Reconstruction of BSDF based on optimization of microrelief normal distribution

V.G. Sokolov[1], D.D. Zhdanov[2], I.S. Potemin[2], N.N. Bogdanov[2], A.D. Zhdanov[2], E.U. Denisov[1]
sokolovv1969@gmail.com|ddzhdanov@mail.ru|ipotemin@yandex.ru|
nnbogdanov@corp.ifmo.ru|adzhdanov@corp.ifmo.ru
[1] The Keldysh Institute of Applied Mathematics RAS, Moscow, Russia;
[2] ITMO University, Saint Petersburg, Russia

The article is devoted to the elaboration of the method of reconstruction of rough surface scattering properties. The rough surface, in this case, is considered as a boundary between dielectric and air. Usually, these properties are described with bi-directional scattering distribution function (BSDF). Direct measurement of such function is either impossible or very expensive. The BSDF reconstruction method, based on the distribution of the surface microrelief heights, requires a complex fitting procedure and often yields not very good results. In the suggested solution the rough surface is simulated with a parametric function emulating distribution density of normals to facets of the surface microrelief. The optimization of distribution density of normals to facets of the surface microrelief show good agreement with desired output.

Keywords: *Microrelief, BSDF, Rough surface, Diffusivity, Rendering, LGP, TIR, Wave optics, Ray optics.*

1. Introduction

The light guiding optical elements with rough surfaces are widely used in devices with complex light propagation. As a rule, there are two main applications of rough surfaces: either to obtain the specific goniometric diagram of the light scattering or to obtain desired spatial luminance distribution for various light guiding devices like illuminating system of displays, car dashboards, LED luminaries, etc. When simulating the light propagates inside of material we are in need of optical properties of the rough surface boundary between two media while optical properties of the whole optical element are senseless. Moreover, the properties are individual from each side of the light incidence to the rough surface. So the correct light simulations have to apply the properties taking into account the side the light does incident on.

An example of rough surface usage is presented on Figure 1. Dots with microrelief are distributed on the bottom face of the light guiding plate (LGP) [1]. They are rough scattering surfaces. A light ray is propagated in LGP due to total internal reflection. After the scattering on dots, the ray deviates from mirror reflection direction and can leave LGP [2]. Variable density of dots allows obtaining a uniform light emitting along output surface.

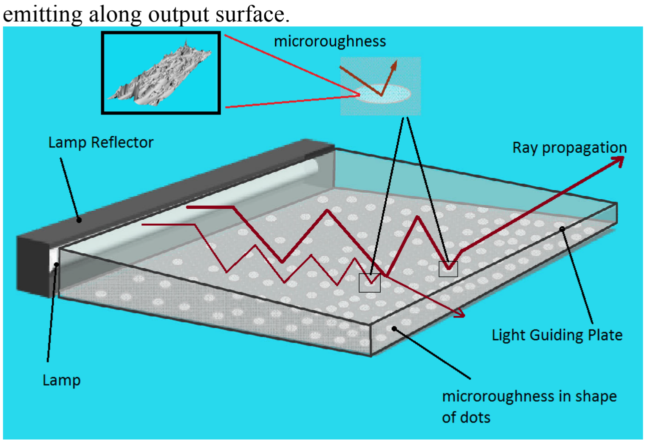
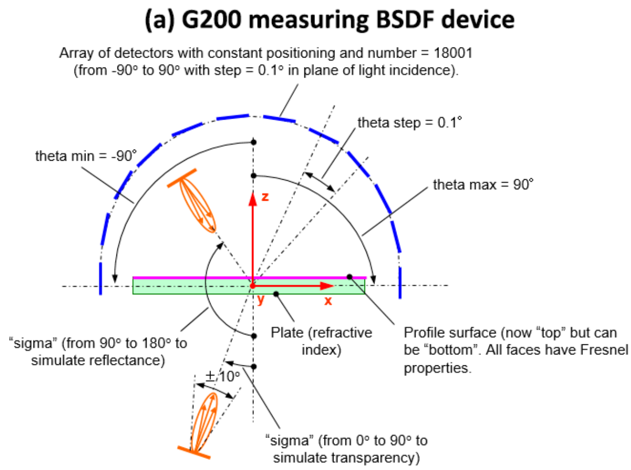


Fig. 1. An example of the application of the LGP with rough dots.

