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A COMPUTATIONAL EXPERIMENT OF SIMULATING LIGHT PROPAGATION IN A FIBRE-CONTAINING PROFILED STRUCTURE

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Abstract: many studies show that profiled structures are the source of attaining desired system characteristics in industrial or other applications. In this short note, we continue considering proposed recently by us the profiled structure such as a beach umbrella based on the principles of origami design. To demonstrate the optical properties of the given model, a developed recursive ray tracing algorithm is used to simulate the propagation of light rays through the modelled paper fiber sample. In this paper, modeling light propagation through a porous structure using ray tracing technique is presented and results of modeling light propagation in a profiled structure with respect to simulated light propagation in fiber structure are discussed.

Keywords: fiber structure, ray tracing technique, bending energy.

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ВЫЧИСЛИТЕЛЬНЫЙ ЭКСПЕРИМЕНТ ПО МОДЕЛИРОВАНИЮ РАСПРОСТРАНЕНИЯ СВЕТА В ВОЛОКНИСТОЙ ПРОФИЛИРОВАННОЙ СТРУКТУРЕ

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Аннотация: в ряде исследований показано, что профилированные структуры позволяют получать требуемые характеристики систем в промышленных и других областях применения. В настоящей краткой статье мы продолжаем рассмотрение недавно предложенных нами профилированных структур — таких, как пляжный зонтик, — основанных на принципе оригами. Для демонстрации оптических свойств данной модели был разработан рекурсивный алгоритм трассировки лучей, выполняющий моделирование распространения световых лучей через модель образца из бумажных волокон. В настоящей статье представлено моделирование прохождения света через пористую структуру методом трассировки лучей, а также обсуждаются результаты моделирования прохождения света в профилированной структуре по сравнению с моделированием прохождения света в волокнистой структуре.

Ключевые слова: волокнистая структура, метод трассировки лучей, энергия деформационного колебания.

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Introduction

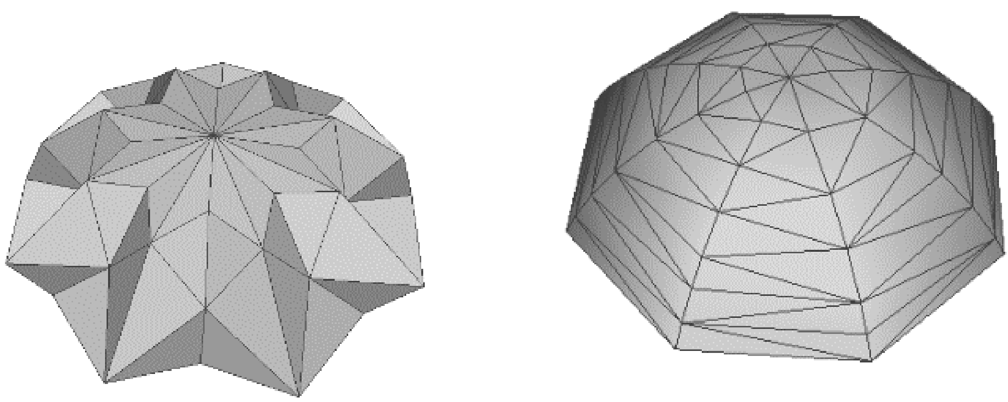
Decreasing harmful effects on human health is important topic for the investigations, see for instance [1], and references therein. Widely used umbrellas and shade structures, which can be made from dense fabrics of cotton, flax, hemp, and natural silk fabrics, provide limited sun radiation. In [2] it was observed that wool knitted fabric with the optimized parameters such as fibre diameter, yarn linear density, yarn twist, cover factor setting can provide high ultraviolet protection to human body.

A wedge-shaped structure is a potentially promising periodic structure for sun light protection that, in fact, was shown in [1]. Washi-paper is widely used in Japan as a material for producing various goods such as lampshades, umbrellas, and etc., see, for instance [3]. The article [1] is devoted to the study of an origami-like screen for protection from sunlight which might reduce the harmful effects of solar radiation on humans. The purpose of the simulation was to show the effectiveness of the profiled structure to redirect light rays in comparison with the non-profiled structure. When light is incident on a material surface, the light wave will either be reflected, transmitted, or absorbed. However, light propagation simulation through a profiled paper structure is based on widely used in various application Kubelka — Munk (K-M) model, see [4], [5], where the light propagation model is considered as a continuum to describe the forward and backward scattering of light.

