Rendering Animation of Lace Curtain Using BRDF/BTDF and Motion Physical Characteristics Based on a Subjective Impression

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***Abstract*—The need for rendering woven fabrics arises frequently in computer graphics. Woven fabrics have a specific appearance, luster, and transparency. A BRDF model is well known as the basic technology employed for expressing the appearance of a woven fabric. In order to represent the transparency of a woven fabric, a BTDF (bidirectional transmittance distribution function) model is required in addition to the BRDF model. Additionally, rendering fabric motion properties is also significant to enhance the texture of materials in animations. In this paper, we propose a new method to render woven fabrics that have both realistic appearance and motion.**

I. Introduction

The need for rendering woven fabrics arises frequently in computer graphics [1]. Woven fabrics have a specific appearance, luster, and transparency. A BRDF (Bidirectional Reflectance Distribution Function) model [2] is well known as the basic technology employed for expressing the appearance of a woven fabric. In order to represent the transparency of a woven fabric, a BTDF (Bidirectional Transmittance Distribution Function) model is required in addition to the BRDF model. In this paper, we propose rendering methods for woven fabrics, particularly transparent fabrics such as lace, based on a BTDF model and applying the BTDF model to a real-time rendering algorithm. Additionally, rendering fabric motion properties is significant in enhancing the texture of materials in animations [3]. Therefore, we performed an experiment to evaluate subjective impressions about relationships between the optic and the motion properties, and to estimate the dynamic properties directly from the optic properties.

II. Related works

Computer graphics(CG) is used in a number of different fields including TV, film production, commercial message, and web contents. In particular, there is a growing need for establishing the digital archive of various merchandise because of the rapid spread of the Internet. The curtain catalog is a typical example. Development of a curtain catalog is expensive because of the many kinds of color, pattern, and material. Additionally, static impressions of a curtain catalog will differ from reality because of the change of color and transparency in placing a curtain to a window. It is necessary to express the change of texture of a curtain due to the actual illumination condition to show the difference from reality.

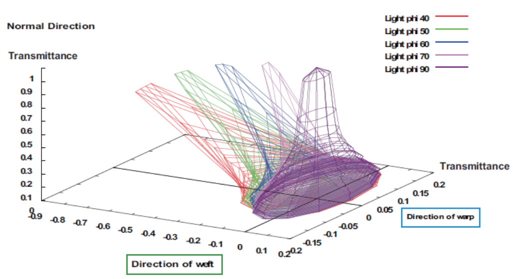
BRDF is commonly used for the texture expression of woven cloth. The Cook-Torrance model [6] is representative of a physically-based BRDF model. In addition, Ashikhmin et al. generated microfacet-based BRDF and modeled satin and velvet cloth [7]. However, they were not concerned with the light transmission characteristics of woven cloth. By contrast, Stam et al. proposed a bidirectional reflectance model and a bidirectional transmittance model to show human skin [8]. Bousquet et al. focused attention on bidirectional reflectance model and bidirectional transmittance of leaves and compared the measured BRDF and BTDF of leaves with a proposed BRDF and BTDF model [9]. Takeda et al. focused attention on Noh costume and estimated the microfacet surface geometry of woven fabrics in considering regular transmission characteristics [10][11]. None of this research, however, was concerned with any of the transmission characteristics of woven cloth other than the regular transmission direction. Woven cloth, such as lace curtains, express the characteristic transparency of soft light. In order to show the characteristic transparency, it is necessary to model the optical property by considering not only the transmission of light but also its light-scattering properties [12].

In this paper, we measure the transmission characteristics and light-scattering property of two different woven cloths and propose a transmission approximate model based on the measurements.

