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MODELING LIGHT DISPERSION IN THE PRINTING SUBSTRATE WITHIN THE MONTE CARLO METHOD

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Original scientific paper

Manufacturing significance of optical properties of paper motivated us to construct a theoretical approach which could be used to determine the reflection and dispersion of light from paper surface. We introduced a method based on the Monte Carlo model of light scattering in paper for better understanding the origin of optical screen values gain and to provide a more realistic description of the medium in which light scattering occurs. The Monte Carlo method was used as a frame within which we were able to describe the diffuse scattering of light which suffers multiple subsurface reflections. Our simulation provides a flexible and at the same time rigorous approach to the transport of light in a medium such as paper. We numerically investigated the effects of the modeled surface on the optical properties of paper throughout subsurface light scattering.

Keywords: *light dispersion, Monte Carlo method, paper optics, substrate surface*

Modeliranje disperzije svjetla u tiskovnom supstratu unutar Monte Carlo metode

Izvorni znanstveni članak

Proizvodni značaj optičkih svojstava papira motivirao nas je na izgradnju teorijskog pristupa koji se može koristiti za određivanje refleksije i disperzije svjetla od površine papira. U radu smo prezentirali metodu temeljenu na Monte Carlo modelu raspršenja svjetlosti za bolje razumijevanje nastanka optičkog prirasta rastertonskih vrijednosti, te kako bi osigurali realističniji opis medija u kojem se raspršenje svjetlosti događa. Monte Carlo metoda je služila kao okvir unutar kojeg smo bili u mogućnosti opisati difuzno raspršenje svjetlosti koja doživljava višestruke podpovršinske refleksije i apsorpcije na komponentama od kojih je papir sačinjen. Naše simulacije pružaju fleksibilan i u isto vrijeme, strog pristup transportu svjetlosti u mediju kao što je papir. Numerički smo istražili učinke modelirane površine na optička svojstva papira zbog podpovršinskog raspršenja svjetlosti.

Ključne riječi: *disperzija svjetlosti, Monte Carlo metoda, optika papira, površina supstrata*

1 Introduction

Paper is today, despite the increase of virtual mass-media, still one of the favorite media for information distribution. It is used in almost all areas of work and industry. In graphic technology its optical properties are very important, as they often identify types of paper according to their purpose.

Identification and characterization of each subprocess in the entire system is the basis of complete control and calibration of the system. In this sense, the print quality (response) of each machine for printing, and in general information transfer process of establishing graphic communication, highly depend on the interaction of light used and the substrate (paper). Creation of realistic description of the material depends on the knowledge of the transport of light in the medium of a well-defined volume and light scattering near the surface. We know from experience that many natural materials such as leather, the leaves of plants, milk, paper, snow, etc. show considerable subsurface light transmission. Starting from the fact that paper is still a dominant medium in graphic communication we focused on modeling paper so we could eventually describe the transfer of graphical information. Paper is partially transparent and is a substrate where the propagation of light rays that fall or leave the paper is determined by the refractive index of the boundary of medium and optical properties of its components. It is therefore necessary to consider the optical properties of paper and the form and quality of the upper and lower boundary surface.

The printing paper industry is the most common substrate which absorbs dyes that form an image (under the image we mean both text and images). Knowing the properties of a paper substrate is important partly because the surface is visible between the printed areas, and partly because it defines the background scattering of light by the printed media. Printing industry continually raises stricter requirements for the paper industry as well as increased variety and quality of products. Optical and mechanical properties, permeability etc. directly affect the quality of prints and production experience [1, 2]. Paper that is made entirely of fibers can hardly meet these requirements. Therefore, various additives are added to it and post-production finishing is applied. For example, the addition of fillers such as kaolin or calcium carbonate increases the coefficient of dispersion, thereby improving the opacity. In the manufacturing process of paper production coating is commonly applied to enhance the mechanical and optical properties of paper. Coated paper can be roughly divided into two parts: the base paper and the coating layer. The base paper may contain fibers of chemical and mechanical pulp, fillers, adhesives, bleachers etc. Most kinds of paper also contain other additives in order to improve some properties such as opacity, brightness or quality of prints.

However, the usual way to improve the surface properties of paper is coating of base paper. The coating consists mainly of high quality pigments and binders. In order to define glossy or matte paper that reaches the desired properties of printability some paper is coated topcoats that define the surface roughness of paper in order to get a shiny and smooth surface. This is reflected as a completely different distribution of reflected radiation than in case of uncoated paper. Results achieved are not available on uncoated paper. Scattering of light from the non-spherical particles gives a strong depolarization response.