Due to the short wavelengths of light compared to the geometrical parameters of the desired structure, the problem of light propagation can be solved by means of geometric optics. In [1] an analysis of the Fresnel formulas [6] shows that the reflection coefficient r increases markedly with increasing the angle of incident φ. Such a correlation between parameters r and φ can be used to create structures with high reflectance. The article implements the idea of using the profiled structures based on origami principles to increase the number of reflections with increasing the angle of incident φ on the flat faces. Problem of optimization of initial or basic structure has been also studied.

Nevertheless, exploring the possibility of applying the profiled structure to create a sun-protection screens made from paper or fabrics shown in Fig. 1(a) is in its early phases. Also there is an obvious problem to design a fabric or paper structure satisfying some conditions, see, for instance [7].

Unfortunately, the K-M paper model does not consider any change in orientation in the angular distribution of light fluxes that can introduce some intrinsic errors. This question is discussed, for instance in [8], where Henyey-Greenstein phase function commonly used to describe light fluxes in turbid media such as human tissues is used. Investigating orientation effects to prove correctness or validity of implementing the K-M theory used in [1] for profiled structures is the main objective of this short note. Another one is the extension of previously developed by us the recursive ray tracing algorithm (RRT) allowing simulating light propagation in porous structures. As an application of the developed software algorithm we mimic and examine the properties of reflection/refraction of the fibre structure such as a washi-paper, which we call washi-like paper. The RRT algorithm is implemented using the C++ programming language and is designed to study the light propagation through the fibres presented by polygons.



(a) *(b)*

Figure 1. *Geometry models [1]. (a) The profiled polygonal model. (b) The non-profiled polygonal model*

Related works

Myriads of articles related to the questions of paper industry were published recently, among them [9-13]. A lot of *applicable* information such as size of fibres, fibre lumens, length, diameter, and others like illustrations of crimped sections of fibres can be found on the web site of Pekka Komulainen.

The main objective of the recent study [7] is the stress analysis of paper, nevertheless, in some way results shown can be used for study of light propagation. Authors investigate the effect of extreme tensile performance of individual softwood fibres. In a particular, simulated networks were generated using a random deposition model that mimics the handsheet filtration. Wall thickness, diameter, length and curl of the fibres, grammage, and density profile of the network are the control parameters in the deposition model. An example of a deposited fibre network is presented in Fig. 2 [7].

The review article [14] highlights progress in understanding the optical properties such as opacity, brightness, color, fluorescent properties, gloss of paper.

Transparent wood (TW) is now considered as building material of the future. In many applications, the total light transmittance is an important property. The [15] discusses potential applications of TW and presents optical, mechanical performance, and functionalization routes for realization of advanced applications. In the paper [16] authors note that better understanding of optical properties of TW is essential for further development of this class of optically functional materials. Light transmittance through a TW is highly influenced by light scattering. The paper studies the light diffusion in media with both absorption and scattering. Diffusion equation for photon transport in a scattering material was modified – two different diffusion coefficients were considered: Dxy (in the plane perpendicular to the fiber direction) and Dz (along the fiber direction). It is found that the angle-integrated total light transmittance of TW has an exponentially decaying dependence on sample thickness.

In geometric optics, an assumption is made that in uniform media, light travels in a straight-line path, which can be approximated by a ray, where the ray is a straight line perpendicular to the wave fronts. When the light wavelength is much less than the feature size of the medium, Maxwell's equations reduce to the eikonal equation, which is the basis of geometric optics [17] or the ray tracing method. In computer graphics, ray tracing is used for rendering the 3D objects by recursively following the path that the incident light takes or by using so called Monte-Carlo method.

