Realtime Rendering of Realistic Fabric with Alternation of Deformed Anisotropy*

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Abstract. In this paper, an efficient method is proposed to produce photorealistic images of woven fabrics without material data such as the measured BRDFs. The proposed method is applicable both to ray tracer based offline renderers and to realtime applications such as games. In order to enhance the realism of cloth rendering, researchers have been utilizing the measured data of surface reflectance properties. Although the example-based approaches drastically enhance the realism of virtual fabric rendering, those methods have serious disadvantage that they require huge amount of storage for the various reflectance properties of diverse materials. The proposed method models the reflectance properties of woven fabric with alternating anisotropy and deformed MDF(microfacet distribution function). The experimental results show the proposed method can be successfully applied to photorealistic rendering of diverse woven fabric materials even in interactive applications.

Keywords: Fabric rendering, alternating anisotropy, deformed anistropy, realtime rendering.

1 Introduction

The goal of physically-based rendering is to produce photorealistic images. The goal can be achieved by modeling the surface reflection properties of virtual objects. In this paper, a new procedural approach is proposed for photorealistic rendering of woven fabric as shown in Figure 1. Fabric appearance is important in industrial applications of computer graphics in the textile, garment, and fabric care industries. There are two main types of fabrics namely, knitwear and woven fabrics. Our goal is to produce photorealistic images of woven fabrics without empirical data such as the measured BRDFs. The physically plausible rendering results can be obtained when the accurate reflection models is found. However, the actual objects in real world usually have complex reflection properties which

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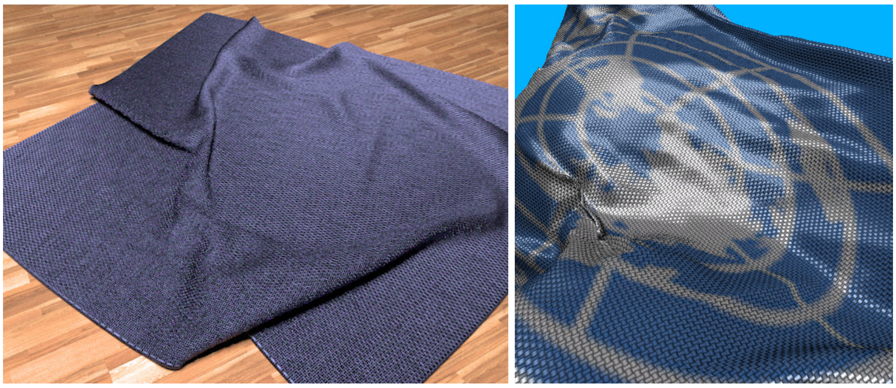


(a) off-line renderer (b) realtime application

Fig. 1. The results of the proposed method

cannot be easily modeled. The method proposed in this paper produces realistic image of virtual woven fabric by procedurally modeling the alternating anisotropic reflection on the fabric surface and deforming the microfacet distribution function(MDF) in accordance with the weave patterns and yarn-level structure.

2 Related Work

Fabrics can be categorized into two classes. One of them is knitted fabric and the other is woven fabric. There have been various research efforts to model and render the knitted fabric[7,8,9,10,15,19]. However, those methods cannot be directly employed for rendering woven fabrics because those methods usually focus on the fluffy texture and the knitted structures.

In this paper, we exploit the microfacet model for modeling the surface reflection property of fabric. The microfacet model was first proposed by Torrance and Sparrow[18], and then introduced to graphics literature by Cook and Torrance[5].

Yasuda *et al.* proposed a shading model for woven fabric by applying anisotropic reflectance according to the yarn direction[20]. This approach is one of the earliest efforts for plausible fabric rendering with procedural techniques. Their method is based on the microfacet model proposed by Blinn and Newell[11]. Although this method is the first approach to woven fabric rendering with weave-based reflectance model, it is not capable of rendering the close-up scene where weave patterns are visible.

Adabala *et al.* proposed a woven fabric rendering method that can be applied to both distant and close-up observations of woven surface[2,1]. Their method is based on the microfacet model proposed by Ashikhmin and Shirley[3,4], and utilizes horizon map proposed by Sloan *et al.*[17]. The distant viewing of the method is the generalized model of the satin fabric rendering in [3]. The major advantage of the method is that it can render various weave patterns and represent the spatially varying reflectance based on the weave patterns. However, this method focuses on variety of weave patterns and treated the light reflection on the yarn surface somewhat lightly.