Radiation transport theory describes the interaction of radiation with the media which scatter and absorb light. The solutions of equations of radiation transport, which were obtained during the last century, are applied to a wide range of neutron diffusion problems, optical tomography, spreading of heat and visible light in the paper, or in prints. Light deflection in paper cannot be solved according to rigorous electromagnetic theory. At the beginning of radiation transport problems were considered to be difficult to solve, though, with the development of mathematical tools and approximations, and with increasing speed and computing power, the solution became more specialized and more efficient.

The traditional and still dominant approach in paper optics is to use variants of the Kubelka-Munk theory which, in its basic form, was introduced in the 1930's [3]. In short, this simple theory provides the light reflectance and transmittance factors of paper by solving a set of differential equations on light flux.

The motivation for the presented simulation was to describe and anticipate the transport of light through a medium such as paper and to see the impact the dispersion had on the optical dot gain. The tone resolution and the reproduction characteristic for all graphics paper products are significantly conditioned by the way the light is scattered in paper. The light that enters the paper between the raster elements can be scattered in the paper in all directions, including below raster element where it remains absorbed which causes the gray scale becoming darker than originally assumed. To manufacture the paper that successfully fulfils the needed optical properties, it is necessary to understand the physical principles of the structure and composition of a paper sheet. This theoretical work was performed within the frame of the Monte Carlo method which describes the transport of light. This is a numerical method for solving mathematical problems based on random sampling from well defined probability distributions. Starting from real physical assumptions the subsurface light scattering in a substrate with a complex structure was modeled [4, 5]. For this kind of problem, where statistics approach offers the best insight and approximation for exact results, a method as Monte Carlo offers a more flexible approach to the transport of photons in a medium such as paper. Even though this model has pure stochastic nature it makes feasible quasi experimental approach in optical dot gain studying.

2 The Monte Carlo method

Description of the Monte Carlo method basically follows the theory given in S. A Prahl's paper "A Monte Carlo Model of Light Propagation in Tissue" [6]. The Monte Carlo program uses a stochastic technique to simulate physical processes. For implementation of this method a stochastic model is constructed in which expected variable value (or combination of variables), is equivalent to the physical value that needs to be determined. The expected value is defined by medium value of multiple independent samples that represent this random variable. We use random generated numbers, which follow the prior selected natural distribution, to construct the desired array of independent samples.

The Monte Carlo method simulations of this type are based on the macroscopic optical properties for which it is assumed that they prevail over small parts of the volume of paper (e.g. cellulose fibers, fillers, adhesives, etc) [7]. We would like to present a typical trajectory of a single photon and the method that describes the local rules of propagation of photons. According to well known procedure each step size between photon - substrate interaction positions is variable and equals

$$-\frac{\ln \xi}{\mu_a + \mu_s} \tag{1}$$

where ξ is a random number and μ_a and μ_s are the absorption and scattering coefficients, respectively. Every photon has assigned statistical weight which decreases from an initial value of 1 as it moves through the substrate, and equals a^n after n steps, where a is the albedo:

$$a = \frac{\mu_s}{\mu_s + \mu_a}. \tag{2}$$

Once the photon packet has been moved the photon packet is ready to be scattered. There will be a deflection angle, $\vartheta \in |\, 0, \pi>$, and an azimuthal angle, $\varphi \in |\, 0, 2\pi>$ to be sampled statistically. The probability distribution for the cosine of the deflection angle, cosϑ, is described by the scattering function that Henyey and Greenstein (1941) originally proposed for galactic scattering:

$$p(\cos\,\vartheta) = \frac{1-g^2}{2\left(1+g^2-2g\cos\vartheta\right)^{\frac{3}{2}}} \tag{3}$$

where the anisotropy, g, equals <cosϑ> and has a value between −1 and 1 (details in [8]). This function is empirically chosen and gives results that coincide well with experimental work. When the photon strikes the surface, a fraction of the photon weight escapes as reflectance and the remaining weight is internally reflected and continues to propagate. Eventually, the photon weight drops below the threshold level and the simulation for that photon is terminated. It is subject to a roulette that will decide the future of the photon. The photon of weight w gets a chance in m to survive with the new weight $m \cdot w$, or else its weight is reduced to zero. In this example, termination occurred when the last significant fraction of remaining photon weight escaped at the surface at some position which differed from incoming point. To satisfy energy conservation law we used photon packet of hundred photons.

