An improved reflectance prediction model for halftone printing dot based on Monte Carlo method

Honghao Liu[1], *Kaixing Zhang[1], Xianxi, Liu[1], Jinxing Wang[1], Heow Pueh Lee [2]

1 College of Mechanical and Electronic Engineering，ShanDong Agricultural University
Taian 271018, China;
2 Department of Mechanical Engineering, National University of Singapore, Singapore 117575, Singapore
* Corresponding author. E-mail address: kaixingzhang@sdau.edu.cn

Abstract

The improved reflectance prediction model for printing dot was established with Monte Carlo method. Reflectance model is a useful approach to predict and control printing quality, which was widely used in color duplication field. The Monte Carlo prediction model for printing dot is a simulation model, satisfying industrial virtual reality needs, which could simulates reflectance data as well as dot shape image. This paper mainly focuses on improving the existing reflectance model for printing dot with simulation program, expanding dot simulation area from one single dot to nine dots. The results showed that the reflectance value closely approached to the measured value with high dot area in particular and the correlation coefficient improved to 0.924. One hundred thousand times was shown to be the optimal number of simulated photon under regular printing condition. The expanding simulation area could significantly eliminate interactive influence among the dots. The photon distribution and dot shape could be sufficiently simulated through this model, providing a reference for quality control. The results indicate that the improved reflectance model increased reflectance accuracy and could further promote optical study about color duplication.
Key words: Tracking photon path, Monte-Carlo method, Reflectance model

1. Introduction

Printing works consisting of paper and colorful ink, almost existing widely, is a necessary media for distribution of text and image. Although the internet has become a powerful media gradually, prints still accounts for 60 percent contribution on information dissemination. Whether information can be exactly described and disseminated, depends on the quality of printing works with art picture in particular. Before actual print with machine, several procedures must be made including color separation, image screening and dot selection. In a typical printing process, printing material, printing speed and machine pressure could raise the difference. High quality prints must be the optimal combination of all influence factors. Because accomplishing one printing job is a large project, which requires huge energy and material. Hence it is not effective to judge the final quality with real printed work. For several decades, relevant researchers have been working on an approach to predict, judge and adjust printing quality before actual print without consuming large energy, and therefore promoting energy conservation. The printing model is a good choice. The printing model that can predict the printing reflectance before actual print is widely used in printing domain.

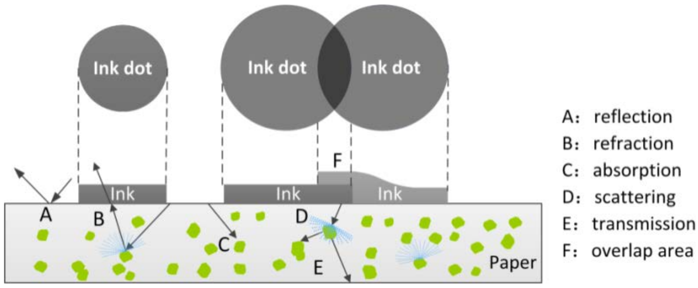

Fig 1 The distribution and interactive results of different dots.

The first printing model that can calculate total the reflectance is the Murray-Davies model [1], which only paid attention to the direct reflection of paper and ink surface. The printing woks have various layers with different reflective characters and multiple reflections between different layers cannot be ignored [2]. Although the Clapper-Yule model [3] that was improved from the Murray-Davies model taken multiple reflection into consideration by introducing correction parameters N, it did not perform better and had low stability in that the correction parameters N was obtained by experience which cannot be quantified objectively [4]. The point spread function model that used the optical radiation theory to calculate reflectance could achieve better performance, but it would need complicated calculation [5]. Relevant studies such as DT2002 and Kubelka-Munk model all improved printing model accuracy to some extant [6-9]. Not until the Monte-Carlo model was introduced into printing field, printing prediction model only output single data. Apart from reflectance prediction, the Monte-Carlo model [10-12] that was widely used in finance, mathematic and medical fields can simulate printing dot shape, and providing a new approach to adjust printing quality. The first Monte-Carlo model used in printing field was proposed by Robert Beuc, which successfully simulated paper surface in 2009 [13]. Based on that, Damir Modric accomplished single printed line simulation in 2012. Besides, relevant studies [14] with Monte-Carlo method achieved different dot shape and photon distribution simulation, which extended the printing model researches into micro field.

