Research on a New Reflectance Model for Printing Based on Dot Shape

Qi Wang, Xi Yang and Honghao Liu

Abstract The relation between dot shape and printing reflectance is researched. Considering the structural characteristics of halftone prints, a new reflectance model of amplitude modulation screening dot is provided. Based on Monte Carlo thinking method, the whole route of photons propagation including incidence, diffusion and termination is simulated in mathematical language according to the particle properties of light. The simulation process not only reflects influencing factors of ink, substrate and dot structure, but also can illustrate two dimensions morphology of screening dots. The results showed that Monte Carlo model indeed can reflect the influence of dot shape. Besides, the simulated value of reflectance model closely approached to the measured data of different dot shape. This new model can visualize various dot structures, which provide a new idea to evaluate printing quality.

Keywords Reflectance model · Monte carlo method · Dot shape

1 Introduction

As an information carrier, prints are important resources for people to obtain information. Presswork is a complex layered structure material, the form of light propagation in prints is diverse, containing mirror reflection, specular transmittance, internal reflection interface, the interface outer reflector and light scattering [1]. Existing studies have focused on different aspects, the minority care about combination effects of ink and paper, and more researchers pay attention to the description of light propagation phenomena. Murray-Davies model was the first

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reflectance models [2, 3]. Yule-Nielsen model incorporated edge effects by introducing correction parameter n [4, 5], based on the Murray-Davies modified model. Clapper-Yule model paid a new attention to the interface reflection and scattering phenomena between the ink and the paper [6].

After the Saunderson correction, Kubelka-Munk theory [7, 8] focusing on the influence of multiple reflections in the medium was produced. Due to the complexity and indescribability of light propagation, the results of these studies were established on a certain kind of simplification and assumption, which could not be able to take various factors into account.

Early S.A. Prahl and M. Keijzer, who described Monte Carlo simulation of light propagation in different mediums [9, 10], and then, Lihong Wang and S.L. Jacques proposed a method to improve the simulation of light propagation in multi-media [11, 12]. Based on that, we propose another Monte Carlo simulation model, which shows a new idea to study the light propagation in halftone prints.

2 Simulation of Light Propagation

When light shines on halftone printing, it will interact with ink, paper and other media and eventually decompose to electromagnetic waves carrying different energy. So the whole process of simulation can be divided into three parts, photon generation, communication in media and photons termination [8, 13].

Photon initialization is to simulate the illuminant that emits photons, including the initialization of photon energy, position and direction. During the simulation, the photon incident direction is supposed to be perpendicular to printed materials. Initialized photon energy artificially defined as w, each photon moves will be accompanied by energy absorption and scattering. Suffering from ones move, part of the photon energy is absorbed; another will scatter out into the next process which can be written as w'.

$$w' = \frac{\sigma_s}{\sigma_a + \sigma_s} w \tag{1}$$

where σ_s and σ_α are the absorption and the scattering coefficients. In three-dimensional media, photon scatter direction can be defined with azimuthal angle $\alpha \in [0, 2\pi]$ and deflection angle $\beta \in [0, \pi]$ shown in Fig. 1.

Judging from whether paper was covered with ink, printing surface can be divided into blank area and inked area. If the position of incident photons locates in inked area, it has to undergo absorption process. When transmittance of the ink is t_i, the photon energy becomes $w * t_i$.

Random sampling of the step-length and direction is the first thing. The step-size can be described by probability density function [8].

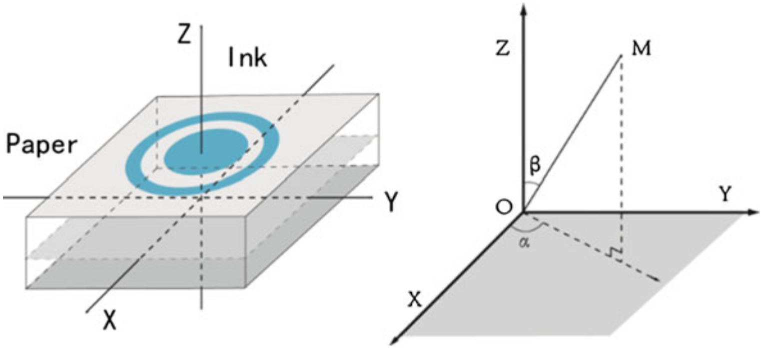

Fig. 1 Illustration of coordinates and angle α, β

$$p(s) = \sigma_t e^{-\sigma_t s} \tag{2}$$

The parameters $\sigma_t, \sigma_\alpha, \sigma_s$ are the attenuation, the absorption, and the scattering coefficients respectively. So, step-size s is

