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Characterization of Total Dot Gain by Microscopic Image Analysis

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Abstract. *Characterization of total dot gain gives a good insight to the study of paper and print. In this article, we propose three approaches based on the Murray–Davies model to obtain total dot gain. In the first approach, the total gain is approximated by minimizing the root-mean-square between the calculated spectrum and the reflected spectrum measured by the spectrophotometer. The other two approaches are based on microscale images captured by a high resolution camera. These two approaches differ in their schemes on how to obtain the gray tone of the full-tone ink. By the use of microscale images, the authors also illustrate the shape of the effective dot area for the investigated paper substrate. They also study the histograms of the reflected and transmitted microscale images. This comparison shows that although the transmitted image has less optical dot gain compared to the reflected image, the transmittance also incorporates some small amount of optical dot gain. © 2011 Society for Imaging Science and Technology.*
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INTRODUCTION

Characterization of total dot gain is an important issue in the study of paper properties and print characteristics. Most of the proposed models in literature are based on spectral models, which calculate the lateral propagation of light into the paper substrate (optical dot gain) and the spreading of the inks (physical dot gain) according to their superposition with the other inks.[1–5]

In this article, we present three different approaches for computing the total dot gain. One of the approaches uses reflectance spectrum obtained by a spectrophotometer and the other two use reflected microscale images captured by a high resolution camera. The idea of using microscale images to characterize the dot gain is already examined by Arney et al.[6]; in their approach, they have added an unprinted (paper) stripe at the side of the halftone area in order to find the border between dots and paper. In one of the proposed microscale image approaches in this paper, we attach two stripes to the halftone area, namely unprinted stripe and 100% ink stripe. In the second microscale image approach, we propose another model that does not require the 100% ink stripe. In this approach, the gray tone of the 100% ink for each halftone patch is calculated from the histograms of the corresponding halftone patch and of the unprinted paper stripe.

In previous works, the total dot gain is mostly analyzed by illustrating its dot gain curve.[7,8] This curve only shows the relationship between the effective and the reference (or nominal) dot coverage, but it does not illustrate the shape of the effective dot area. In this article, we not only show the dot gain curve but also illustrate the shape of the effective dot area by using microscale images.

It has previously been claimed that when the paper is perpendicularly illuminated by light from below, the light will pass through the paper without any scattering. Therefore, these authors claim that there is no optical dot gain effect included in the transmitted light.[9–11] By studying the histograms of the reflected and transmitted microscale images, we show that although the transmitted image has less optical dot gain compared to the reflected image, the transmittance also incorporates optical dot gain.

This article is organized as follows. First, we present the framework of the model in detail. It is followed by a section in which we present three different approaches to calculate the total dot gain using spectrophotometer and high resolution camera. A graphical illustration of dot gain behavior is also illustrated in this section. In the Comparison of Transmitted and Reflected Dot Gain section, we discuss why transmittance also incorporates optical dot gain, which is followed by Conclusions.

MODEL FRAMEWORK

The approaches developed in the current study are derived from the Murray–Davies equation. The approaches are based on experimental measurements of reflected and transmitted light. For this purpose, 21 patches with different coverage of gray have been printed. All the patches are halftoned by amplitude modulation (AM) (150 lpi and 1200 dpi) and printed on a commercial offset press (Heidelberg) on coated paper (150 gr/m^2). An effort is made to keep the density of ink constant. The reference dot area coverage of the patches are (0, 5, 10, …, 95, 100%), respectively. A spectrophotometer (Barbieri) is used to measure the spectrum of reflectance and transmittance. A high resolution camera, with a resolution of (1.9 μm/pixel) and with a field of view of (2.7 × 2 mm) is also used for microscale image capture.