The aim of this paper is to propose an improved printing reflectance model with Monte-Carlo method by expanding the simulation area, further promoting printing quality control and optical study.

2 Improving reflectance model

The Monte-Carlo method proposed by Metropolis is essentially a probabilistic method [15]. It assumes that a sample can reflect population attributes as long as sample number is sufficient. Monte-Carlo method has been applied in various simulation fields that has random properties. The comprehensive phenomenon of random problem is affected by various factors. It is quite difficult to study the affluence of each factor through doing real experience. Using computer simulation technology with Monte-Carlo method could solve random problem effectively. As the requirement of environment protection increases, prediction model of Monte-Carlo method attracts increasing attentions of relevant researchers all over the world [16].

Compared with other printing reflectance model, the reasons why Monte–Carlo model perform better rely on that it take different factors into consideration such as, paper property, ink attribute and various light phenomenon. The color sense that finally formed in brain is the comprehensive results between light of prints surface and visual nerve. There are almost no differences of visual nerve for healthy people, therefore the attributes of light coming from prints surface becomes the main symbol to predict prints quality. The light that finally coming into eye from prints surface contain different parts including direct reflectance, scattering parts and refraction parts showed by Fig 1, all of which can be simulated with Monte-Carlo reflectance model. It has been proven that light is composed of photon. The basic principle of Monte-Carlo used in this study is to simulate light propagation trajectory in prints. When the number of photon trajectory satisfy statistical requirement, reflectance information of prints can be obtained through statistic calculation.

The first simulation procedure proposed by Modric [13] within the Monte-Carlo method accomplished modeling of light scattering in paper. That work built the foundation for the following study. The simulation procedure mainly contains four steps, initialization, direction change, energy record and shape design. In the initialization step, light location and moving distance of photon was initialized. The light that reflected from prints surface is assumed to be parallel light with the location *(x, y, z)*. The moving distance also called step-size is a significant parameter deciding the accuracy of reflectance model. The simulated photon cannot be reflected by different layers in paper before leaving prints if step-size is too long. Photon moving distance in prints is a random variable. It follows Beer law and decided by scattering coefficient σ_s and absorption coefficient σ_α shown by formula 1. Parameter ε is random value ranging from *0* to *1*.

$$s = \frac{-\ln \varepsilon}{\sigma_a + \sigma_s} \tag{1}$$

For printing reflectance model, scattering phenomenon play an important role in calculating optical dot gain. In the simulation process, the scattering phenomenon in prints involves photon direction change caused by the interaction between paper coating and photon. Three phase functions can be used to describe photon direction change including, Henyey-Greenstein function， Mie function and exponential cosine function [17,18]. Henyey-Greenstein function is short to H-G function. It is widely used in simulation domain for its calculation superiority presented by formula 2. The parameter *β, g* are deflection angle and anisotropic coefficient separately.

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

Each photon of light is supposed to be carried with energy *w* to satisfy the statistical requirement. Photon energy will decrease with step moving and ink absorption. It is necessary to point out that photon energy variation only refers to statistic energy decrease in this study, with which printing information can be obtained eventually. After each step movement, photon energy can be recorded *w'* shown by formula 3.

$$w' = \frac{\sigma_s}{\sigma_a + \sigma_s} w \tag{3}$$

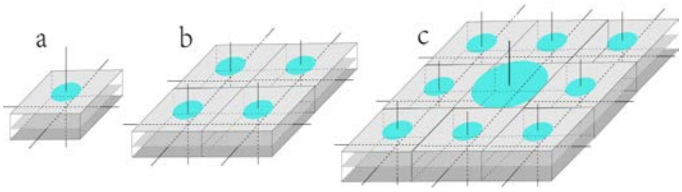

Fig 2 The simulated area of different number of photons.(a) one dot.(b) four dots.(c) nine dots