$$s = \frac{-\ln \varepsilon}{\sigma_a + \sigma_s} \tag{3}$$

Sampling of scattering direction is to define the value of azimuthal angle α and declination angle β. Azimuth α is a uniform distribution in the interval [0, 2π], and could be determined by random variable ε'

$$\alpha = 2\pi\varepsilon' \tag{4}$$

Deflection angle β follows the probability distribution function of Henyey-Greenstein [5].

$$p(\cos\beta, g) = \frac{1 - g^2}{2(1 + g^2 - 2g\cos\beta)^{3/2}} \tag{5}$$

The parameter $g \in [-1, 1]$ is anisotropy coefficient Deflection angle β can then be determined by using another random value $\varepsilon \in [0, 1]$.

$$\cos\beta = \begin{cases} \frac{1}{2g}\left\{1 + g^2 - \left[\frac{1-g^2}{1-g+2g\varepsilon}\right]\right\} & g \neq 0 \\ 2\varepsilon - 1 & g = 0 \end{cases} \tag{6}$$

Scattering direction $\left(u'_x, u'_y, u'_z\right)$ satisfies the following formula:

If $|u_z| > 0.99999$

$$\begin{cases} u'_x = \cos\alpha\sin\beta \\ u'_y = \sin\alpha\sin\beta \\ u'_z = \frac{u_z}{|u_z|}\cos\beta \end{cases} \quad (7)$$

If $|u_z| \leq 0.99999$

$$\begin{cases} u'_x = \frac{\sin\beta}{\sqrt{1-u_z^2}}\left(u_x u_z\cos\alpha - u_y\sin\alpha\right) + u_x\cos\beta \\ u'_y = \frac{\sin\beta}{\sqrt{1-u_z^2}}\left(u_y u_z\cos\alpha - u_y\sin\alpha\right) + u_y\cos\beta \\ u'_z = \frac{-\cos\alpha\sin\beta}{\sqrt{1-u_z^2}} + u_z\cos\beta \end{cases}$$

Photon energy loss occurs in propagation. When the photon energy is extremely small, either the final photon is reflected or transmitted from the medium; its effect is quite limited. To avoid endless calculation and improve simulation efficiency, roulette filtering rule is proposed [7]. That means when the photon energy is less than a certain threshold w'', photons have the chance of $1/m$ to survive and then their energy becomes $m * w''$, otherwise photon can be completely regard as absorbed photon. Surviving photons will continue to move until they leave the printing or be absorbed. Roulette filtering rule come true with the help of presetting value m and generating a random number between $\varepsilon \in [0, 1]$

$$w'' = \begin{cases} mw'' & \varepsilon \leq \frac{1}{m} \\ 0 & \varepsilon > \frac{1}{m} \end{cases} \quad (8)$$

When each photon moves as step-size s, it is likely to strike the interface between the air and the media and then leave the media, or be internally reflected. Whether the internal reflection will occur depends on the moving step and the angle between moving direction and interface. The refractive index of the media and the air are n_i, n_t. Total reflection occurs when photons moving angle α_i is greater than the total reflection angle α_c.

$$\alpha_i = \cos^{-1}(|u_z|) \quad (9)$$

$$\alpha_c = \sin^{-1}(n_t/n_i) \quad (10)$$

In other cases, total reflection is determined by Fresnel reflection coefficient $R(\alpha_i)$

$$R(\alpha_i) = \frac{1}{2}\left[\frac{\sin^2(\alpha_i - \alpha_t)}{\sin^2(\alpha_i + \alpha_t)} + \frac{\tan^2(\alpha_i - \alpha_t)}{\tan^2(\alpha_i + \alpha_t)}\right] \quad (11)$$

According to Snell's law, the relationship between angle of incidence on the boundary α_i and the angle of transmission α_t is

$$n_i \sin \alpha_i = n_t \sin \alpha_t \tag{12}$$

The random number ε can be used to decide whether photon will emit or internally reflect. When $\varepsilon \leq R(\alpha_i)$, the photon is internally reflected, otherwise the photons emit from media. By calculating the point (x, y, z) and the direction cosine (u_x, u_y, u_z), the location where photon will emit can be deduced. If the photon is internally reflected, the direction of movement will correspondingly change to $(u_x, u_y, -u_z)$. If the photon emits from the top surface, it is recorded as reflected light. When photon emits from the bottom, then it is deemed as transmitted light.