3 Modeling of the substrate surface

Surface roughness is an important feature of the paper. It affects the optical properties of paper as an example of gloss. In offset printing high roughness of the paper reduces the contact surface between the paper and the ink, resulting in poor transfer to the surface of the paper. On the other hand, rough surface contains various cracks and openings that enable penetration of the ink into the paper. Penetration of the ink determines how much ink will remain on the surface of the paper. Low penetration gives a higher tone density of prints. The surface structure of the real paper [8, 9, 10] demanded improvement of model in order to approach a more realistic description of the surface.

Observing the relationship between the thickness and the surface area of paper about the assumption of infinitely large paper is satisfactory. Furthermore, in our first approximation we assumed that our paper surface was perfectly flat and that it stretched infinitely in the X and Y plane, which was satisfactory for the first steps that we did when checking plausibility of our model [11].

Calculations of specular reflection from the surface of the paper yielded no satisfactory value [12, 13]. We modeled the surface of the paper leading to the idea of mikrofacetes. Spatial orientation of individual mikrofacete was randomly generated in order to obtain realistic values.

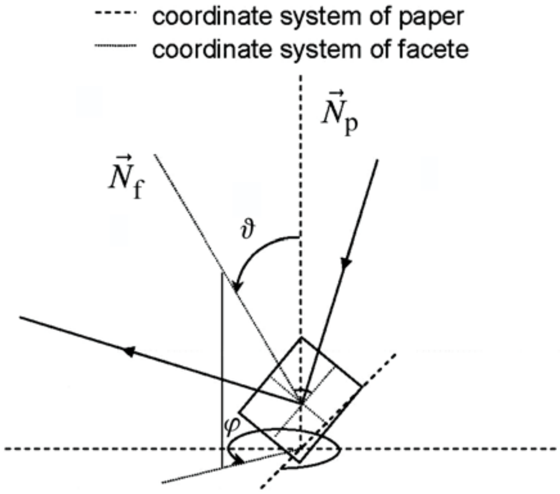

Figure 1 Review of basic values for describing paper surface with microfacetes: $\varphi \in [0, 2\pi]$ and $\vartheta \in [0, \vartheta_g]$ (two related systems – paper and microfacete system)

As can be seen from Fig. 1, azimuthal angle ϑ is the angle that defines the roughness of the paper. Namely each photon packet falls on a microfacete which has randomly selected orientation relative to the plane of the paper. In determining the value of the random angle φ could take any value from $[0, 2\pi]$, while $\vartheta \in [0, \vartheta_g]$ was limited to a value defined by the roughness of the paper.

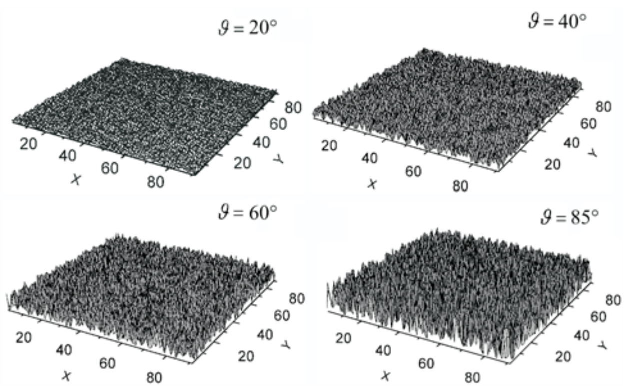

Figure 2 The results of modeling the surface of the paper based on the microfacet idea. The parameter ϑ determines the smoothness of the paper $\vartheta \in [0, \vartheta_g]$.

Fig. 2 clearly shows that for a realistic description of the paper ϑ_g angle limit value should not exceed the value 30°. For gloss paper [12] limit value of ϑ_g is approximately twenty degrees. On the other hand if uncoated paper of greater roughness was modeled ϑ_g can take even greater value. Of course, to the existing microfacet structure can be superimposed a macrostructure that would suit calendared or embossed papers.

4 Angular distribution of scattered radiation

To determine the behavior of substrate illuminated by white light, we generated the distribution of scattering with four wavelengths of 400, 500 600 and 700 nm with which we covered the entire spectrum of visible light. The parameters used in the model are shown in Tab. 1, and the results in Fig. 3.

