

Efficient Image-based Anisotropic Reflectance Modeling based on Microfacet Geometry of Woven Fabrics

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1 Introduction

One of the most challenging problems in computer graphics and computer vision is modeling of deformable objects with anisotropic reflection properties such as textile fabrics. Research on cloth simulation in CG started at late 1980th. First, wrinkles and drapes generation had attempted by modeling dynamic behavior of fabric [1]~[4]. Anisotropic reflection of fabric had been studied based on its bi-directional characteristics and various models such as anisotropic extension of Phong model had proposed [6]~[10]. The reflection characteristics of fabric surface can be described by the bi-directional reflectance distribution function (BRDF). Several method had proposed to generate BRDF based on the micro facet geometry of fabric surface [12, 13], where complex luster and texture of satin or velvet was generated by modeling the microfacet geometric structure of a fabric surface.

An image-based anisotropic rendering method to obtain BRDF based on Ward's Gaussian reflectance model [9] was also reported [11], however, anisotropic reflection was not reconstructed with high accuracy. Recently, an image-based method was proposed using newly developed optical gyro measuring machine (OGM) of omnidirection type [14]. However, it requires enormous data to obtain high resolution BRDF.

In this paper, we propose an efficient image-based anisotropic reflectance modeling method of textile fabrics based the microfacet surface geometry determined by the cross-sectional shape of fibers, twist of strings, and a type of weave. We first examine the relationship between the reflectance properties and the microfacet surface geometry of a textile fabric using a silk-like synthesized fabric. We then develop an anisotropic model, which provides a bi-directional reflectance distribution function (BRDF) from small numbers of images observing the orthogonal characteristics of textile fabrics, based on KES (Kawabata's Evaluation system for fabrics) method. Experimental results show the efficiency and effectiveness of the proposed approach.

2 Cross-sectional Shape of Fiber

Synthetic fibers have various cross-sectional shapes to reproduce luster and texture of natural fibers as shown in Figure 1. A silk fiber is made of two fibroins and sericin that covers these fibroins as in Figure 2(a). Refinement after woven into fabric eliminates sericin to give the luster of silk. The silk-like synthetic fiber such as polyester has a triangular cross-sectional shape, as in Figure 2(b), since the cross-sectional shapes of the fibroin is rounded and flattened triangle.

In this work, we choose a polyester satin of filament strings, as our objective woven fabric, in which the cross-section shape of the fibers is a dominant factor to determine the micro facet geometry of the objective fabric, since a filament fiber of silk-like polyester is untwisted and the ratio of a warp to weft of satin is large. Figure 3(a) and (b) show the weave and cross-section shape of fibers of our polyester satin. These characteristics of satin work as advantages to analyze and model the mutual relation between the cross-sectional shape of fibers, structure of weave and reflection characteristics in the micro facet geometry.

3 Dynamic Anisotropy of Woven Fabrics

Fabric industry use Kawabata's Evaluation System for Fabric (KES) as the method to measure dynamic characteristics of fabric such as tensile or a bending properties. Originally, KES was developed for quantization of fabric texture from properties of warp and weft. Sakaguchi [3] extended KES so that it could take properties in bias directions.

In the extended KES, dynamic properties are given by the following equations (1) and (2).

$$\begin{aligned} \rho_{KES}(\phi, \gamma) \\ = \frac{\cos^4 \phi}{\rho(0, \gamma)} + G' \sin^2 \phi \cos^2 \phi + \frac{\sin^4 \phi}{\rho(\frac{\pi}{2}, \gamma)}^{\frac{3}{4}-1} \end{aligned} \quad (1)$$

$$G' = \frac{4}{\rho(\frac{\pi}{4}, \gamma)} - \frac{1}{\rho(0, \gamma)} - \frac{1}{\rho(\frac{\pi}{2}, \gamma)} \quad (2)$$

where, $\rho(0, \gamma)$, $\rho(\frac{\pi}{2}, \gamma)$ and $\rho(\frac{\pi}{4}, \gamma)$ are dynamic properties in the warp, weft and $\frac{\pi}{4}$ bias direction such as tensile and bending properties, ϕ is an angle against the weft direction, γ is force.