3 Simulation of Dot Structure

The concentric dot is a double ring structure which is similar to the AM round dot, and the inked area is called strip, the blank area is called empty shown in Fig. 2.

When the screening lines and dot area are defined as L, a, the radius of the round dot is obtained by the equation

$$r = \frac{2.54}{L}\sqrt{\frac{a}{\pi}} \tag{13}$$

The particular feature of concentric dot is a fixed ratio of empty arguments. Its image area is called strip and the blank part is called empty. The empty ratio refers to the ratio between the empty and the stripe. The stripe width is t. The width of the empty is described as k and the ratio m/n. Figure 2 [14] shows the details. The

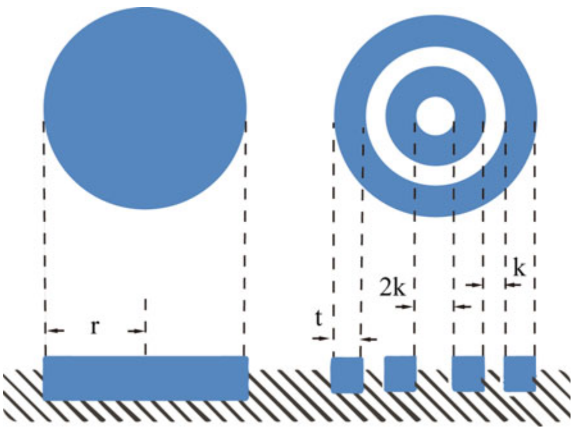

Fig. 2 Geometry of round and concentric dot

formula 14 shows the calculation of t through certain screening value L and dot area ratio a

$$\begin{cases} t = \frac{2.54}{L}\sqrt{\frac{am}{\pi(4m+6n)}} \\ k = \frac{tn}{m} \end{cases} \quad (14)$$

In order to easily distinguish the inked area and blank part, when building a coordinate system, the center of the screening grid can be regarded as the origin of XY coordinate system [15]. By comparing the radius size with the distance between the origin and the location of photon, whether photon is in the inked area can be judged. The distance between the location of photon and the origin is written as d and the round radius is r. If $d \le r$, photons will appear in the inking dot area, the ink layer will absorb the photon energy. If $d > r$, photons will appear in the blank area, the photons energy will not decay.

In the same way, round, diamond, oval and square dot can be simulated separately.

4 Result and Discussion

According to the Monte Carlo simulation flow, algorithms for different dot structures can be obtained. The algorithm has strong applicability and scalability. The printing parameter including line screens, dot shape, dot area, paper properties, or ink attributes can be set accordingly.

4.1 *Printing Dot Shape Simulation*

Various dot structures can be simulated according to different dot area. Figure 3 shows the simulation results of concentric dot.

Figure 3 shows that in the simulation diagram, concentric dot is illustrated perfectly. Dot shape varies according to dot area. Overall, the simulation algorithm can intuitively reflect microstructure. In addition, different dot structures also can be simulated. The results are shown in Fig. 4.

In order to verify the new model rationality, the comparison result has to be made. Figure 5 shows the compared result. Only from the point of dot shape, printed dots are much close to the simulated dots. There are only two differences. The real printed dots have a blurred edge and the variation of grey scale is more obvious than the simulated results. These could be caused by the low resolution of

