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Simulation and Rendering Algorithms for Optically Complex Materials by the Example of Fabric[1]

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Abstract—Described is a new physically based method for calculating optical properties of textile fabrics accounting for their optical and structural characteristics. An algorithm is suggested for calculating optical properties of fabric fibers that accounts for the interaction of light not only with the surface of fibers but also with their volume. An algorithm for calculating optical properties of fabric based on optical properties of its fibers has been developed. The optical properties of fibers and fabrics are represented with the help of the bidirectional reflectance distribution function (BRDF). The calculated BRDFs can be used for assigning physically correct optical properties of fabrics in virtual scenes. The developed solution demonstrates qualitative, quantitative, numerical, and visual correspondence of the calculated and actually measured fabric optical properties. The optical properties data for actual fabric were obtained through measurements performed using special measuring equipment.

Key words: fabric simulation and rendering, cloth rendering, physically based lighting simulation, BRDF, BSSRDF, surface reflection, volume scattering, BRDF measurement.

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1. INTRODUCTION

The research and development of methods of physically based simulation and rendering of optically complex materials is one of the traditional and rapidly developing branches of computer graphics.

The physically based simulation of light propagation in a virtual scene accounts for physical laws, describing the interaction between light and object surfaces. The methods and approaches used for calculations grow more complicated, and the spectrum of physical phenomena that are accounted for is broadened.

The main target of the physically based rendering of optically complex materials is the calculation of their optical properties on the basis of the laws of physics and optics. The optical properties of a material govern the way the material interacts with the incident light. The optical properties calculated with the help of a physically based method are important for enhancing the reality of visualized images of virtual scenes, and for improving the accuracy of computer calculations. The examples of this are as follows:

1) *Enhancing the reality of acquired images of virtual scenes with the help of global illumination calculation.*

Methods for global illumination calculation make it possible to enhance the reality of images, acquired during rendering of virtual scenes through physically based evaluation of radiance of light incident on the surface of objects. The methods for global illumination calculation account for not only the light coming directly from the light sources, but also the light re-reflected from other objects present in the scene. The way light is reflected from object surfaces is determined by their optical properties. Therefore, in order to increase the accuracy of global illumination calculation it is important that the assignment of optical properties of the objects which determine their interaction with light is physically correct.

2) *Assessment of illumination of designed premises such as classrooms, car and airplane passenger compartments.*

Computer modeling used in interior design allows not only obtaining the images of the designed premises, but also performing various calculations, for example, of illumination of interiors being designed. For many premises (for example, classrooms) their illumination is to comply with existing standards and regulations. The computer modeling can help to make sure that illumination in a designed premise conforms to the existing requirements. Therefore, for global illumination calculation, likewise the realistic rendering, it is important that the assignment of optical properties of objects that determine their interaction with light is physically correct.

3) *Development of new materials with specified properties.*

[1] The article was translated by the authors.

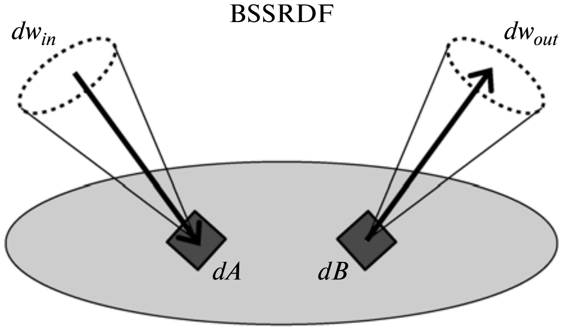


Fig. 1. Definition of BSSRDF.

Before developing a physical prototype of a new optically complex material, for example, modern car paint, it is expedient to create its computer model. Criteria-based assessment of a computer generated prototype of a new material helps to make a decision about its pilot production. To enhance the reality of the computer generated prototype its optical properties shall be assigned in a physically correct way.

Typically, real world objects have complex optical properties. The functions describing the angular and spectral distribution of reflected, refracted, and absorbed light can have a rather complicated nature.

The calculation of object optical properties is a separate problem, and quite a few methods have been offered for its solution.

Cloth and other textile materials are widely used in everyday life, and, accordingly, it is often required to assign their optical properties in computer graphic software applications.

The case study of physically based modeling and visualization of fabrics belongs to the borderline area of two classes of computer graphics methods:

• methods specially designed for simulation and rendering of textile materials;

• methods designed for calculation of optical properties of arbitrary objects.

1.1. Simulation and Rendering of Textile Materials

Among the methods specially designed for simulation of textile materials there is a subclass of studies devoted to modeling of physical deformation of textile materials [1, 2]. Other methods described below are devoted to rendering visual features of the materials.

The studies [3, 4] describe a method that involves photographing textile materials under various light conditions. The resulting photographs are used for creation of textures which are assigned to clothes 3D polygonal models. Realistic images obtained by the authors with the help of this method are presented there.