We tried to obtain omnidirectional anisotropic reflectance properties of a fabric by interpolating reflectance among the warp, weft and two bias directional measurements, using the extended KES, since 1) the optical anisotropy of fabric seems to originate from orthogonal weave structure in which the warp and the weft are orthogonal as well as the dynamic anisotropy, and 2) the bias directions agree with the characteristic direction in which incident light penetrate most.

Thus, we measure the reflectance of the objective fabric in only four directions by rotating it by $\frac{\pi}{4}$ degrees at each time.

Figure 4 shows our omnidirectional optical gyro measuring machine (OGM) of 4 DOF.

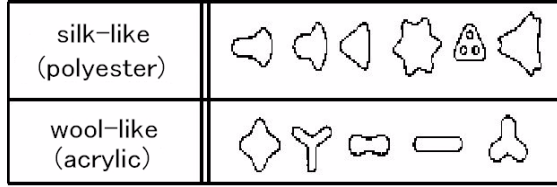
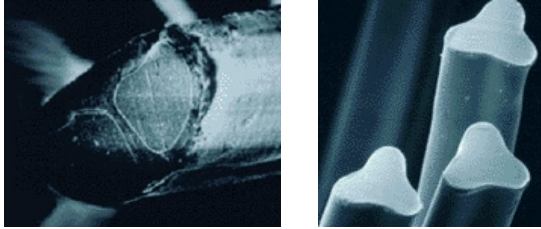
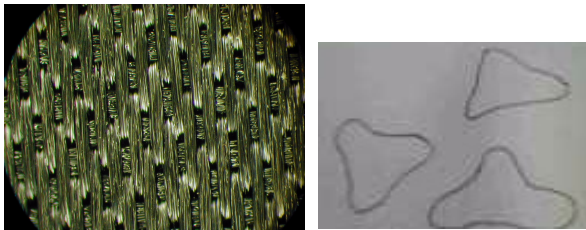


Figure 1: The cross-sectional shape of synthetic fiber



(a) Natural silk fiber (b) Polyester fiber

Figure 2: Cross-Section of natural v.s. synthesized silk



(a) Satin weave (b) Cross-Section of fibers

Figure 3: Our Objective Fabric of Polyester Satin

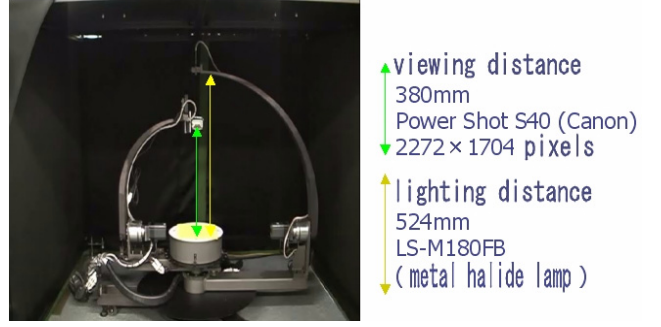


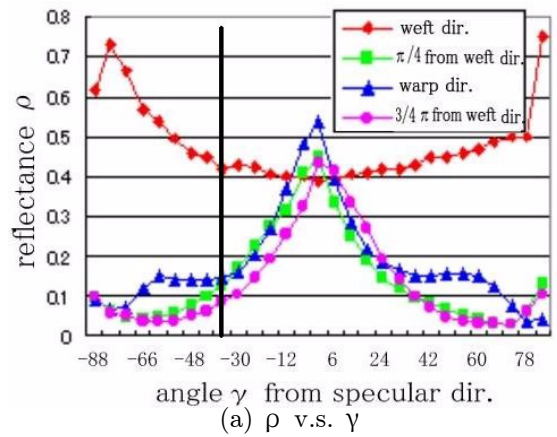
Figure 4: OGM(Optical Gyro Measuring Machine)

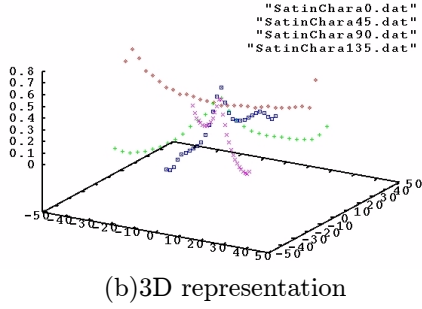
4 Modeling Steps

Step1. Reflection Measuring in Warp, Weft, $\frac{\pi}{4}$ and $\frac{3\pi}{4}$ Bias Directions

Reflection properties of various fabrics differs depending on their material, we need enormous number of measurement of reflectance values for each combination of incident direction and viewing directions in order to get a BRDF with high resolution. However, we can limit measurements at only four directions, since 1) a fabric has orthogonal bi-directional anisotropy and a string has unidirectional anisotropy and 2) measurements among the four directions are enough as long as the orthogonal anisotropy of a fabric can be interpolated by the extended KES.

