Physically Based Lighting Model for Cloth and its Validation

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Abstract

We present a new approach to modeling lighting in cloth based on a confirmed assumption that cloth yarns are scattering media. The paper proposes a way to calculate Bi-directional Reflectance Distribution Function (BRDF) of a yarn by integrating the yarn's Bi-directional Sub-Surface Scattering Reflectance Distribution Function (BSSRDF) over the yarn's surface. The yarn's BSSRDF is obtained via a Monte-Carlo ray tracing simulation of scattering and absorption of light within yarn's volume.

We demonstrate that the new approach is physically plausible by showing the correspondence of scattering patterns of the incident light between our modeled cloth sample and a piece of a real cotton cloth. The scattering pattern of a real cloth is acquired via direct measurement performed with a proprietary measurement apparatus. We outline some characteristics that a yarn's BRDF shall possess to support good correspondence of modeled and real cloths' scattering patterns.

Keywords: *Cloth modeling, physically based lighting simulation, BRDF, BSSRDF, surface reflectance, subsurface scattering, BRDF measurements.*

1. INTRODUCTION

There are many methods available for modeling and visualization of objects made out of cloth, knitwear, fur and other similar materials in 3D scenes. Some of these methods were specifically designed to model physical deformations of materials in static and dynamic environments [1, 2]. Some were more concerned with providing the "look and feel" of the modeled materials [3-6].

Works [3, 4] of Sattler et al. and Muller et al. describe an approach when a number of different textile materials were photographed under different illumination conditions. The acquired photographs were used to obtain textures, which were assigned to polygonal meshes producing highly photorealistic images of garments in 3D scenes. The work of Xu et al. [5] introduced the concept of lumislice for modeling knitwear. A lumislice is a special representation of a yarn cross-section. A yarn in knitwear is formed by multiplication and rotation of the lumislice around the yarn axis. Approach [6] by Adabala et al. used a combination of techniques such as presenting the surface of a yarn with a 2-dimensional procedural texture and separately generating Bi-directional Reflectance Distribution Function (BRDF) to model woven cloth. Their BRDF was created relying on the information about the cloth weave pattern; the cloth surface was modeled as consisting of micro-facets with different orientations.

However, it seems that the primary goal of the named methods was the acquisition of photorealistic images of garments in 3D scenes, not the explicit creation or definition of the physically accurate optical properties (BRDF-s for example) of textile materials or of their components (yarns or fibers).

The goal of the work presented in this paper is to create a lighting model of cloth such that it would 1) produce visually appropriate models of cloth samples that 2) would scatter light incident on them in a manner similar to that of a real cloth. The results of the model development are shown to be physically plausible and can be used to specify the optical properties of cloth objects in 3D scenes determining the way these objects interact with the incident light. The validation of the model was performed by comparing the pattern in which created cloth sample scatters light against the light scattering pattern of a real piece of cloth, measured with the apparatus [7].

1.1 Modeling Optical Properties of Arbitrary Surfaces

One of the major questions considered in computer graphics is how to specify the optical properties of different objects present in 3D scenes. Optical properties define the way in which objects interact with light incident upon them. Usually this interaction is ascribed to reflection of light from objects' surfaces. In some cases, such as in [14] for example, the interaction of light and object's volume is as well considered. Though the work presented in this paper is primarily concerned with modeling of cloth, it stems from the analysis and modeling of general surfaces' optical properties

There exists a vast variety of different surface reflectance models. The goal of a reflectance model is to provide a way to calculate what fraction of light incident upon an object's surface from one direction will be reflected by the surface into some other direction. These models traditionally decompose the reflected light into two components: *specular* and *diffuse*. The specular component being there due to perfect mirror-like reflection from object's surface and diffuse being explained as due to multiple scattering of light on surface micro-geometry and to scattering of light in the object's volume. In the classical works of Phong [8], Blinn [9] and Cook and Torrance [10] the diffuse term was approximated by an isotropic Lambert's function [9]. However later works, for example those of Westin et al. [11], Lafortune et al. [12] and He et al. [13] introduced a directional-diffuse surface behavior, as purely isotropic diffuse term lacked physical accuracy.

In accordance with Fresnel's equations for many real-life objects whose refractive index is close to the refractive index of water, up to 95% (in case of normal incidence) of light incident on their surface will enter the object's volume. (water refractive index is 1.33, averaged refractive index of textile fibers is about 1.5). Some of this refracted light will be absorbed within the object's volume and some will exit back to the original medium as a result of multiple scattering. The scattering occurs due to object's volume optical irregularities, such as, for example, inclusions into the main object's medium of particles with varying refractive index. The angular distribution of exiting light will not necessarily be isotropic [14].