The study [5] is devoted to photorealistic rendering of knitwear. It offers an original concept of using special representation of a fiber cross section, which is "threaded" on a fiber trajectory assigned according to a specific interweaving of the clothes fibers.

The study [6] uses a combination of two methods for fabric simulation: representation of fiber surfaces with the help of procedural textures and assignment of optical properties of a fabric surface with the help of bidirectional reflectance distribution function (BRDF). BRDF is assigned for the entire fabric without taking into account separate fibers. BRDF is built on the basis of the information on fibers interweaving in a fabric and the method which implies representation of a fabric surface consisting of numerous micro facets with various orientations.

The aforesaid methods are not targeted to the obvious purpose of calculation of physically correct optical properties of a fabric or its constituents (for example, fibers). Therefore, the second class of methods has been considered, the methods that perform calculation of optical properties of arbitrary objects.

1.2. Calculation of Optical Properties of Arbitrary Objects

Computer graphics utilizes many methods for calculating optical properties of objects in virtual scenes. During calculations the most frequently considered interaction between an object and incident light is limited to the light reflection from its surface. Classic models of interaction between light and object split the reflected light into two components: reflected and diffuse ones. The reflection component is the light reflected directly from the surface (that is why the component is also referred to as the surface component), whereas the diffuse component approximates the light subjected to multiple diffusion inside or on the surface of the modeled object (that is why this component is often referred to as volume component). In the classic studies by Phong [7], Blinn [8], Cook and Torrance [9] the diffuse component is represented with the help of the isotropic Lambert function. However, the later studies [10–12] use directional diffuse function, because an ideal diffuse component often does not have physical reliability.

Bi-directional reflectance distribution function (BRDF) is often used in order to assign complex optical properties of the objects. BRDF is a function that represents the relation of the radiance of a described object in the given direction of observation w_{out} to its illumination from the direction w_{in}. BRDF can account for various aspects of interaction between light and the object.

There is a range of BRDF representations that are used in computer graphics software applications. Our system uses BRDFs based on various physical data, and they can be measured or modeled. That is why tabular representation is considered to be the most universal practical way of representing such BRDFs. In tabular representation BRDF is assigned on the grid of input and output directions. The grid can have various dimensionality depending on the requirements for response speed and accuracy of the representation.

2. PROPERTIES OF TEXTILE FIBERS

From the literature in textile materials science [13–16] it is known that the surface of natural and synthetic fibers and threads is rough. Measurements have been made for many textile fibers, and their averaged refractive indices are published [16]. On the average the indices proved to be close to 1.5.

It is known that the medium of textile fibers is optically non-uniform. For example, it is shown that cotton fibers consist not only of cellulose but also contain up to 12% of wax, pectin, and mineral formations [13]. The fibers and threads can also contain air inclusions. Synthetic fibers can be specially filled with particles that have a high refractive index to eliminate excessive shine. The bulk of a fiber can contain specks of dust and impurities of various kinds. Such optical non-uniformities in the medium of filaments lead to light scattering within it.

According to the Fresnel equations, for many real world objects which refractive index is close to that of water (1.33), up to 95% of light incident on their surface (in case of normal incidence) will penetrate inside the object. Part of the refracted light will travel back to the object's surface due to multiple scattering caused by optical non-uniformities present inside the object's bulk. Angular distribution of this light generally is not isotropic [17].

Since the volume light scattering can significantly influence the optical properties of such materials as textile fabric, the authors have developed a model of interaction between fabric and light. This model accounts for light scattering inside the fibers. The behavior of light inside the fiber was simulated with the help of Monte Carlo ray tracing method. The study suggests that BRDF of fibers is calculated first, and then on their basis BRDF of the whole fabric is calculated. Below is the description of the suggested method and its results.

3. CALCULATION OF OPTICAL PROPERTIES OF FABRIC

3.1. Calculation of BRDF of Fibers

As described above, the contributions to optical properties of a fabric (i.e. to BRDF of a fabric) will be due to both light reflection from the fibers' surfaces and to light scattering in their bulk. In this connection it is suggested to separate the BRDF of fiber into two components: surface and volume:

$$BRDF(w_{in}, w_{out})$$
$$= BRDF_{surf}(w_{in}, w_{out}) + BRDF_{vol}(w_{in}, w_{out}).$$