Thus, we measure brightness of reflected ray by changing the direction of incident ray from $\frac{\pi}{2}$ to 0 and the viewing angle from 0 to $\frac{\pi}{2}$ at every 3 degrees. The same measurement is done in the warp, weft, $\frac{\pi}{4}$ and $\frac{3\pi}{4}$ bias directions and we obtain a set of total 116 BRDF values. Figure 5(a) and (b) shows reflectance values measured along 0, $\frac{\pi}{4}$, $\frac{\pi}{2}$, $\frac{3\pi}{4}$ directions.





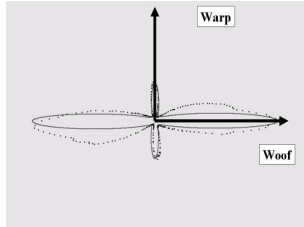
(b)3D representation
Figure 5: Reflectance ρ v.s. an angle γ from the direction of specular reflection

Step2. Interpolating Anisotropic Reflection with the extended KES method

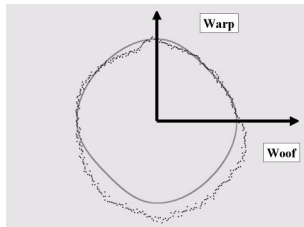
We interpolate reflectance properties from the 4 directional measurements using the extended KES [2].

For each γ , an angle from the direction of specular reflection, we obtain reflectance of $\rho(0, \gamma)$, $\rho(\frac{\pi}{4}, \gamma)$, $\rho(\frac{\pi}{2}, \gamma)$, $\rho(\frac{3\pi}{4}, \gamma)$. These values correspond to the four points on the vertical line in Figure 5(a). Then using equations (1) and (2), we interpolate the reflectance $\rho(\phi, \gamma)$ for an arbitrary direction ϕ . Figure 6 shows the comparison between the KES interpolation values (a solid curve) and measured values (a dashed curve) at $\gamma = -\frac{\pi}{3}, 0$ respectively.

These results show the efficiency in reflectance interpolation by the extended KES method.



(a) $\gamma = -\frac{\pi}{3}$



(b) $\gamma = 0$ (at specular dir.)

Figure 6: Measured(dashed) v.s. KES interpolated values(solid) of reflectance

Step3. Observing Anisotropic Reflection

In order to observe and analyze the relation between the micro facet geometry of a fabric surface and the distribution of reflection, we measure omnidirectional reflectance distribution for incident ray in the warp, weft and bias directions.

The incident angles selected for observation are 0, 15, 30, 45, 60 and 75 degrees for each warp, weft and 45, 135 degrees bias directions. We obtain total of 127,440 reflected ray data by taking images of the fabric using OGM in the warp, weft and bias direction while changing viewing angle from 0 to 87 degrees by 3 degrees in the direction of regular reflection and the opposite direction.

Figures 10, 11 and 12 show the results on the omnidirectional measurement of the fabric in the warp, weft and bias directions with incident angle of 45 degrees. Each of reflectance distribution with the incident angles of 0, 15, 30, 45, 60 and 75 degrees are painted by light blue, white, green, yellow, red and blue lines, respectively.