The design of printing dot shape is the final step. Whether photon will go through ink area depends on photon location and dot shape. In the case of round shape with radius *r*, photon has to pass ink layer before arriving to paper layer if radius *r* is greater than the distance from center to photon location*(x, y, z)*. The relationship between screening line *L* and radius *r* is presented by formula 4.

$$r = \frac{2.54}{L}\sqrt{\frac{a}{\pi}} \tag{4}$$

For printing project, dot shape is an important parameter. According to digital screening method, there are two types of dot. These are the *FM* dot and the *AM* dot [19]. Relevant studies have built reflectance model for one single printing dot using Monte-Carlo method, in which the reflectance accuracy would still need improvement especially in large dot area. Single round dot shape is shown in Fig 2(a). As the dot area grows larger, the interaction of dot will affect model accuracy. Modeling for four dots may be an improved approach, while it cannot eliminate interactive influence completely. The only revolution is expanding simulation area from one dot to nine dots as shown in Fig (c). Based on the above theory and the former study [14], an improved reflectance prediction model was established by expanding the simulated area from one dot to nine dots.

3 Results and discussion

The Monte-Carlo model for printing dot can simulate photon propagation. Apart from outputting reflectance value, the Monte-Carlo model can provide dot and photon distribution image which broadens the evaluation of quality control. The improved reflectance model for printing dot was built by expanding the simulation area. For computational model, the final aim is to provide a simulation value for designer to improve product quality. More attention should be paid on effectiveness and applicability

3.1 Optimization of simulation time

Visible light is a certain portion of the whole spectrum. Wave particle duality is the main attributes of light. The Monte-Carlo model for printing dot only concern light particle attributes. Therefore light can be regarded as a stream of particles. For printing model with Monte-Carlo method, the process of building the model is to simulate the moving path of photon in paper. The photon number required for statistic calculation, determining model effectiveness, has to be optimized. For medical field, Monte-Carlo model are commonly used to simulate radiation particles treatment [20]. Excessive dose will do harm to the body. There will be no efficacy if it is not enough. Besides, radiation treatment varies with each individual according to physical conditions. Similarly, it is necessary to confirm the required number of simulation photon in order to build an effective model for printing dot.

Comparative experiment was conducted with in Matlab 2016. The simulated results of different number of photon are presented in Fig 3. One of the refreshing aspects of Monte-Carlo model is directly outputting simulated results in the form of image. Fig 3(a) illustrate that single printing line becomes increasingly distinct with more simulated photons. Meanwhile, more time is required. Therefore, the compromise has to be made between accuracy and effectiveness. The required time with different number of photon is shown in Fig 3(b) showing as exponential function shape, which indicates that simulation number should not exceed 20 thousands. According to the simulated image and reflectance deviation, 10 thousand times is the optimized. Fig.3(c) show the 3D simulated result with 10 thousand photons.