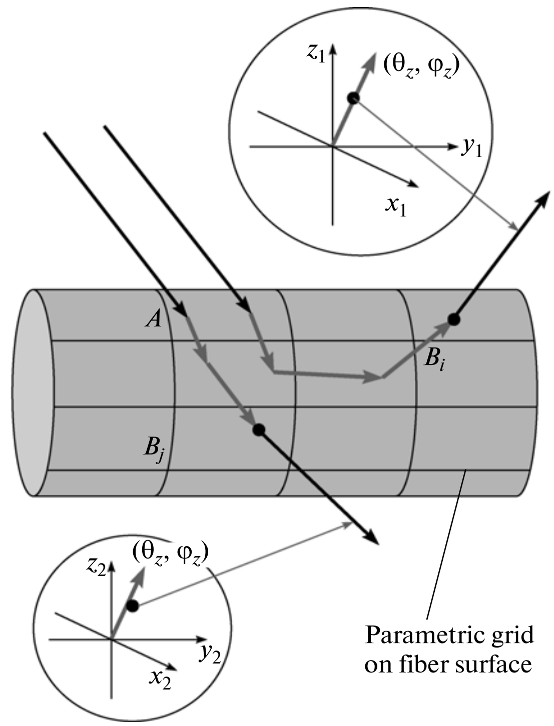


Fig. 2 Light scattering in fiber.

The surface component of BRDF of fiber is suggested to be calculated according to the classic method of calculating surface optical properties of objects, proposed by Cook and Torrance [9]. This method was selected in view of the following considerations:

1) it implements a physically based model of interaction between the light and a rough surface of an object;

2) it accounts for optical properties of a simulated object, namely, its refractive index;

3) it has low computational complexity.

Suggested is the original method of calculation of the volume component of the BRDF.

For calculation of the bulk component of BRDF of fiber, a model is defined in which the bulk of a fiber is filled with the medium that has the refractive index equal to the averaged refractive index of cotton fibers (n = 1.557), and spherical particles with refractive index different from the basic one are distributed within the host medium. Based on this data, with the help of Mie theory, the parameters that determine light scattering within optically non-uniform medium can be calculated, and in particular, the phase function of scattering particles ($p(\theta)$), their scattering cross-section (σ_{sc}), absorption (σ_{abs}), and extinction (σ_{ext}). These values are further used during Monte Carlo ray tracing within the medium of a fiber bulk. Geometrically the fiber is represented in the shape of a smooth cylinder with the circular base (the surface's roughness was not actually modeled but taken into account dur-

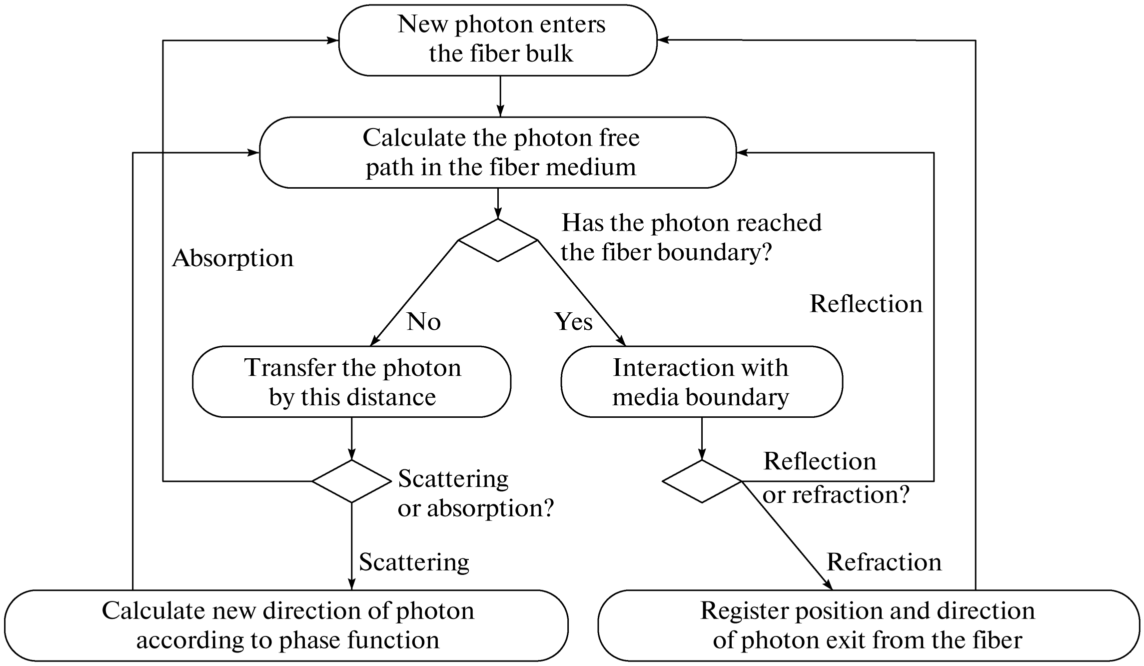


Fig. 3. Monte Carlo ray tracing within a fiber bulk.