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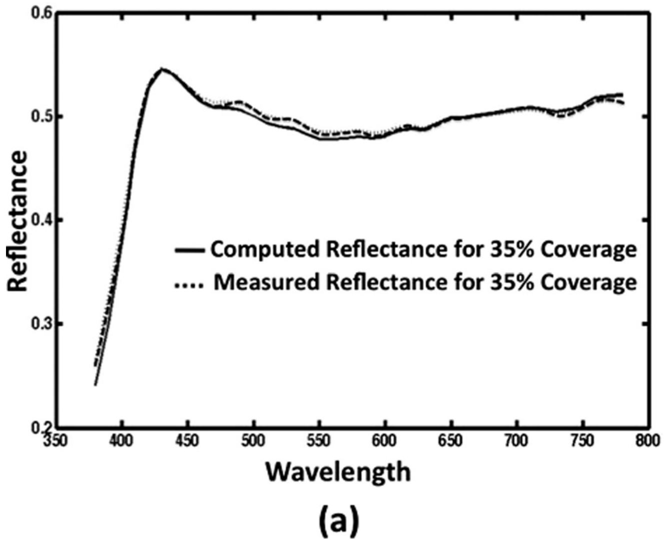

Figure 1. (a) The computed and measured reflectance spectra for 35% halftone patch. (b) The total dot gain computed by the spectroscopic approach.

This field of view 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. Hence, the camera can capture images in both reflected and transmitted light.

TOTAL DOT GAIN

One of the most famous and simplest models to predict the reflectance of a halftone print is the Murray–Davies model:[12]

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

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 that all three reflectance values are a function of wavelength. Note that, in this model, the fractional dot area a is supposed to be the physical dot coverage after printing, excluding optical dot gain. However, this model is often used to approximate the effective dot area after printing including physical and optical dot gain, due to the fact that the measured reflectance spectrum includes the effect of optical dot gain.

By using the Murray–Davies model, we can estimate the effective dot area $a_{\mathrm{eff},R}(a_{\mathrm{ref}})$, which includes both physical and optical dot gain, by minimizing the root-mean-square Δrms between calculated [Eq. (2)] and the measured reflectance spectrum:

$$R_{\lambda,\mathrm{Calc}} = a_{\mathrm{eff},R}(a_{\mathrm{ref}})R_{\lambda,i} + (1 - a_{\mathrm{eff},R}(a_{\mathrm{ref}}))R_{\lambda,p}, \tag{2}$$

where a_{ref} and $a_{\mathrm{eff},R}(a_{\mathrm{ref}})$ are the nominal areas in the digital bitmap (referred to as the reference area) and the effective dot area after print, respectively. The R subscripts indicate that the estimation is based on reflectance measurements. The total dot gain Δa_{tot} is then given by the difference between the effective dot area, $a_{\mathrm{eff},R}(a_{\mathrm{ref}})$, and the reference one, a_{ref}:

$$\Delta a_{\mathrm{tot}} = a_{\mathrm{eff},R}(a_{\mathrm{ref}}) - a_{\mathrm{ref}}. \tag{3}$$

Table I. Differences between computed reflectance and measured spectra for all coverage.

	max(Δrms)	ave(Δrms)	max(ΔE_{Lab})	ave(ΔE_{Lab})
Reflectance	0.0064	0.0040	1.1487	0.5564

Spectrophotometric Approach

The spectrophotometer is one of the conventional instruments used to measure the reflectance and transmittance spectra. In this study, to measure the reflectance spectra, the spectrophotometer is used and calibrated for each patch individually. By minimizing Δrms between the calculated [Eq. (2)] and measured reflectances, we can find $a_{\mathrm{eff},R}(a_{\mathrm{ref}})$ for each reference coverage. Accordingly $a_{\mathrm{eff},R}(a_{\mathrm{ref}})$ is fitted for each halftone patch to make the measured and interpolated spectra as identical as possible.

Figure 1(a) shows the spectrum computed with the Murray–Davies equation and spectrum measured by spectrophotometer for the reflectance of a 35% halftone patch. As can be seen in this figure, the model works very well for reflectance spectra estimations.

Table I shows both maximum and average Δrms and ΔE_{Lab} between the computed and measured spectra for all patches. Small values of ΔE_{Lab} clearly verify that the Murray–Davies equation can be used to calculate the total dot gain from reflectance spectra for black ink. Also note that the smallest Δrms does not necessarily result in the lowest ΔE_{Lab}, but small ΔE_{Lab} values in Table I indicate that the calculated spectra are very close to the measured ones viewed by human eye.