Knowing that subsurface (or volume) scattering must play a significant role in the overall cloth reflectance we decided to create a model that would account for it. We chose to directly simulate the behavior of light once it enters a cloth yarn with the Monte-Carlo ray tracing. We then calculated the functions defining the interaction of light and yarn's volume based on this simulation. The calculated functions were yarn's Bidirectional Sub-Surface Scattering Reflectance Distribution Function (BSSRDF) [9] and yarn's BRDF. The calculated BSSRDF was defined with respect to yarn's cylindrical shape and BRDF was calculated by integrating BSSRDF over yarn's surface. This paper presents the results of such approach.

2. BASIC IDEAS

Cloth is an optically complex object that possesses a set of characteristics defining its interaction with incident light. To define our cloth model we chose a set of parameters described in the following sections.

Upon the implementation of the model we validated it by comparing the pattern in which created cloth sample scatters light with the pattern in which the light is scattered by a piece of a real 100% cotton red cloth. The light scattering pattern of a real piece of cloth was measured with the apparatus [7] and the comparison was performed in accordance with the method presented in [15].

2.1 Cloth Model Parameters

We chose the following parameters to identify our model:

1. Cloth weave
2. Cloth yarns' structure (surface and volume)
3. Approach to calculate yarns' optical properties (BSSRDF and BRDF)

Let's consider the last parameter in greater detail.

To approximate the *specular* component of the reflected light – or in other words the light that is directly reflected from yarn's surface – we chose to use the model of Cook and Torrance [10].

To calculate the volume component of the overall yarn reflectance (encapsulated in the *diffuse* term of the reflected light) we decided to perform the simulation of the scattering and absorption of light within yarn's volume with the Monte-Carlo ray tracing technique. As a result of this simulation we generated two functions characterizing interaction of light and yarn's volume – BSSRDF and BRDF. BRDF was calculated as an integral of BSSDRF over yarn's surface.

3. DEVELOPMENT OF CLOTH MODEL

Our cloth model was developed in a series of iterations. Initially, we implemented a model described in detail in [16]. Below we provide a short overview of the initial model implementation.

Let's consider briefly each of the parameters of the model as they were implemented originally.

3.1 Cloth Weave

There was implemented a weave similar to that of the real cloth against which we performed the comparison. This weave is presented on Figure 1.

3.2 Yarns Structure

Yarn's surface is not smooth. Therefore, we decided to use the approach proposed by Cook and Torrance to model its' interaction with the incident light.

We assumed that yarn is a light scattering medium. This assumption is confirmed, for example, by the study of textile materials performed in works [17-20]. This means that yarns are optically non-uniform media with varying refractive index. The cloth yarns were defined as being filled with a main medium with refractive index equal to an averaged refractive index of cotton fibers (n = 1.557) [20]. The main medium had spherical particles with differing refractive index dispersed in it.

A yarn was modeled as a cylinder with a circle in its base. For visualization purposes the yarns in the created cloth sample were triangulated.

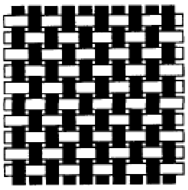


Figure 1. The structure of the weave of the model and the real cloth

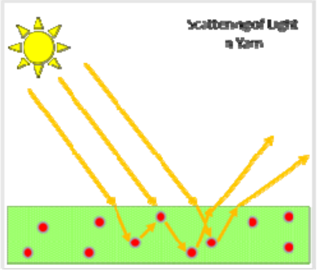


Figure 2 Illustration of scattering of light in yarn. Spherical particles with dissimilar refractive index are dispersed in the main yarn medium

3.3 Approach to Calculate Yarns' Optical Properties

Let's consider a small area on a yarn that is illuminated by light arriving from some direction. In accordance with the Fresnel equations, part of this light enters the yarn. The light entering the yarn is partially absorbed and partially scattered within its volume. The light which is not absorbed exits from the yarn. See Figure 2.

This process of absorption and scattering of light in yarn's volume was simulated with the Monte-Carlo ray tracing. To register the results of this process we introduced a spatial grid of parametric coordinates u and v on the yarn's surface and the angular grids of light incidence and exit directions specified in spherical coordinates θ and φ. The spatial grid had total of 128 elements and each of the angular grids had total of 144 elements. See Figure 8 a).

We traced a number of rays starting from a quadrant of the spatial grid on the yarn surface into the yarn's volume. The rays' incidence directions were defined in accordance with the light incidence angular grid. Each ray was represented with a spectrogram.

In accordance with the parameters of the medium, each of the rays was either absorbed or exited from the yarn as a result of multiple scattering in its volume. The scattering properties of yarn's volume such as scattering cross-sections and phase functions were calculated from the Mie theory.