The scattering properties of the rough surface are described by a bidirectional scattering distribution function (BSDF). This function has complex multi-dimensional representation and depends on many parameters: incident light direction, output observation direction, and spectrum (color). For flat thin samples, like shown in Fig. 2a (‘‘surface’’ model), the BSDF can be measured by any goniophotometer. If the thickness of object with microroughness can be ignored and the BSDF is assigned to single surface the measured BSDF model will be physically correct. The model can be applied to various diffuse sheets and filters. Unfortunately, the model is not applicable if the thickness of the element with the roughness is important for the light propagation inside of the transparent element. The “solid” model presented in Fig. 2b should be used in this case. It means that we need two BSDFs of the rough surfaces, one from the air to the glass and another one from the glass to the air.



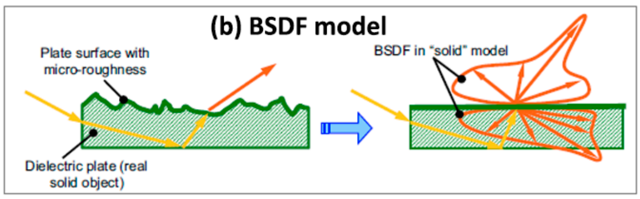


Fig. 2. ‘‘Surface’’ vs. ‘‘Solid’’ BSDF application models.

The main problem is that BSDF of the rough surface cannot be measured directly. There is a number of reasons. The first one is multiple reflections between the rough surface and other surfaces of the measured sample. Another reason — it is impossible to illuminate the sample or detect light under grazing angles of the light incidence (observation) to the rough surface. The solution of the problem is very expensive and requires special equipment to exclude multiple reflections between sample faces and refraction on the side opposite to the measured rough one.

An alternative way of BSDF reconstruction is computer simulation of light scattering on the microrelief boundary of the sample media [5]. This indirect way has a number of disadvantages as well. In particular, variations of surface profile can be comparable with a wavelength of illuminating light. It means that computations have to use the wave optics approach which, at first, is very complex and, at second, can be inaccurate due to not sufficient accuracy of the surface profile measurement. In the current article, a combined approach is proposed. It utilizes optimization of BSDF shape based on an approximation of the shape by Cauchy and Gauss functions with a limited number of parameters. This approach provides a more accurate reconstruction of BSDF than the method proposed in [5].

Many of scientists are engaged in solving of the problem of difficult reconstruction BRDF [6-13]. Many of articles [6-10, 12] are devoted to accurate and physical correct reconstruction in comparing with MERL BRDF database [14]. This database contains reflectance functions of 100 different materials. Authors of MERL BRDF database describe in article [15], their method of gating BRDF, but question about measurement correctness is appeared. In our research the certificated measurement equipment GCMS-4 was used [16], which allows us, making physical accurate measurement of BRDF. It's difficult to say that measuring BDRF in MERL database was accurate, because there is not information about certificated equipment. That's why, question about validity of measurements is appeared. That is also great, that some authors could make BRDF reconstruction and have a not bad results [6-10, 12], but they compared results only with measurements from MERL BRDF database. In our research we reconstructed BRDF and compare results with BRDF measurements from GCSM 4, and we can be sure that our result are physical accurate.

Many authors consider issue only about reconstruction BRDF, but not about BSDF in general. As a rule, BRDF is applied only for surfaces, but it does not enough for accurate modelling, for example, frosted/opal glass.

We suggest method for BSDF reconstruction, which allow making accurate modeling for difficult scenes with frosted/opal glass. Our research in BRDF reconstruction has good results and the modelling accuracy is approved by comparing with measurements from GCMS-4 [16].

2. Numerical methods of BSDF reconstruction

There are several numerical approaches of BSDF calculation for rough surface based on an approximation of the ray optics as well as the wave optics. In the previous article, we describe the solution, where surface microrelief is represented as the height distribution of the representative sample area [5].