A model based on Monte-Carlo ray tracing for simulating scattering and linear polarization by particles with arbitrary shapes and size is presented in [18]. Authors examine absorption and scattering behaviour of single irregular particles. Particle shapes, size, and optical constants are taken into account for exploring the relationship between actual physical properties and of large particles and the single-particle parameters. In [19] authors demonstrate that the values of the reflection and transmission through the optical medium consisting of air, cell sap, chloroplast, and cell wall of a leaf found from ray tracing agree closely with experimental results.

The paper [20] presents an approach which describes the behavior of light in matter as a special kind of random walk. The paper presents a Markov chain modelling the K-M-like scattering process and studies its combinatorial properties.

The paper [21] introduces an open source Monte–Carlo simulation tool for the modelling of light scattering in paper and prints. Surface scattering is treated as a combination of two effects. The long-range topographic structure, called the surface waviness, deflects incident wave packets according to Snell's law and the Fresnel equations. In addition, the short-range topographic structure, called the microroughness, scatters the light diffusely in a Lambertian manner. Within a homogenous turbid medium representing a fibre wall, the scattering process is controlled by three parameters, the scattering and absorption coefficients, and the asymmetry factor which is used to compute the new direction of the wave packet. Each sheet was modelled as a statistical layer bounded by two surfaces, simulating a sheet with constant thickness. Fibres were modelled as rough hollow cylinders, stretched out into an elliptic shape and a homogeneously distributed along the thickness direction of the sheet, and isotropically oriented in the plane of the paper. The only contribution to light scattering came from light reflections at fibre and layer boundaries. The refractive index of the layer and fibre wall was set to 1.5. The applicability of the simulation tool was demonstrated by modelling the effect of a structure modification on the light scattering.

Let us emphasize or repeat mentioned above that our intention is to estimate possible relations between intensity values of falling light fluxes on a sheet of simulated paper material and values of transmitted light fluxes.

Paper model and simulating light intensity by ray tracing

Paper's ability to scatter and absorb visible light is highly dependent on many factors including paper structure and its chemical composition. A geometry model of the sample of paper, the image of which is shown in Fig.2 (produced by our algorithm), is considered to simulate light propagation as it is described below.

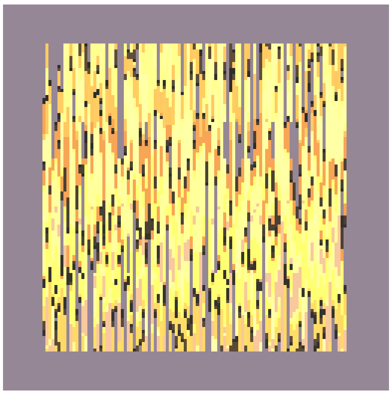


Figure 2. *Image of simulated fibre structure generated by ray tracing*

For estimation of light propagation characteristics of a simulated paper model we use the idea of voxel visualization [22] to demonstrate the distribution of light rays in the areas inside and below the structures under consideration. A cubic (voxel) volume represents the area of reception of each ray location. Following this concept, we define the 3D volume with cells as identical sub-cubes, where we store the input and output data such as the simulated light intensity data.

There are many effective algorithms for spatial partitioning of 3D space to reduce vast amount of calculations arising in ray tracing algorithms, see, for instance, [23] and references therein. In our application, a developed by us 3D chained list (a series of records) is composed of input data to store geometry data or other. Such list allows easily to store also the contribution of each individual ray to the resulting output data like the electric field strength amplitude, phase, and polarization for each position on an arbitrary ray at a specified distance from the source.

The light is scattered but it is being transmitted through the gaps between the paper fibres. The fibres are not absolutely opaque as it can be seen in Fig. 3. In this study, one record of input data contains coordinates x,y,z of the fibre centre and 3 coefficients of essential matrix defining space orientation of single fibres, modelled as hollow cylinders, stretched out into an elliptic shape by a scaling factor. Fibres were modelled as hollow cylinders with a fibre wall thickness d = 3.1μm, stretched out from initially almost circular cross-sectional shape with radius 17 μm into an elliptic shape and non isotropically oriented in the plane of the paper. Slight angular deviation in y (vertical in our system of coordinates) direction is also produced. Fibres contact and intersection were taken into account by allowing formation of pores what can be observed in the Fig 2. Length of the fibre is about 3.2 mm. The mentioned above modelling parameters approximately correspond to parameters of the modelled washi-like paper.