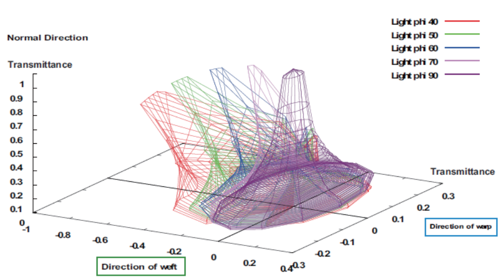
III. Rendering of woven cloth using BRDF and BTDF

A. Measurement of BRDF and BTDF of woven cloth

We measured the BTDF of the two woven fabrics by using a BRDF instrument (OGM-3 [4]), which consists of a fixed digital camera, a movable light source (metal halide), and a movable sample plate. 2400 points per cloth were measured by repositioning the lamp and the plate. As shown in Fig.1, we made the following observations: (1) a woven fabric has the property of bidirectional transmittance and scattering and (2) transmitted light consists of two components, diffusional and directional transmission.



(a) Material A



(b) Material B

Fig. 1. Comparison of two woven fabrics.

B. BTDF model and parameter estimation

1) Proposed BTDF model: In order to render high-quality images of various woven cloths at low computational cost, the use of a standardized BTDF model is essential to represent the measurement data within a few parameters. In general, the transmittance property of an object can be described by BTDF, which is defined as a ratio of the intensity of transmitted light to the intensity of incident light. BTDF is given by the following formula;

$$BTDF(\theta_t, \phi_t, \theta_i, \phi_i) = \frac{L_t(\theta_t, \phi_t, \theta_i, \phi_i)}{L_i(\theta_i, \phi_i)\cos\theta_i} \tag{1}$$

Here, $L_i(\theta_i, \phi_i)$ is the intensity of incident light from the direction of the light source, and $L_t(\theta_t, \phi_t)$ is the intensity of transmitted light to the direction of view point. As shown in Fig.2, the transmitted light to yarn is scattering into the yarn.

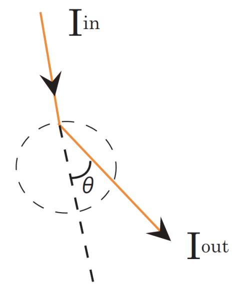


Fig. 2. The light through the yarn

As a result of the measurement as shown in Fig.1, we found that transmitted light consists of a diffuse transmittance component (scattering light) and a directional transmittance component (specular transmittance light). Based on the above understanding, we propose a new BTDF model for woven clothes. This model includes a diffuse transmittance component and a directional transmittance component, each of which is expressed by the Henyey-Greenstein function [5]. The Henyey-Greenstein function is a scattered model that explains the dispersion of dust in the galaxy. This function was applied to the scattering of yarn with following formula.

$$ph(\theta) = \frac{1-g^2}{4\pi(1+g^2-2gcos\theta)^{1.5}} \tag{2}$$

Here, $g \in [-1, 1]$ is a weighting factor that decides the phase of scattering. For g positive, the scattering peaks in the forward scattering direction. For g negative, the scattering peaks in the backward scattering direction. Thus, we give a definition of the intensity of light transmitted to an arbitrary view direction.

$$\begin{aligned} I_{out}(\theta_t) = I_D + k_d I_{in} exp(-\tau) ph_{diff}(\theta_t)\rho + \\ k_s I_{in} exp(-\tau) ph_{spec}(\theta_t)\rho \end{aligned} \tag{3}$$

Here, $I_{out}(\theta_t)$ is the light intensity transmitted, I_{in} is the light intensity, I_D the light intensity transmitted by the gaps in woven cloth, k_d is the diffusional transmittance coefficient, $exp(-\tau)$ is the absorption coefficient, τ is the optical depth (filar width), $ph_{diff}(\theta_t)$ is the Henyey-Greenstein function for the diffusional transmitted light, ρ is the filar density, k_s is the directional transmittance coefficient, and $ph_{spec}(\theta_t)$ is the Henyey-Greenstein function for the directional transmitted light.

