

UC San Diego

UC San Diego Electronic Theses and Dissertations

Title

An Evaluation of Appearance Models for Cloth Rendering

Permalink

<https://escholarship.org/uc/item/50s195dq>

Author

Fecho, Marlena

Publication Date

2013

Supplemental Material

<https://escholarship.org/uc/item/50s195dq#supplemental>

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, SAN DIEGO

An Evaluation of Appearance Models for Cloth Rendering

A thesis submitted in partial satisfaction of the
requirements for the degree
Master of Science

in

Computer Science

by

Marlena Fecho

Committee in charge:

Henrik Wann Jensen, Chair
David Kriegman
Jurgen Schulze

2013

Copyright
Marlena Fecho, 2013
All rights reserved.

The thesis of Marlana Fecho is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2013

TABLE OF CONTENTS

Signature Page	iii
Table of Contents	iv
List of Figures	vi
List of Tables	x
Acknowledgements	xi
Abstract of the Thesis	xii
Chapter 1 Introduction	1
1.1 Previous Work	3
1.2 Contributions	4
1.3 Thesis Organization	5
Chapter 2 Cloth Appearance	6
2.1 Light Scattering	6
2.1.1 Bidirectional Reflectance Distribution Function	6
2.1.2 Scattering on Microfacets	7
2.1.3 Scattering on Microcylinders	8
2.2 Cloth Structure	9
2.2.1 Threads: Twisted Fibers	9
2.2.2 Woven Threads	10
2.2.3 Knitted Threads	11
2.2.4 Fuzz: Nap, Pile and Felt	11
Chapter 3 Appearance Models for Cloth	14
3.1 Simple Models	14
3.1.1 Lambertian	14
3.1.2 Oren-Nayar	14
3.1.3 Torrance-Sparrow	15
3.2 Advanced Models	15
3.2.1 Irawan	16
3.2.2 Sadeghi	19
Chapter 4 Comparison of Irawan's and Sadeghi's Models	25
4.1 Method	25
4.1.1 Implementation Details	25
4.1.2 Comparison Method	26
4.2 Results	28

	4.3 Analysis	28
Chapter 5	Measurements of New Cloth Types	38
	5.1 Measurements	38
	5.1.1 Setup	38
	5.1.2 Cloth Samples	39
	5.2 Fitting to Sadeghi’s model	41
	5.3 Results	41
Chapter 6	Discussion and Future Work	51
	6.1 Knitted Fabrics	51
	6.1.1 Knitted Structure	53
	6.1.2 Non-Perpendicular Thread Directions	54
	6.1.3 Improved Reflectance Visualization	54
	6.2 Texture	57
	6.2.1 Large-Scale: Dyed Cloth	57
	6.2.2 Medium-Scale: Mixed Cloth Types	58
	6.3 Fuzz	58
	6.4 Tailoring the model for artists	59
Chapter 7	Conclusion	60
	7.1 Contributions	60
	7.2 Future Work	60
Appendix A	Sadeghi Parameters	62
Appendix A	Additional Rendered Images	66
Bibliography		69

LIST OF FIGURES

Figure 1.1:	Artwork capturing the complex appearance of various fabrics. Left: <i>Sir Thomas More</i> , painted by Hans Holbein the Younger [32]. Right: <i>Woman in satin dress holding mirror</i> , photographer unknown, from the George Eastman House Collection [34].	2
Figure 2.1:	Example BRDFs	7
Figure 2.2:	Light scattering on a microfacet surface	8
Figure 2.3:	Shadowing (blue) and masking (red) on a microfacet surface.	8
Figure 2.4:	Light scattering on a cylinder	9
Figure 2.5:	Photograph of silk fibers twisted into a thread. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.	10
Figure 2.6:	Warp and weft threads in a plain weave.	10
Figure 2.7:	Top view and side view of various weave patterns. The weaves, from left to right, are plain, crepe de chine and satin charmeuse.	11
Figure 2.8:	Polyester Satin Charmeuse under a microscope. Left: Weave pattern. Middle: Weft threads. Right: Warp threads, under three different light angles. The deviations of the warp thread tangents affect the reflection. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.	12
Figure 2.9:	A simple knitted fabric. Top: Knitted structure. Bottom: Photographs of the front (left) and back (right) face of knitted fabric.	13
Figure 2.10:	Corduroy. Top: Side-view of weave structure. Bottom: Photograph of corduroy fabric.	13
Figure 3.1:	Angles and dimensions in Irawan’s model. u is the longitudinal angle from the $\mathbf{z}$ axis. v is the azimuthal angle around the thread circumference. ψ is the fiber twist angle. a is the cross sectional radius, and l is the projected thread segment length along the $\mathbf{y}$ axis. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.	16
Figure 3.2:	Thread spine curve and κ values. Higher κ values specify a flatter spine curve. More negative values specify a more pointed spine curve. [15] Reprinted by permission.	17
Figure 3.3:	Thread-based coordinate system. The thread tangent vector $\mathbf{t}$ is the vector which runs down the length of the thread. The surface tangent vector $\mathbf{s}$, is perpendicular to $\mathbf{t}$, and tangent to the surface of the cloth. The normal vector $\mathbf{n}$ is the vector which is perpendicular to both $\mathbf{t}$ and $\mathbf{s}$	20

Figure 3.4:	Angles and dimensions in Sadeghi’s model. The vectors ω_i and ω_r refer to the incident and reflected light paths, respectively. The azimuthal angle, ϕ , is the angle between the projections of ω and $\mathbf{n}$ on the $\mathbf{n}$ - $\mathbf{s}$ plane. The longitudinal angle, θ , is the angle between ω and $\mathbf{t}$. The angle ψ is the angle between the projections of ω and $\mathbf{t}$ on the $\mathbf{n}$ - $\mathbf{t}$ plane. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.	21
Figure 3.5:	Warp (blue) and weft (orange) threads in a charmeuse weave. left: Weaving pattern. right: Tangent curves for warp and weft. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.	22
Figure 4.1:	Cylinders setup used by Sadeghi et al. to validate their model. We use this same setup to compare Sadeghi’s and Irawan’s models. We refer to the orientation of the warp threads in describing each of these cylinders.	26
Figure 4.2:	Comparison results for Plain Linen.	29
Figure 4.3:	Comparison results for Silk Crepe de Chine.	30
Figure 4.4:	Comparison results for Polyester Satin Charmeuse, front face.	31
Figure 4.5:	Comparison results for Polyester Satin Charmeuse, back face.	32
Figure 4.6:	Comparison results for Silk Shot Fabric.	33
Figure 4.7:	Comparison results for Velvet.	34
Figure 4.8:	Relationship between thread segment shape and highlight location for Sadeghi’s model (left) and Irawan’s model (right), using results for Polyester Satin Charmeuse. Top: Looking down the length of a cylinder, illustrating how horizontal threads lie on its surface. The arrows indicate the locally flattest regions of the curve. Red arrows indicate regions of curve responsible for front-facing highlights.	35
Figure 5.1:	Measurement setup. Cloth samples were wrapped around a cylinder and photographed with the light source and camera approximately collocated.	39
Figure 5.2:	Fabric samples	40
Figure 5.3:	Denim. Top: Reference photo. Bottom: Rendered result using Sadeghi’s model.	42
Figure 5.4:	Pink Lining. Top: Reference photo. Bottom: Rendered result using Sadeghi’s model.	42
Figure 5.5:	A side-view of the measurement scene, illustrating reflections on vertical threads as they lie on the cylinder. At grazing angles, vertical threads reflect all incoming light back towards the camera, causing a highlight.	43
Figure 5.6:	Polka-dot Lining.	44