Thus, for simulating light propagation through the sample of washi-like paper where the two sides of the base are of length approximately 3.1 mm and 3.2 mm respectively, and the height (thickness) of the sample is 0.1 mm, a cubic volume with 8 x 3 x 128 cells size is used in x,y,z directions, respectively.

The simplest (Lambertian) reflection model is applied as a model for diffuse reflection. It is known that the intensity of light should decrease exponentially with the distance d that it enters an absorbing medium. According to Bouguer's experiment, an exponential relationship $T_\lambda = t_\lambda pow(d)$ was found between the thickness and the spectral transmittance. T_λ and t_λ are the spectral transmittance of a transparent object and spectral transmittance according to the unit thickness, respectively. A 0.9 transmittance for the unit thickness was used in our experiment. Refraction is calculated in accordance with a quantity of the refraction indices by using Snell's law for a given pair of media air and fibre. This process of reflection/refractions continues iteratively.

Traditionally for modelling reflectance and transmittance of particle structures spherical or cylindrical parametrically defined objects are used. In our application polygonal model of fibres is used. Total number of polygons is 31720.

In our implementation of recursive ray tracing discussed in [1], a set of refraction/reflection events is considered as n- layered material obtained using the adding method, see [5]. In the adding method n is treated with respect to the number of ray intersections with modelled walls.

As we mentioned above, the K-M model does not consider any change in orientation in the angular distribution of light fluxes. For realization of modelling propagation of the paper sample dependence outlined above in investigation of propagating light in the profiled and non-profiled structures we have to take into account orientations in the angular distribution of the paper sample. For that, we precalculate and store light intensity of transparent light in an analogy of look up table, an array that replaces runtime computation. In the table we store direction vectors of the incident light rays and values reflected and transmitted light intensities. Each ray is continued until it ended up as reflection or transmission from the considered paper sample. To reduce the time and efforts required in ray tracing some of the rays are discontinued after 5 levels of recursion.

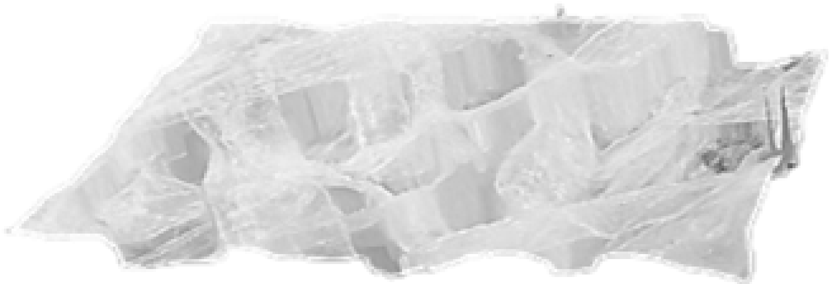
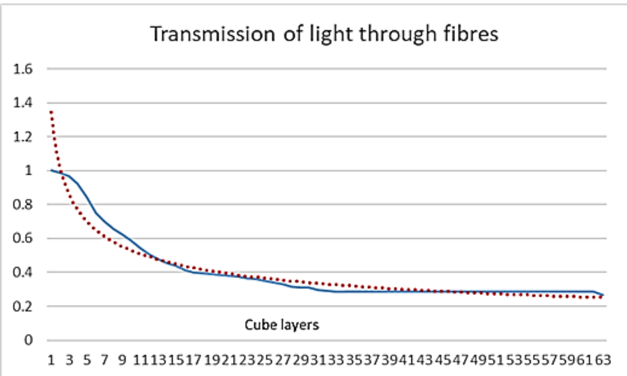