For each of the rays leaving the yarn we registered its exit coordinate on the spatial grid and its exit direction on the angular grid associated with given spatial grid exitant quadrant.

The described simulation gave us the pattern in which light is scattered within yarn's volume. These data with some modifications can be considered to be a BSSRDF (these modifications are defined in section 5.3.1). The BSSRDF is dependent on three parameters – the direction of incidence of light, the exit coordinate and exit direction of light leaving the yarn. Each of the parameters is a vector of values in their turn.

However, in the initial implementation of the model for each of the sampled exit coordinates we removed the dependency on the exit direction and used an averaged value of exiting energy instead. Therefore, the light leaving the yarn surface was presented as ideally diffuse in accordance with the Lambert's law, and the BSSRDF was actually simplified to be dependent only on two parameters – the direction of light incidence and the coordinate of light exiting the yarn. The function values were translated from spectral representation to RGB.

With some extensions presented in detail in [16] we used the described BSSRDF-like function to assign color to yarn points during cloth sample visualization. The function defined the diffuse component of the yarn point color and the specular component was calculated in accordance with Phong's method or the method proposed by Cook and Torrance [10] per the implementation proposed by Blinn [21].

The described model gave satisfactory visual results presented on Figure 3 (a, b).

Figure 3. a) Enlarged piece of modeled cloth sample of a size approximately 0.3 by 0.3 cm. Visualized only with diffuse component

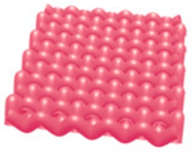


Figure. 3. b) Enlarged piece of modeled cloth sample of a size approximately 0.3 by 0.3 cm. Visualized with diffuse and specular components

Because our goal was to create the cloth lighting model that would enable the modeled cloth sample to scatter light in a way similar to the real cloth it was necessary to perform the comparison of the light scattering patters of the modeled and real cloth to see if the goal was achieved.

Our next step was to develop an approach to perform this comparison or in other words to perform the validation of the implemented lighting model. The validation approach is described in detail in [15]. Here we give its brief outline.

4. BRIEF OUTLINE OF VALIDATION APPROACH

We measured the scattering properties of a red cotton cloth utilizing the measurement apparatus [7].

A piece of cloth was illuminated with a nearly parallel beam of monochromatic light. Measurements were performed for the wavelengths in the range of 390 to 730 nm with a 10 nm step. This allowed us to have full spectral measurements to be converted later into RGB representation. The energy of the reflected light (or in other words the energy of light scattered outwards by the cloth surface) was registered for a set of reflection directions. Afterwards the BRDF values for cloth were calculated and output to a file of a special format.

To compare the pattern in which our cloth sample model and the real cloth scatter light, we measured the scattering properties of the sample. The measurements were done in the way analogues to the measurement process of actual cloth:

1. There was chosen a subset of the real measured data – in other words there was picked one incidence direction and a number of light reflection directions
2. In a scene with the cloth sample model there was placed a source of parallel white light with direction equal to the one chosen at the previous step
3. For each of the light reflection directions a camera was set up and the visualization of cloth sample was performed
4. The colors of the pixels belonging to cloth were summed
5. The obtained sums of RED, GREEN and BLUE components were normalized and divided by the cosine of the viewing direction. The normalization was performed by equating the value of the RGB sum obtained by illuminating the cloth model with normally incident light and measuring the reflected energy in the normal direction to the corresponding measured value of the real cloth. The correspondence coefficient was calculated and all of the sums were multiplied by it.

As a result we could visualize and compare the graphs of the scattering of light by the model and real cloth.

After performing the described validation for the initial model we encountered a number of discrepancies. As an example of such we present here the graphs of scattering of light by the model (Figure 4. b) and real cloth (Figure 4. a) in the plane of light incidence for the incidence angle equal to 60 degrees. The abscissa of the graph shows the direction of the scattered light in the light incidence plane. The zero value of abscissa is equal to the direction of perfect specular reflection (60 degrees from the normal). The values grow as the scattering direction moves away from the normal. Ordinates show the values of cloth BRDF multiplied by π.

Such a result gave us an opportunity to perform a detailed analysis of the implemented model and to look for ways for its optimization. The result of this analysis was the development of the enhanced model of cloth that 1) demonstrates correspondence of light scattering patterns with the real cloth and 2) has similar to the real cloth color when illuminated under different conditions.