Table 1 The values of the parameters used in the model. (g - anisotropy; % - percentage of representation of individual components of the "paper")

	%	g	Scattering coefficient μ_s / m²/kg				Absorption coefficient μ_a / m²/kg			
			λ / nm				λ / nm			
			400	500	600	700	400	500	600	700
Filler	13	0,7	25	25	25	25	0,5	0,5	0,5	0,5
Mechanical pulp	31	0,5	25	75	70	70	29	6	1	0,5
Chemical pulp	29	0,75	25	108	115	110	29	6	1	0,5
Coating	17	0,02	30	30	30	30	0,02	0,02	0,02	0,02
Air	10	0	0	0	0	0	0	0	0	0

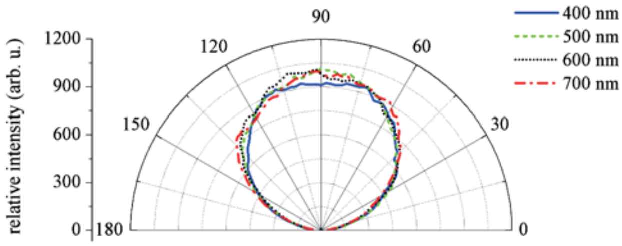

Figure 3 Calculated distribution of scattered light for the wavelengths: 400, 500, 600 and 700 nm. This simulated white light, and the results agree with the observations of reflection on white paper.

Capacity of the model to demonstrate the angular distribution of radiation is shown in Figs. 4 and 5 where one can see the distribution of scattered radiation in the plane defined by the entrance ray and the detector geometry 0/45°. Spectrometer measurements differ depending on the geometry of the instrument i.e. how the sample is illuminated and how the reflected light is measured. There are two primary spectroscopic standard geometries: the so-called bidirectional and integrating sphere. Description of the two-way geometry will be given below and more details about the geometry of the integrating sphere can be found in the work of Kubelka [14]. According to the two-way geometry, which we follow in defining the parameters and geometry of the problem, the sample is illuminated under 0°, the reflected light is measured at an angle of 45°, or vice versa, whereby the input beam falls at an angle of 45°, and is measured in the 0°. Consequently the geometry is called 0/45°, or 45/0°, and we consider them equivalent. All angles are defined relative to the normal to the surface of the sample. This geometry excludes any specularly reflected light because the detector is located far from the angle of reflection. Since our method does not take into account the specular reflection, we did not have to take care of it, which gave us the freedom to observe scattering in the case when entrance and scattered rays coincide. Such geometry cannot be achieved experimentally, and the possibility of computing with such geometry provides a new quality of model.

In our simulation was taken the substrate (paper) coated on both sides with a thickness of 10 % of the thickness of the substrate. A refractive index n = 1,95 was taken into account, corresponding to the coating of titanium dioxide.

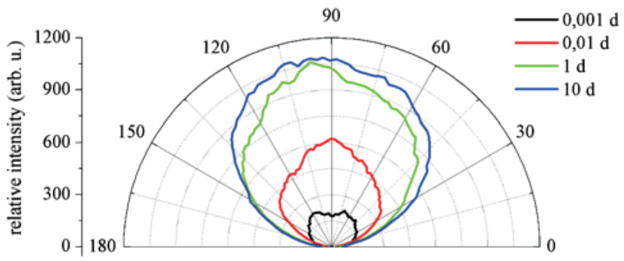

Figure 4 Distribution of scattered radiation for coated paper in 180° in a plane defined with the input beam for different thickness of the substrate. One can see a noticeable decrease in intensity with decreasing thickness of paper that corresponds to higher transmission. Thickness of paper is expressed in relative units.

For paper thickness was taken relative value d corresponding to a thickness of about 50 μm. Fig. 3 shows that the distribution of scattered light from the paper is almost independent of the thickness of the substrate (paper), as illustrated in the case when the substrate has a thickness equal to d and $10\cdot d$. With such a defined thickness, it is clear why the relative value of the diffuse scattering of small to very thin securities ($0{,}001\cdot d$ and $0{,}01\cdot d$). Such a small thickness leads to greater light transmission and decreases the amount of scattered light.

It can be seen from Figs. 5 and 6 that there is no direction that favors scattered light, which indicates that the input light completely "forgets" its incident direction regardless of the incoming angle and the roughness of the paper.