Figure 5.7:	Swimwear.	45
Figure 5.8:	T-shirt, white. Top: Reference photo. Bottom: Rendered using Sadeghi’s model.	46
Figure 5.9:	Black T-shirt.	47
Figure 5.10:	Faux suede. Top: Reference photo. Bottom: Rendered result using Sadeghi’s model.	48
Figure 5.11:	Corduroy. Top: Reference photo. Bottom: Rendered result using Sadeghi’s model.	49
Figure 5.12:	Rendered fabric samples. The Pink Lining and Swimwear samples were rendered under lower light intensity to avoid saturating the image.	50
Figure 6.1:	Additional photographs (top) and corresponding rendered results using Sadeghi’s model (bottom) of the Swimwear sample. Note the absence of the grazing angle highlights in the rendered images. Left: Front face of fabric, oriented 65 degrees about the normal. Right: Back face of fabric, oriented 20 degrees about the normal.	52
Figure 6.2:	Knitted structure. Left: Simple weft knit. Right: Simple warp knit.	53
Figure 6.3:	Weft knit simplified into the three dominant thread directions.	53
Figure 6.4:	Thread direction curve (left) and thread tangent curve (right) for weft knit. The red, blue and green markers each indicate corresponding locations on the two curves.	54
Figure 6.5:	Left: Typical sphere mapping. Right: Proposed mapping of cloth on a sphere for test renders. Blue lines indicate the warp direction, and orange lines indicate the weft. In the proposed mapping, the material wraps away from the center of the sphere towards all grazing angles.	55
Figure 6.6:	The proposed sphere mapping captures all cylinder orientations in a single view. To illustrate this point we’ve outlined the vertical (red), horizontal (green), and diagonal (blue) cylinders on the sphere.	56
Figure 6.7:	Swimwear sample stretched around a sphere to visualize highlight behavior at all orientations simultaneously. Top: Front face. Bottom: Back face.	56
Figure 6.8:	All non-textured cloths from this paper rendered on a sphere as described. First row: Linen, Silk Crepe de Chine, Polyester Satin Charmeuse (front), Polyester Satin Charmeuse (back), Silk Shot Fabric. Second row: Velvet, Denim, Polyester Lining, Swimwear (front), Swimwear (back). Third row: White T-shirt, Black T-shirt (front), Black T-shirt (back), Faux Suede, Corduroy.	57

Figure 6.9: Proposed pattern of two cloth types for corduroy.	58
Figure 6.10: Rendered corduroy using alternating stripes of different materials.	58
Figure 6.11: Left: Photograph of velvet stretched around a sphere. Right: Rendered sphere using Sadeghi velvet model from Chapter 4. . .	59
Figure A.1: Sadeghi’s model is able to reproduce a wide range of cloth appearances, including the strong specular highlights found in polyester lining (left), the matte appearance of faux suede (center), and the asymmetric grazing highlights found in velvet (right). . .	66
Figure A.2: A curtain made of the Polka-dot Lining fabric, rendered using Sadeghi’s model.	67
Figure A.3: A curtain made from two orientations of the same Lining fabric, rendered using Sadeghi’s model.	67
Figure A.4: Pant fabrics, rendered using Sadeghi’s model. Left: Denim, Right: Corduroy	68

LIST OF TABLES

Table 3.1: Irawan parameters.	19
Table 3.2: Sadeghi parameters.	24
Table 4.1: Method used for matching Irawan parameters from Sadeghi parameters.	27
Table 5.1: Fabric samples.	39
Table A.1: Sadeghi parameters for Denim.	62
Table A.2: Sadeghi parameters for Polyester Lining.	63
Table A.3: Sadeghi parameters for Polka-dot Polyester Lining.	63
Table A.4: Sadeghi parameters for Swimwear, front.	63
Table A.5: Sadeghi parameters for Swimwear, back.	64
Table A.6: Sadeghi parameters for White T-shirt.	64
Table A.7: Sadeghi parameters for Black T-shirt, front.	64
Table A.8: Sadeghi parameters for Black T-shirt, back.	65
Table A.9: Sadeghi parameters for Faux Suede.	65
Table A.10: Sadeghi parameters for Corduroy.	65

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Henrik Wann Jensen, for inspiring me to seek an understanding of all visual phenomena, and for supporting and mentoring me in my research. I would also like to thank my committee members, Dr. David Kriegman and Dr. Jurgen Schulze, for their constructive feedback in reviewing this thesis.

I would especially like to thank Iman Sadeghi and Oleg Bisker for taking the time out of their busy lives to answer my numerous questions about their research and for including me in the revision process of their paper.

I would like to thank my colleagues in the Computer Graphics Lab who provided much useful feedback on my research, and made working there a fun and stimulating experience: Jason Greco, Zhe Fu, Jorge Schwarzhaupt and Phi Nguyen.

I would also like to thank several members of the Vision Lab, who helped me considerably with my equipment needs, including David Kriegman, Sam Kwak, Oscar Beijbom, Zach Murez and Talia Treibitz.

Finally, I'd like to thank my coauthors: Daniel Tenedorio, Jorge Schwarzhaupt, Robert Pardridge, James Lue, Quintin Cutts, Sarah Esper, Stephen Foster and Beth Simon. It was a pleasure working with these talented individuals in a diverse set of research areas.

Chapters 3 and 4 contains several images which are reproduced from a published paper, in which the thesis author contributed significantly to the comparison of the proposed model and a previous model by Irawan et al. [15]. The Irawan shader used to produce renders in this chapter was based on a shader by Yang [39].

Iman Sadeghi, Oleg Bisker, Joachim De Deken, and Henrik Wann Jensen. A practical microcylinder appearance model for cloth rendering. *ACM Trans. Graph.*, 32(2):14:1–14:12, April 2013.

ABSTRACT OF THE THESIS

An Evaluation of Appearance Models for Cloth Rendering

by

Marlena Fecho

Master of Science in Computer Science

University of California, San Diego, 2013

Henrik Wann Jensen, Chair

Cloth is a common material which exhibits complex, anisotropic reflection behavior. Because cloth is such an important material class in human-centric environments, many models have attempted to describe its appearance. This thesis aims to clarify the state of the art of cloth rendering by comparing two recent models, by Irawan et al. and by Sadeghi et al., which both describe cloth as woven microcylinders. We fit each of these models to a set of measured fabrics and link the resulting differences to theoretical elements of the models. Through this comparison, we find that Sadeghi’s model is able to more closely match the appearance of complex fabrics.