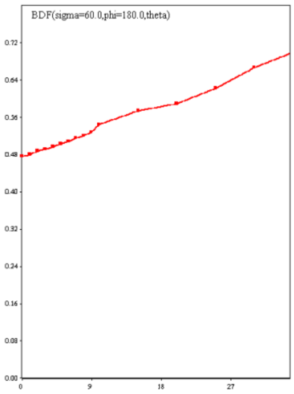


Figure. 4. a) Light scattering pattern of a real cloth

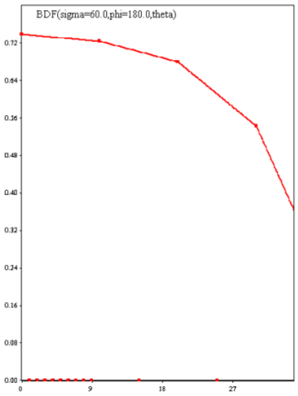


Figure. 4. b) Light scattering pattern of a modeled cloth

5. ENHANCED CLOTH MODEL

5.1 Cloth Weave

The cloth weave remained the same as the one used during the first model implementation.

5.2 Yarns Structure

The structure of yarns' volume remained the same as described in the previous section. However, there was introduced a change to the surface representation of the yarns.

On the first iteration of the model development the specular component was calculated based upon the data about the geometrical shape of each of the yarns. This resulted in the image of the cloth having brighter areas on the surface of the yarns where the normals to the surface were directed closely to the halfway vector H = (L + V)/2 (L is the direction of illumination and V – of observation). This effect is presented on Figure 3. b).

On the second iteration we decided to consider another approach to the definition of the specular component for yarns in cloth.

The alternative approach we utilized was to calculate the specular component of a point based on the direction of the normal to the piece of cloth; not on the direction of the normal to an individual yarn.

We used the method developed in [10] in accordance with the implementation proposed in [21] to calculate the specular component of the cloth points' colors.

Paper [17] presents a discussion about the light reflected from a red cloth being composed of two components: the white light reflected from the surface of the cloth and the red light reflected from the cloth due to subsurface scattering. As a result the overall color of cloth is less intensively red that it would have been if there was present only the subsurface component present. The same effect was obtained for our cloth sample model as well. It is presented on Figures 5 a) and b).

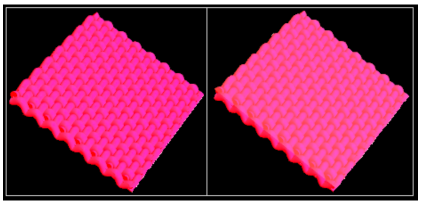


Figure 5 a) Cloth model visualized only with diffuse component b) with diffuse and specular components

5.3 Approach to Calculate Yarns' Optical Properties

It is traditional in computer graphics to use BRDF-s to specify optical properties of objects in 3D scenes.

In accordance with [9] a BRDF for a differential surface *dA*, for light incidence direction dw_{in} and light reflection direction dw_{out} is defined in the following way:

$$BRDF\,(dw_{in}, dw_{out}) = dL(dw_{in}, dw_{out}) \,/\, dE(dw_{in}), \qquad (1)$$

BRDF shows the ratio of the radiance of the surface *dL* in direction dw_{out} to the irradiance of the surface *dE* arriving from direction dw_{in}. It is assumed that the radiance *dL* is created only by the irradiance *dE*. Solid angles dw_{in} and dw_{out} are defined in respect to the local coordinate system at *dA*.

However, because our research is concerned with volume scattering as well as with surface reflection we need to define and use another function called BSSRDF. See Figures 6 and 7.

In accordance with [9] we define BSSRDF in the following way.

Let a differential surface *dA* be illuminated by light arriving from direction dw_{in}.

Then per [9], a BSSRDF for a differential surface *dB* and light reflection direction dw_{out} is as follows:

$$BSSRDF(dw_{in}, dA, dw_{out}, dB) = dL(dw_{in}, dA, dw_{out}, dB) \,/\, dF(dw_{in}, dA), \qquad (2)$$

BSSRDF shows the ratio of the radiance *dL* of the surface *dB* in direction dw_{out} to the flux *dF* arriving at *dA* from direction dw_{in}. It is assumed that the radiance *dL* is created only by the flux *dF*.

If BSSRDF-s are known for some neighborhood of the differential surface *dB*, the BRDF for *dB* can be calculated by integrating the known BSSRDF-s over this neighborhood [9]:

$$BRDF(dw_{in}, dw_{out}) = \int BSSRDF(dw_{in}, dA, dw_{out}, dB)\,dA, \quad (3)$$

Now, let us consider how we used these theoretical formulas to implement our cloth model.