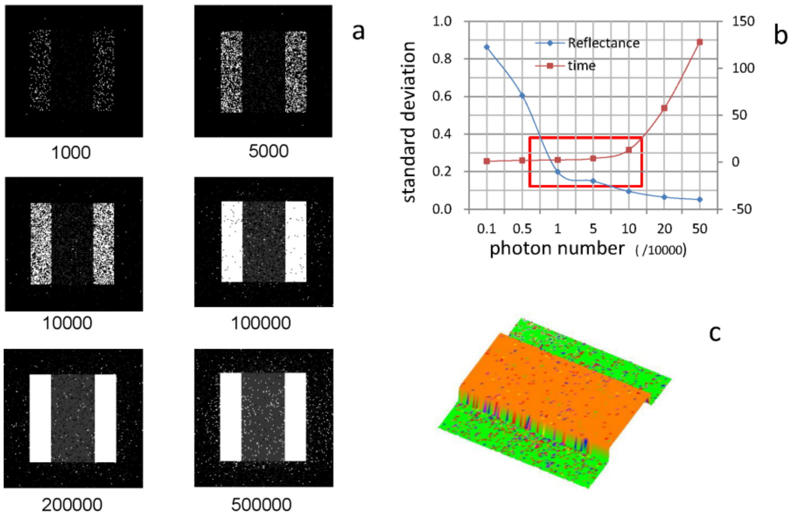

Fig.3 The simulation results with different number of photon（a）the simulation of single printing line with different number of photon ranging from one thousand to fifty thousands,（b）standard deviation of reflectance and requiring time (c) 3-D simulated results of single printing line with ten thousand photons

3.2 Reflectance simulation

The reflectance model that can provide a reference value before actual printing is a useful tool to make quality control. This is because printing is related to systems engineering, which needs several different technological processes. Any negligence in a process step could cause big effect. For a simple image made by digital camera, three main processes must be conducted to obtain high quality duplication. Digital screening is the first process for any original prints. That is because that ink cannot reflect different tone if it cover on paper uniformly. The ink that covered on the duplication is not continues. The ink distribute separately in the form of different dot shapes after digital screening. Under the characteristics of low pass filter of human eye, dots with different size could present multiple color tone.

Besides, digital screening can be divided into two types involving frequency and amplitude modulation screening according to screening theory. Both of them have advantage and drawback. The frequency screening can satisfy the tendency of fast print and print on demand with digital printing press. Although frequency screening is developing continually in recent year, amplitude screening still dominate in printing field for its excellent stability. The printing press will print sheets with received screening information. Through measure and analysis, the reflectance value can be obtained. In the case of amplitude screening, Fig.4 shows the main process of duplication. The traditional printing process is relatively complicated. With the assistance of computer science especially for virtual reality, printing model can simulate printing quality. Fig.5 presents the comparative reflectance value of printing dot.

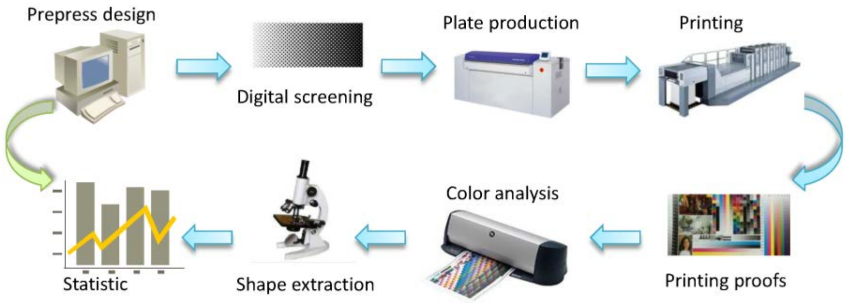

Fig.4 The main process of printing duplication

Using Monte-Carlo method and optical parameters of printing material, the printing model can smoothly simulate reflectance of printing dot with computer. Fig 5 showed the compared results of original model and the improved model. For a round dot in Fig.5(a,b), there is no apparent difference in the range of 0 to 60 percent area. But above 60 percent, the simulated value approach much close to the measured value. In the unit square area, the round dot will expand beyond the edge of screening unit when its area is bigger than 60 percent, which means that more interaction between dots occur gradually. As shown in Fig.1, bigger dot will cover on neighborhood dot and the overlap area could change photon moving path. In addition to that, printing ink is a kind of viscous fluid [21]. When ink approach on paper, it will spread around the center. Simultaneously, it also could permeate into the paper under the pressure of capillary effect of fibers [22]. Therefore, it is difficult to keep a round shape and to spread evenly. The original model could not take into account the overlap factors sufficiently. The comparative results in large dot area proved that the modified model indeed made an improvement.