Photorealistic rendering of woven fabric requires spatially varying anisotropic reflectance model. Some researchers tried to capture the spatially varying BRDF (SVBRDF) for realistic representation of the fabric material [6,13,14]. However, capturing the SVBRDF requires expensive devices and huge amount of storage. Wang *et al* proposed a SVBRDF measuring techniques using data captured from a single view[12]. This method made it possible to capture SVBRDF with low-cost measuring device by synthesizing microfacet model based on measured partial normal distribution functions. Although this method can reproduce photorealistic image of woven fabric, it still requires huge amount of storage for SVBRDF. Moreover, one needs to measure all kinds of fabric which will be possibly used in rendering.

Sattler *et al*. employed BTF(bidirectional texture function) proposed by Dana *et al*.[6] to render photorealistic woven fabric[16]. However, this method also suffers from the common disadvantages of example-based approach. The measured data requires huge amount of storage, and the reflectance property of rendered fabric cannot be easily controlled.

Zinke and Weber proposed bidirectional fiber scattering distribution function(BFSDF) for physically plausible rendering of dielectric filament fiber[21]. However, the BFSDF is 8 dimensional function so that it cannot be easily dealt. They introduced various approximation techniques to reduce the dimensionality of the scattering function. The disadvantage of this method is that this method requires geometry for the fiber. Therefore, an extremely complex geometry is required to represent a woven fabric object.

3 Woven Fabric Rendering

In this section, we will introduce a procedural techniques that represent the surface reflectance of woven fabric. The proposed method is based on microfacet model and the microfacet distribution function is deformed in order to express the peculiar reflectance of woven fabric.

3.1 Alternating Anisotropy and Weave Control

The reflectance property of microfacet model is dominated by the MDF (microfacet distribution function) $D(\omega_h)$ which gives the probability that the normal vector of a microfacet is oriented to ω_h. Ashikhmin *et al*. proposed an anisotropic reflectance model as follows[3]:

$$D(\omega_h) = \frac{\sqrt{(e_x+1)(e_y+1)}}{2\pi}(\omega_h \cdot \mathbf{n})^{e_x \cos^2\phi + e_y \sin^2\phi} \quad (1)$$

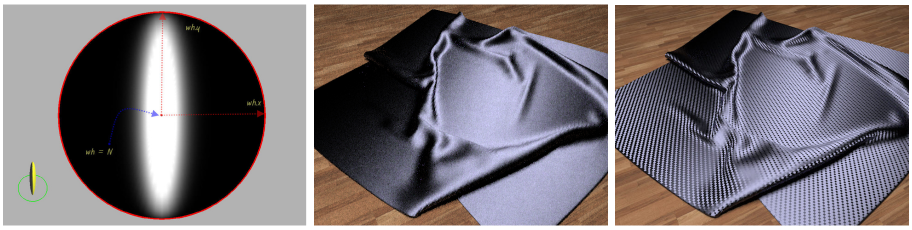
where e_x and e_y are the exponents for the distribution function for controlling the anisotropy of the reflectance, and ϕ denotes the azimuthal angle of the half vector

ω_h. One can easily control the anisotropic reflectance by changing the parameters e_x and e_y. These two parameters control the shape of the specular lobe. Since ω_h is a unit direction vector, it can be represented as $(\omega_{h.x}, \omega_{h.y}, \sqrt{1-\omega_{h.x}^2-\omega_{h.y}^2})$

Woven fabric has weft and warp yarns. Because the yarns are oriented in different directions, the reflectance anisotropy is alternating according to the yarn direction. Therefore, we employed alternating anisotropy for woven fabric, and the anisotropy is determined by the underlying weave patterns. We can easily alternate the anisotropy by swapping the parameters e_x and e_y. First we determine whether the sampled point is weft yarn, warp yarn, or inter-yarn gap. We then apply different distribution functions D_{weft} and D_{warp} for weft yarns and warp yarns respectively as follows:

$$\begin{aligned} D_{weft}(\omega_h) &= \frac{\sqrt{(e_x+1)(e_y+1)}}{2\pi}(\omega_h \cdot \mathbf{n})^{e_x \cos^2\phi + e_y \sin^2\phi} \\ D_{warp}(\omega_h) &= \frac{\sqrt{(e_x+1)(e_y+1)}}{2\pi}(\omega_h \cdot \mathbf{n})^{e_x \sin^2\phi + e_y \cos^2\phi} \end{aligned} \tag{2}$$

The method proposed in this paper is based on the anisotropy that is determined by weave patterns. Therefore, it is very important to define the weave pattern and determine whether the sampled point is on a weft yarn or a warp yarn. Once the yarn direction is determined, the alternating MDFs described in Eq. 2 are applied.