2) Estimation method of parameters: In order to apply the proposed model to the measurement data, a method for automatic estimation of parameters is required. We estimate the parameters by using the Levenberg-Marquardt algorithm (LMA). LMA is one of the optimization algorithms that is applied to various problems. To apply optimization to vast amounts of the measured BTDF data is necessary to estimate high-quality appearance. However, the way is not efficient because computation time cost is huge. Because we optimize these parameters by 40 points, which appropriately represents a diffuse transmittance component and a directional transmittance component in the measured BTDF data.

To estimate them by M numbers of input data the merit function is given by the following formula.

$$E(p) = \sum_{f=1}^{F} \sum_{p \in \Omega} r_{fp}^{T} r_{fp} \tag{4}$$

Here,

$$r_{fp} = I_{out}(\theta_t) - I_{out}(\theta_t; a_{fp}) \tag{5}$$

where p is the estimated parameter vector, F is the number of input data, and Ω is the target data aggregate.

Based on the merit function estimates parameters, where the parameter vector defines p_k in case of k, we use the merit function in equation 4.

$$E(p_k) = \sum_{f=1}^{F} \sum_{\in \Omega} (r_{fp}^{k})^{T} r_{fp} \qquad k = 1, 2, ..., M \tag{6}$$

Here, r_{fp}^{k} is the residual vector based on equation 5 in case of k. Then the updated parameters by LMA is given by the following formula.

$$p_{k+1} = p_k - (J_k^T J_k + \lambda_k I)^{-1} J_k^T r_k \tag{7}$$

Here is

$$J_k = \delta_{rk} / \delta_{pk}^{T}, \quad r_k = \begin{pmatrix} \vdots \\ r_{fp}^{k} \\ \vdots \end{pmatrix} \tag{8}$$

where the λ_k is the stabilization parameter to hold divergence and I is the unit matrix. Iterating to the converse is necessary since the minimum is at best only a statistical estimate of the parameters.

3) Comparison between the measured BTDF and the modeled BTDF: The comparison between the measured BTDF and the result of fitting the BTDF model by estimation parameters is shown in Fig.3. The model assumes that the size of the warp yarn and the weft yarn is the same. In comparing the proposed model to the measured value, we found that the peak of the specular transmittance of the model was in agreement with the measured value, and the curve of the diffuse transmittance of the model also corresponded with the measured value.

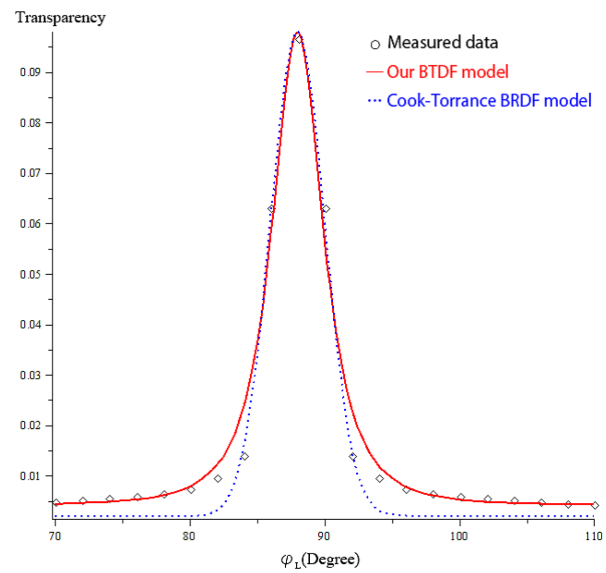


Fig. 3. Comparison between measured BTDF and modeled BTDF.

C. Rendering with the modeled BTDF

The results of rendering based on the measured BTDF and the modeled BTDF are presented in Figs.4 and 5. Both the rendering algorithms are implemented as shader plug-ins for Maya. In both images, we can observe that the transmission factor differs according to the position of the curtains, and the resulting shadows display uneven shading. These results demonstrate that the modeled BTDF is as effective in depicting the transmission property as is the measured BTDF.