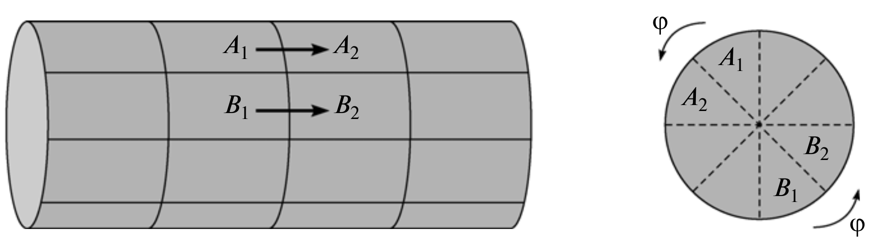


Fig. 4. If the illuminated element "shifts" along the fiber and/or "turns" around its center, then the whole BSSRDF also "shifts" and/or "turns".

ing calculation of surface component of BRDF, as described above).

To calculate the bulk component of BRDF, it is suggested that the Bidirectional Subsurface Scattering Reflectance Distribution Function (BSSRDF) is calculated first with the help of Monte Carlo ray tracing method in the fiber bulk. Further it is suggested that the bulk component of BRDF is calculated through integrating BSSRDF over the fiber surface represented by a cylinder.

Let us define BSSRDF. Let the light be incident onto a surface dA from the direction dw_{in}. Then

$$BSSRDF(dw_{in}, dA, dw_{out}, dB)$$
$$= dL_{out}(dw_{in}, dA, dw_{out}, dB)/dF_{in}(dw_{in}, dA).$$

BSSRDF describes the ratio of the radiance of light dL_{out} scattered by the surface dB in the solid angle dw_{out} to the flux dF_{in}, arriving to the surface dA from dw_{in}. It is assumed that radiance of the surface dB is created only by the flux dF_{in} due to bulk scattering in the object's medium. The determination of BSSRDF is shown on Fig. 1.

If for some vicinity (defined as V) of a surface element dB BSSRDF is assigned, then BRDF for the dB can be calculated through integrating BSSRDF over this vicinity.

$$BRDF_{dB}(dw_{in}, dw_{out})$$
$$= \int BSSRDF(dw_{in}, dA, dw_{out}, dB)dA,$$

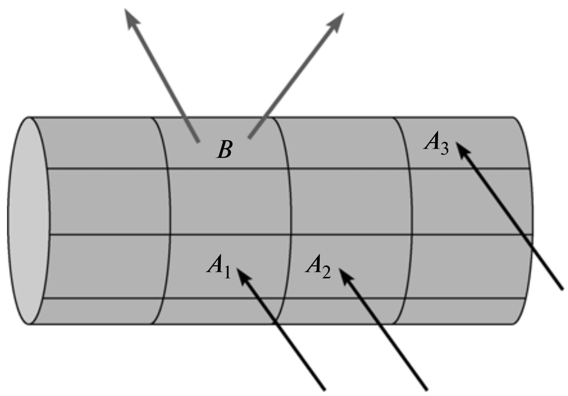


Fig. 5. Summation of contributions to the cell radiance from surrounding cells.

where the integral is taken over the vicinity V of the surface element dB.

Let us demonstrate the calculation of BSSRDF and BRDF of fibers on the basis of the above theoretical calculations.

To calculate BSSRDF it is necessary to perform the Monte Carlo ray tracing within the fiber bulk as follows. On the flowchart of the algorithm shown on Fig. 3 and in the algorithm description instead of the term "ray" another term, synonymic to it from the computer graphics perspective, is used and referred to as "photon."

For a small area of a fiber surface a multitude of photons are emitted in the direction of the fiber bulk from the hemisphere of input directions of light incidence. According to the parameters of the scattering medium, represented by the fiber bulk, each photon is either absorbed or released to the fiber surface due to multiple scattering.

For every released photon the point and direction of its exit are registered. The process is shown on Fig. 2. A spatial parametric grid (u, v) is assigned on the surface of the fiber, which ensures convenient registration of locations of photons which exit the fiber. Reference systems and the corresponding angular used for registration of photon exit directions are assigned for every element of the spatial grid, determined by the coordinates (u_i, v_i),

The Fig. 3 shows the ray tracing algorithm for the fiber bulk.

Ray tracing consists of the following main stages:

1) *Calculation of the free length l*

The free length is calculated according to the following equation:

$$Pr(l) = e^{-l\sigma_{ext}N},$$

where $Pr(l)$ is the probability of a photon not to be absorbed or scattered in the media on passing the distance l, σ_{ext} is cross-section of the extinction, and N is the concentration of absorbing and scattering particles.

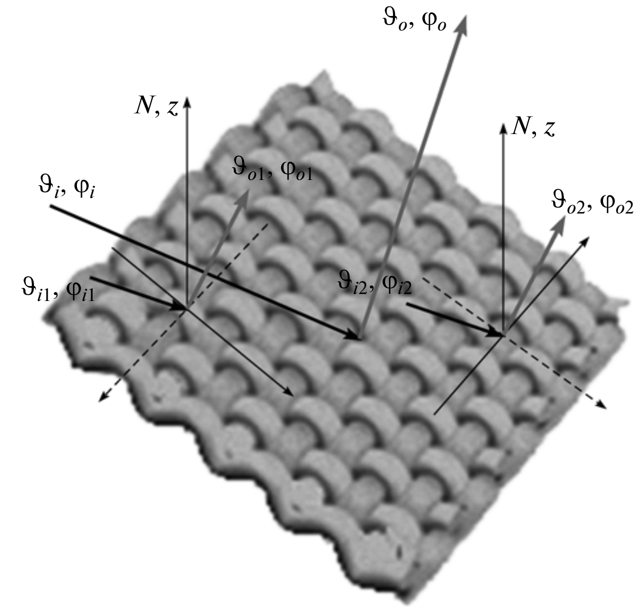


Fig. 6. Reference systems.