(a) 2D MDF (b) Anisotropic reflectance (c) Alternating Anisotropy

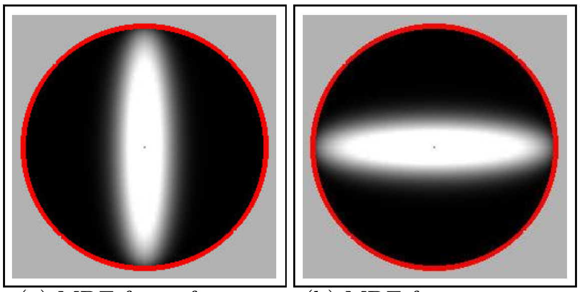
Fig. 2. Alternating anisotropic reflectance

Figure 2 demonstrates the effect of the the alternating anisotropy. The distribution function can be easily visualized in 2D space where two axis are aligned with $\omega_{h.x}$ and $\omega_{h.y}$ as shown in Figure 2 (a). Figure 2 (b) shows the simple anisotropic reflectance and (c) shows the result when the anisotropy is alternated along the yarn direction by applying the distribution functions shown in Eq. 2.

The MDFs shown in Eq. 2 are in fact the same because we can easily rotate one MDF to coincide with another. This concept is described in Figure 3.

3.2 Deformed MDF for Woven Surface Representation

The alternating anisotropy can be efficiently and effectively utilized for describing the woven fabric reflectance. However, the alternating anisotropy cannot represent



(a) MDF for weft yarns (b) MDF for warp yarns

Fig. 3. MDF Rotation for Alternating Anisotropy

the bumpy surface of woven fabric. In order to produce realistic bumpy surface caused by woven structure, we used deformed MDFs rather than the original base MDFs shown in Eq. 2.

If we can rotate the MDF in order to represent the alternating anisotropic reflectance on the woven surface as shown in Figure 3, we can also deform the MDF to represent the different reflectance on the bumpy surface.

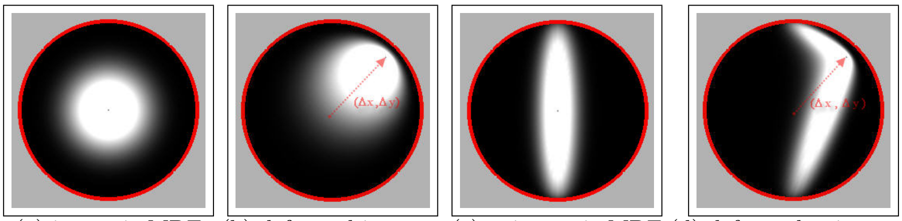
The result shown in Figure 2 assumes that the most probable normal direction of the sampled point is exactly the same as the normal given by underlying geometry. However, our goal is to procedurally generate the bumpy woven surfaces defined by weave patterns. The normal vectors on woven surface should be perturbed according to the defined weave patterns.

In order to perturb the normal vector at the sampled point, we need to know how far the sampled point is from the axis of the yarn The offsets in weft and warp yarns are denoted as σ^v and σ^u respectively. These offsets range from -1 to 1. The offset value is 0 when the sampled point is on the axis of the yarn, and 1 or -1 at the both ends of the yarn.

Let us denote the perturbed normal as $\tilde{\mathbf{N}}$ while the original normal given by mesh data is denoted as $\mathbf{N}$. In the surface coordinate system (tangent space), $\mathbf{N}$ is always represented as $(0, 0, 1)$. Therefore, the perturbed normal $\tilde{\mathbf{N}}$ can be easily denoted as $(\Delta x, \Delta y, \sqrt{1 - \Delta x^2 - \Delta y^2})$. The basic idea of this paper is that we can easily obtain the approximate reflectance at the sampled point with the perturbed normal by deforming the base MDF. The deformation translates the center of the distribution function with the amount of $(\Delta x, \Delta y)$.