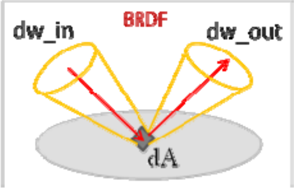


Figure 6. BRDF

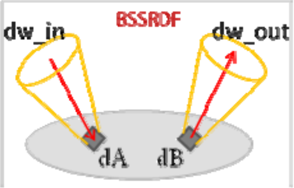


Figure 7. BSSRDF

5.3.1 *BSSRDF Calculation*

As it was previously mentioned, we use the Monte-Carlo ray tracing to simulate the scattering and absorption of light within the yarn volume. A number of rays are traced from an area *dA* on the yarn surface into the yarn volume. For all rays that manage to leave the yarn, their exit coordinates and directions are registered on spatial and angular grids correspondingly. See Figure 8. (a) (*dA, dB1, dBn* are cells of spatial grid, the angular grid is not explicitly shown on the picture).

After the scattering simulation is complete we calculate a BSSRDF for each of the *dB* cells and solid angles dw_{in}, dw_{out} in the following way:

$$BSSRDF\,(dw_{in}, dA, dw_{out}, dB) = \frac{F_{out}}{dw_{out} * \cos(theta_{out}) * F_{in}}, \quad (4)$$

where F_{out} is the sum of energies of all rays leaving *dB* in the direction defined by dw_{out}, F_{in} – sum of energies of all rays incident on *dA* from direction dw_{in}, $theta_{out}$ –central direction of dw_{out}. Equation (4) is an expanded form of equation (2).

There is one significant fact that needs to be discussed in regards to the calculated BSSRDF that plays a key role in the developed approach of calculation of yarn BRDF from yarn BSSRDF. Due to the fact that yarn is assumed to be symmetrical and is represented by a cylinder, which is symmetrical around its central axis, the BSSRDF acquired initially for one quadrant of the spatial yarn grid (*dA*) is valid for all quadrants of the grid. Therefore the following is true:

$$BSSRDF\,(dw_{in}, dA1, dw_{out}, dB1) = BSSRDF\,(dw_{in}, dA2, dw_{out}, dB2),$$

for *dA1, dA2, dB1* and *dB2* defined as shown on Figure 8 (b) and dw_{in}, dw_{out} defined in local coordinate systems on the grid quadrants. This observation facilitates the calculation of the yarn BRDF from the yarn BSSRDF.

5.3.2 *BRDF Calculation*

BRDF of a surface point is an integral of BSSRDF over a neighborhood of this point [9].

To calculate the BRDF of yarn points we propose the following BSSRDF integration approach (we rely on the fact that the cloth being modeled is illuminated by parallel light).

The following sum (5) may be used as an approximation of the BSSRDF integral (3) over the yarn surface (Figure 8 (c):

$$BRDF(dw_{in}, dw_{out}) = \sum_{A_i} BSSRDF(dw_{in}, dA_i, dw_{out}, dB) * \cos(theta_{in_i}) * f(theta_{in_i})$$

Where

1. $theta_{in_i}$ is the angle between the light incidence direction and the normal to dA_i
2. $\cos(theta_{in_i})$ accounts for the change of the light flux with the change of the angle between the direction of light incidence and the normal to the surface area dA_i. See Figure 8(d).
3. $f(theta_{in_i}) = 1, if \cos(theta_{in_i}) > 0,$
   $f(theta_{in_i}) = 0, if \cos(theta_{in_i}) \leq 0,$
   $f(theta_{in_i})$ is used to assure that only those dA_i-s that are directly illuminated by the light source are taken into account during the BRDF calculation.

After performing the described calculations we acquire the BRDF for yarn points determining the way they interact with incident light.

It is important to emphasize here that the calculated BRDF is defined not only for the positive hemisphere of light incidence directions, but for the full sphere of all possible directions.

Full sphere BRDF definition is possible because when the simulation of scattering of light in yarn volume is performed, light rays can exit from any side of the yarn. Therefore, the BSSRDF is defined all over the yarn surface and thus the yarn BRDF can be validly calculated for both positive and negative light incidence directions.

During cloth visualization we use the obtained BRDF function to assign color to yarn points. Figure 10 presents some results of our work.

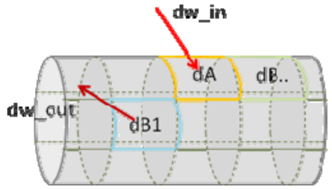


Figure 8. a) Scattering of light arriving at dA over the surfaces dBi

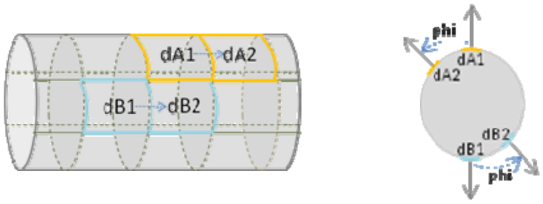


Figure 8. b) If an original cell is shifted along the yarn axis or turned around its center the whole BSSRDF “shifts” and “turns” in the same direction