Additionally, we present measurements of 8 fabric samples, which exhibit several different structural characteristics. These samples include woven, knitted,

nap and pile fabrics. Sadeghi’s model is used to reproduce the appearance of the samples. This both allows us to further evaluate this model, and expands the library of cloth types which Sadeghi’s model has been used to describe. We find the model to be largely successful in matching the samples, although we also discover a key limitation inherent to woven cloth models. To address this, we suggest an extension, called the *thread direction curve* which would further generalize the model.

Chapter 1

Introduction



It is a common goal of computer graphics to model the appearance of the various materials which make up our world. Cloth is a particularly common material class which is present in any human-centric environment, making it a fixture in both computer generated films and games. Yet, because cloth exhibits such complex reflection behavior, it can be a challenge to model well. The fact that cloth is such an integral part of our lives makes us, as observers, more sensitive to physical inaccuracies in rendered images.

Humans have a long history with cloth which spans several millennia. The earliest cloth was purely functional - it was worn to shield oneself from the cold and the wind. But as humans are a creative animal, what started out as protection, soon became a form of art and expression. It was discovered that the appearance could be controlled by varying the small-scale structure. Some fabrics, like velvet and satin (see Figure 1.1), exhibit quite complex reflections. These and other luxury fabrics are chosen specifically for their appearance, rather than for their function. From plain linen to lustrous velvet, cloth has a rather diverse material class.

Throughout the history of computer graphics, numerous models have attempted to capture the complexities of cloth appearance. The wide range of appearance can make it difficult to design an all-encompassing appearance model for cloth. These models exhibit a broad spectrum of physical accuracy. The more naïve models are often isotropic and have little to no physical basis, while some models simulate the material structure down to micro-scale levels. However, the more accurate models are generally so cumbersome to use that the naïve models are favored in practice.



Figure 1.1: Artwork capturing the complex appearance of various fabrics. Left: *Sir Thomas More*, painted by Hans Holbein the Younger [32]. Right: *Woman in satin dress holding mirror*, photographer unknown, from the George Eastman House Collection [34].

1.1 Previous Work

Traditionally, the appearance of cloth has been described using general isotropic models such as Oren-Nayar [25], Cook-Torrance [7], and in some cases, even Lambertian [17].

However, it has been demonstrated that many of the illumination effects observed are unique to cloth, due to the structure of the threads and fibers which make up the fabric [37, 2, 13, 10]. So cloth-specific models often attempt to recreate these effects by accounting for the thread structure [36, 12]. Some models have addressed this by sampling a small patch of woven or knitted geometry [37, 9]. Westin proposed sampling a small patch of woven geometry, and compressing the BRDF with spherical harmonics [37]. Ashikhmin extended the traditional microfacet model to create a microfacet BRDF with arbitrary geometry, and demonstrated satin rendering using a woven microgeometry [2]. Adabala further extended this model to support a multi-colored weave pattern, with fiber detail [1]. Xu proposed a volumetric approach for rendering knitted fabrics [38]. Although these models are based on the physical structure of cloth, they were not validated using measured data, and fail to capture the full behavior.

More recently, there has been an increased focus on using direct measurements to improve or validate the accuracy of cloth models. Data-driven approaches, such as Bidirectional Texture Function (BTF) [8, 22, 23] and volumetric CT scans [41] are aimed entirely at accuracy. They are able to produce extremely high fidelity results, but at the cost of expensive measurements, storage and calculations. Also, because these models rely on measurements of the fabric they represent, they are inflexible to tuning the appearance or extending the model to new fabrics.

The current state of the art of cloth rendering is shared by two empirical models, by Irawan et al. [13, 14, 15] and by Sadeghi et al. [30, 29, 4]. Irawan’s model provides convincing procedural small-scale texture synthesis, as well as a large-scale BRDF. This model describes cloth as curved segments of perfectly specular cylinders. Sadeghi’s model is a purely large-scale reflectance model, with a similar approach. This model builds up the appearance from a BRDF model of threads,

which is based on a model for hair [31]. Bisker extended this model to support thread-level detail [4]. Both Irawan’s and Sadeghi’s models are based on measured BRDFs, and have improved the accuracy over earlier models, while being more generalizable than the data-driven approaches. But despite the wealth of research which has gone into cloth rendering, still many applications use naïve isotropic models, because the more advanced models are either too costly to performance, or too difficult to control.

With so many options for cloth appearance modeling, it becomes necessary to evaluate their relative merits including appearance, physical accuracy, flexibility and practicality. Some efforts have been made to evaluate the success of the various models. Yuen qualitatively compared a wide range of cloth-specific models, although this evaluation lacked any concrete results or error analysis [40]. Others have based their evaluations on measured data [24, 10]. Using extensive BRDF measurements, De Deken demonstrated that the most popular naïve models are insufficient to reproduce the illumination behavior of cloth [10]. These results emphasize the importance of using such measurements to validate future models.

Part of why there are so many models is there are many types of cloth (woven, knitted, pile, felted, etc.), which vary in the small scale structure of the material. In general, the more successful models have targeted only a single fabric type [38, 6, 11, 15]. A few models, however, have been used to describe multiple types of fabrics [9, 30], which suggests that it may be possible to generalize across more fabric types.

1.2 Contributions

The contributions of this thesis include

- A side-by-side comparison of Irawan’s and Sadeghi’s models, relating the theory, implementation and results.
- A set of measured cloth samples, which represent a wide variety of cloth types, including woven, knitted, nap and pile fabrics.

- The parameters which fit Sadeghi’s model to these new measurements.
- A suggested extension to Sadeghi’s model, called the *thread direction curve*, which would further generalize the thread structures this model can describe.
- A test scene which can be used to visualize the reflection behavior of rendered cloth.

Like [24, 10, 40], our goal is to better understand existing appearance models for cloth rendering. This thesis aims to clarify the state of the art by comparing two recent models, by Irawan et al. [15] and by Sadeghi et al. [30]. We fit each of these models to a set of measured fabrics and link the resulting differences to theoretical elements of each model. Through this comparison, we find Sadeghi’s model is able to more closely match the appearance of complex fabrics. With a new set of targeted measurements, we further evaluate the ability of Sadeghi’s model to reproduce a wider range of cloth types, for which find the model largely successful. We also discover a key limitation inherent to woven cloth models, and propose an extension, called the *thread direction curve* which further generalizes the model.

1.3 Thesis Organization

Chapter 2 provides some background on light scattering as described in computer graphics, followed by an overview of cloth as it pertains to the scattering of light. Chapter 3 describes several methods used to describe the appearance of cloth, including two state-of-the-art models, by Sadeghi et al and by Irawan et al. Chapter 4 provides a side-by-side comparison of these two models, delving into the theory, implementation, and results for each. Chapter 5, then offers a host of measurements of a wide range of cloth types, and fits Sadeghi’s model to them. Chapter 6 discusses a few limitations of the model which were discovered in fitting the new materials, and suggests some possible improvements to the model. Chapter 7 summarizes the contributions of this thesis. Additionally, the Appendix includes the Sadeghi parameters for all materials used in this paper.