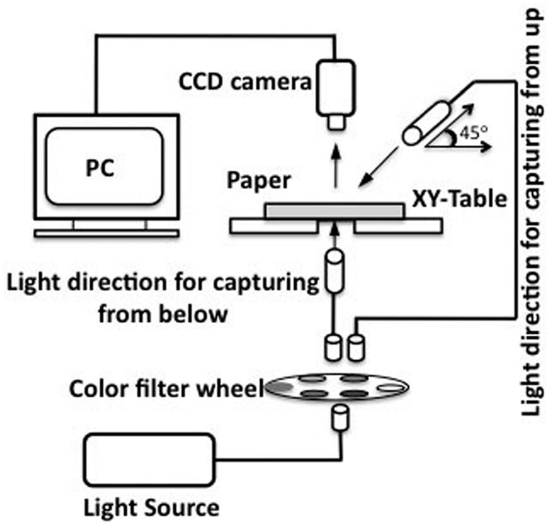

Figure 2. The high resolution camera setup for reflectance and transmittance imaging.

In this study, the reflectance spectrum has been measured for all 21 patches. From Eq. (3) the total dot gain has been calculated. Fig. 1(b) shows the total dot gain that is obtained from the reflectance spectra.

Microscale Image Approaches

In the microscale image approach, the high resolution camera (Oden Scanner) is used to capture the images. In the Oden scanner, the illumination is provided by a tungsten halogen lamp, which is close to D_{65}, and is transferred by optical fibers. The optical fibers transfer the light in two different paths: from above and from below the paper; see Figure 2.

In this study, we propose two approaches to obtain the total dot gain from the microscale images. The first approach is to use an unprinted stripe and a black stripe, i.e., 100% ink, placed at the side of each halftone patch. In the second approach, we propose another model that does not require the black stripe. In the latter approach, the gray tone of 100% ink for each patch is calculated from the histogram of the corresponding halftone patch and the unprinted paper stripe.

Figures 3(a) and 3(b) show the halftone patch at 35% captured by the camera when the light was illuminated from above (reflected image) and from below (transmitted image), respectively. In order to magnify the dots in these two figures, we are only showing a small part of the original image compared with the entire image field of view. The gray tone of paper and of 100% ink is changed from one patch to the next due to different acquisition conditions. Therefore, we decided to place two narrow stripes of unprinted paper and 100% ink beside each patch, as shown in Fig. 3, as we wanted to make sure that we used correct gray tone values for paper and 100% ink for each patch.

With Black Stripe

In this section, we discuss how the total dot gain is obtained by using unprinted and black stripes added beside each halftone patch [see Fig. 3]. By using these stripes, the gray tones of the paper and the full-tone coverage are computed by taking the averages of the pixel values of the unprinted and black stripes, respectively. From the Murray–Davies model, the total dot gain can be estimated by putting these averages into

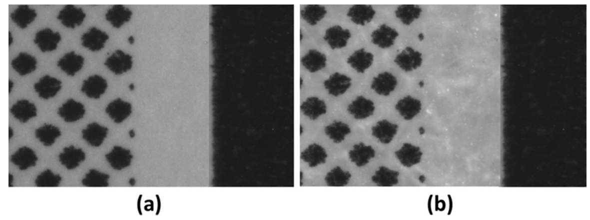

Figure 3. Microscale images with 35% reference coverage, unprinted paper, and 100% ink stripe, (a) reflected image; (b) transmitted image.

$$a_{\mathrm{eff},I}(a_{\mathrm{ref}}) = \frac{I_{\mathrm{ave}}(a_{\mathrm{ref}}) - I_p}{I_i - I_p}, \tag{4}$$

where $I_{\mathrm{ave}}(a_{\mathrm{ref}})$ is the average of the halftone patch with the reference dot area a_{ref}. I_p and I_i are the averages of the unprinted and 100% ink, respectively. $a_{\mathrm{eff},I}(a_{\mathrm{ref}})$ is the effective dot area including the optical dot gain.

Figure 4 shows the total dot gains estimated using the spectroscopic and the microscale image (with black stripe) approaches. As seen in this figure, the estimations are very close, with a maximum difference of around 1%. The micro-image method is thus a simple way to calculate the total dot gain. One disadvantage with this method is that we need to have a black stripe beside each patch. In the next part, we propose a new model to obtain the total dot gain without having a black stripe beside the halftone patches.

Without Black Stripe

Now we assume that there is no black stripe beside each patch. In order to find the gray tone value of 100% ink, the reflectance histogram obtained from the reflected image is used. A histogram indicates how the pixel values of the image are distributed. Figure 5 shows the histogram of the reflected image for the 35% halftone patch and its adjacent unprinted paper stripe, respectively. In Fig. 5, we can see there are three peaks corresponding to the unprinted stripe R_p, paper between dots, and ink dots R_i. Therefore, we can conclude that due to the optical dot gain, the peak for the paper between dots has been shifted to the left in comparison to the peak from the bulk paper.