Reconstruction of BSDF of the plate with the rough surface was based on two sets of measured data: the microprofile height distribution and BSDF of whole sample (transparency and/or reflectance). Often results of the reconstruction were not quite good and require complex optimization of the microprofile (reducing to scaling and filtration of the profile). However, the filtration cannot guarantee the success.

The new approach is based on the only kind of data: measured transparency or/and reflectance of a plane sample measured as a one-sheet element. In spite of the difference with previous algorithm base model of the new approach is the same. The source of the reconstructed BSDF is an intensity distribution calculated after the ray transformations on the microfacets boundary of two media. The only difference is that microfacets are defined as a distribution density of normals. Application of the OPTOS MicroRelief tool [18] of Lumicept [17] provides correct calculations of the intensity distribution, scattered on the microrelief.

An initial distribution of the normal facets necessary for light simulations can be restored from the measured BRDF of the sample. Without shadowing of one facet by another one the normal distribution is about 2 times narrower than BRDF. Of course, it is a rough approximation but can be used as an initial step of the whole BSDF reconstruction.

For BSDF reconstruction we use a real flat sample (plate) in which one of the surfaces is smooth and the other is rough. The plate is illuminated by a collimated beam of light. For each incident light direction, the reflected and transmitted light intensities are measured by the Integra's spectral scatterometer [3, 4]. For the simplification, the measurements are performed in a single plane—in the plane of light incidence. The simulation scheme is similar to measurements. Parallel light illuminates a plate with the same angular deviation and aperture. The rough surface of a sample is simulated with help of BSDF calculated by Lumicept BSDF generator using the distribution of normals. Light scattered with the plate was collected on circular detectors placed on some angular grid. The distance from detectors to the measured sample and radius of detectors corresponds to the characteristics of measuring device: mutual position of the sample and sensor of goniophotometer, angular and spatial resolution of a goniophotometer.

Figure 3 presents measured and simulated angular distribution of light transmitted through the plate sample with one rough surface. The combined graph contains light transmittance for all measured incident light directions. The measurements and simulations were fulfilled for the following directions of the light incidence: 0º, 15º, 30º, 45º, 60º, 75º (angle between normal and incident light direction). They are marked with different colors. Note that all measurements and simulations are made in the plane of light incidence. The solid plots present result of the real sample measurements. Dash-line plots correspond to simulated sample with reconstructed BSDF. It is seen that there is the essential difference between simulated and measured results. The same tendency can be observed on graphs with reflectance data (omitted in the article).

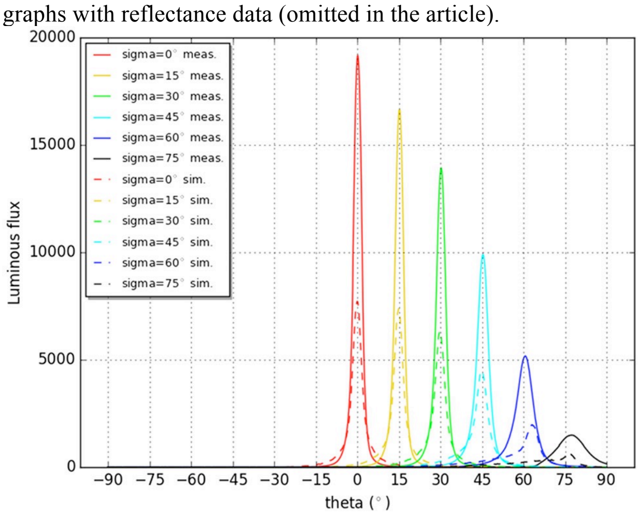


Fig. 3. Comparison of measured and calculated transparency.

3. Optimization of BSDF reconstruction procedure based on the distribution density of normals

Figure 3 shows the high deviation of measured BSDF from the reconstructed one. The main reason for the difference, the initially reconstructed model of deviation of normals does not fit to the real model of the light scattering on the sample. On the other hand, the distribution density of normals is the way of the indirect BSDF definition. Thus, an optimization of the angular distribution density of normals to facets allows reach target BSDF of the sample.