Chapter 2

Cloth Appearance

2.1 Light Scattering

2.1.1 Bidirectional Reflectance Distribution Function

The appearance of a material depends on how incoming light energy scatters on its surface. In computer graphics, this scattering is often described using the *Bidirectional Reflectance Distribution Function*, or BRDF. The BRDF is a four-dimensional function of both the incoming light direction, ω_i , and the reflected direction, ω_r . The BRDF is defined as follows:

$$f_r(\omega_i, \omega_r) = \frac{dL_r(\omega_r)}{L_i(\omega_i) \cos \theta_i d\omega_i} \quad (2.1)$$

where L is the radiance, and θ_i is the angle between the incoming vector, ω_i and the surface normal. According to Lewis [18], in order to be physically plausible, a BRDF must satisfy two criteria:

- **Energy conservation:** The total reflected light energy is positive and does not exceed the total incoming light energy.
- **Helmholtz Reciprocity:** The BRDF is reversible, such that

$$f_r(\omega_i, \omega_r) = f_r(\omega_r, \omega_i)$$

A simple example of a BRDF is a perfect mirror. An incoming ray of light is completely reflected in the specular direction, which is the angle about the surface

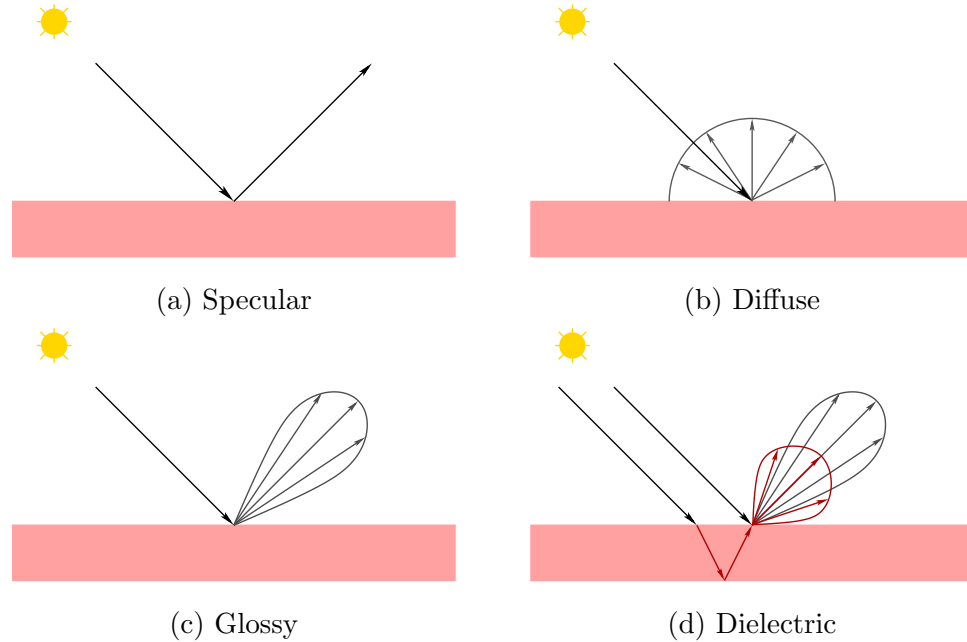


Figure 2.1: Example BRDFs

normal equal to the incident angle. On a diffuse (Lambertian) surface, incoming light energy is scattered uniformly in all directions. On a glossy surface, this energy may be scattered in a lobe centered on the specular direction. These examples are illustrated in Figure 2.1.

Dielectric materials possess both surface and volume scattering components. Unlike the surface reflection, the volume component is tinted by the material’s color. This is because some of the light energy enters the material, and is absorbed before exiting.

2.1.2 Scattering on Microfacets

A wide variety of surfaces, both matte and glossy, can be described with microfacet theory. Microfacets are tiny surface grooves or divots, as illustrated in Figure 2.2. These microfacets can be modeled as either diffuse [25] or specular [33], and there are many models which describe the distribution of these microfacets differently [7, 35, 25, 2]. Additionally, microfacets may occlude one another in both light and eye paths, which is called shadowing and masking, respectively.

This effect is illustrated in Figure 2.3. Shadowing and masking must be accounted for in microfacet models in order for the BRDF to be energy conserving.

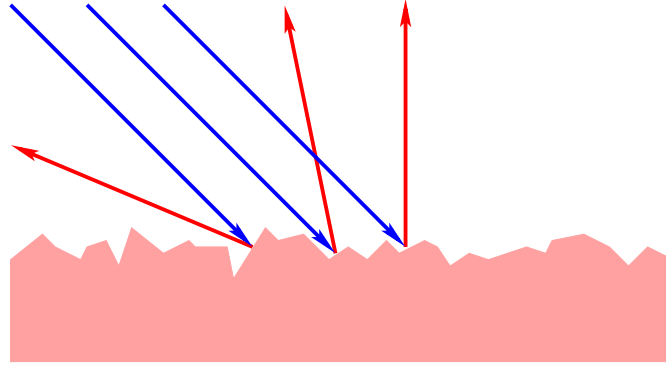


Figure 2.2: Light scattering on a microfacet surface

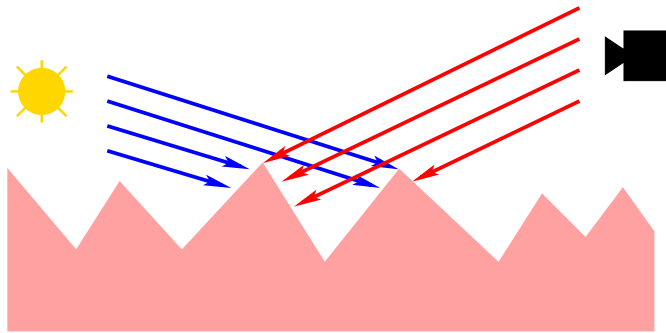


Figure 2.3: Shadowing (blue) and masking (red) on a microfacet surface.

2.1.3 Scattering on Microcylinders

A surface with unidirectional parallel grooves or bumps, like a compact disk or brushed aluminum, can often be described using a specific microfacet surface made of microcylinders. Poulin described a model which captures the anisotropic, or directionally dependent, appearance of such a surface, while accounting for the shadowing and masking [28]. Light reflects on the surfaces of a specular cylinder in the shape of a cone [16, 20]. This is due to the fact that the normals on a cylinder point in all directions azimuthally around the cylinder, as shown in Figure 2.4b. This reflection pattern is responsible for the anisotropy of microcylindrical surfaces.