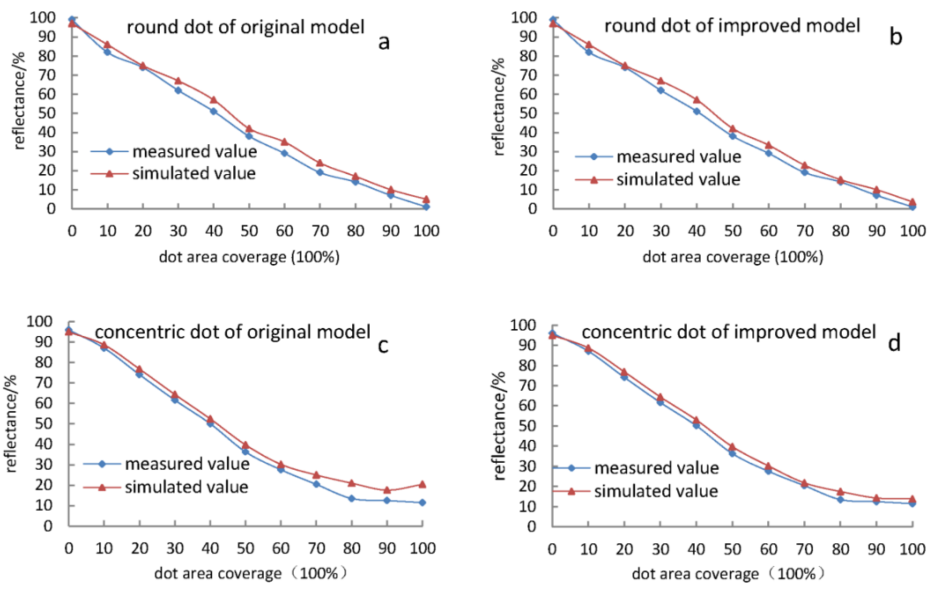

Fig 5. The reflectance simulation results of original model and modified model. (a) round dot with original model.(b) round dot with modified model (c) concentric dot with original model (d) concentric dot with modified model. The simulated paper was 157g/m^2 coated paper. The measured value was obtained by IC-Plate and X-rite530.

Concentric dot that has double ring structure raises increasing attention in recent year for two reasons. Firstly, printing works with concentric dot appears more saturated, which means using concentric dot can save printing ink to some extent. Secondly, concentric dot is good at duplicating warm tone, which is widely used to depict face figure. The only drawback exists in its special structure, costing much time in printing plate production. Moreover, reflectance character of concentric dot is unique as shown in Fig.5(c), indicating almost no change above 80 percent. This maybe caused by the compromise of ink overlap region and blank gap between double rings. The prototype model had not focused on the overlap ink region and just calculated within single dot unit neglecting interactive effect, which would not achieve ideal results for large dot area. The improved model showed better result in Fig.5(d). The correlation coefficient between the measured and the simulated value improved from 0.875 to 0.924. With simulated reflectance value, printing worker can adjust dot compensation to print exquisite duplication.

3.3 Photon distribution

The improved reflectance model can effectively record photon location when photon leaves paper and propagates into the air. Learning from geometric optical theory, three types of photon can be defined according to photon position. If photons leave from the upper or lower surface, those portions are called as reflection and transmission separately. The absorption refers to the photon whose supposed energy exhausted in paper. The simulated result of 9 round dots with one thousand photons is illustrated in Fig.6. The nine dots are the minimal unit for studying interactive effect between dots. Besides, one thousand photons are enough to describe the main characters of photon distribution.