Now the question is how to use this histogram to find the average gray tone of 100% ink. Accordingly, we need to find a threshold to separate the dots from the paper. For example, in Fig. 5, we seek for the threshold R_t that separates the full-tone dots from the paper. As can be seen in the gray tone of this histogram, values around 0.13 have the highest concentration in the dot area. As we travel toward the paper (i.e., as the gray tones become lighter), we notice a rapid drop, which indicates that we are leaving the dot area.

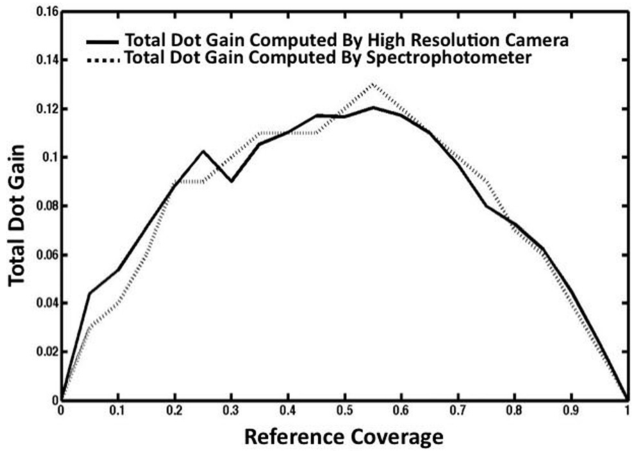

Figure 4. Total dot gain estimated by microscale image and spectroscopic approach.

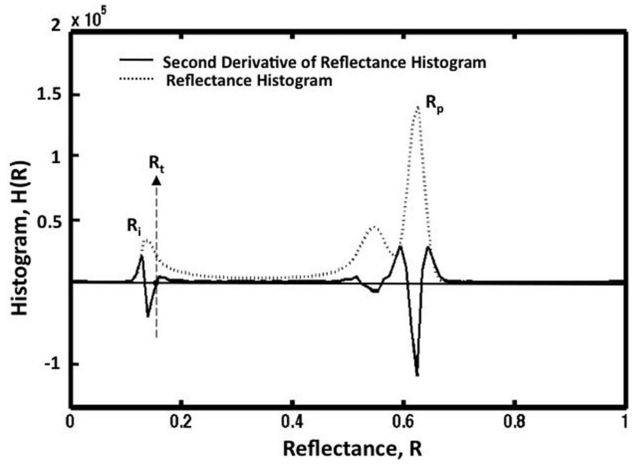

Figure 6. The reflectance histogram (dashed line) and its second derivative (solid line).

Therefore, we assume that the threshold occurs where the histogram drops the most. Mathematically, this means that the threshold is where the first minimum of the first derivative of the histogram occurs, i.e., the threshold is where the second derivative is zero and the curve of the histogram switches from convex down to convex up. In our approach, we, therefore, first find the zero point of the second derivatives of the histograms:

$$H''(R) = \frac{d^2 H(R)}{dR^2} = \frac{d}{dR}\left(\frac{dH(R)}{dR}\right). \tag{5}$$

That means we find the threshold for which the second derivative for the first time intersects with the reflectance axis of the histogram while going from negative to positive [see Figure 6].

In Eq. (5), $H(R)$ and $H''(R)$ denote the reflectance histogram and its second derivative, respectively. When the second derivative becomes zero, the histogram curve will change its convexity direction. The solid curve in Fig. 6 illustrates the second derivative of the histogram. In Fig. 6, we find the first zero value where the second derivative changes sign from negative to positive [see R_t]. Gray tone values smaller (darker tones) than these thresholds define the dot areas. The gray tone value of full-tone ink for reflected images can now be calculated by means of Eq. (6). As the measurement setup varies from patch to patch, R_{ink} should be calculated for each patch individually.