2) *Finding the intersection with the fiber boundary, determination of the distance to the boundary*

The study suggests using an implicit representation of a fiber surface. To find the intersection of the fiber with the photon trajectory, an analytic solution of the corresponding geometrical problem was suggested and performed.

3) *Selection of the event of absorption/scattering*

Absorption or scattering event is selected randomly according to the following probabilities:

$$Pr_{sc} = \sigma_{sc}/\sigma_{ext}, \quad Pr_{abs} = 1 - Pr_{sc},$$

where Pr_{sc} and Pr_{abs} are the probabilities of scattering and absorption events, respectively. If the absorption event is chosen, the photon stops its propagation within the fiber bulk. Scattering event process is described in step 4.

4) *Scattering*

When choosing a scattering event, a new direction of photon propagation is defined and assigned according to the phase function of scattering particles.

5) *Registration of position and direction of photon exit from the fiber*

The position and direction of photon exit, as well as its energy are registered on the spatial grid (u, v) and the angular grid (θ_{out}, φ_{out}) associated with the element (u_i, v_i).

Upon completion of modeling the light propagation within the fiber bulk the BSSRDF of the fiber is calculated as follows:

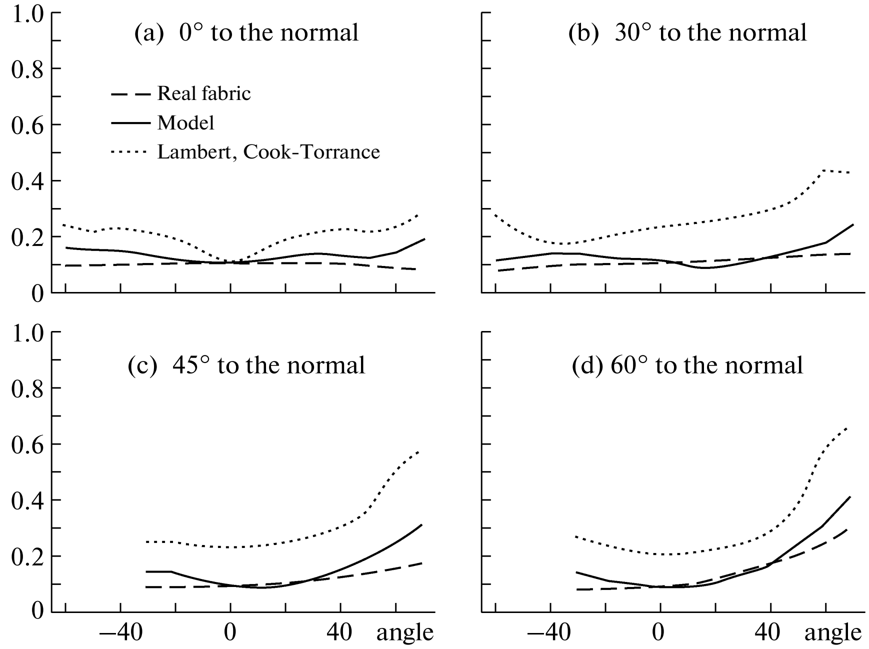


Fig. 7. Light scattering for the classic model, suggested model, and a real model at various directions of light incidence.

$$BSSRDF(w_{in}, A, w_{out}, B_i)$$
$$= F_{out}/(w_{out}B_i\cos(\theta_{out})F_{in}),$$

where F_{out} is the sum of energies of all rays that exited in the direction w_{out} from the element B_i, F_{in} is the sum of energies of all rays that arrive to A from the direction w_{in}, θ_{out} is the direction, determined by w_{out}. It should be noted that the calculated BSSRDF of the fiber has an important property, which helps to calculate BRDF with the help of the method suggested herein. Since the fiber is a circular cylinder, then if the illuminated element of the grid on the fiber surface "shifts" along the fiber and/or "turns" around its center, then the whole BSSRDF "shifts" and/or "turns." That is, for A_1, A_2, B_1, and B_2, determined as shown on Fig. 4, the following holds:

$$BSSRDF(w_{in}, A_1, w_{out}, B_1)$$
$$= BSSRDF(w_{in}, A_2, w_{out}, B_2).$$

For approximation of the BSSRDF integral over the fiber surface it is suggested in the developed solution that the following summation is used:

$$BRDF_{vol}(w_{in}, w_{out}) \approx \sum A_i\, BSSRDF(w_{in}, A_i, w_{out}, B)$$
$$\times A_i\cos(\theta_{in_i})f(\theta_{in_i}),$$

where:

