A high-resolution scanner (Oden Scanner) is used, with a resolution of 1.9μm/pixel and with a field of view of 2.7×2 mm, which makes the small halftone dots and their surroundings clearly visible. It is also possible to illuminate the paper surface, both from above and below, by means of this camera; therefore, it can capture both the reflected and transmitted lights. Since the transmitted light does not carry the effect of the light diffusion in paper the optical dot gain has no effect on the transmitted light.

Transmittance Spectrum Approach

A spectrophotometer is one of the conventional instruments, which is able to measure the reflectance and transmittance. In this study the spectrophotometer (BARBIERI) was used and calibrated for each patch individually. By minimizing the difference between root mean square (Δrms) of the calculated (see Equation 6) and measured transmittance we can find $a_{eff,T}$ (a_{ref}) for each reference coverage.

$$T_{calc} = a_{eff,T}(a_{ref})T_i + (1 - a_{eff,T}(a_{ref}))T_p \qquad \text{Equation 6}$$

Where T_{calc} is the calculated transmittance spectrum, $a_{eff,T}$ (a_{ref}) is the effective fractional of physical dot area, T_i is the transmittance spectrum of ink at full coverage, and T_p, is the transmittance spectrum of paper. The effective total dot coverage $a_{eff,R}$ (a_{ref}) is estimated by a similar approach where the transmittance spectra in Equation 6 are replaced by reflectance spectrum.

Figure 1a and 1b show the spectrum computed by the Murray-Davies equation and measured spectrum by spectrophotometer for reflectance and transmittance of a 35% halftone patch, respectively. As seen in this figure the model works very well for both reflectance and transmittance estimations, but it is clearly visible that the estimation is better for transmittance.

Table 1. *The differences between computed transmittance and reflectance spectra with measured spectra for all coverage.*

	max(Δrms)	ave(Δrms)	max(ΔE_{Lab})	ave(ΔE_{Lab})
Transmittance	0.0014	0.0006	0.4047	0.2158
Reflectance	0.0064	0.0040	1.1487	0.5564

Table 1 shows both maximum and average Δrms and ΔE_{Lab} between the computed and measured spectra for all patches. Small ΔE_{Lab} clearly verify that the Murray-Davies equation can be used to calculate the total dot gain from reflectance spectra for black ink. The reason that it works better for transmittance is that in the Murray-Davies model the optical dot gain is neglected. Since even in the case of reflectance ΔE_{Lab} is small, this model can even be utilized to estimate the total dot gain for black ink. It should also be noticed that the smallest Δrms does not necessarily result in the lowest ΔE_{Lab}, but small ΔE_{Lab} in Table 1 indicates that the calculated spectra are very close to the measured ones viewed by human eye.

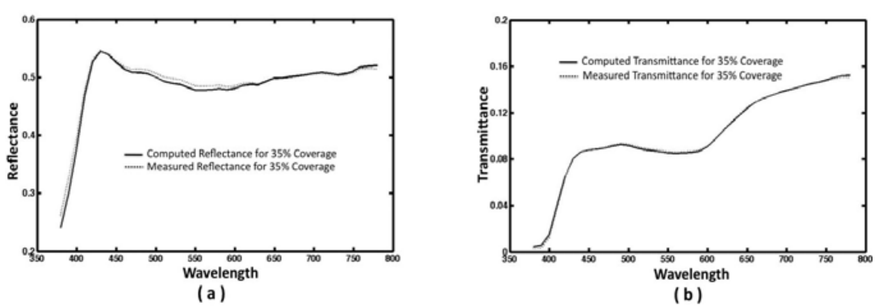

Figure 1. *The computed and measured transmittance and reflectance for 35% halftone patch.*

In this study the spectrum of reflectance and transmittance have been measured for all 21 patches, and by using Equation 2 and Equation 4 the total dot gain and physical dot gain have been calculated. By subtracting physical dot gain from total dot gain, optical dot gain can be obtained (Equation 7).

$$\Delta a_{opt} = \Delta a_{tot} - \Delta a_{phy} = a_{eff,R}(a_{ref}) - a_{eff,T}(a_{ref}) \qquad \text{Equation 7}$$

Figure 2 shows the total, physical, and optical dot gain that are obtained from the reflectance and transmittance spectrum. The somewhat strange form of physical dot gain can be due the fact that the transmittance measurements are much more sensitive to calibration variations.