The main idea of proposed optimization method is to use only one set of data: sample transparency characteristics. Figure 4 illustrates the optimization procedure step by step. The rough surface is defined by the distribution density of normals to the surface facets. Optimization procedure consists of the following step:

1. At first input data about sample sizes, refractive index, sample transparency, initial parameters for the function description of the distribution density of normals.
2. The second step consists of tuning scene, generation of tabular function for microfacets based on initial parameters. After that, the microfacets distribution is added the OPTOS MicroRelief plugin of Lumicept BSDF simulator [18].
3. The third step calculates an intensity distribution for the prepared sample.
4. Further, the optimizer compares measured and simulated results and calculates deviations (as RMS).
5. The next step is analyzing of deviations between optimized and measured results to take the decision to stop or to continue optimization process.

5.1. If the optimizer does not reach the desired deviation, then the optimizer changes parameters of the distribution density of normals and goes to the step 2 to continue the process.

5.2 Afterwards, if deviations are suitable, the final BSDF is generated with the help of the “BSDFCalculator” tool.

6. Finally, the optimizer plots graphs of BSDF of the measured sample vs. BSDF of the reconstructed sample.

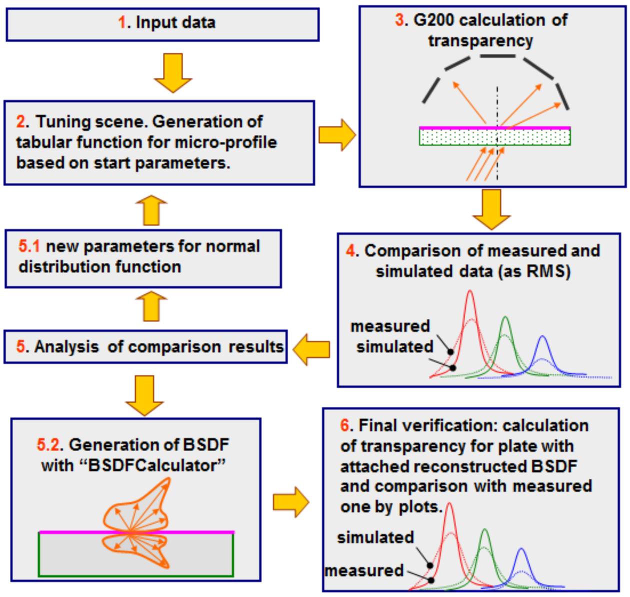


Fig. 4. Optimization scheme of BSDF reconstruction.

It is important that BSDF is reconstructed on the basis of the distribution density of normals to the surface facets. However, a tabular definition of the distribution is not suitable for most of the optimization tools (the multiparametric procedure is very time consuming one) and the most suitable representation of the law of distribution is an analytical function with a minimal number of parameters. Experiments allowed selecting two base kinds of functions: “Gauss-like” and “Cauchy-like”. In the most of the cases, the “Cauchy-like” distribution gives better output while for some microreliefs the “Gauss-like” approximation seems better. It seems that “Gaussian” approximation gives good agreement in BTDF zones of high transparency (at least from viewpoint of RMS between simulated and measured results). So it is reasonable to use both types of function in the optimization process. The general view of Gauss and Cauchy functions are shown in figure 5. One can see that Cauchy distribution is wider in zones of far theta angles (x). The parameter x_0 specifying a shift of distribution peak along theta angles is rather formal parameters because of the most of distributions density of normals have a maximum for $x_0 = 0$. But this parameter was reserved for “advanced” optimization.

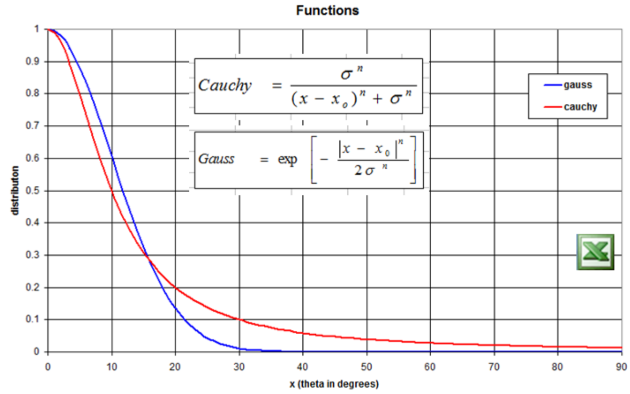


Fig. 5. Cauchy distribution and Gauss distribution.