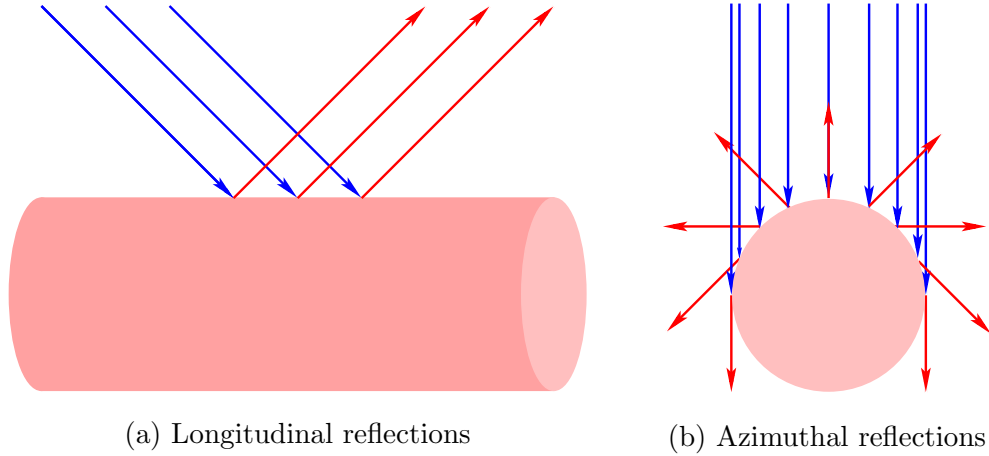


Figure 2.4: Light scattering on a cylinder

As cloth can be thought of as woven microcylinders, this reflection cone is very relevant to its appearance.

2.2 Cloth Structure

The mili-scale and micro-scale geometry of cloth are important to the final appearance. To better understand the appearance behavior, it is helpful to examine the various levels of its structure.

2.2.1 Threads: Twisted Fibers

The materials which compose threads are called fibers. These are either natural or synthetic strands which are grouped or twisted into threads. There are two main categories of fibers: *staple* and *filament*. *Staple* fibers are relatively short segments, and are usually, though not necessarily, natural materials like cotton or wool. Because these fibers are short, threads made of staple fibers must be tightly twisted and rely on friction in order to hold their shape. *Filament* fibers, on the other hand, are long continuous strands. As a result, threads made from filaments may be either twisted or untwisted, as desired. Examples of filament fibers are silk and many synthetic fibers, like polyester.



Figure 2.5: Photograph of silk fibers twisted into a thread. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

2.2.2 Woven Threads

In woven fabrics, perpendicular *warp* and *weft* threads are woven together. *Warp* threads are held taut across a loom, while *weft* threads are passed over and under the warp threads to form the fabric. This is illustrated in Figure 2.6.

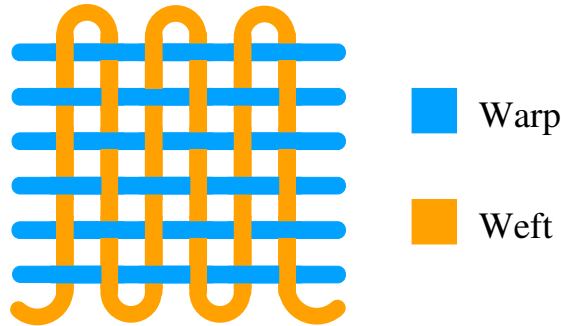


Figure 2.6: Warp and weft threads in a plain weave.

The weave pattern has a strong impact on the appearance of the fabrics, which can range from matte to highly reflective. Because the threads are passing over and under one another, they do not simply lie flat on the surface of the material, as illustrated in Figure 2.7. As demonstrated by Westin [37], these deviations from the surface normal affect the specular component of the reflection, as shown in Figure 2.8.

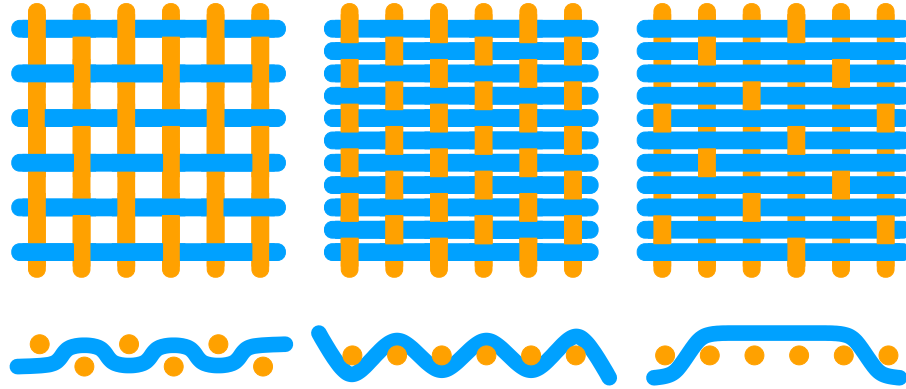


Figure 2.7: Top view and side view of various weave patterns. The weaves, from left to right, are plain, crepe de chine and satin charmeuse.

2.2.3 Knitted Threads

The key difference between knitted and woven structures is that in a knitted structure, the threads are not limited to two perpendicular directions. Instead, threads pass over, under, and around one another, with the direction changing continuously. In addition, in most simple knits, the fabric is composed of only one continuous thread, rather than many separate threads. A simple knitted structure is illustrated in Figure 2.9.

2.2.4 Fuzz: Nap, Pile and Felt

During the process of knitting or weaving threads together, some fibers may loosen from the twist of the thread, and point in stray directions. These stray fibers are referred to as the *nap*, which causes a fuzzy appearance marked by grazing angle highlights. When undesirable, the nap is trimmed in the final stages of production. The nap may also be exaggerated by brushing the fabric to pull more fibers astray.

In *pile* fabrics, a stronger nap is intentionally added, by weaving or knitting in extra threads or fibers, which usually point away from the surface of the cloth. Examples of pile fabrics are velvet, fleece, and corduroy (see Figure 2.10).

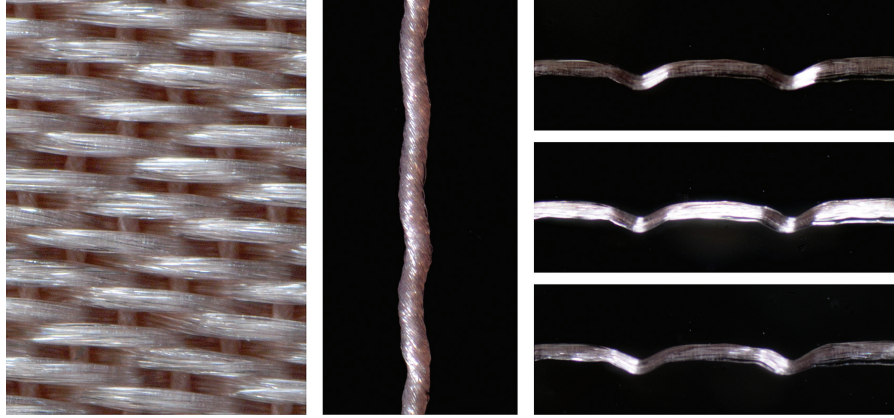


Figure 2.8: Polyester Satin Charmeuse under a microscope. Left: Weave pattern. Middle: Weft threads. Right: Warp threads, under three different light angles. The deviations of the warp thread tangents affect the reflection. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

Felt is an entirely different fabric type, which contains no threads. Instead, clumps of raw fibers are pressed and agitated so they intertwine in a flat sheet. In the final product, the fibers point in all directions, causing an isotropic appearance.