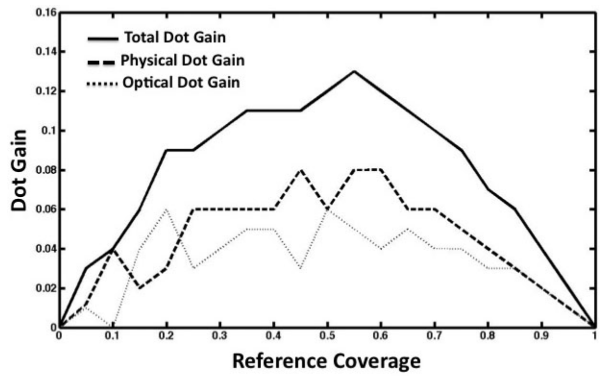

Figure 2. *The total, physical, and optical dot gain computed by spectrum.*

Micro-Scale Image Approach

In the micro-scale image approach the high-resolution scanner (Oden Scanner) is used to capture the images. In this scanner illumination is provided by tungsten halogen lamp (daylight) and transferred by optical fibers. The optical fibers transmit the light through two different paths, from top and bottom of the paper, see Figure 3. One of images is resulted from the light illuminated at 45° on the paper and reflected from paper, and another one is resulted from the light that passes perpendicularly from the bottom of the paper. During the capturing all the patches are fixed in the same position while being captured from above and below, see Figure 4.

Because of calibration variation, the gray tone of paper and 100% ink is changed from one patch to the next. Therefore, we decided to place two narrow stripes of unprinted paper and 100% ink beside each patch, see Figure 4. The reason is to make sure that we use correct gray tone values for paper and 100% ink for each patch.

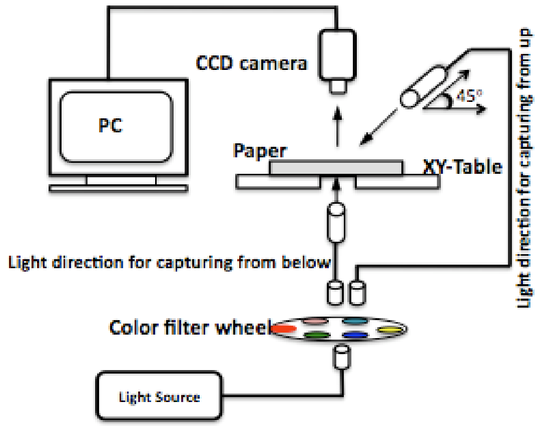

Figure 3. *The high-resolution scanner setup for reflectance and transmittance imaging.*

In the images that have been captured from above, the incident light may be scattered and emerged from the paper between the dots. In this situation, the dot appears to be larger than its physical size, which is by the definition the optical dot gain. In the images captured from below, the light, which enters the paper perpendicularly, passes the paper without any scattering and thus the paper between dots has the same intensity as the unprinted stripe. We can conclude that there is no optical dot gain when the image is captured from below.