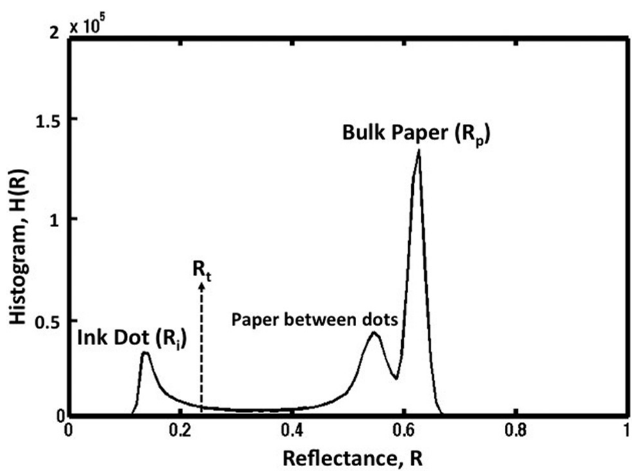

Figure 5. Normalized histogram of the reflected image for 35% halftone patch including bulk paper.

$$R_{\text{ink}} = \frac{\int_0^{R_t} R \cdot H(R)dr}{\int_0^{R_t} H(R)dr} = \frac{\sum_{R=0}^{R_t} R \cdot H(R)}{\sum_{R=0}^{R_t} H(R)}. \tag{6}$$

The total dot gain can be approximated by Murray–Davies equation:

$$a_{\text{eff},R}(a_{\text{ref}}) = \frac{R_{\text{ave}} - R_{\text{paper}}}{R_{\text{ink}} - R_{\text{paper}}}, \tag{7}$$

where R_{ave} and R_{paper} denote the average value of the halftone patch and the unprinted paper stripe for the reflected images, respectively. As described earlier in this section, R_{ink} is calculated by Eq. (6).

Figure 7 shows the total dot gain obtained by the two approaches presented in this section, namely the microscale image approach with and without the black stripe. It is observable from the figure that the estimations are very close. The maximum difference between these two approaches is again around 1%.

So far, we have only illustrated the average numerical value of the total dot gain. By use of microscale images, it is possible to graphically illustrate how the dot gain behaves. This illustration is also useful to characterize the properties of different papers. Figure 8(a) shows the reflected image of a 35% halftone patch. Since we already estimated the average value of the total dot gain at 35%, we can use it to find a threshold to separate the dots from the paper. The

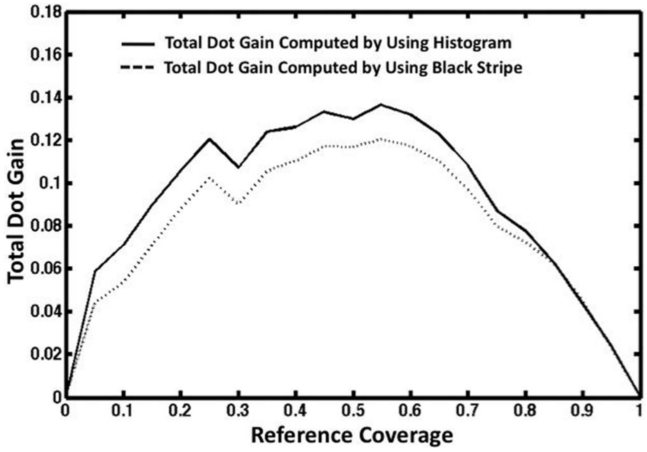

Figure 7. Total dot gain estimated by the microscale image approaches: solid line, without black stripe; dashed line, with black stripe.

reflected image of the halftone patch at 35% is denoted by IU_{35}, and the effective dot coverage calculated by Murray–Davies is denoted by $a_{\mathrm{eff},35}$. The threshold T can be found by

$$\mathrm{mean}(IU_{35} < T) = a_{\mathrm{eff},35}. \tag{8}$$

The threshold operator $(IU_{35} < T)$ means that the effective dot area corresponds to the area where the pixel values are less than T and zero otherwise. The average pixel value is calculated by the (mean) operator. Fig. 8(b) shows the effective dot area with an average denoted by $a_{\mathrm{eff},35}$, which includes the physical and optical dot gains.

COMPARISON OF TRANSMITTED AND REFLECTED DOT GAIN

It has previously been claimed in the literature that when the paper is perpendicularly illuminated by light from below, the light will pass through the paper without any scattering.[9–11] Therefore, the reflected images include both physical and optical dot gain effects, while the transmitted images only have the physical dot gain effect. In contrast, we show in this section that light scatters inside the paper even when it is illuminated perpendicularly from below. However, the amount of scattering is much less than when the printed paper is illuminated from the top at 45° angle.