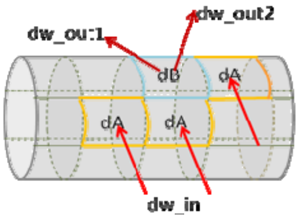


Figure 8. c) Integrating BSSRDF to acquire BRDF

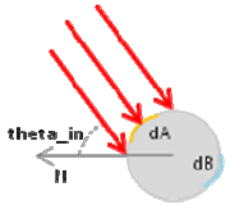


Figure 8. d) Parallel light inciden on a yarn

6. CLOTH MODEL VALIDATION

After the completion of the cloth lighting model development we performed its validation in a way that has already been described in section 4. Below there are presented the graphs of light being scattered by our cloth model and by a real cloth in the plane of light incidence (in other words in the plane that contains the vector identifying the light incidence direction, the light perfect mirror reflection direction and the normal to the surface of the cloth).

On all of the graphs abcissas show the zenith of the scattering directions. The values of angles are between -60 and 70 degrees. Negative values correspond to directions lying to the same side of the normal as the incidence direction, positive – to the same side as the perfect mirror reflection direction, 0 corresponds to normal direction. The graphs demonstrate qualitative correspondence of light scattering patterns. Ordinates show the value of cloth BRDF (without multiplication by π as in the first example).

To see how our model compares with the existing solution, we performed the same measurements for a classical approach of defining object’s optical properties:

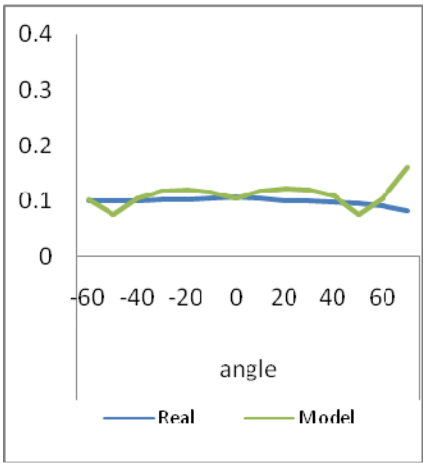
- Diffuse component was set in accordance with Lambert’s law. Per [14] the upper bound of the subsurface reflectance is R = 1 - $\left(\frac{\eta_i - \eta_t}{\eta_i + \eta_t}\right)^2$, where in our case η_i is the refractive index of vacuum and η_t – the refractive index of cotton (1.557). For our case R equals about 0.6. Thus we set the value of the diffuse coefficient to (0.6/π, 0, 0).
- Specular component was calculated in accordance with [10] per implementation proposed in [21]. The specular component was calculated against the normal to the piece of cloth. The constant that defines the smoothness of the surface in the Cook and Torrance model was set to 0.8.

Graphs 1-6 show the results of this comparison. It may be observed that the developed model produces results that have overall better correspondence to the measured data than the ones shown by the Lambert and Cook and Torrance approach.

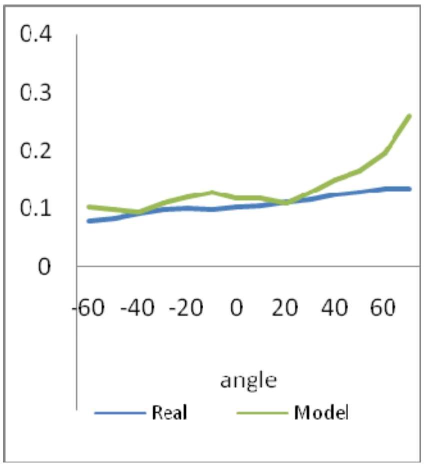
6.1 Color Correspondence

Besides the qualitative correspondence of light scattering patterns between the cloth model and the real cloth we were as well able to achieve appropriate results in modeling the color of cloth under different illumination conditions.

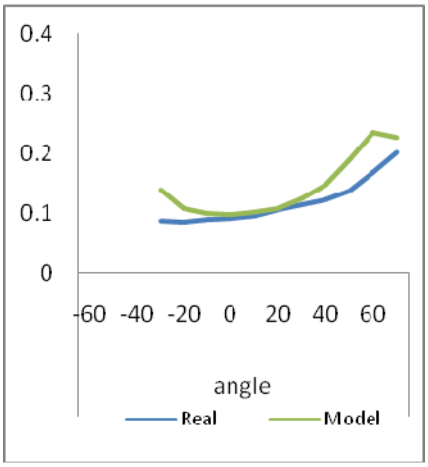
On the Figure 9 (a, b) one may see a photograph of a real red cloth illuminated by day light from the front side and from the back sides. The color of the cloth changes from purplish when illuminated from the front to dark red when illuminated from reverse.