D. Real-time rendering of the BTDF

A real-time rendering algorithm of this BTDF model was implemented by using a combination of OpenGL and Nvidia' Cg. The algorithm was programmed using texture sampling by means of an LUT, which was constructed as a two-dimensional bitmap image translated from the four-dimensional BTDF data (Fig.6). The transmitted and reflected light obtained from the LUT, the background light defined by cube mapping, and a texture element were added during rendering.

IV. Estimation Physical Characteristic of Woven Cloth from Subjective Impression

A. Experiment of impression evaluation

We performed an experiment to evaluate subjective impressions about relationships between the optic and the motion

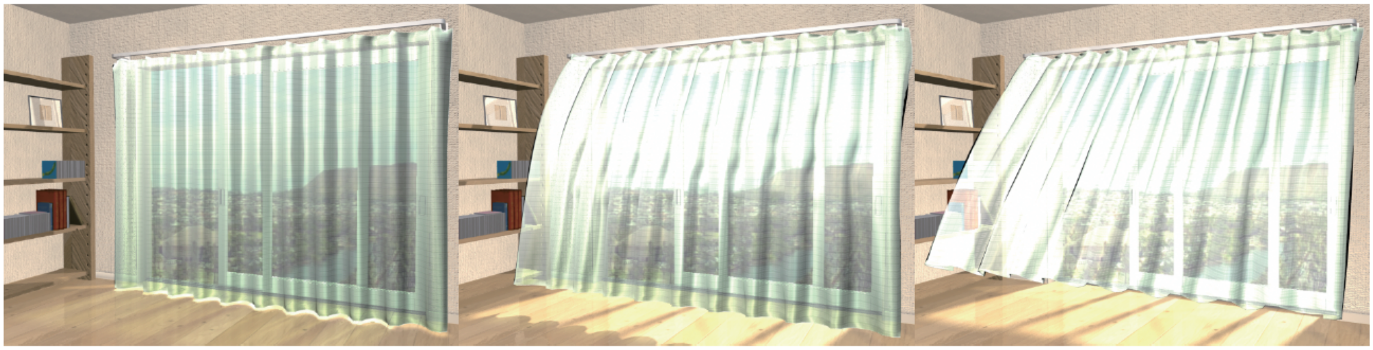


Fig. 4. Rendering of images with the measured BTDF

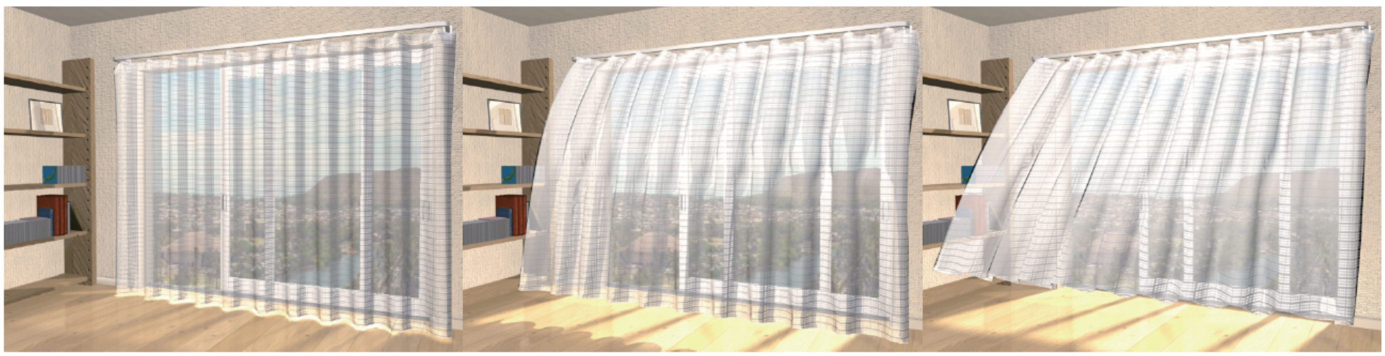


Fig. 5. Rendering of images with the modeled BTDF

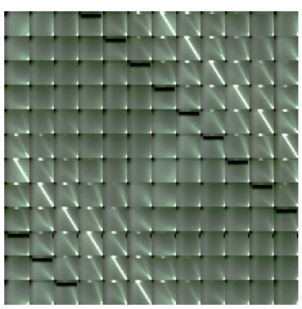


Fig. 6. Lookup table as bitmap image translated from measured BTDF data.