Taking into account that the general tabular function representation of the distribution density of normals is not a good solution for optimization procedure an alternative “mixing” solution was selected. Base function of the distribution density of normals can be specified with “Gauss-like” or “Cauchy-like” approximation while some areas of the function can be exchanged to locally tabular one. It can be explained with graphs below (figure 8 and 9). Short description of the algorithm.

1. Let’s suppose that optimization procedure with the analytical function of distribution density of normals cannot fit the BSDF in the area close to zero theta. It means that the distribution density of normals in the area of zero angular deviation have to be changed with the tabular function.
2. Then the optimizer adds a number of points to the tabular representation of the distribution density of normals in the area and continues optimization of the mixed function. If a number of added points is not high the optimization procedure can find a solution.

4. Comparison of the BSDF reconstruction methods based on the distribution of heights and based on the distribution density of normals

To test new tool several problematic examples from the past [5] have been selected. These samples required complex fitting procedure based on filtration and scaling of measured profiles, for some of them artificial profile data were used (measured for different samples, for example). See results achieved in the past in figure 6.

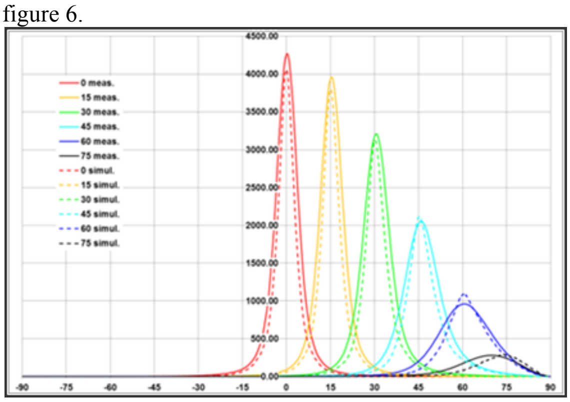


Fig. 6. Results of BSDF reconstruction based on microprofile fitting.

Results of BSDF reconstruction based on Cauchy-like function are shown in figure 7.

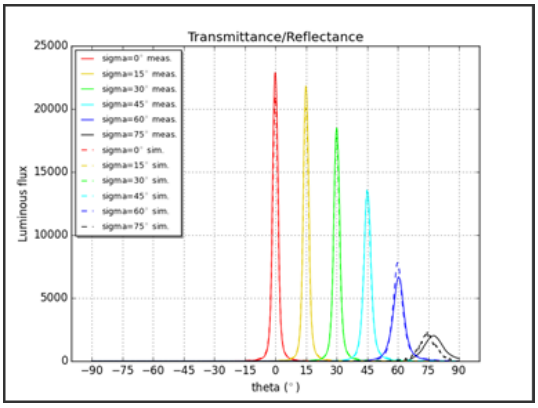


Fig. 7. Results of BSDF reconstruction based on Cauchy-like function.

Results of BSDF reconstruction based on Gauss-like function are shown in figure 8.

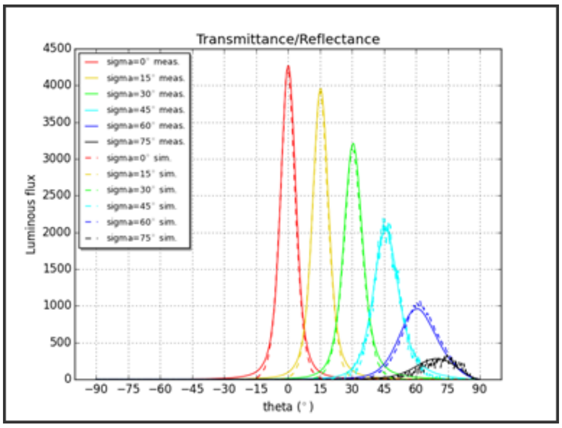


Fig. 8. Results of BSDF reconstruction based on Gauss-like function.

We can finally say that the optimization results of distribution density of normals show good agreement with desired output (at least in the scope investigation samples). In the most of the cases, the Cauchy-like function gives acceptable results at least not worse than a design with measured microrelief [5]. The Gauss-like function in some cases is useful too. All this allows going to a conclusion that precise measurements of the microrelief are not necessary at all.