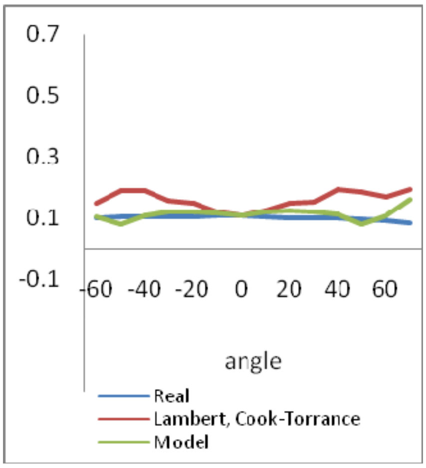
Graph 1. Scattering of light by our model and real cloth. Angle of incidence is 0 degrees with normal to cloth



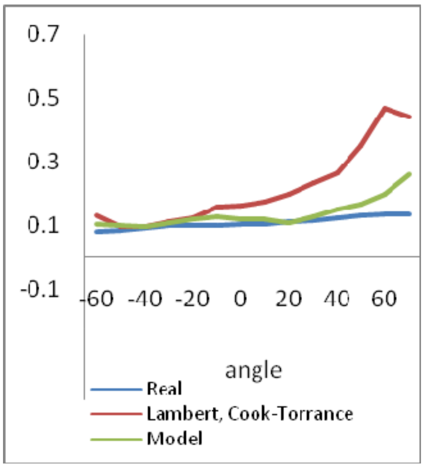
Graph 2. Scattering of light by our model and real clot. Angle of incidence is 30 degrees with normal to cloth



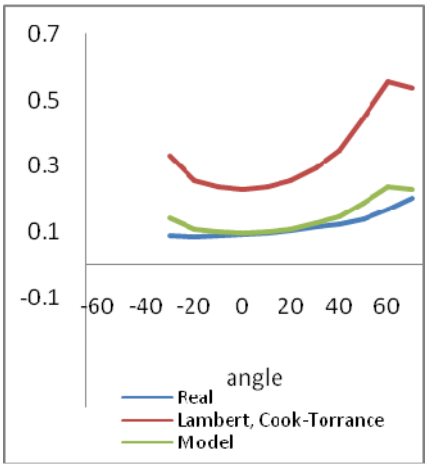
Graph 3. Scattering of light by our model and real cloth. Angle of incidence is 60 degrees with normal to cloth



Graph 4. Scattering of light by our model, real cloth and a Lambert, Cook and Torrance approach. Angle of incidence is 0 degrees with normal to cloth



Graph 5. Scattering of light by our model, real cloth and a Lambert, Cook and Torrance approach. Angle of incidence is 30 degrees with normal to cloth



Graph 6. Scattering of light by our model, real cloth and a Lambert, Cook and Torrance approach. Angle of incidence is 60 degrees with normal to cloth

The similar results presented on Figure 10 (a, b) were obtained for the implemented cloth model. It can be seen that the model shows decent correspondence to the color balance of the real cloth.

In addition to the visual comparison of the cloth color there was performed the mathematical comparison of the RED, GREEN and BLUE components. We calculated the ratios of BLUE/RED and GREEN/RED components for real and modeled cloth for normal illumination direction. The data presented in Table 1 supports the visual comparison.

	BLUE/RED	GREEN/RED
Real cloth	0.08	0.011
Cloth model	About 0.05 - 0.25 Depends on the parameters of the scattering medium	About 0.001 - 0.017 Depends on the parameters of the scattering medium

Table 1. The correlation of RED, GREEN and BLUE components in the real and modeled cloth

Figure 9. a) A photograph of a real red cloth illuminated with day light from the front

Figure 9. b) A photograph of a real red cloth illuminated with day light from reverse

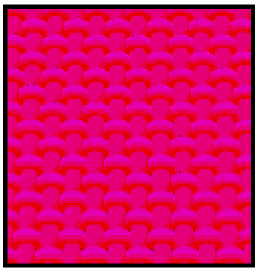


Figure 10. a) A model of red cloth illuminated with day light from the front

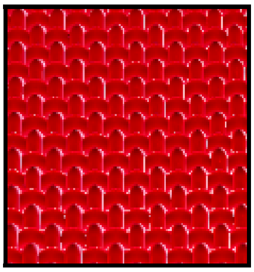


Figure 10. b) A model of red cloth illuminated with day light from reverse

6.2 Model Tuning

The main tuning parameters of our model are the characteristics of the scattering media that represent yarns. These characteristics are as follows:

1. Refractive index of the main medium that has scattering particles dispersed in it
2. Refractive index of the scattering particles
3. The size of the scattering particles
4. The concentration of the scattering particles in yarn volume

Another important property is the concentration of dye in the yarns. This concentration was specified in accordance with the known data [22] that is within the range of 1% - 5% of pigment weight concentration.

