Spectral Based Analysis and Modeling of Dot Gain in Ink-jet Printing

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Abstract

We propose a new model to predict the color reproduction of digital halftone image based on the physical model of dot gain. In the previous papers, we reported that the transparency image of halftone is not influenced by optical dot gain. On the basis of this experimental result, in this paper we analyze the optical and mechanical dot gain separately by using the optical microscopes which can take the transparency and reflectance images of the same area. Transparency images of an ink dot are taken with an optical microscope with a six-band camera and the spectral transmittance of each pixel in an ink dot is estimated by the multiple regression estimation method. This obtained spectral transmittance is converted into the amount of cyan, magenta, and yellow (c,m,y) inks in each pixel. Then we can estimate the shape of ink dot by polynomial fitting of ink amount.

The transmittance of c,m,y inks of printed images is estimated by using the proposed method and compared with that of practical printed images. This results show that the proposed method is significant to predict the density of ink-jet images.

Introduction

Ink-jet printers have been widely used in various fields because of its reasonable cost and acceptable image quality. The quality of ink-jet images is dependent on inks, halftoning algorithms, particularly kind of papers. For example, quality of images printed on to coated paper is better than that of uncoated paper. Our goal in this research is to develop the algorithm for prediction of ink-jet image quality. For a long time, many researches have been done to predict the tone and color reproduction of halftone such as Murray-Davies equation, Neugebauer equations, Yule-Nielsen equation. However, precise prediction of them is not easy due to the *dot gain* effect in printing. Dot gain effect makes the actual image appear darker than that of the ideal reproduced images. Dot gain can be categorized into two types of dot gain; one is *mechanical dot gain*, the other is *optical dot gain*. Mechanical dot gain is the phenomenon that the size of ink dot increases because of ink spreading, while optical dot gain is the phenomenon that ink dot appears larger by light scattering in the paper. Mechanical and optical dot gain simultaneously affect to the appearance of images. Therefore it is difficult to measure separately the effect of mechanical and optical dot gain.

In a previous paper,[1] we proposed a method for separating mechanical and optical dot gain in monochrome printed images based on that transparency images of halftone are not influenced by optical dot gain. In this paper, we extend the previous model to color halftone image. First, transparency images are calculated by using an optical microscope with a six-band camera. Second, Spectral transmittance are calculated from the transparency images by a multiple regression estimation method. Third, the amount of cyan, magenta and yellow ink density is estimated using the method proposed by Takeya *et al.*[2] Finally, The shape of an ink dot and its density distribution is modeled by ellipse and polynomial equation.

Transparency and Reflection Image Model

S. Inoue *et al.* proposed a color prediction model for halftone images called the *reflection image model.*[3] In the reflection image model, a printed image is assumed to be optically separated into ink layer and paper as shown in Fig. 1. The reflectance distribution $r(x,y)$ is represented on this model as follows:

$$r(x, y) = r_{paper}\left[t_{ink}(x, y) * psf_{paper}(x, y)\right] t_{ink}(x, y), \qquad (1)$$

where r_{paper} is the reflectance of the paper, $t_{ink}(x,y)$ is the transmittance of the ink layer, $psf_{paper}(x,y)$ is the point spread function of paper, and the (*) denotes the convolution operation.

Reflectance distribution $r(x,y)$ is the influenced by the mechanical and optical dot gain. The influence of mechanical dot gain is introduced into the term $t_{ink}(x,y)$, which is measured using image printed on transparency films. On the other hand, the effect of optical dot gain is introduced into the term $psf_{paper}(x,y)$, which represents the optical light scattering in paper.

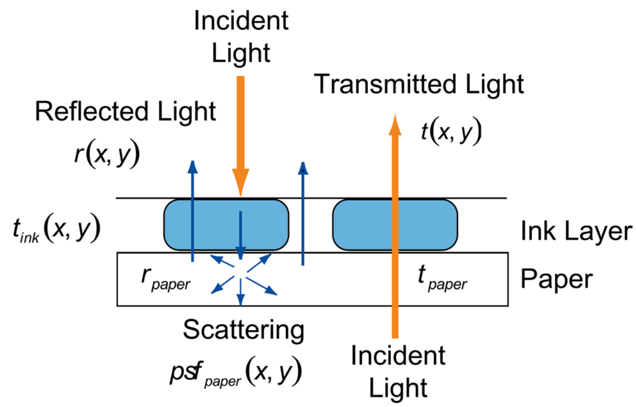

Figure 1. Reflection and Transparency Image model left: Reflection image, right: Transparency image