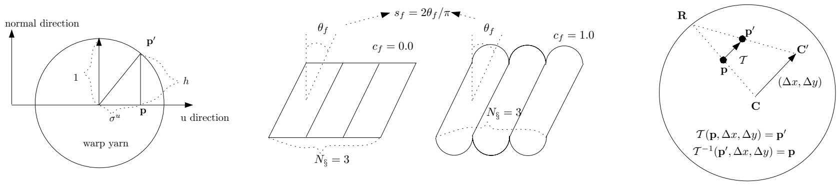
Figure 4 shows the basic concept of the deformed MDF. Figure 4 (a) and (c) show the base MDFs, and (b) and (d) show the corresponding deformed MDFs with the amount of $(\Delta x, \Delta y)$.

Figure 5 (a) shows the cross section of a perfectly circular warp yarn. As shown in the figure, the sampled point $\mathbf{p}$ should be rendered as if it is located at the displaced point $\mathbf{p}'$. We can easily notice that the x component of the perturbed normal is proportional to the offset ratio σ^u which ranges from -1 to 1. Therefore, the MDF of the sampled point on a warp yarn can be described by deforming the base MDF with $(c_y\sigma^u, 0)$ where c_y denotes the yarn curvature



(a) isotropic MDF (b) deformed isotropy (c) anisotropic MDF (d) deformed anisotropy

Fig. 4. Visualization of MDF deformation



(a) Circular yarn cross section (b) Twisted fiber parameters (c) MDF deformation concept

Fig. 5. Bumpy cloth model and reflectance deformation

control parameter ranging from 0 to 1. We can similarly model the MDF of a sampled point on a weft yarn with the deformation amount of $(0, c_y\sigma^v)$.

A single yarn is usually the collection of twisted fibers. Figure 5 (b) shows the parameters for controlling the reflectance of a yarn based on the twist. θ_f is the slope angle of the twist, and c_f is the curvature control parameter for twisted fiber. For simplicity, we denoted $2\theta_f/\pi$ as s_f to control the slope, and then s_f ranges from 0 to 1. As shown in the figure, the twisted fiber is flat when c_f is zero, and curvature increases as c_f increases. The parameter $N_§$ denotes the number of twists within a weave element space. We can easily notice that the twisted structure affects the y components of MDF deformations for warp yarns while it affects the x components for weft yarns. For the warp yarns, the deformation caused by twisted fiber is $(0, c_f(2\mathbf{fract}(N_§(v_w - s_f\sigma^v)) - 1)$ where the function $\mathbf{fract}(x)$ returns $x - \lfloor x \rfloor$. The MDF deformation for weft yarns caused by the twisted structure can also similarly described. Therefore, the MDF deformation on woven surface can be finally described as follows:

$$
\begin{aligned}
&(\Delta x, \Delta y) \\
&for\ weft : (c_f(2\mathbf{fract}(N_§(u_w - s_f\sigma^u)) - 1, c_y\sigma^v) \\
&for\ warp : (c_y\sigma^u, c_f(2\mathbf{fract}(N_§(v_w - s_f\sigma^v)) - 1)
\end{aligned}
\tag{3}
$$

It is obviously inefficient to compute the deformed MDF for every sampled point. Instead, we used only the original base MDF $D(w)$ shown in Eq. 2 and transformed coordinate. Figure 5 (c) shows the MDF deformation concept. The value at the point $\mathbf{p}$ will be moved to $\mathbf{p}'$ in the deformed MDF. We can define a function that transforms the point $\mathbf{p}$ to $\mathbf{p}'$ as $\mathcal{T}$. Then we can easily obtain the inverse function $\mathcal{T}^{-1}$. Let $\mathbf{R}$ be the intersection point of the circumference of the MDF and the ray from the deformed center $\mathbf{C}'$ passing through the deformed point $\mathbf{p}'$. We can easily notice that the deformed point and the original point $\mathbf{p}$ are related as follows:

$$\mathcal{T}^{-1}(\mathbf{p}', \Delta x, \Delta y) = \mathbf{p}' - \frac{|\mathbf{R} - \mathbf{p}'|}{|\mathbf{R} - \mathbf{C}'|}(\Delta x, \Delta y) \quad (4)$$

In order to compute the reflectance intensity at a sampled point where the normal is perturbed with the amount $(\Delta x, \Delta y)$, we simply apply usual microfacet based procedural BRDF with $D(\mathcal{T}^{-1}(\omega_h, \Delta x, \Delta y))$.