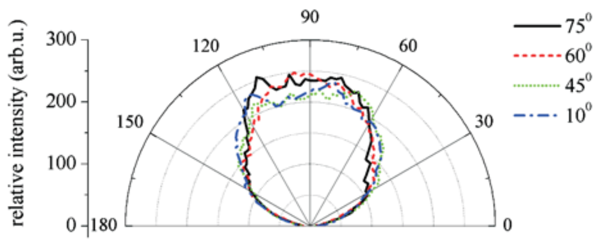

Figure 5 Distribution of scattered radiation for coated paper in 180° in a plane defined input beam for various incident angles: 10°, 45°, 60° and 75°.

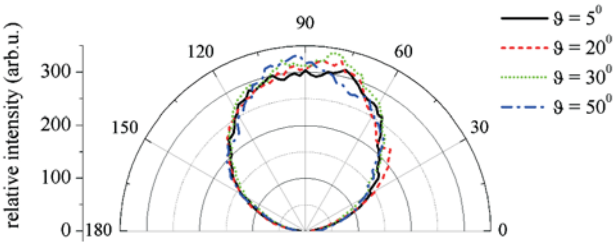

Figure 6 Distribution of scattered radiation for coated paper in 180° in a plane defined with the input beam for the vertical incidence angle for the paper of various roughness [15]. The paper shows the same diffusion properties independently of surface roughness.

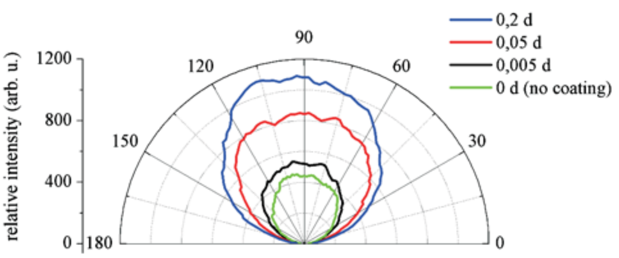

Figure 7 Computed distribution of outgoing (scattered) photons for different coating thickness. For comparison is also presented the case of paper with no coating. (for coated paper was taken roughness parameter $\vartheta = 20°$)

This is the result of a fully stochastic structure of the substrate (in this case paper) because light, after multiple scattering in the substrate, no longer contains information about its input characteristics (losing information on the input angle, as well as the input polarization which here plays no role).

There are substrates (such as for example, fabric, hair, etc.) that have additional superstructure, which then defines the output distribution of scattered radiation (the hair or silk fabric to call it "glow"). Of course there are techniques for further processing of paper (e.g. calendaring) that can superimpose some superstructure on the substrate and thus in some way modulate the distribution of scattered light to obtain the effects of the substrate that combined with specific printing techniques give some special effect impression.

Fig. 7 shows clear dependence of the diffuse scattered light on the thickness of the coating. The model takes into account that there is a partial reflection of light on the border between coating and of paper base in both directions of propagation. Since the refractive index of coating exceeds the refractive index of components of paper base the reflection of light from boundary into the coating is dominant. This is evident from the fact that the relative reflectance increases with the thickness of the coating. The reason for the weak diffuse scattering for uncoated paper partly lies in the fact that the light penetrates deeper into the substrate which increases the transmission as in the case of real uncoated paper.

It is evident that there is no distinct structure of the distribution of radiation which is again the reason for stochastic nature of the substrate model. The structure of the surface distribution is a consequence of the numerical nature of the model. With more incoming photons distribution surface would be smoother, but still not show any reproducible structure that would indicate some characteristics of the substrate.

Our approach to subsurface propagation of photons in the Monte Carlo method applied to the paper differs from the above methods and is based on Phral's work [7]. The Monte Carlo simulation of photon propagation offers a flexible, yet rigorous approach to the transport of photons in a medium such as paper. The method describes the local rules of propagation of photons, which are expressed in the simplest case, as a probability distribution that describes the step size (mean free path) movement of photons between the two points of interaction of photon - substrate, and the angles of deflection from previous direction, the photon after scattering occurs in the given point. The nature of method is statistical [16, 17] and relies on the calculation of the propagation path of a large number of photons which consumes much computer time.