Step4. Generating an Anisotropic Reflection Model

Figure 13 shows the spherical representation of reflectance curves of the same γ , an angle from the specular dir., where x, y and z axis represents the the direction of weft, warp and specular reflection respectively and a radius $\rho(\phi, \gamma)$ represents the reflectance. We call this graph as the anisotropic reflection model ρ_{KES} , which represents the reflectance distribution with an incident angle $=0$, i.e. the light source is right above the fabric surface, as shown in Figure 13. The BRDF will be obtained by the following equation (3). The details of the deliberation can be referred to [15].

$$\rho_{bd}(\theta_r, \phi_r, \theta_i, \phi_i) = \frac{\rho_d}{\pi} + \rho_s \frac{1}{\cos\theta_i \cos\theta_r} \rho_{KES}(\frac{\pi}{2} - \phi, \gamma') \quad (3)$$

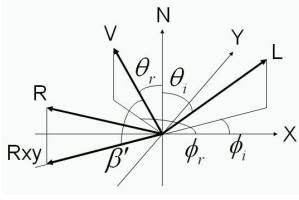
where, (θ_r, ϕ_r) is the reflection(viewing) direction, (θ_i, ϕ_i) is the incident ray direction, ρ_d is diffuse reflectance, ρ_s is specular reflectance, $\phi = \frac{\beta\phi_r}{\beta^0}$, $\gamma' = \frac{\pi}{2} - \frac{\beta}{\beta^0}(\frac{\pi}{2} - \theta_r)$, $\beta' = \beta - \theta_i \sin\beta$, $\sin^2 \frac{\beta^0}{2} = \sin^2 \frac{\phi_r}{2} + \frac{1}{4} \cos^2 \theta_r$.

These angular parameters and vectors of directions are illustrated in Figure 7. X is the vector of weft direction, Y is the vector of warp direction, N is the normal vector of a fabric, L is the vector of light source, V is the vector of viewpoint, R is the vector of reflected ray, R_{xy} is the projection vector of R to the XY plane, ϕ_i is the angle between the projection vector of L to the XY plane and the direction of weft,

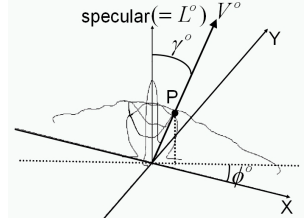
θ_i is the angle of incident ray, ϕ_r is the angle between the projection vector of $\mathbf{V}$ to the XY plane and the direction of weft, θ_r is the angle between the normal vector and the viewpoint vector $\mathbf{V}$, β' is the angle between $\mathbf{R}_{xy}$ and $\mathbf{V}$, as shown in Figure 7(a). $\mathbf{V}^o$ is a viewing direction with an angle γ^o from the specular direction in our anisotropic reflection model ρ_{KES} . $\mathbf{V}^o$ is shifted to $\mathbf{V}$ with the incident ray $\mathbf{L}^o$ from the top inclined to $\mathbf{L}(\theta_i, \phi_i)$, as shown in Figure 7(b). γ^o is the angle between $\mathbf{N}$ and $\mathbf{V}^o$, ϕ^o is the angle between the projection vector of $\mathbf{V}^o$ to the XY plane and the direction of weft, $\mathbf{P}$ is a surface intersection point of $\mathbf{V}^o$ with ρ_{KES} , β is the angle between $\mathbf{R}_{xy}$ and $\mathbf{V}^o$, as shown in Figure 7(c).

As shown in Figure 7(d), ϕ^o , γ^o , and β' are approximated lineally using the following relation on the plane defined by its normal $\mathbf{n} = \mathbf{R}_{xy} \times \mathbf{V}$.

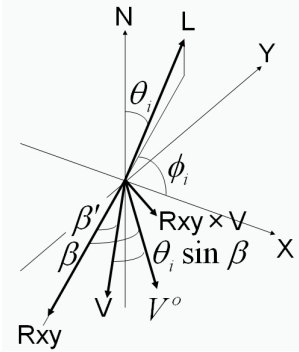
$$\beta'/\beta = (\phi_r - \phi_i - \pi)/(\phi - \phi_i - \pi) = (\frac{\pi}{2} - \theta_r)/(\frac{\pi}{2} - \gamma') \quad (4)$$



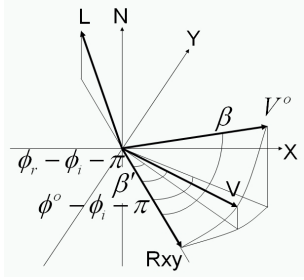
(a) Angular parameters



(b) $\mathbf{V}^o$ in Anisotropic Reflection Model ρ_{KES}



(c) Relation btwn $\mathbf{V}$ and $\mathbf{V}^o$



(d) Relation btwn β and β'