C. Koopipat *et al.* proposed a model for transparency halftone images called the *transparency image model.*[4] From this model, the transmittance image $t(x,y)$ can be represented as follows:

$$t(x,y) = t_{paper} \cdot t_{ink}(x,y)\,, \tag{2}$$

where t_{paper} is the transmittance of paper, and $t_{ink}(x,y)$ is the transmittance of ink layer. Therefore it becomes possible to separate the mechanical and optical dot gain by analyzing $t_{ink}(x,y)$ and $r(x,y)$.

Instrument for Measurement

Figure 2 illustrates the microscope for the transmittance and reflectance measurement.[4] This instrument consists of a monochrome digital camera (Kodak DCS420) attached to a microscope. The effective resolution of the CCD sensor in this camera is 1012×1524 pixels with 9µm pitch and the magnification of the optical system is x10. To eliminate the specular reflection component, two polarizing filter are placed in front of each light source.

The reflectance image $r(x,y)$ can be obtained through the illuminant from the light source A as shown in the solid line in Figure 2, while The transmittance image $t(x,y)$ is obtained through the illuminant from the light source B as shown in the broken line in Figure 2.

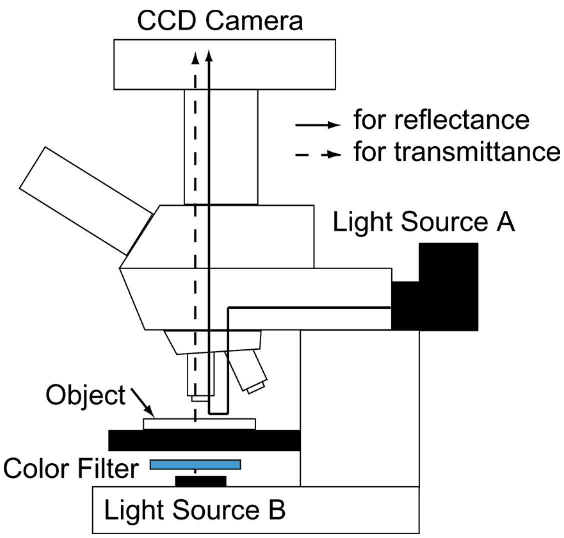

Figure 2. Microscope for reflectance and transmittance measurement

Estimation of Spectral Transmittance Using Multiple Regression Estimation Method

To measure the spectral transmittance of the object $\boldsymbol{o}_{xy}$, six-band images $\boldsymbol{v}_{xy}$ are taken with six filter shown in Fig. 3. The spectral transmittance at each pixel in the image, $\boldsymbol{o}_{xy}$ is calculated by Eq. 4:

$$\boldsymbol{o}_{xy} = \boldsymbol{G}\boldsymbol{v}_{xy}\,, \tag{3}$$

where, $\boldsymbol{G}$ is the estimation matrix. As well known, the matrix $\boldsymbol{G}$ is calculated as follows:

$$\boldsymbol{G} = <\boldsymbol{o}\boldsymbol{v}^T><\boldsymbol{v}\boldsymbol{v}^T>^{-1}\,, \tag{4}$$

where $\boldsymbol{o}$ is the transmittance matrix, $\boldsymbol{v}$ is the sensor response matrix. 30 color patches were used to calculate the estimation matrix $\boldsymbol{G}$. Then, we can get the spectral transmittance image $\boldsymbol{o}_{xy}$ by Eq. 3.

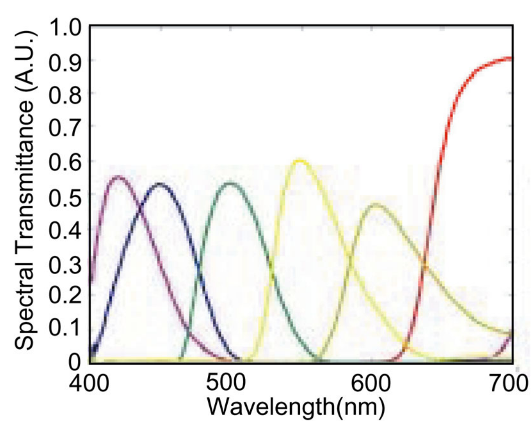

Figure 3. The spectral transmittance of six color filters

Analysis and Modeling of Dot Gain

We analyzed the shape of an individual ink dot using following procedures:

1. The spectral transmittance at each pixel is estimated from six images taken by a six-band camera with the spectral transmittance as shown in Fig. 3 by the multiple regression estimation method.
2. The spectral transmittance is converted into the amount of c,m,y ink by Takeya's method.[2]
3. The shape of an ink dot and its density distribution is modeled by ellipse and polynomial equation.