• θ_{in_i} is the angle between the direction of light incidence and the normal to A_i;

• $\cos(\theta_{in_i})$ is required for taking account of the change in the value of the light flux incident on A_i at the angle θ_{in_i};

• $f(\theta_{in_i}) = 1$, provided $\cos(\theta_{in_i}) > 0$;

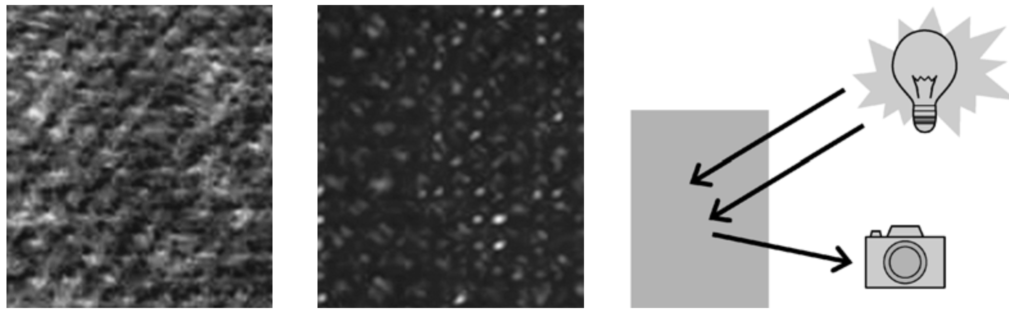
$f(\theta_{in_i}) = 0$, provided $\cos(\theta_{in_i}) \le 0$;

$f(\theta_{in_i})$ controls that the calculation is performed only for those A_i, which are directly illuminated by the source light;

• summation is performed for all cells A_i of the spatial parametric grid (u, v).

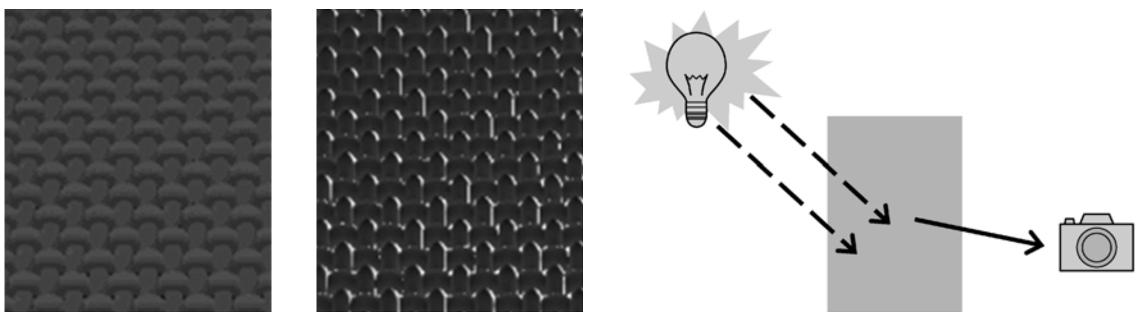
An algorithm has been developed which performs calculation of BRDF according to the above equation. The idea behind the algorithm is that the fiber is illuminated with parallel light from a certain direction, and the contributions to the radiance of some preselected cell B from the surrounding cells A_i are summed according to the BSSRDF which is already known and calculated (Fig. 5).

It should be noted that the obtained BRDF of the fiber is defined for all possible directions of light incidence, not only for those ones that belong to the positive hemisphere relative to the fiber surface (i.e. for those directions that make an acute angle with the normal to the fiber surface). This is due to the fact that during light scattering inside the fiber the rays can exit at any point on its surface, including the reverse side. Thus, BSSRDF is determined over the entire fiber surface, which allows BRDF calculation both for the pos-



(a) reflection (b) transmission reflection

Fig. 8. Photo of a real fabric.



(a) reflection (b) transmission transmission

Fig. 9. Image of fabric model.

itive and negative directions of the light incidence relative to the fiber surface.

3.2. Calculation of BRDF of Fabrics

BRDF of the fabric can be calculated by two methods. The first one is the summation of BRDFs of fibers, and the second one is the calculation of BRDF of the fabric using Monte Carlo ray tracing.