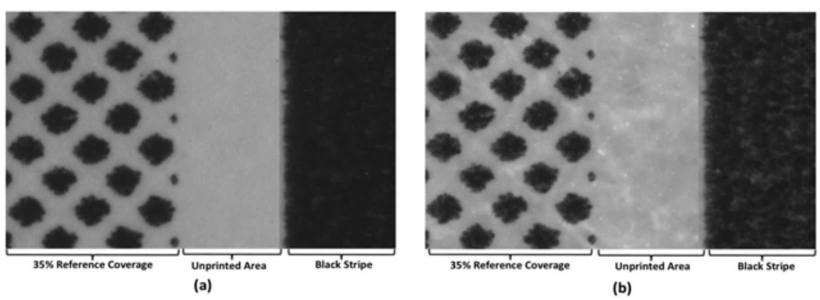

Figure 4. *Micro-scale image of a 35% reference patch, and unprinted area, and 100% ink stripe,*
(a) Captured from above. (b) Captured from below.

Figure 5a and 5b show the reflectance and transmittance histograms for 35% halftone patch captured from above and below, respectively. The histogram is used to illustrate how the pixel values of the image are distributed. In Figure 5a, we can see that there are three peaks corresponding to the unprinted stripe (R_p), paper between the dots, and ink (R_i). As seen in Figure 5b, the transmittance histogram, on the other hand, has only two peaks; one peak for paper (T_p) and the other one for the ink (T_i). This also verifies our previous conclusion that the optical dot gain has no impact on the transmitted light. The transmittance histogram in Figure 5b illustrates a left shift compared to the histogram in Figure 5a, which is due to reduced intensity of the light while passing the paper.

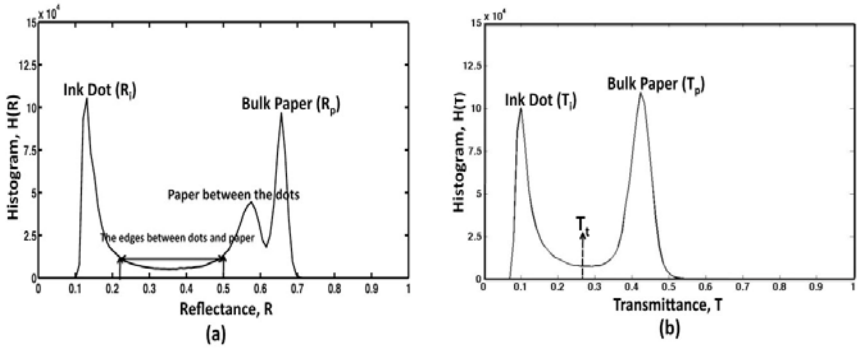

Figure 5. *(a) Reflectance histogram for 35% coverage, (b) Transmittance histogram for 35% coverage.*

As mentioned earlier, due to the calibration variations during capturing, the unprinted and black stripes are placed beside each patch. By using these stripes the gray tones of the paper and full tone coverage are computed from the average of pixel values of the unprinted stripe and black stripe, respectively. By replacing R_i and R_p with these averages in Equation 2 and Equation 3 the total dot gain (Δ [illegible]$_{tot}$) is estimated. Figure 6 shows the total dot gain, estimated using the two approaches presented in this paper, namely by the reflectance spectrum and by the micro-scale image approach. As seen in this figure, the estimations are very close, with a maximum difference of around 1%.

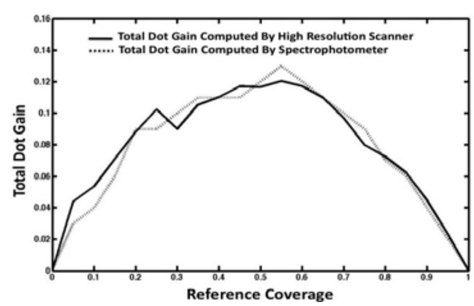

Figure 6. *Total dot gain of black ink prints on coated paper.*
Solid line: estimated from micro-scale image approach.
Dashed line: estimated from reflectance spectra.

By using transmitted images the paper value (T_p) and ink value (T_i) are computed from the average of pixel values of the unprinted stripe and black stripe, respectively. With the same logic as above the physical dot gain will be calculated by the difference between the dot area $\alpha_{eff,T}$ (α_{ref}), and the nominal one, α_{ref}. Figure 7 shows the physical dot gains, which are computed with transmittance spectrum and the micro-scale image approach. As seen in this figure, the estimations are quite close (with a maximum difference of around 3%) but not as close as the estimations for the total dot gain. The reason is that both the high-resolution scanner and the spectrophotometer are much more sensitive to calibration variations when capturing the transmitted light.