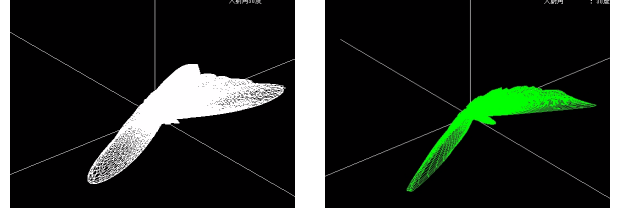
Figure 7: Geometry in Reflection

5 Experiments

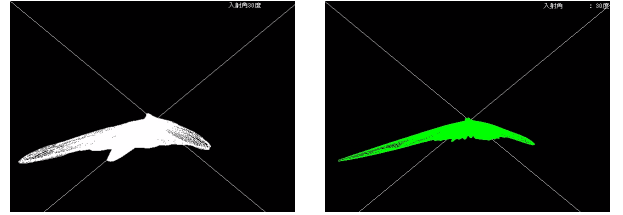
We evaluated our model by comparing the simulated reflection values of the satin cloth by our model with the real reflection values, measured by OGM.

Figures 8(a)(b) show the comparison results by the incident ray, of $(\theta_i = \frac{\pi}{6}, \phi_i = \frac{\pi}{2})$ and $(\theta_i = \frac{\pi}{6}, \phi_i = \frac{\pi}{4})$, respectively.

Figure 9 shows dressing simulation with anisotropic reflection rendering using our proposal model.



(a) simulated(left) and real(right) reflectance at $(\theta_i = \frac{\pi}{6}, \phi_i = \frac{\pi}{2})$



(b) simulated(left) and real(right) reflectance at $(\theta_i = \frac{\pi}{6}, \phi_i = \frac{\pi}{4})$

Figure 8: Simulated v.s. real reflectance of a satin cloth.

6 Conclusion

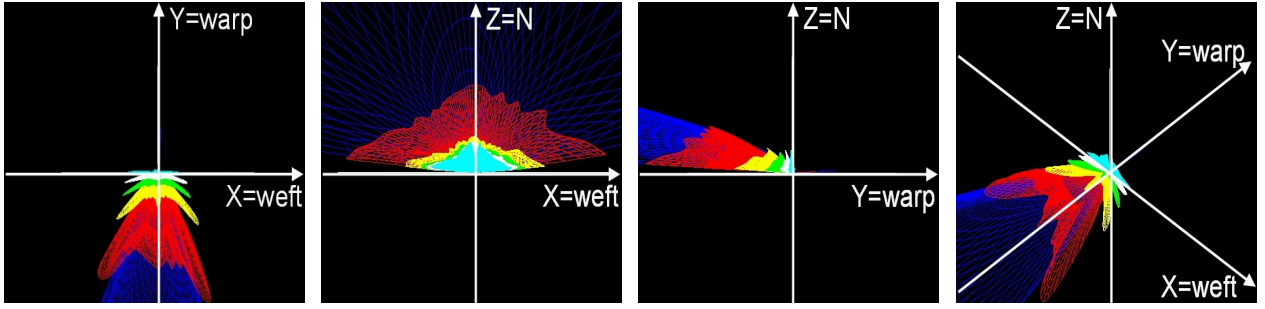
We proposed an efficient image-based anisotropic reflection modeling method of textile fabrics based the microfacet surface geometry determined by the cross-section shape of fibers, twist of strings, and a type of weave. The experimental results on dressing simulation of satin cloth, achieved with about 1/100 of image data used in [14], demonstrated the performance of our model.