The main idea behind the BRDF summation algorithm is that BRDF of the fabric is an averaged value of BRDFs of the fibers that make up the fabric. For example, for a fabric consisting of one type of fibers BRDF can be approximated as follows:

$$BRDF_{fabric}(w_{in}, w_{out}) = 1/2\sum_i BRDF_{fiber}(w_{in_i}, w_{out_i}),$$

where the parameter i varies from 0 to 1 so as to account for the fact that one and the same fiber in the fabric can be located in parallel and perpendicularly to a certain selected direction. It means that the direction of light incidence and scattering selected in the reference system corresponding to the fabric surface will have other coordinates in the reference systems corresponding to the fibers' surfaces. On Fig. 6, (θ_i, φ_i) and (θ_o, φ_o) are assigned in the reference system corresponding to the fabric surface, (θ_{i1-2}, φ_{i1-2}) and (θ_{o1-2}, φ_{o1-2}) are assigned in the reference systems corresponding to the fibers in the fabric.

An alternative method for BRDF calculation of the fabric on the basis of calculated BRDFs of fibers is Monte Carlo ray tracing. The ray tracing shall be performed for a triangulated fabric sample (similar to the example shown on Fig. 6) obtained with the help of the methods developed in [18]. The fibers in the fabric should be assigned with BRDFs previously calculated. The advantage of Monte Carlo ray tracing over BRDF summation is that it accounts for light re-reflections between the fibers. The drawback of the method is its complexity and, accordingly, a long calculation time that it requires.

4. BRIEF DESCRIPTION OF METHOD VERIFICATION MECHANISM

For the purposes of checking the validity of the developed method, BRDF of a real sample of red cotton fabric was measured with the help of the equipment, described in [19].

The measurements of the fabric optical properties were performed according to the layout described in [20]. The fabric sample was illuminated with almost parallel beam of monochromatic light. The energy of the light reflected by the sample was registered for multiple output directions. The measurements were made for the incident light wavelengths within the range of 390–710 nm with 10 nm increment.

The measurements yielded a set of radiance coefficient values of the fabric for multiple directions of light incidence and reflection. The radiance coefficient is the ratio of the radiance of the measured sample to the radiance of an ideal diffuse reflector in the same illumination conditions and measurement directions. The radiance coefficient is directly proportional to the energy of light reflected by the sample in the given direction and inversely proportional to the cosine of reflection angle. The obtained spectral data were converted into RGB representation and saved in a special format file.

To compare the calculated and the measured optical properties of the fiber on the basis of the calculated data it was necessary to obtain data similar to the measured radiance coefficient of a real fabric [20]. In order to do to this, first of all, it was necessary to create a 3D model of the fabric sample, and assign the calculated optical properties (BRDF) for the fibers. Then this model was incorporated in the 3D virtual scene and the following calculations were performed:

1) A certain cross-section was chosen out of the measured data range (in other words, a certain direction of parallel beam of light incidence and multiple observation directions were chosen).

2) A source of parallel white light, with the same direction as the one selected in the previous step, was installed in the scene with the fabric model.

3) For each of the selected observation directions a camera was installed and the fabric rendering was performed.

4) The pixel values corresponding to the fabric were summed.

5) On the basis of the obtained sums of RGB, the values (let us call them C), proportional to the radiance coefficients of the real fabric, were calculated.

6) Each value of C was normalized as follows. The value of C for the fabric model with normal incidence and reflection of light was set equal to the corresponding measured radiance coefficient value. Then the coefficient of concordance was calculated, and all other values C were multiplied by it.

As a result, it became possible to compare the calculated and the measured data.

4.1. Comparison Results

Figure 7 shows the diagrams of light scattering for the fabric model (continuous curve) and the real sample (dashed curve) in the plane of light incidence (i.e. in the plane that contains the normal to the sample, the vector defining the direction of light incidence, and the vector defining the direction of mirror reflection).

On all diagrams the directions of light incidence are plotted along the abscissa. The diagrams feature the angle values within the range minus 60–70 degrees. Negative values correspond to the directions which are located on the same side from the surface normal as the illumination directions; the positive values are located on the same side as the directions of the mirror reflection. Zero on the diagrams corresponds to the direction of the surface normal. The values of radiance coefficients, divided by π, are plotted along the axis of ordinates.

Also the diagrams show the data obtained when assigning fibers' optical properties using the following classical way (dot-dashed curve):

• Bulk component is assigned according to the Lambert's law.

• Surface component is calculated according to the Cook and Torrance method.

It can be seen from the diagrams that the light scattering for the model and the real fabric shows qualitative match, and the implemented method improves the matching of light scattering patterns for the model and the real fabric as compared with the classic method.

Color components in HSV system for measured and calculated data

	H (hue) 0 to 1	S (saturation) 0 to 1	V* (radiance) 0 to 1
Real fabric	0.98	0.99	0.8
Calculated data	0.97–0.99	0.99	0.8

* The resultant screen image brightness is determined by the illumination of this object in the given 3D scene.

4.2. Color Match

Besides qualitative match of the light scattering diagrams, it proved possible to achieve a certain match in terms of modeling the fabric color under various light conditions.

Figure 8 shows photographs of a red cotton fabric:[2] Fig. 8a is the photograph of the fabric for the light source and the camera being located on the same side of the fabric. On Fig. 8b the light source and the camera are located on different sides of the fabric. It can be seen that depending on illumination, the fabric color varies from purple to dark-red.