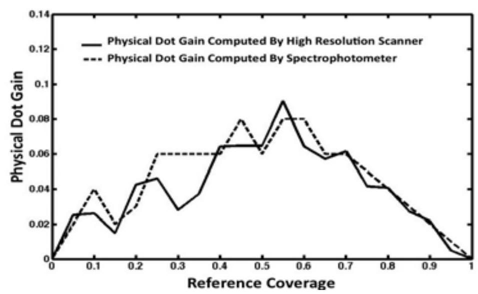

***Figure 7.** Physical dot gain of black ink prints on coated paper. Solid line: estimated from micro scale image approach. Dashed line: estimated from transmittance spectra.*

So far we have only illustrated the numerical average value of physical and optical dot gain. Since we have the possibility to use the high-resolution images it would be interesting to graphically illustrate how dot gain behaves. This illustration can also be used to characterize the properties of different papers. Figure 8a shows the reflected image of a 35% halftone patch. Since we already estimated the average value of the total dot gain at 35%, now we can use that to find a threshold to separate the dots from the paper. Figure 8b shows the total dot coverage. Using the same logic we can find another threshold to separate the physical dots from the paper, Figure 8c. By subtracting the physical dot gain from total dot gain we can illustrate the optical dot gain, see Figure 8d. As can be seen in Figure 8d, the behavior of optical dot gain is symmetrical for this type of paper (coated). It might be different for other types of paper, especially uncoated.

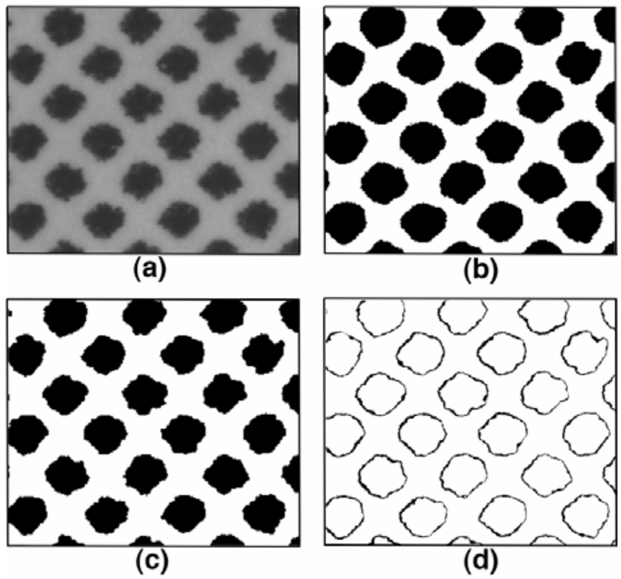

Figure 8. *(a) Micro-scale image of 35% halftone patch printed on coated paper. (b) Total dot gain configuration, (c) Physical dot gain configuration, (d) Optical dot gain configuration.*

Conclusions

In this paper two different approaches to determine the physical dot gain and separate it from the optical dot gain have been evaluated. The two different methods to estimate the physical dot gain produce similar results. It is clearly illustrated that the optical dot gain follows the physical dot shape (including the physical dot gain) and not the dot shape in the original bitmap. One of the most important factors that causes optical dot gain is the structure of the substrate. With this model it is also possible to estimate the point spread function, which is a conditional probability density that characterizes the photon migration within the paper. Therefore, this model can be useful for the paper industry to examine the properties of their products.

It can also be concluded that with this model, we can also find how ink dot is distributed by studying the physical dot shapes, see Figure 8c. It is possible to characterize ink dot placement, ink spreading on the paper, and how the light is scattered around the dots, etc.

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