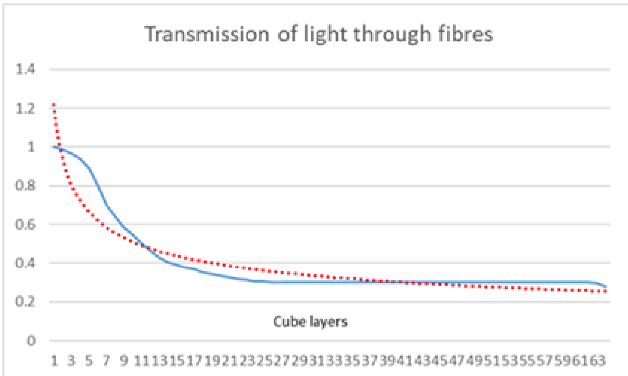
Figure 3. *Microscopic image of washi-paper structure (the top view)*

Results of simulations

Results of simulating light propagation in the sample of the washi-like paper structure are shown in Fig 4.



(a)



(b)

Figure 4. *The ray tracing simulation of light propagation in the modelled sample of washi-like paper. (a) Graph of the normalized light intensity (in blue) and power fit of the data (red dots). (b) graph of the normalized intensity of linearly polarized light (in blue) and power fit of the data (red dots)*

For simulating light propagation in profiled and non-profiled models (Fig.1), they are embedded in the cube of cells size 128 x 128 x 128. Tracing rays of light with wavelength of 400 nm with correspondent reflection/refraction indices 1 and 1.5 is produced to calculate the integral value of the photon energy E for each sub-cube.

Each ray is continued until it ended up as reflection or transmission from the cube. To reduce the time and efforts required in ray tracing some of the rays are discontinued after 5 levels of recursion in analogy to ray tracing of the paper sample. The same level of recursion is used to calculate light propagation in the paper sample.

In the RRT algorithm, we consider light intensity as the rate at which light energy is delivered to a sub-cube. We consider an optimal design of the given geometry model that is optimal with respect to the basic designed profile model. Coordinates of vertices of the 3D polygonal model are modified and the resulting warped shape is evaluated with the help of the RRT algorithm, which allows us to take into account a collection of light intensities of refracted and reflected rays stored in the area under the profiled structure. The combination of ray tracing and the optimization techniques based on Genetic Algorithms (GA) for the modification of the model shape is used. Resulting light distribution for profiled model after 331 steps of GA is shown in Fig.5. Our experiments show that with the evolutionary optimization of the geometry of the profiled model, we can improve the shading effect with respect to the basic design. Fig. 5 also illustrates that profiled structures with using paper as a material can provide reasonable decreasing light intensity in the area under the structures.

We may note that with the evolutionary optimization of the profiled model we can improve the shading effect with respect to the basic design by about 2%, it is shown in (Fig. 6 a).

In our own experience, we have found that important problems in computer simulation, surface reconstruction, animation, and geometry processing, can be solved by involving the methods related to a bending energy quantity $\boldsymbol{h}^t\ \boldsymbol{A}^{-1}\boldsymbol{h}$. $\boldsymbol{A}^{-1}$is the bending energy matrix, $\boldsymbol{h}$ is a vector of so called heights. Questions related to definition matrix $\boldsymbol{A}$ based on using radial basis functions are discussed remarkably well in [24]. So-called heights $\boldsymbol{h}$, in our case, are space transformations defined by the initial and final (destination) points engaged in the process of the model shape modification by implementation of GA optimization. Fig.6 exposes stimulating for further investigation of the relationship between bending energy and light propagation through the profiled structure.