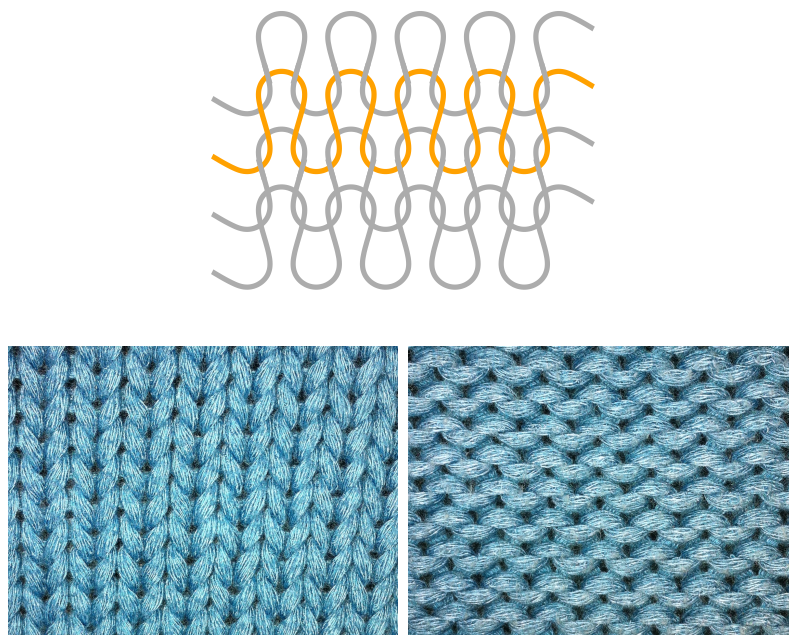


Figure 2.9: A simple knitted fabric. Top: Knitted structure. Bottom: Photographs of the front (left) and back (right) face of knitted fabric.



Figure 2.10: Corduroy. Top: Side-view of weave structure. Bottom: Photograph of corduroy fabric.

Chapter 3

Appearance Models for Cloth

3.1 Simple Models

There are many models which have sought to describe the appearance of cloth. Despite this vast wealth of research, just a few naïve models, which were not specifically designed for cloth, are most often used in practice.

3.1.1 Lambertian

The Lambertian BRDF is one of the simplest shading models [17]. It provides a coarse approximation of many matte surfaces, and is most often used in real-time settings, where performance is more important than realism. The Lambertian BRDF is

$$f_r(\omega_i, \omega_r) = \frac{\rho}{\pi} \quad (3.1)$$

where ρ is the albedo of the material.

3.1.2 Oren-Nayar

Perhaps the most commonly used appearance model for cloth is Oren-Nayar [25]. This model describes rough surfaces as collections of lambertian microfacets, or v-shaped grooves. The BRDF for this model is

$$f_r(\omega_i, \omega_r) = \frac{\rho_d}{\pi} (A + B * \max(0, \cos(\phi_i - \phi_r)) \sin \alpha \tan \beta) \quad (3.2)$$

where

$$\begin{aligned} A &= 1 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33} \\ B &= 0.45 \frac{\sigma^2}{\sigma^2 + 0.09} \\ \alpha &= \max(\theta_i, \theta_r) \\ \beta &= \min(\theta_i, \theta_r) \end{aligned}$$

A major limitation of Oren-Nayar is that, as a diffuse model, it is unable to reproduce any specular effects, such as are observed in satin. To aid this, it is sometimes combined with the non-physical Blinn model [5], which provides a glossy highlight.

3.1.3 Torrance-Sparrow

Torrance-Sparrow is similar to Oren-Nayar, only instead of diffuse microfacets, it describes perfectly specular microfacets [33]. As a result, it is able to reproduce specular effects. It is most often used to model brushed metal surfaces. The model was introduced to computer graphics by Cook-Torrance [7]. The BRDF is

$$f_r(\omega_i, \omega_r) = \frac{D(\omega_h)G(\omega_i, \omega_r)F_r(\omega_r)}{4 \cos \theta_r \cos \theta_i} \quad (3.3)$$

where $D(\omega_h)$ is the microfacet distribution function, $G(\omega_i, \omega_r)$ accounts for shadowing and masking of the microfacets, and $F_r(\omega_r)$ is the Fresnel term. Ashikhmin demonstrated that this model, plus a diffuse term, with the correct microfacet distribution was able to reproduce the general appearance of satin [2]. Adabala’s woven cloth model is also based on Torrance-Sparrow [1]. However, getting just the right distribution function can be rather difficult, yet is crucial to adequately reproducing a fabric’s appearance.

3.2 Advanced Models

By comparing the above three models against measured BRDFs of cloth samples, De Deken demonstrated that these naïve models are insufficient to re-

produce the more complex scattering behavior of cloth [10]. The major deficiencies were the lack of support for anisotropic scattering as well as shadowing and masking. Oren-Nayar, despite being the most commonly used model for cloth, performed the worst of the three.

Current state-of-the-art cloth models are based on the observation that the appearance of cloth depends on the threads which compose it. We describe two models in this section, by Irawan [15] and by Sadeghi [30], which are based on modeling cloth as interwoven specular cylinders.

3.2.1 Irawan

Irawan et al. described both a large-scale reflectance model and a small-scale texture model [13, 14, 15]. In this thesis we will only discuss the large-scale reflectance model. This model assumes cloth is composed of specular thread segments, which are curved cylinders. The *thread spine curve* of a thread segment is described as a conic section (ellipse, circle or hyperbola), which is illustrated in Figure 3.2. The thread segment dimensions and angles are illustrated in Figure 3.1.