5 Conclusion

Influence of the media surface has already been studied. These studies give a number of models named after their authors (e.g., Cook-Torrance model, Ward model or Lafortune model), and differ in their approaches to determining the distribution of microfacete tilt relative to the observer. These are all fairly complex approaches that have been caused by the need to model the scattering of light in the media that differ from paper, such as leather, marble, metal surfaces, etc. Our model takes into account the fact that the paper is not an ideal plane and shows that we can model the surface of differentiating matt and glossy surface The contribution of this work is clearly connected with the demands of an optimal reproduction and print quality. All paper components such as mechanical and/or chemical pulp, whiteners, fillings, adhesives, etc., affect the way the light scatters in paper as well as its surface properties. It is evident that paper appearance is not a consequence generally of its surface topography but also of its subsurface optical properties. This work has shown that after penetration of photons into substrate they rapidly "forget" their initial parameters such as incoming direction, polarization, etc. It is evident that the component of reflected light that occurs due to subsurface scattering is completely diffuse.

Our model offers the possibility of "experimenting" with various combinations and amounts of paper components to verify some ideas without the long-lasting and expensive realizing of actual paper. Given the combination and variation possibilities of the composition share of each paper component, this model can study the optical properties of any type of paper, including the recycled ones, where as one component appear the particle remains of the dyes and the treated components of previous paper.

It is important to emphasize that our simulation does not take into account the wave nature of light, and that it ignores the quantities such as phase or polarization of light. The motivation for this simulation was to predict and describe the transport of light through a medium such as paper and see the impact of the dispersion on the dot gain. Inside the paper, which is an extremely complex medium, the photons experience multiple scattering and phase and polarization are rapidly randomized so that initially it does not affect much the energy transport.

6 References

[1] Niskanen, K.; Kajanto, I.; Pakarinen, P. Paper Physics, Chap. 1, Fapet Oy, Helsinki, Finland, 1998.
[2] Baker, C. F. (ed.) Handbook of Paper Science, Pira International, Letherhead, 1997.
[3] Kubelka, P.; Munk, F. Ein Beitrag zur Optik der Farbanstriche. // Z. Tech. Phys., 11a (1931), pp 593-601.
[4] Emmel, P.; Hersch, R. D. Towards a color prediction model for printed patches, IEEE Comp. Graphics and Appl. 19, (1999), pp 54-60.
[5] Mourad, M. S. Color predicting modelfor electrophotographic prints on common office paper. // PhD thesis, Ecole Polytechnique Federale de Lausnne, 2002.
[6] Prahl, S. A.; Keijzer, M.; Jacques, S. L.; Welch, A. J. A Monte Carlo Model of Light Propagation in Tissue. // Dosimetry of Laser Radiation in Medicine and Biology, SPIE Institute Series, IS 5, (1989), pp. 102-111.
[7] Veach, E. Robust Monte Carlo Methods for Light Transport Simulation. // PhD thesis, Stanford University, 1997.
[8] Bristow, J. A. The pore structure and the absorption of liquids. // Paper structure and properties, Marcel Dekker Inc., New York, 1986., pp. 183-202.
[9] Chinga, G. Structural studies of LWC paper coating layers using SEM and image analysis techniques. // PhD Thesis, Norwegian University of Science and Technology, 2002.
[10] Cocheril, Y.; Vauzelle, R. A New Ray-Tracing Based Wave Propagation Model Including Rough Surfaces Scattering. // Progress In Electromagnetics Research, PIER 75, (2007), pp. 357-381.
[11] Modrić, D.; Beuc, R.; Bolanča, S. Monte Carlo Modeling of Light Scattering in Paper. // J. Imag Sci Tech, 53, 2(2009), 020201–020201-8.
[12] MacGregor, M. A.; Johansson, P.-Ĺ. Gloss Uniformity in Coated Paper. // TAPPI Proceedings, Coating Conference, 1991., pp. 495-504
[13] Nicodemus, F. E. Directional reflectance and emissivity of an opaque surface. // Appl. Opt. 4, (1965), pp. 767-773.
[14] Kubelka, P. New Contributions to the Optics of Intensely Light-Scattering Materials, Part I. // J. Optical Society of America, 38, (1948), pp. 448-457.
[15] Lindstrand, M. A conceptual approach to describe gloss variation in printing paper. // Proceedings of the International Printing and Graphic Arts Conference, Minneapolis MN, September, 1996.
[16] Cashwell, E. D.; Everett, C. J. A Practical Manual on the Monte Carlo Method for Random Walk Problems. // Pergamon Press, New York, 1959.
[17] Sobol', I. M. A Primer for the Monte Carlo Method. // Mir Publishers, Moskva, 1975.

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