properties, and estimated the dynamic properties from the optic properties directly. The experiment was performed by using ten evaluative word pairs. All evaluative words were adjectives related to the optic and motion properties (e.g., pliable or stiff, heavy or light, and so on). Experimental stimuli were eight curtain animations that differed in values of bend and shear. We adopted Scheffe's paired comparison method as an experimental method. Participants were required to compare eight paired curtain animations with each evaluative word pairs on a five-point scale. The participants were seven men and three women in their twenties.

B. Measurement of BRDF, BTDF and KES of woven cloth

We measured the optic and motion properties of the three woven fabric samples. For optical properties, BRDF and BTDF

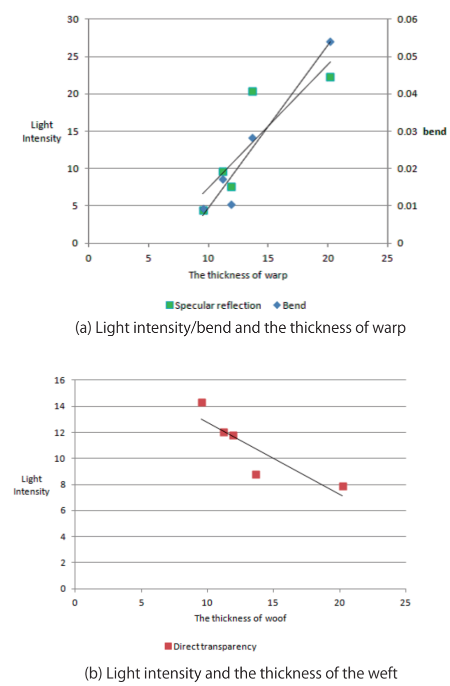


Fig. 7. Relationship between optic and motion properties.

were measured by using a BRDF instrument, OGM-3. For motion properties, bend, shear, and compression were measured by using a handle instrument, KES (Kawabata Evaluation

System).

C. Relationship between optics and motions

The results of the experiment on impression evaluation revealed the impressions of flexibility (pliable or stiff) and weight (heavy or light) are influences on the characteristics of curtain motion. The impressions of flexibility and of weight depend on the bend and the rate of specular reflection. For flexibility, curtain motions were evaluated as more stiff by people when the value of bend and rate of specular reflection were also higher. For weight, curtain motions were evaluated as lighter when the value of bend was lower and rate of diffuse transparency was higher. The value of bend increased in proportion to the thickness of warp. The specular reflectance and the directional transmittance decreased in proportion to the thickness of weft, as shown Fig.7.

D. Rendering animations

We performed the rendering of animations with different subjective impressions by using Maya' shader plug-ins, and compared in Fig.8. The rendering environments are a 3.40 GHz Intel Core i7 processor, 16 GB of RAM, and nVIDIA Quadro 4000 graphics processor.

(a) Stiff and heavy impression. Both warp and weft are thick, the specular reflectance is high and the directional transmittance is low.

(b) Pliable and middle weight impression. The middle appearance of (a) and (c).

(c) Pliable and light impression. Both warp and weft are thin, the specularreflectance is low and the directional transmittance is high.

Fig. 8. The results of curtain animations with different subjective impressions. These images are rendered in the same frame time.

V. CONCLUSIONS

We have proposed a BTDF model and two algorithms for both the off-line and real-time rendering of woven fabrics. Furthermore, the results of the evaluation on subjective impression showed the possibility of estimating the dynamic properties by the optic properties more directly. The rendering animation with the new method, which adopted the evaluations of subjective impressions, enhanced both realistic appearance and motion. We are planning to generate a catalog of curtain animations that can express various types of woven fabrics under arbitrary light conditions.

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