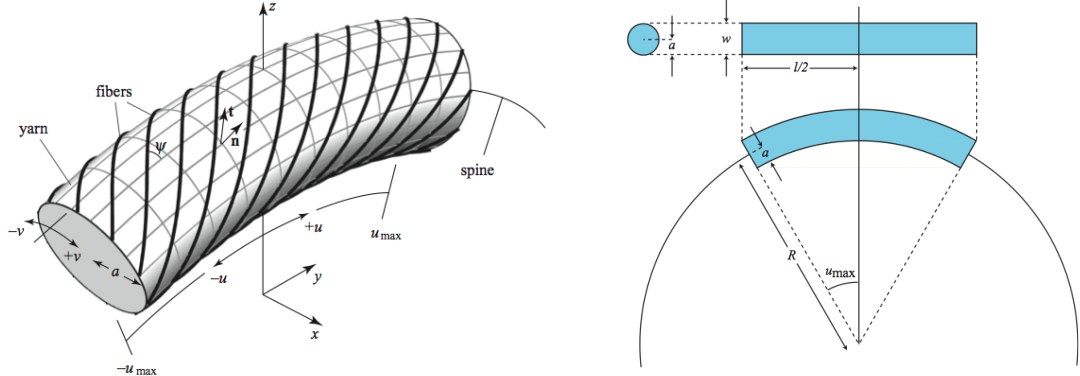


Figure 3.1: Angles and dimensions in Irawan’s model. u is the longitudinal angle from the $\mathbf{z}$ axis. v is the azimuthal angle around the thread circumference. ψ is the fiber twist angle. a is the cross sectional radius, and l is the projected thread segment length along the $\mathbf{y}$ axis. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

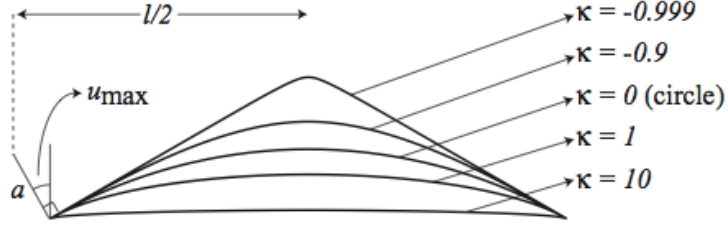


Figure 3.2: Thread spine curve and κ values. Higher κ values specify a flatter spine curve. More negative values specify a more pointed spine curve. [15] Reprinted by permission.

The Irawan BRDF is

$$f_s = k_d + \sum_j k_{s,j} f_{r,j}(\omega_i, \omega_r) \quad (3.4)$$

which is a combination of a diffuse component and a per-thread specular component, where the specular component is a function of the thread orientation. The diffuse and specular coefficients are k_d and k_s , respectively.

Irawan describes two kinds of threads, staple and filament (as discussed in Chapter 1), which reflect the light differently. The term f_r is the scattering function, which captures the specular behavior of either staple or filament threads.

$$f_{r,staple} = \int_{-u_{\max}}^{u_{\max}} G_v f_c A \, du \quad (3.5)$$

$$f_{r,filament} = \int_0^{2\pi} G_u f_c A \, dv \quad (3.6)$$

The scattering function is computed by integrating along the ideal specular reflection on the thread segment. Because this reflection on a filament thread is only a function of v , with constant u , this integral must be computed along v . For a more in-depth explanation of this difference, see [15]. The location of the ideal

specular highlight can be found using

$$v(\omega_i, u, \omega_r) = \arctan(-\mathbf{h}_y \sin u - \mathbf{h}_z \cos u, \mathbf{h}_x) \pm \arccos(D) \quad (3.7)$$

$$D = \frac{\mathbf{h}_y \cos u - \mathbf{h}_z \sin u}{\sqrt{\mathbf{h}_y^2 + (\mathbf{h}_y \sin u + \mathbf{h}_z \cos u)^2}} \cot \psi$$

$$u(\omega_i, v, \omega_r) = \arctan(-\mathbf{h}_z, \mathbf{h}_y) \pm \frac{\pi}{2} \quad (3.8)$$

The geometry factor, G , accounts for the shape of the spine curve and the twist of the thread. $R(u)$ is the radius of curvature of the spine curve, the full equation for which can be found in [15].

$$G_v(\omega_i, u, \omega_r) = \frac{a(R(u) + a \cos v)}{|\omega_i + \omega_r|(\mathbf{n} \cdot \mathbf{h}) \sin \psi} \quad (3.9)$$

$$G_u(\omega_i, v, \omega_r) = \frac{a(R(u) + a \cos v)}{|\omega_i + \omega_r| |(\mathbf{t} \times \mathbf{h})_x|} \quad (3.10)$$

The phase function, f_c , is the sum of a uniform scattering lobe and a forward scattering lobe. The forward scattering lobe uses a von Mises distribution, as given in Equation (3.12).

$$f_c(\theta_r, \phi) = \alpha + g(-\omega_i \cdot \omega_r, \beta) \quad (3.11)$$

$$g(\cos x, b) = \frac{\exp(b \cos x)}{2\pi I_0(b)} \quad (3.12)$$

The term, A , accounts for the attenuation within the thread material, and follows Seeliger's Law. For filament threads, this term is multiplied by a cubic smooth-step function, $s(x)$, to soften the boundaries of the highlights, as in Equation (3.14).

$$A(\omega_i, u, v, \omega_r) = \frac{\sigma_s (\omega_i \cdot \mathbf{n})(\omega_r \cdot \mathbf{n})}{\sigma_t \omega_i \cdot \mathbf{n} + \omega_r \cdot \mathbf{n}} \quad (3.13)$$

$$A_s(u) = A(u) \left(1 - s \left(\frac{|u| - (1 - \delta)u_{\max}}{\delta u_{\max}} \right) \right) \quad (3.14)$$

The parameters for controlling the appearance of rendered cloth using Irawan's model are summarized in Table 3.1.

Table 3.1: Irawan parameters.

Parameter	Type	Meaning
α	float	Uniform scattering of specular lobe
β	float	Forward scattering of specular lobe
δ	float	Smoothstep applied to specular lobe, for filament threads
ψ	float	Fiber twist angle (in degrees)
$u_{\max}$	float	Maximum inclination angle (in degrees). Controls extent of highlights
κ	float	Thread spine curvature. (See Figure 3.2)
w	float	Width of segment rectangle
l	float	Length of segment rectangle
k_s	color	Specular coefficient
k_d	color	Diffuse coefficient

3.2.2 Sadeghi

Sadeghi’s model is a large-scale (at a distance) model, which treats fabric as interwoven specular cylinders [29, 30]. It is capable of reproducing a wide range of cloth appearances, ranging from plain linen to polyester satin charmeuse. Particularly, it allows fine control in reproducing multiple off-specular highlights.

For this model, we will refer to a thread-based coordinate system, illustrated in Figure 3.3. The thread tangent vector $\mathbf{t}$ is the vector which runs down the length of the thread. The surface tangent vector $\mathbf{s}$, is perpendicular to $\mathbf{t}$, and tangent to the surface of the cloth. The normal vector $\mathbf{n}$ is the vector which is perpendicular to both $\mathbf{t}$ and $\mathbf{s}$. For threads which lie flat in the surface of the cloth, $\mathbf{n}$ is equivalent to the surface normal.

Figure 3.4 depicts the relevant angles. The vectors ω_i and ω_r refer to the incident and reflected light paths, respectively. The azimuthal angle, ϕ , is the angle between the projections of ω and $\mathbf{n}$ on the $\mathbf{n}$ - $\mathbf{s}$ plane. The longitudinal angle, θ , is the angle between ω and $\mathbf{t}$. The angle ψ is the angle between the projections of ω and $\mathbf{t}$ on the $\mathbf{n}$ - $\mathbf{t}$ plane. The equations in this model refer to the following half angles and difference angles: $\theta_h = (\theta_i + \theta_r)/2$, $\theta_d = (\theta_i - \theta_r)/2$, and $\phi_d = \phi_i - \phi_r$.