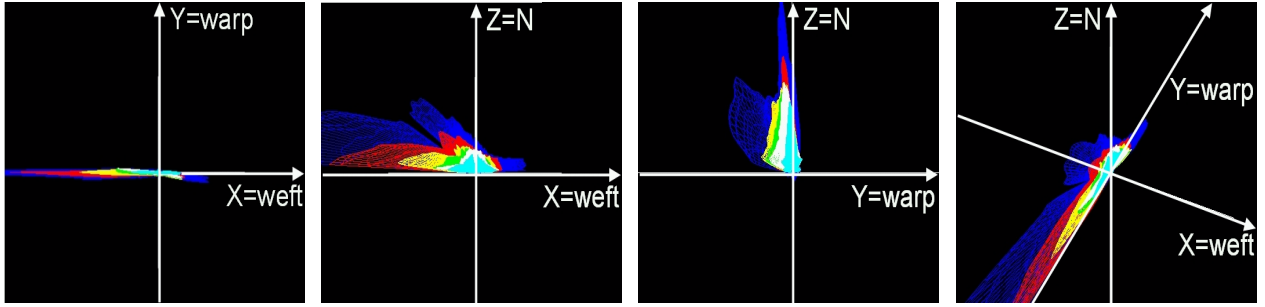
Figure 9: Dressing simulation with anisotropic reflection rendering

Reference

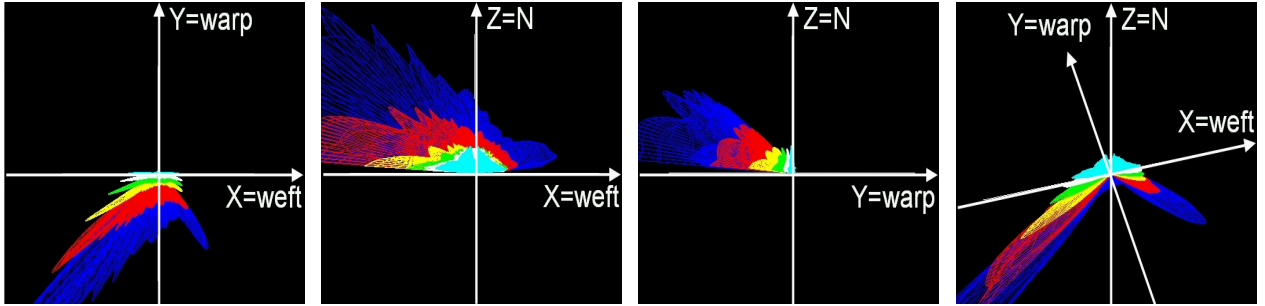
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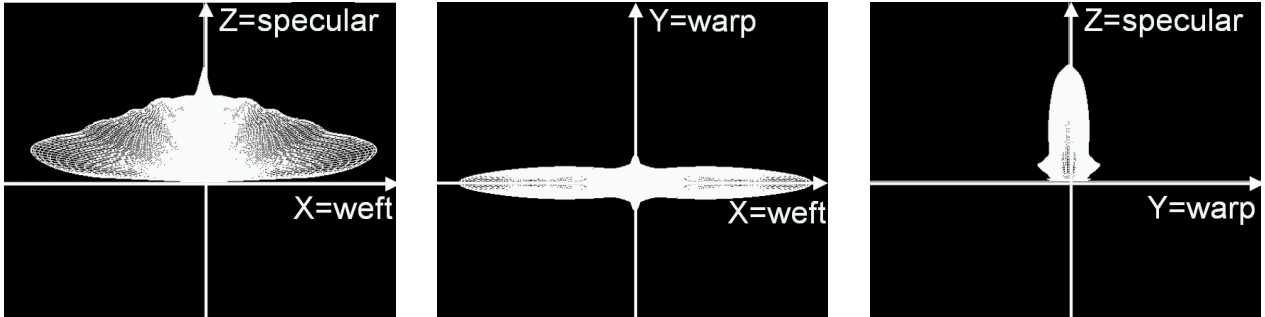
(a) Projection on XY plane (b) Projection on XZ plane (c) Projection on YZ plane (d) a bird's-eye view
Figure 10: Omnidirectional reflectance distribution (incident ray in the warp dir.)



(a) Projection on XY plane (b) Projection on XZ plane (c) Projection on YZ plane (d) a bird's-eye view
Figure 11: Omnidirectional reflectance distribution (incident ray in the weft dir.)



(a) Projection on XY plane (b) Projection on XZ plane (c) Projection on YZ plane (d) a bird's-eye view
Figure 12: Omnidirectional reflectance distribution (incident ray in the bias dir.)



(a) Projection on XZ plane (b) Projection on XY plane (c) Projection on YZ plane
Figure 13: Anisotropic reflection model ρ_{KES} (in the spherical coordinate system).