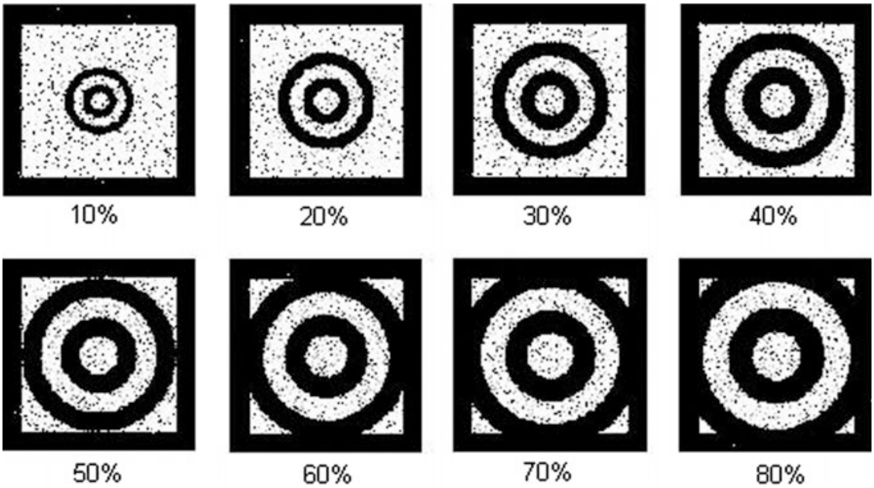

Fig. 3 Simulation of concentric dot. Concentric dot *screen line* is 175 lpi, and empty strip ratio is 1.8/1.3. *Dot area* ranges from 10 to 80%

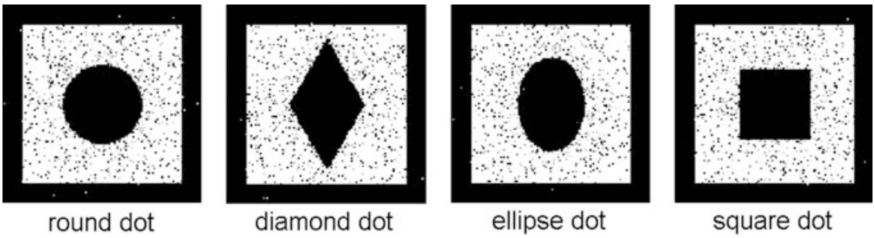

Fig. 4 Simulation of different dot structures including *round*, *diamond*, *ellipse* and *square dot*. *Screen lines* are all 175 lpi and *dot area* is 20%

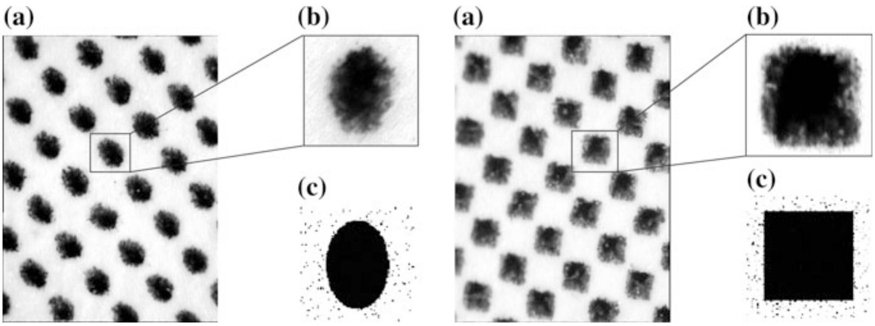

Fig. 5 Comparison result between printed dots and simulated dots. **a** The real printed sheet of *ellipse* and *square dot* which were obtained by DT2000 microscope.in 10 times magnification. **b** The selected *single dot* of printed sheet. **c** The simulation result of reflective model

display. The simulated results have to make a compromise between good display and high efficiency. Besides, the printed sheet has been made for a long time before microscope research. The property of printing ink is changed, which could also cause that difference [16]. Figure 5 proves that the new reflectance model can rationally give simulated dot shape.

4.2 Reflective Verification of the Simulation

After deciding the optimal parameters and showing the stability of simulation results, this paper verifies the accuracy of models for ellipse and concentric dot structure. Figure 6 shows the result which obtained by the spectroeye.

In the range of whole tonal, the measured reflectance of ellipse dot is much consistent with simulated reflectance, which indicates that the Monte Carlo model of ellipse dot is accurate.

Figure 6 shows that: in tonal range of 10–60%, the simulation results of concentric dot are reasonable, but when dot area is more than 60%, big deviation occurs. The interaction between dots and dots cause that deviation. Interactive effects appear for 175 lpi concentric dots when dot area is above 60%. The higher dot area rate is, the more seriously overlap phenomenon occurs [17], resulting in data deviation increases.

The new model has a fresh feature that it also can show photons distribution of various dots, which provide a new way to research printing quality. As what was shown in Fig. 7a, three different kinds of photons were illustrated. The top layer was reflected photons which show a clear ellipse dot shape. The absorbed photon was distributed in the middle and the transmission photon was in the bottom layer. How many photons were absorbed or reflected were illustrated in Fig. 7b. Different parts of photons varied with dot area. With this information, farther study can be made to improve printing quality.