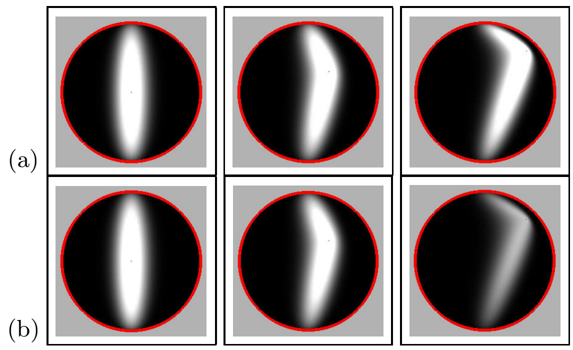
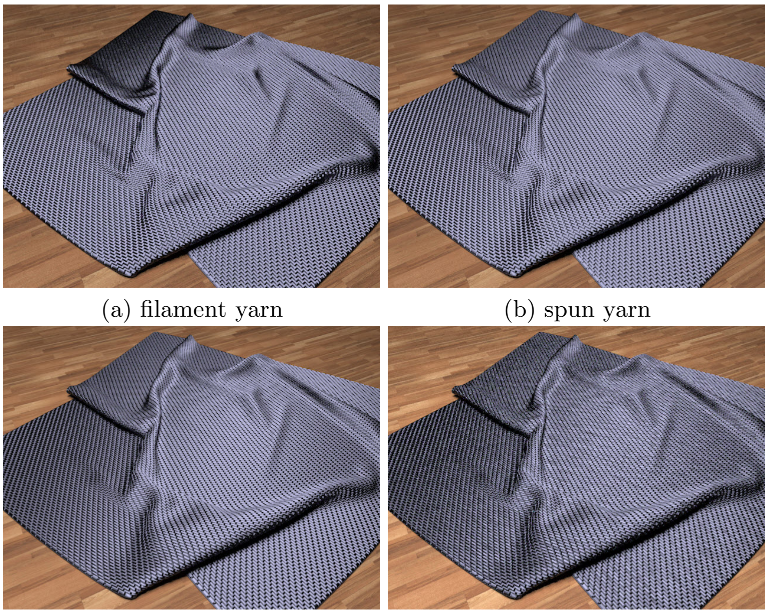


Fig. 6. Approximate ambient occlusion for MDF deformation: (a) simple MDF deformations, (b) MDF deformations with approximate ambient occlusion effects

Although the deformed MDFs of the sampled points on the woven surface effectively perturb the reflectance on the surface, the sampled points are still on a flat plane. Therefore the self-shadowing by the bumpy structure of the woven surface cannot be represented with deformed MDFs. In this paper, we approximated the ambient occlusion to increase the realism of rendered woven fabrics. Instead of casting rays in every direction from the surface, we simply approximated the ambient occlusion with the amount of the MDF deformation. Therefore, the reflected intensity was scaled by $(1 - \sqrt{\Delta x^2 + \Delta y^2})$. Figure 6 shows the effect of the approximate ambient occlusion. The row (a) shows the simple MDF deformation while (b) shows the deformed MDF with the consideration of the approximate ambient occlusion.

4 Experiments

We implemented the proposed method for both physically based renderer and realtime application.



(a) filament yarn (b) spun yarn

(c) approx. ambient occlusion (d) noise added

Fig. 7. The effect of the proposed techniques: (a) MDF deformation without twisted structure ($e_x = 100, e_y = 0.1, c_y = 0.5$), (b) MDF deformation with twisted structure ($c_f = 0.75, N_\S = 4$), (c) approximate ambient occlusion applied to MDF, and (d) realism enhanced with noise

Figure 7 shows the effect of the proposed techniques when applied to ray tracing based renderer. Figure 7 (a) shows the result when MDF was deformed to represent the curved surface of the cylinder-shaped filament yarns while (b) shows the result when the twisted fiber structure is also considered. As shown in the figure, the spun yarn model reduces the specularity, and brightens and smoothens the shaded area on the woven surface. The result shown in Figure. 7 (c) shows the effect of the approximate ambient occlusion and (d) shows the effect of the thread-wise noise.

Figure 8 compares the real fabric images and rendered images of virtual fabric. As shown in the figure, the proposed method can produce plausible virtual fabric objects.