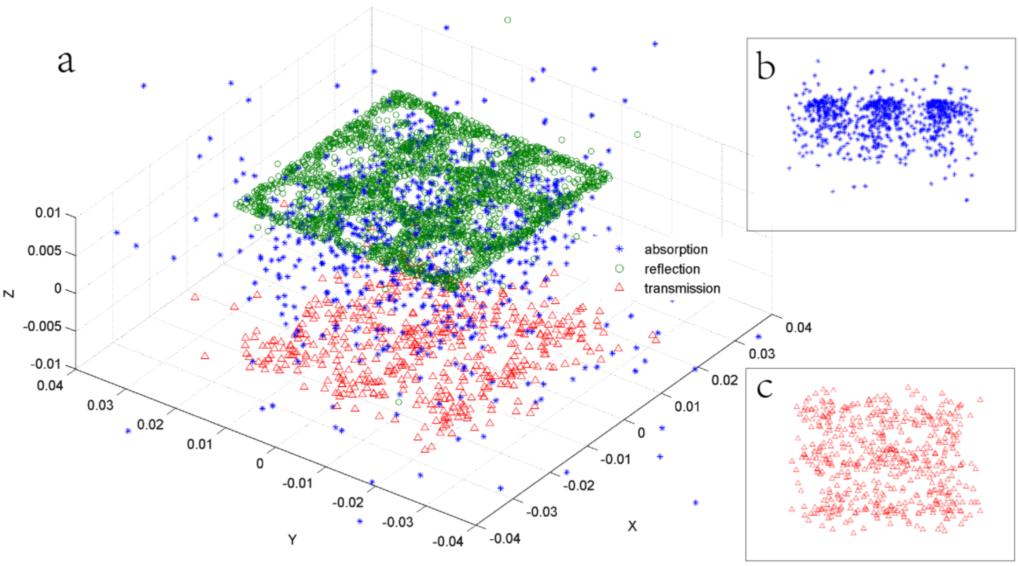

Fig. 6. The photon distribution of nine round dots Parameters include photons numbers = 1000, dot area = 70%,and 157 g/m^2 coated paper.(a) the 3-D distribution of simulated photons when photons escape prints.(b) the side view of the absorbed photons.(c) the top view of transmitted photons.

The reflection part domain the whole photons in Fig.6(a), which proved that most of photons were reflected by paper surface and only a small portion of photons have opportunity to get into the paper. The blank reign among reflected photons shows round shape corresponding to original screening state. The side view in Fig.6(b) shows regions where photons are absorbed completely. The absorbed photons mainly locate in the middle layer of the paper, providing useful reference for paper making process. If paper making factory needs low transparency paper, more light absorbing material such as coating and filler should be concentrated in the middle layer. The transmission part of photons did not show apparent shape character in the top view Fig.6(c). This is because photons change its original way after several collision against fiber or filler. The distribution information outputted by reflectance model provides a new approach to research printing dot optical attributes and also make it possible to take targeted measure to instruct paper making production.

4 Conclusions

In this paper an improved reflectance prediction model for printing dot was proposed with the Monte Carlo method. Based on the prototype model, this paper mainly focuses on improving reflectance model accuracy by expanding dot simulation area from one single dot to nine dots. The results showed that the simulated value closely approached to the measured value with high dot area in particular and the correlation coefficient improved from 0.875 to 0.924. One hundred thousand photon packets proved to be the optimal number of simulated photon under regular printing condition. Apart from outputting reflectance value, the improved Monte-Carlo model can simulate dot shape as well as photon distribution, which make it possible to further promote optical study about color duplication. Future works could focus on simulate reflectance of various colors and finally realize spectrum simulation.

Acknowledgment

This work was supported by the project of national key research and development (2017YFD0700102) and the funds of Shandong “Double Tops” with grant number of SYL2017XTTD14.

References

[1] Arney, J. S., Engeldrum, P. G., and Zeng, H. (1995). An expanded Murray-Davies model of tone reproduction in halftone imaging, *Journal of imaging science and technology*,*39*(6), 502-508.

[2] Huntsman, J. R. (1987). A new model of dot gain and its application to a multilayer color proof, *Journal of Printing Science and Technology*,*24*(3), 189-202.

[3] Hébert, M., and Hersch, R. D. (2011). Yule–Nielsen based recto–verso color halftone transmittance prediction model, *Applied Optics*,*50*(4), 519-525.