Depending on the balance of the chosen parameters the model demonstrates different behavior.

Our goal was to use the known data about textile fibers to the maximum extent to specify the scattering medium characteristics. For example, work [19] shows that cotton fiber is composed of 50% of crystallites of a size of tens of nanometers. Paper [17] states that cotton yarns are composed of not only cellulose, but as well of up to 12% of wax, pectin and minerals. As well, the cotton fibers may contain air voids. Synthetic fibers can be impregnated with particles with high refractive index to remove their extensive luster.

The graphs 1 – 6 are calculated for the medium with the following characteristics:

1. Refractive index of the main medium – 1.557
2. Refractive index of the scattering particles – 1.61
3. Size of the scattering particles – 150 nm
4. Particles concentration – 0.14

Let us present here a short analysis of different yarn BRDF-s that we were able to generate specifying different parameters for the yarn scattering medium. Some scattering media produce a BRDF that has a shape similar to the one presented on Figure 11 a) which is more isotropic, some have a shape like the one presented on Figure 11 b). To support the growth of a cloth BRDF with the increasing incidence and viewing angles (as it is for example for the measured cotton cloth) the BRDF-s of the second type are more appropriate.

Therefore to obtain the correspondence in the scattering pattern where the BRDF of cloth grows with the incidence and viewing angles one needs to select such a yarn BRDF that shows the similar behavior itself.

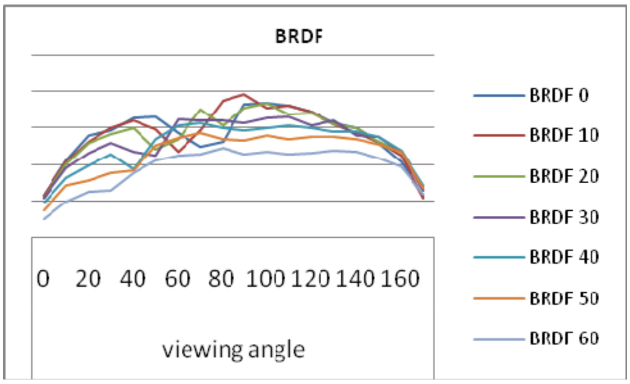


Figure 11. a) Example of BRDF 1

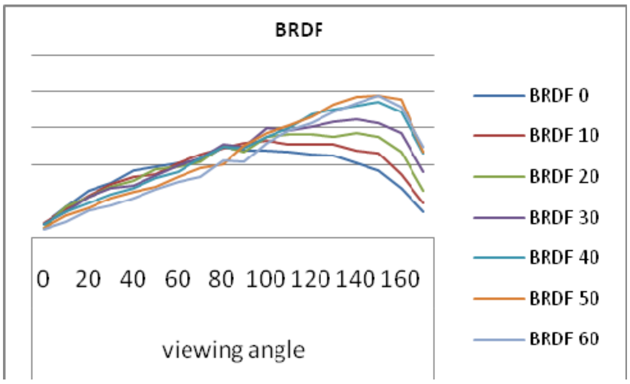


Figure 11. b) Example of BRDF 2

7. CONSTRAINTS, APPLICATIONS AND WAYS TO ENHANCE

The developed model has the following constraints and ways of enhancement:

- The model does not account for such an important factor as light inter-reflection between cloth yarns. Modeling of this effect can be the next step in model enhancement
- Presently, the yarns are represented by cylinders having circles at their bases. It seems that the visual reality of the model can be enhanced if the base for the cylinders would be an ellipse [11] or shapes of greater complexity.

- It would be valuable to create and evaluate models of cloths with different weaves and composed of yarns of different types

Besides having an interesting theoretical result, the present work can also be applied to problems that require physically accurate calculation of illumination. One may use the precalculated yarn BRDF-s to calculate BRDF-s of cloths composed of similar yarns, but with different weaves. The calculated cloths' BRDF-s can be used in physically accurate calculations of illumination in 3D scenes containing cloth objects.

8. CONCLUSIONS

Based upon the confirmed assumption that yarns in cloth are scattering media, we proposed a new approach to model lighting in cloth.

The paper proposes a way to calculate yarn's BRDF by integrating yarn's BSSRDF over its surface. The BSSRDF is acquired via a Monte-Carlo ray tracing simulation of scattering and absorption of light in yarn's volume.

The implemented model (the implementation language is C++) demonstrates both appropriate visual results and reasonable correspondence of the light scattering patterns of a real piece of cloth and of a modeled cloth that had the calculated BRDF associated with its yarns.

The publication with color illustrations can be found at:

- http://www.graphicon.ru/2008/
- http://www.keldysh.ru/pages/cgraph/publications/cgd_publ.htm

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