The proposed method can be easily implemented with GPU programming languages and applied to realtime applications. Figure 9 demonstrates the proposed method can effectively render the woven surface even in realtime applications. The results were obtained by implementing a hardware shader with OpenGL shading language and the spatially varying reflectance on the woven surface is plausibly expressed. Table 1 show the comparison result when the time expenses taken by proposed rendering method and other rendering methods is compared with the cost of OpenGL default Gouraud shading. As shown in the table, the

(a) real fabric (d) rendered fabric

Fig. 8. The comparison of real fabric and rendered virtual fabric: (a) real fabric image, (b) virtual fabric rendered with the proposed method

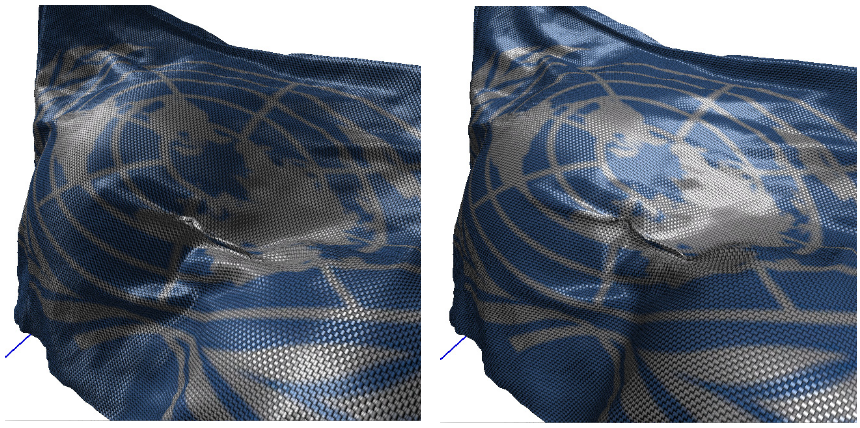


Fig. 9. Spatially varying reflectance according to the light movement in a realtime application

proposed method is efficient enough to be used in realtime applications. For the experiment, the proposed method was test on Mac OS X with 2.26 GHz intel core 2 CPU, 2G 1067 Mhz DDR3 RAM, and NVIDIA GeForce 2400M Graphics Hardware.

Table 1. Time expenses of rendering methods are compared with OpenGL default Gouraud shading

	Gouraud shading	Per-pixel lighting	Alternating anisotropy	Proposed method
Time Cost	1	1.415	1.785	1.846

Figure 10 shows the various rendering results by changing the distance between the observation camera and the fabric objects. As shown in the figure, the proposed method can effectively generate realistic fabric in arbitrary distances both in realtime applications and in offline renderers.

(a) realtime rendering
(b) closeup rendering (realtime)
(c) global illumination
(d) closeup rendering (global illumination)

Fig. 10. Rendering of woven surface with varying observation distance: (a) and (b) realtime rendering results, (c) and (d) offline rendering with global illumination

(a) Satin Weave
(b) Twill Weave

Fig. 11. The rendering results according to the weave patterns with $e_x = 20$ and $e_y = 2$: (a) satin fabric ($n_w = \infty$) (b) twill fabric ($n_w = 2, n_\pi = 1, n_\sigma = 1$)

Figure 11 demonstrates the effect of weave pattern control. As shown in the figure, we can effectively generate various fabric reflectance by simply control the weave pattern parameters, n_w and n_σ. Figure 11 (a) shows the rendering result with satin weave while (b) is rendered with twill weave pattern.

5 Conclusion

In this paper, a procedural approach to photorealistic fabric rendering is proposed. The proposed method reproduces natural reflectance of woven fabric by alternating the anisotropy. Moreover, the proposed method generates the bumpy illusion on the woven fabric by deforming the microfacet distribution function(MDF). The proposed method takes into account the weave patterns and twisted fiber structure. The twisted fiber model and realism enhancement of the proposed method drastically increase the rendering quality.

The experimental results show that the proposed method can be successfully employed for photorealistic rendering of diverse woven fabric materials even in realtime applications such as games and VR systems. The proposed method was successfully implemented with OpenGL shading language and produced realistic cloth image in a realtime rendering application.

Since the reflectance properties of the woven surface was procedurally modeled, the observation of the virtual fabric can be performed in arbitrary distance. The experimental results show that the proposed method always provides plausible rendering results regardless of the observation distance.

Even the simple BRDF data usually requires heavy data so that an extremely large amount of storage will be required to express various material. Even worse, the spatially varying BRDF (SVBRDF) is essential for plausible representation of woven fabric, and the SVBRDF data requires far larger amount of storage. However, the proposed method efficiently renders plausible woven fabric objects without any expensive measured data.

The efficiency and the procedural approach of the proposed method enable interactive applications such as games to employ the rendering techniques to express realistic woven fabric.

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