In 1953, Clapper and Yule proposed a model in which the refractive index of the medium affects the light scattering.[13] In the model proposed by Clapper and Yule, the light is reflected many times from below the ink surface and from the background. The total reflected light is the sum of the light fractions that emerge after each internal reflection cycle.[14,15]

In 2007, Yang et al. proposed an approach, which is derived from the model proposed by Clapper and Yule, to estimate the physical dot gain using images scanned in transmitted light.[16] In this approach, the light scattering inside the paper and the light reflection from the interfaces between air and paper and air and ink have been considered, and the physical dot gain of the image has been described mathematically.

According to the above discussion, when the printed paper is illuminated from below, the photons traverse through the ink layer. At the air–ink interface, some fraction of the photons transit toward the air, and a large number of photons also reflect back to the paper bulk and scatter again inside the paper. Due to lateral propagation, optical dot gain may occur; see Figure 9.

In this study, we have captured the reflected and transmitted images. Figures 10(a) and 10(c) illustrate the reflected and transmitted images for the 35% halftone patch, respectively. The histograms of the halftoned patch area and the paper area are separately normalized and plotted, and they are shown in the same figure. From the histograms of the reflected image in Fig. 10(b), we can observe that, due to the optical dot gain, the peak for the paper between dots has been shifted to the left in comparison to the peak of the bulk paper. The histograms of the transmitted image in Fig. 10(d) show that the peak for the paper between the dots has also been slightly shifted from the peak of the bulk paper. This observation shows that although the transmitted image includes less optical dot gain compared to the reflected image, we cannot say that there is no optical dot gain in the transmitted image.

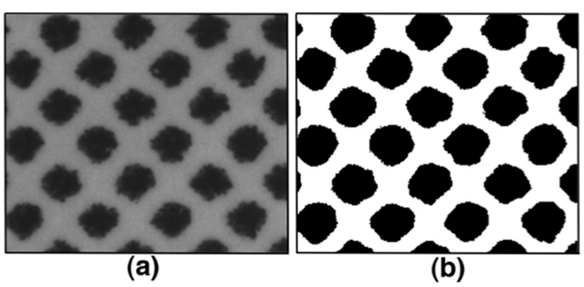

Figure 8. (a) The microscale image of 35% halftone patch printed on coated paper. (b) The effective dot area shape.

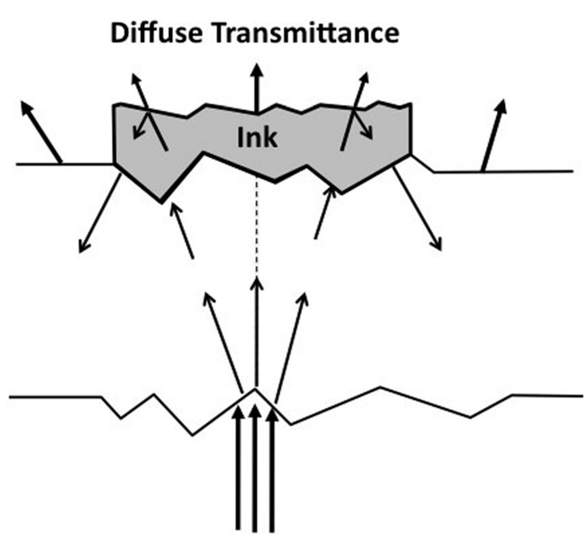

Figure 9. Diffuse transmittance when the light is illuminated perpendicularly.