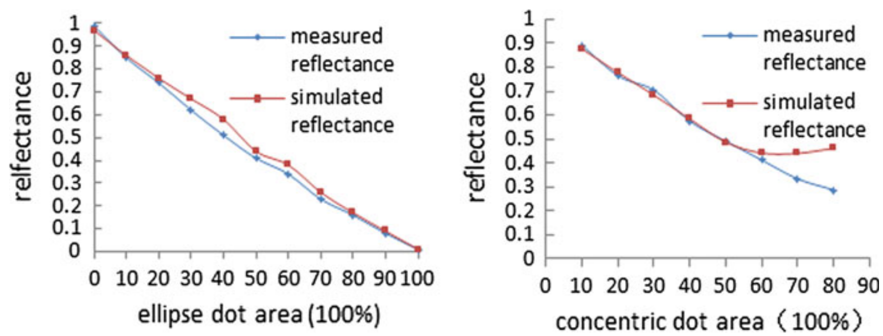

Fig. 6 Verification of concentric and ellipse dot

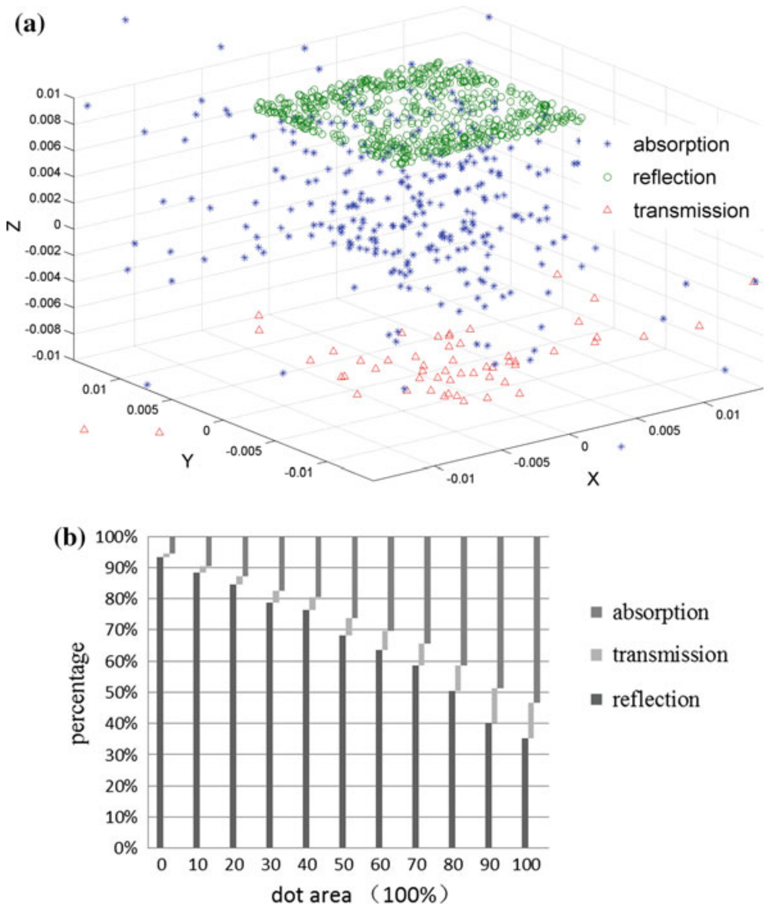

Fig. 7 Distribution of simulated photons. **a** The photon state when photons escapes prints. Parameters include photons numbers = 1000, dot area = 70% and 157 g/m^2 coated paper. **b** The proportion of three different kinds of photons for ellipse dot shape

5 Conclusions

This paper provides a new way to study the behavior of light propagation in halftone printing within Monte Carlo method. The method can reasonably reflect the interplay between light and printed materials, which is useful for microscopic quality control for printed products. The simulation process contains several kinds of interactive forms between substrate and ink. Based on Monte Carlo method and combined with dot shape and dot area, light propagation behavior is completely simulated. Besides, the results of reflectance prove the method is practicable. Although this paper only roughly shows the reflective results of 175 lpi ellipse and concentric dots, at least it provides new ideas for microscopic research and quality control of printed materials. The method can continue to be improved from different aspects in the future, such as transmission, absorption and distribution of the position of the energy. In addition, it is also a good idea to study how different dot structures and paper parameters affect the quality of prints

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