The average color difference ΔE_{94} between measured and estimated 30 color patches printed on the three kind of paper was from 1.51 to 1.83 as shown in Table 1. These results indicate that the proposed method has sufficient accuracy to estimate spectral transmittance of ink-jet image.

Table 1. The average color difference ΔE_{94} between measured and estimated 30 color patches

paper	Max.	Min.	Average
glossy	5.53	0.13	1.83
coat	4.67	0.12	1.51
normal	4.72	0.11	1.52

Ink Separation from Spectral Transmittance Image

To analyze the individual ink dot of CMY inks separately, a spectral transmittance image must be converted into CMY ink images, which conversion is called the *ink separation*.

Takeya *et al.* proposed a method for ink separation from a spectral transmittance image.[2] The spectral density $D(x,y;\lambda)$ at the coordinate (x,y) is defined as follows:

$$D(x,y;\lambda) = -\log T(x,y;\lambda), \quad (5)$$

where $T(x,y;\lambda)$ is the spectral transmittance at the coordinate (x,y). If we assume the Lambert Beer's law, the spectral density of ink-jet image $D(x,y;\lambda)$ at (x,y) is represented as

$$D(x,y;\lambda) = \varepsilon(\lambda)c(x,y)d(x,y), \quad (6)$$

where $\varepsilon(\lambda)$ is the spectral absorption coefficient. $c(x,y)$ and $d(x,y)$ are the concentration and the thickness of the ink at (x,y), respectively. If we assume that $c(x_0,y_0)d(x_0,y_0)$ is equal to unity at (x_0,y_0) as shown in Fig.4, Eq. 6 at (x_0,y_0) becomes

$$D(x,y;\lambda) = a(x,y)D(x_0,y_0;\lambda), \quad (7)$$

where $a(x,y)$ is the amount of ink at (x,y) relative to that at (x_0,y_0). Therefore, spectral integrated density $D(\lambda)$ is represented by

$$D(\lambda) = a_c D_c(\lambda) + a_m D_m(\lambda) + a_y D_y(\lambda), \quad (8)$$

where a_c, a_m, a_y is the relative amount of c,m,y ink, and $D_c(\lambda)$, $D_c(\lambda)$, $D_c(\lambda)$ is the spectral analytical density of c,m,y inks. The a_c, a_m, a_y are optimized to minimize the root mean square error between the original and reproduction spectral density. Using Eq. 8, we can estimate the amount of c,m,y ink from the spectral transmittance. Original and separated images are shown in Fig. 5.

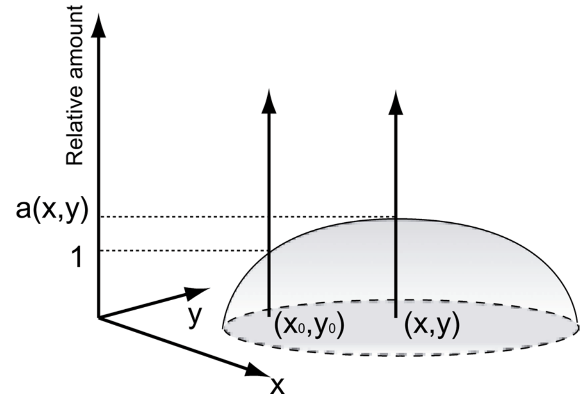

Figure 4. Schematic diagram of two-dimensional distribution of relative amount of ink on the transparency.[2]

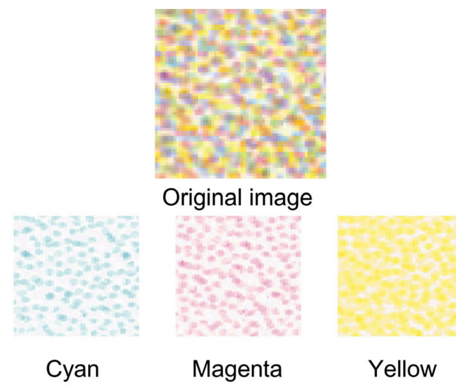

Figure 5. Original image consisting CMY ink (upper) and separated CMY ink image (lower)

Analysis and Modeling of Dot Gain

CMY ink image contains an individual ink dot profile as shown in Fig. 6. An individual ink dot is extracted and modeled using Eqs. 9 and 10. We assume that the dot shape can be represented as the ellipse

$$ax^2 + by^2 = r^2, \quad (9)$$

where *a ,b, r* are positive and not zero.