[4] Ke, N., He, X., Wang, Y., and Zhang, Y. (2014). Improving Clapper–Yule model of the reflectance prediction by the path branching factor depending on the screen frequency of color halftone imaging, *Optik-International Journal for Light and Electron Optics*,*125*(20), 6242-6244.

[5] Balasubramanian, R. (1999). Optimization of the spectral Neugebauer model for printer characterization, *Journal of Electronic Imaging*,*8*(2), 156-167.

[6] Yang, L. (2010). Probabilistic spectral model of color halftone incorporating substrate fluorescence and interface reflections, *JOSA A*,*27*(10), 2115-2122.

[7] Edström, P. (2004). Comparison of the DORT2002 radiative transfer solution method and the Kubelka-Munk model, *Nordic Pulp & Paper Research Journal*,*19*(3), 397-403.

[8] Džimbeg-Malčić, V., Barbarić-Mikočević, Ž., and Itrić, K. (2012). Kubelka-Munk theory in describing optical properties of paper (II), *Tehnički vjesnik*,*19*(1), 191-196.

[9] Neuman, M., Coppel, L. G., and Edström, P. (2011). Point spreading in turbid media with anisotropic single scattering,*Optics express*,*19*(3), 1915-1920.

[10] Oshima, S., and Sankai, Y. (2011). Development of Red Blood Cell–Photon Simulator for Optical Propagation Analysis in Blood using Monte Carlo Method, *IEEE Transactions on Information Technology in Biomedicine*,*15*(3), 356-363.

[11] Zoia, A., Brun, E., Damian, F., and Malvagi, F. (2015). Monte Carlo methods for reactor period calculations, *Annals of Nuclear Energy*,*75*, 627-634.

[12] Lutsyshyn, Y. (2015). Fast quantum Monte Carlo on a GPU, *Computer Physics Communications*,*187*, 162-174.

[13] Modrić, D., Bolanča, S., and Beuc, R. (2009). Monte Carlo modeling of light scattering in paper, *Journal of Imaging Science and Technology*,*53*(2), 20201-1.

[14] Wang, Q., Yu, Y., Wang, T., and Liu, H. (2016). Research on a new reflectance prediction model of frequency modulated dots,*Optik*,*127*(22), 10539-10545.
[15] Walter, J. C. and Barkema, G. T. (2015). An introduction to Monte Carlo methods, *Physica A: Statistical Mechanics and its Applications*,*418*, 78-87.
[16] Reif, R., A'Amar, O., and Bigio, I. J. (2007). Analytical model of light reflectance for extraction of the optical properties in small volumes of turbid media, *Applied optics*,*46*(29), 7317-7328.
[17] Kattawar, G. W. (1975). A three-parameter analytic phase function for multiple scattering calculations, *Journal of Quantitative Spectroscopy and Radiative Transfer*,*15*(9), 839-849.
[18] Tancrez, M., and Taine, J. (2004). Direct identification of absorption and scattering coefficients and phase function of a porous medium by a Monte Carlo technique, *International Journal of Heat and Mass Transfer*,*47*(2), 373-383.
[19] He, Z., and Bouman, C. A. (2004). AM/FM halftoning: digital halftoning through simultaneous modulation of dot size and dot density, *Journal of Electronic Imaging*,*13*(2), 286-303.
[20] Yadavalli, V. K., Russell, R. J., Pishko, M. V., McShane, M. J., & Coté, G. L. (2005). A Monte Carlo simulation of photon propagation in fluorescent poly (ethylene glycol) hydrogel microsensors, *Sensors and Actuators B: Chemical*,*105*(2), 365-377.
[21] Fatkhullina D, Zhukova E. Study of ink optical properties by ATR spectroscopy, Conference Proceedings. 2013, 205-211.
[22] Alava, M., and Niskanen, K. (2006). The physics of paper, *Reports on progress in physics*,*69*(3), 669.