The usage of OPTOS MicroRelief plugin [18] allows excluding BSDFGenerator of Lumicept [17] from the optimization procedure. It accelerates optimization process as it is not required to generate BSDF on each optimization step that requires significant calculation time.

Attempt to apply the tabular function of the distribution density of normals to facets as a parameter optimization was failed. Optimization of the multiparametric function is the very time-consuming procedure and all benefit caused by the freeform shape of distribution density of normals function is killed by slowdown and general divergence of the optimization procedure.

We can see good agreement between measured and simulated results for incident angles close to normal direction and acceptable agreement for other incident angles. In the article, we demonstrate the results for light transmittance only. However, the optimization procedure can be applied to reflectance as well. Usually, optimization of transparency results improves the reflectance too.

Also, we made a photorealistic rendering of the plate with a rough surface. The visual appearance of the plate with the rough surface BSDF before optimization (i.e. when initially measured profile was used) is presented in Fig. 9a. The visual appearance of the plate with the optimized rough surface BSDF is presented in Fig. 9b.

The images on Fig. 9 were synthesized with physically accurate rendering tool based on path tracing integrated to the Lumicept software package [17]. The scene consists of a plate with BSDF assigned to the outer plate surface. The plate is placed over chessboard-like substratum and illuminated with a set of light sources creating complex diffuse illumination.

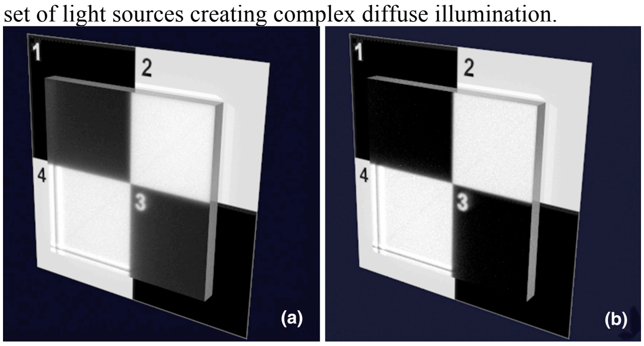


Fig. 9. Visual appearance of a plate with rough surface.

5. Conclusion

The results of optimization method of the distribution density of normals for BSDF reconstruction show good agreement with desired output (at least in the scope investigated samples).

In the most of the cases, the Cauchy-like function gives acceptable results at least not worse than a design with measured microrelief [5]. Moreover, the Gauss-like function in some cases is also useful. That allows making a conclusion about the possibility to exclude measurements of the microprofile at all to reconstruct BSDF accurately.

6. Acknowledgements

This research has been supported by the RFBR grants No. 17-01-00363 and No. 15-01-01147, Financial support of the leading universities of Russian Federation (subsidy 074-U01), as well as by Integra Inc.

7. References

[1] Zhdanov, D.D., Zhdanov, A.D., Potemin, I.S., Venediktov, V.Yu., Galaktionov, V.A. A Method of Fast Building of Locally Equidistant Distributions of Geometrical Objects of Illumination Systems// Optics and Spectroscopy, 2015, Vol. 119, No. 2, pp. 311–317. DOI: 10.1134/S0030400X15080263.

[2] Zhdanov, D.D., Garbul, A.A., Maiorov, V.A., Potemin, I.S., Sokolov, V.G. Indeterminate ray tracing in problems of the analysis of light scattering and the design of illuminating systems // J. Opt. Technol. – 2014, , Vol. 81, Issue 6, pp. 322-326. DOI:10.1364/JOT.81.000322.

[3] Zhdanov, D., Sokolov, V., Potemin, I., Voloboy, A., Galaktionov, V., Kirilov, N.// Opt. Rev.– 2014. – 21(5), – 642 (2014).

[4] Letunov, A.A., Barladian, B., Galaktionov, V.A., Ershov, S.V., Voloboy, A., Zueva, E.// Proc. 22nd Int. DAAAM Symp., pp. 1459 (2011).