On the other hand, we also assume that the density distribution of the ellipse spot is represented as polynomial equation

$$d = c_1 r^4 + c_2, \quad (10)$$

where d is the relative amount of ink at the pixel, and c_1,,c_2 are coefficient. Noise is added to the modeled ink dot toward the r (radius) axis orientation. Modeled and measured ink dots of coated, matte, and uncoated types of paper are shown in Fig. 6.

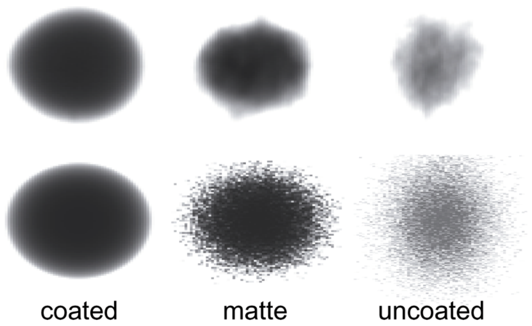

Figure 6. Modeled ink dot (upper) and measured ink dot (lower)

Prediction of the Transmittance of Images

We predicted the transmittance of images using the dot model. The prediction is performed following procedures as shown in Fig. 7. First, the center location of dot impact is calculated using the high resolution grid. The center location vibrates randomly to simulate the dot impact of real printers. Second, the average transmittance of the transparency image is calculated using Eq. 2.

Figure 8 shows the relationship between transmittance and dot area of halftone for cyan. The accuracy of prediction for the dot area below 60 percent is sufficient. On the other hand, the accuracy for the dot area over 60 percent is insufficient. We consider that the prediction error is mainly due to the change of ink dots area by overlapping of each ink.

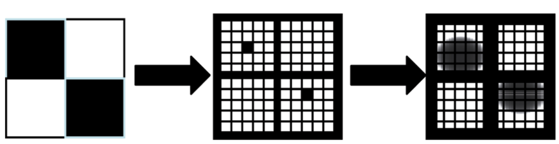

Figure 7. Dot impact model

Conclusion

In this paper, we estimated the spectral transmittance of transparency images using an optical microscope with the six-band camera. Then, we performed ink separation from the transmittance image. Using the separated CMY ink image, the shape of the individual ink dot was analyzed and modeled.

We also predicted the transmittance of cyan color patches based on modeled ink dot. The accuracy of prediction was sufficient for the dot area below 60 percent, whereas insufficient for the dot area over 60 percent.

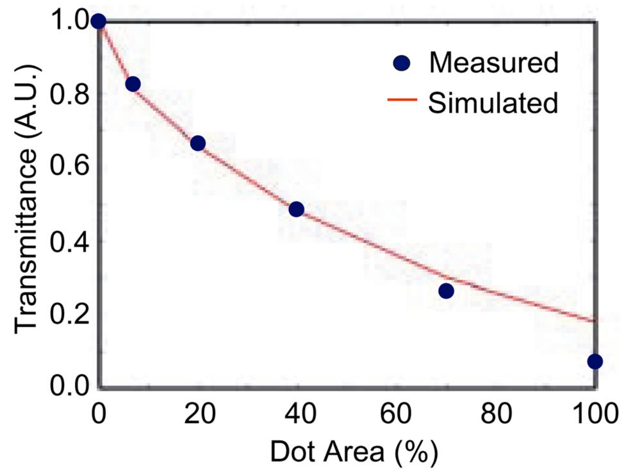

Figure 8. Relationship between transmittance and dot area of halftone for cyan patches

Our future work is to improve the accuracy of prediction in every dot area. Furthermore, we would apply the proposed model to predict tone and color reproduction of ink-jet image.

References

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Biography

Jun Yamashita was born in Saitama, Japan, on 23 April, 1979. He is currently a master course student at Chiba University.