[2] This article with coloured figures can be found by the address: http://www.keldysh.ru/pages/cgraph/publications/cgd.publ.htm.

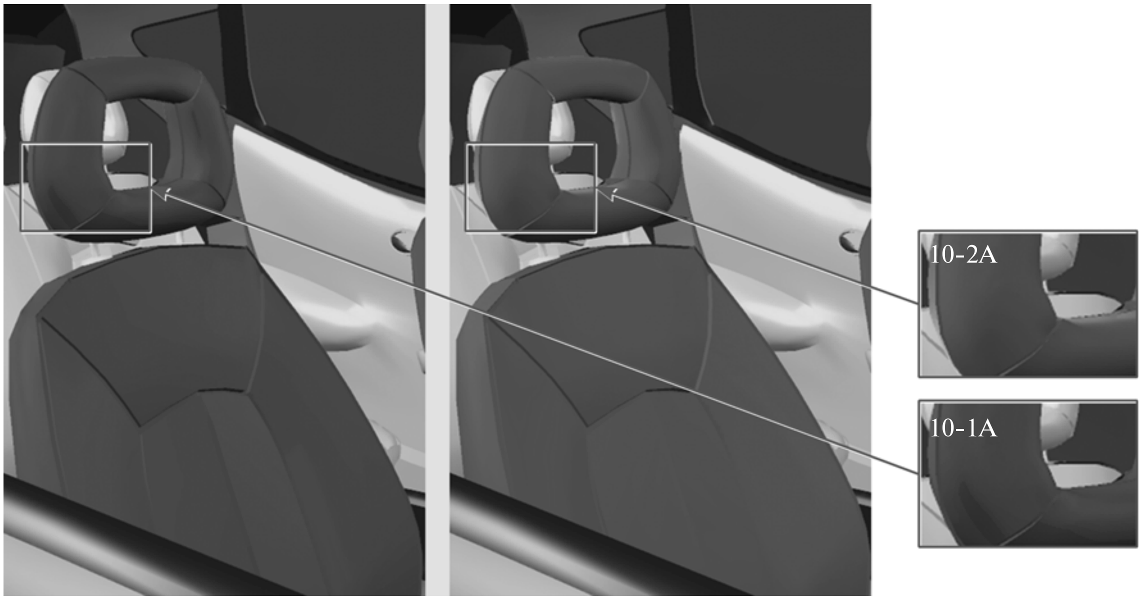


Fig. 10. On the left figure (Fig. 10-1) the measured BRDF was applied to the car seat upholstery, the right figure (Fig. 10-2) is the calculated BRDF. Figures 10-1A and 10-2A are the enlarged fragments of figures 10-1 and 10-2. The developed solution makes it possible to render both the shades on the fabric and the fabric color.

Similar results were obtained for the calculated data. Figure 9 shows the fabric model illuminated in the similar way. It can be seen that the color of the fabric model, similar to the color of the real fabric, changes from purple to dark-red depending on illumination.

In addition to visual color comparison of the fiber illuminated from various sides, the color components were compared in HSV system for the calculated and measured data. The comparison results are presented in the Table 1.

Figure 10 shows the examples of BRDF application to the car seat upholstery. The left figure (Fig. 10-1) shows the measured BRDF applied to the car seat upholstery, the right figure (Fig. 10-2) shows BRDF of the fabric calculated with the help of the suggested summation method for BRDFs of fibers. Figures 10-1A and 10-2A are enlarged fragments of the Figs. 10-1 and 10-2. The figures demonstrate that the developed solution makes it possible to render both the main color of the fabric and its shades.

5. CONCLUSIONS

On the basis of the data on fibers in a fabric representing a scattering medium, a method for calculating optical properties of fabrics was suggested. Described is a method for obtaining the BRDF of a fiber from BSSRDF though integrating BSSRDF over the fiber surface represented by a cylinder. BSSRDF in its turn was calculated through simulation of light scattering and absorption in a fiber medium with the help of Monte Carlo ray tracing method.

The developed solution provides acceptable results for rendering of a fabric color under various light conditions, and also shows qualitative match of light scattering patterns for the model and a real sample of cotton fabric.

The developed algorithms are applied to the problems which require physically based simulation of illumination in a scene. The calculated BSSRDF of a fiber can be used for generation of BRDFs of fabrics with various interweaving. The obtained physically based BRDFs of fabrics can be used for physically correct calculations of illumination in 3D scenes which contain fabric-covered objects. For example, they can be used for analyzing the illumination of car or airplane passenger compartments, interior design, and other similar tasks.

The approach was implemented in C++. The code was integrated with a software product for physically accurate simulation of interaction of light with different media developed by the team of researchers of the department of the computer graphics and computational optics of the Keldysh Institute for Applied Mathematics.

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