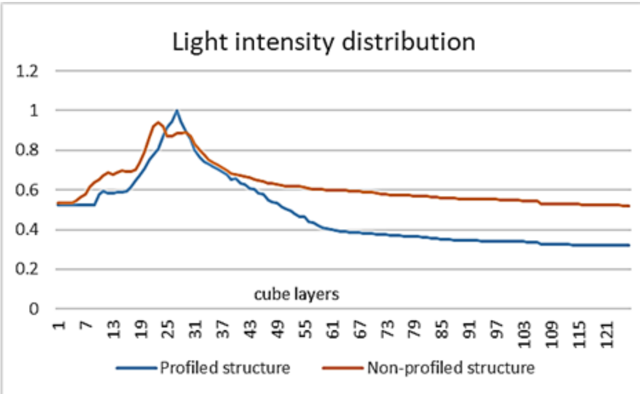


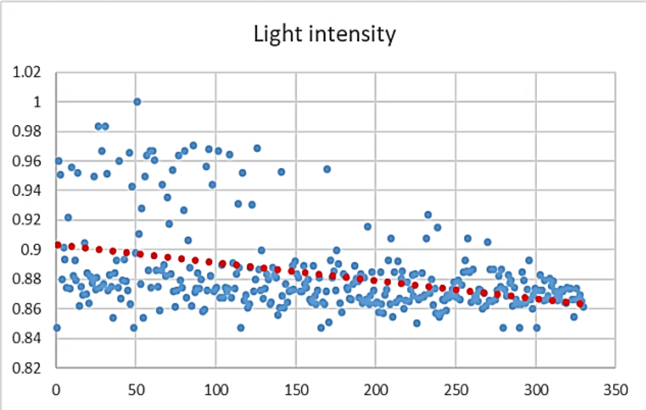
Figure 5. *The ray tracing simulation: graphs of the resulting data in the layers of the cube. The light intensities normalised according to values of the profile model are shown on the vertical axis. The area between the layers 4 and 28 represents the region of the model inside the cube*

Conclusion remarks

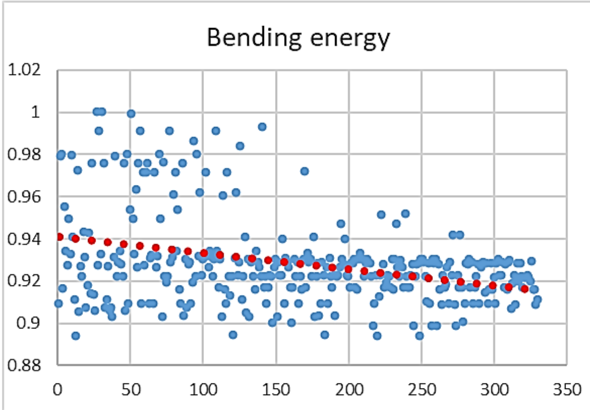
One of the directions of using the RRT algorithm discussed in this note might be the development of models of light reflection/refraction/absorption phenomena in various types of paper structures based on the analysis of their microscopic images. But processing time (the time it takes to complete one calculating step) for the considered modelled sample of paper is about approximately 29 sec on Intel Pentium 2.50 GHz processor. It is obvious that parallel or distributed processing is necessary for such applications.

This study actually supports our idea or even prove that the given structures with using paper as a material can provide reasonable decreasing light intensity in the area under the structures.

According to the simulation results of the modelled paper sample, we also considered an optimal design of the given geometry model that is optimal with respect to the basic designed profiled model. The criterion for the distribution of light intensity using geometric field tracing is implemented in the form of the RRT algorithm. We do not present here results of shape improving with respect to the simulated



(a)



(b)

Figure 6. *(a) Illustration of light intensity distribution during GA iteration steps. (b) Bending energy values. In both plots, red dots illustrate a linear dependency*

light propagation characteristic. Let us notice that there is no distinct difference between the improved model attained by using the K-M light propagation model [1] and discussed in this paper. Nevertheless, to prove applicability developed paper model we have to show agreement between modelled light propagation data and measurements that is seen as our urgent future task. There is an interesting question of defining a fitness function for optimization of profiled models. Polarized light is produced by the interactions of unpolarized light with materials, particles, and surfaces. So, we can define a fitness function as a result of all propagated lights through a media or as a flux of polarized light. This is an open question which requires future consideration. There is also intriguing question of obvious correlation between bending energy of the profiled models and light scattering distribution.

Naturally, to confirm the results obtained in this study, more experiments would need to be conducted. Nevertheless, our numerical simulation of light propagation through a fibre like structure shows almost exponentially decaying dependence on the thickness of the paper sample.

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