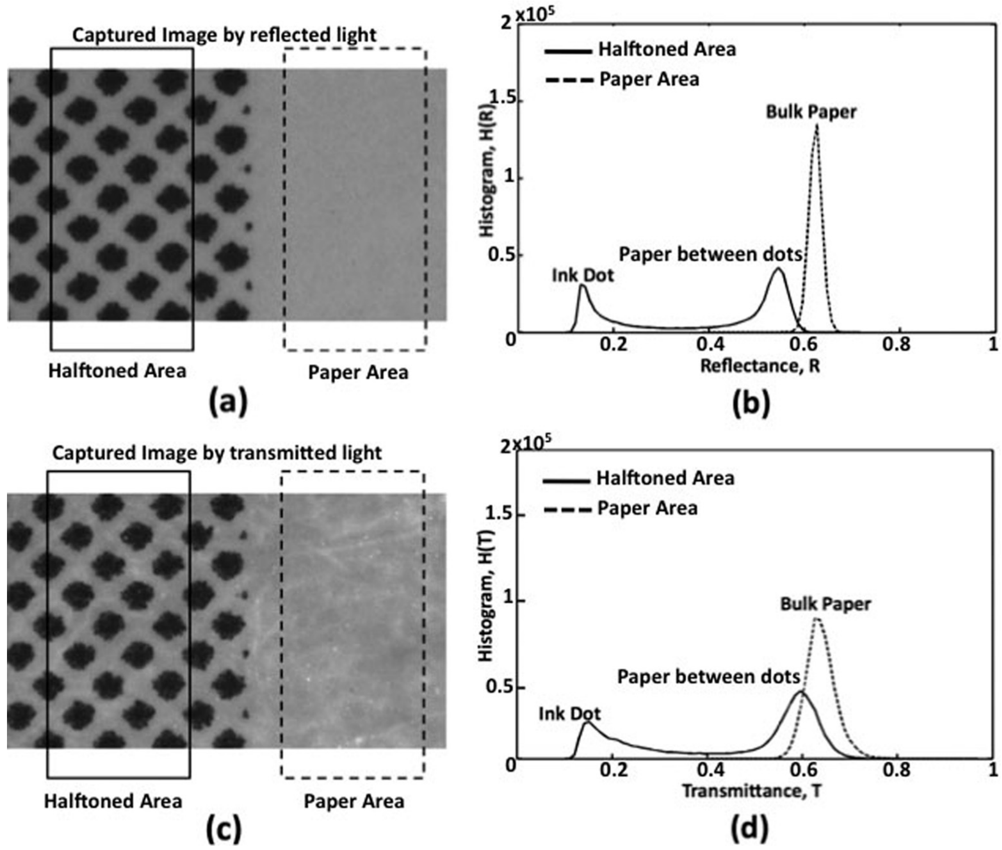

Figure 10. (a) Reflected image for 35% halftone patch. (b) Histograms of halftoned and paper areas in reflected image. (c) Transmitted image for 35% halftone patch. (d) Histograms of halftoned area and paper in transmitted image.

In Figure 11, the total dot gain using transmitted and reflected microscale images are illustrated. As expected, the total dot gain for transmitted light is smaller because the optical dot gain has a smaller effect on the transmitted light. However, since the transmittance also incorporates optical dot gain, one cannot claim that this curve represents the physical dot gain.

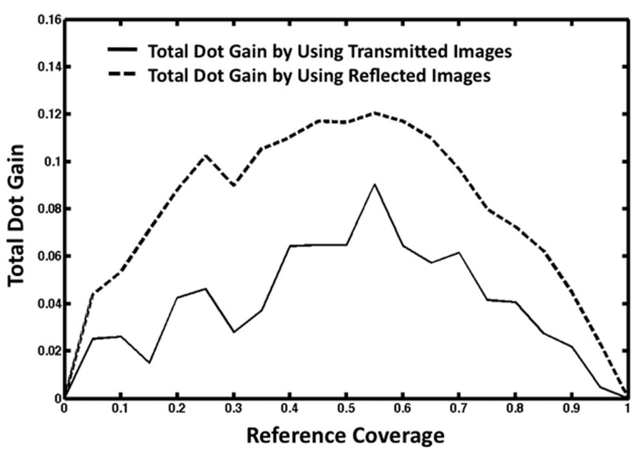

Figure 11. Total dot gain estimated by microscale image approaches: solid line, using transmitted microscale images; dashed line, using reflected microscale images.

CONCLUSIONS

In this article, three approaches to estimate the total dot gain have been proposed and evaluated. One of the approaches is based on measurements carried out using a spectrophotometer. The two other approaches are based on captured microscale images taken by a high resolution camera. It has been shown that all three approaches produce similar results. By use of the high resolution camera, the effective dot area has been graphically illustrated. It has also been shown that transmittance incorporates optical dot gain. We anticipate that this study can help the paper and graphic arts industries to develop their products more efficiently. We propose testing the approaches on other types of papers and halftoning and on color print as an extension to the current study.

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