[5] Sokolov, V.G., Zhdanov D.D., Potemin, I.S., Garbul, A.A., Voloboy, A.G., Galaktionov, V.A., Kirilov N.. Reconstruction of scattering properties of rough air-dielectric boundary // Optical Review. – 2016. – 23(5). – 834-841, DOI: 10.1007/s10043-016-0250-6.

[6] Nurcan Seylan, Serkan Ergun, Aydın Öztürk "BRDF Reconstruction Using Compressive Sensing"// 21st International Conference on Computer Graphics, Visualization and Computer Vision 2013. – pp. 88-94. ISBN 978-80-86943-74-9.
[7] Jannik Boll Nielsen, Henrik Wann Jensen, Ravi Ramamoorthi "On Optimal, Minimal BRDF Sampling for Reflectance Acquisition"// ACM TOG 34(6). – 2015. – pp. 1-11.
[8] Doris Antensteiner and Svorad ˇ Stolc "Full BRDF Reconstruction Using CNNs from Partial Photometric Stereo-Light Field Data" // Workshop on Light Fields for Computer Vision at ECCV-2017 – 2017. – pp. 13-21.
[9] Feng Lu, Xiaowu Chen, Imari Sato, and Yoichi Sato "SymPS: BRDF Symmetry Guided Photometric Stereo for Shape and Light Source Estimation" // IEEE Transactions on Pattern Analysis and Machine Intelligence. – Issue: 99. – pp. 1-14.
[10] Manmohan Chandraker, Jiamin Bai, and Ravi Ramamoorthi "On Differential Photometric Reconstruction for Unknown, Isotropic BRDFs"// IEEE Transactions on Pattern Analysis and Machine Intelligence. – 2013. – Vol. 35. – No. 12. – pp. 2941-2954.
[11] Sing Yee Chuaa, Xin Wanga*, Ningqun Guoa, Ching Seong Tan "Performance of Range Gated Reconstruction: A Theoretical Analysis"// Proc. of SPIE. – Vol. 10250. – pp. 1-5.
[12] Jirí Filip, Michal Havlí, Radomír Vávra "Adaptive highlights stencils for modeling of multi-axial BRDF anisotropy"// The Visual Computer. – 2017. – Volume 33. – Issue 1. – pp. 5–15.
[13] Guojun Chen, Yue Dong, Pieter Peers, Jiawan Zhang, Xin Tong "Reflectance Scanning: Estimating Shading Frame and BRDF with Generalized Linear Light Sources"// OOPSLA '94. – 1994. – Volume 5. – Issue 4, Oct. 1994 – pp. 67-71.
[14] MERL BRDF database http://people.csail.mit.edu/wojciech/BRDFDatabase/
[15] Wojciech Matusik, Hanspeter Pfister, Matt Brand and Leonard McMillan "A Data-Driven Reflectance model"// ACM Transactions on Graphics 22, 3(2003), 759-769.
[16] Muracami Color Research Laboratory, http://www.mcrl.co.jp/english/index.html.
[17] Lumicept – Hybrid Light Simulation Software, http://www.integra.jp/en.
[18] Ershov S.V., Zhdanov D.D. Efficient application of Optical Objects in light simulation software // Proc. 15th International Conference on Computer Graphics and Applications - GraphiCon-2005, Russia, Novosibirsk, June 20-24, 2005, p. 284-288.

About the authors

V.G. Sokolov, research officer at the Keldysh Institute of Applied Mathematics RAS.
His e-mail: sokolovv1969@gmail.com.
D.D. Zhdanov, PhD. Associate professor at ITMO University. Head of the Visualization Technology chair.
His e-mail: ddzhdanov@mail.ru.
I.S. Potemin, PhD. Associate professor at ITMO University. Assistant of the Visualization Technology chair.
His e-mail: ipotemin@yandex.ru.
N.N. Bogdanov, PhD student at ITMO University, Visualization Technology chair.
His e-mail: nnbogdanov@corp.ifmo.ru.
A.D. Zhdanov, PhD student at ITMO University, Visualization Technology chair.
His e-mail: adzhdanov@corp.ifmo.ru.
E.U. Denisov, research officer at the Keldysh Institute of Applied Mathematics RAS.
His e-mail: eed@gin.keldysh.ru.