Because threads pass over and under one another in a weave, they do not lie flat in the plane of the fabric. Instead, the thread tangent deviates from the surface

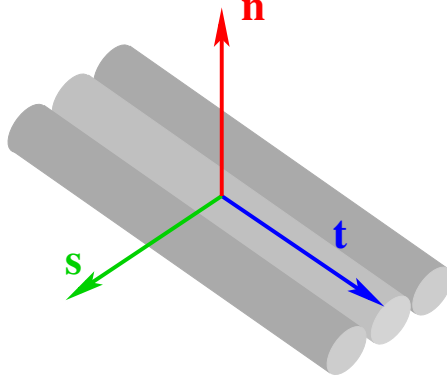


Figure 3.3: Thread-based coordinate system. The thread tangent vector $\mathbf{t}$ is the vector which runs down the length of the thread. The surface tangent vector $\mathbf{s}$, is perpendicular to $\mathbf{t}$, and tangent to the surface of the cloth. The normal vector $\mathbf{n}$ is the vector which is perpendicular to both $\mathbf{t}$ and $\mathbf{s}$.

tangent, as illustrated in Figure 3.5. Light scatters according to these deviated thread tangents. Sadeghi introduces the concept of a tangent distribution curve, which represents the distribution of tangents in either the warp or weft direction for a particular weave. This curve may represent the actual shape side-view of the thread segment, but because this is a large-scale model, this is not a restriction.

The model is as follows:

$$L_r(\omega_r) = a_1 \times L_{r,1}(\omega_r) + a_2 \times L_{r,2}(\omega_r) \quad (3.15)$$

Equation (3.15) describes the combined reflected radiance from two perpendicular thread directions, where a_j is the ratio of the cloth surface area covered by the j_{th} thread direction. The radiance for each thread direction is

$$L_{r,j}(\omega_r) = \frac{1}{Q} \frac{1}{N_j} \sum_t \int L_i(\omega_i) f_s(t, \omega_i, \omega_r) M(t) P(t) \cos \theta_i d\omega_i, \quad (3.16)$$

which is computed by sampling its tangent distribution curve, thus determining the local thread space. N_j is the number of samples for the j^{th} thread direction. We will explain the remaining terms in this paragraphs that follow.

The thread BRDF is

$$f_s(t, \omega_i, \omega_r) = (f_{r,s}(t, \omega_i, \omega_r) + f_{r,v}(t, \omega_i, \omega_r)) / \cos^2 \theta_d, \quad (3.17)$$

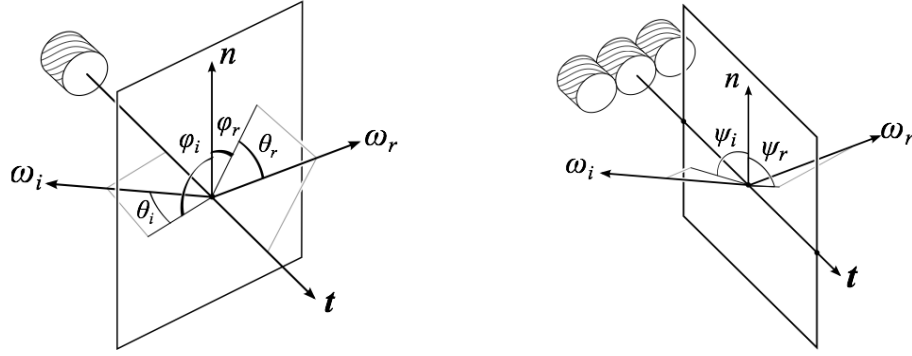


Figure 3.4: Angles and dimensions in Sadeghi's model. The vectors ω_i and ω_r refer to the incident and reflected light paths, respectively. The azimuthal angle, ϕ , is the angle between the projections of ω and $\mathbf{n}$ on the $\mathbf{n}$ - $\mathbf{s}$ plane. The longitudinal angle, θ , is the angle between ω and $\mathbf{t}$. The angle ψ is the angle between the projections of ω and $\mathbf{t}$ on the $\mathbf{n}$ - $\mathbf{t}$ plane. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

where,

$$f_{r,s}(t, \omega_i, \omega_r) = F_r(\eta, \omega_i) \cos(\phi_d/2) g(\gamma_s, \theta_h) \quad (3.18)$$

$$f_{r,v}(t, \omega_i, \omega_r) = F \frac{(1 - k_d)g(\gamma_v, \theta_h) + k_d}{\cos \theta_i + \cos \theta_r} A \quad (3.19)$$

$$F = F_t(\eta, \omega_i) F_t(\eta', \omega'_r),$$

which is based on the model for human hair, described by Sadeghi et al. [31]. This model treats hair fibers as glossy cylinders, which have separate reflection cones for surface and volume scattering (see Equations (3.18) and (3.19), respectively). In general, fiber materials are dielectrics, which exhibit untinted surface scattering and tinted volume scattering. Hence, the volume scattering term is scaled by the thread albedo, A . The widths of the specular lobes are controlled by unit gaussians, g , about the longitudinal angle, θ , accounting for the twist of fibers in the threads. With specular materials, the fraction of light which is reflected and transmitted depends on the index of refraction, which is accounted for in the Fresnel terms, F_r and F . In the volume scattering term, F is the product of a reflection and a transmission Fresnel, to account for energy which scatters within the medium

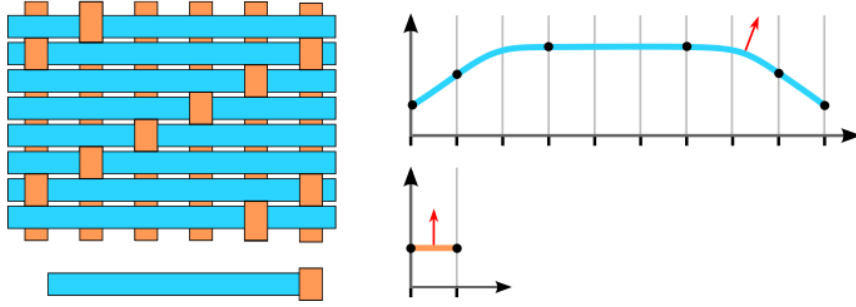


Figure 3.5: Warp (blue) and weft (orange) threads in a charmeuse weave.

left: Weaving pattern. right: Tangent curves for warp and weft. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

before reaching the eye. To accommodate materials, like cotton, which exhibit isotropic scattering, an adjustable fraction of the volume scattering is modeled as diffuse.

The shadowing and masking term is

$$M(t, \omega_i, \omega_r) = (1 - u(\phi_d)) M(t, \omega_i) \times M(t, \omega_r) + u(\phi_d) \min(M(t, \omega_i), M(t, \omega_r)), \quad (3.20)$$

where,

$$M(t, \omega_i) = \max(\cos \phi_i, 0) \quad (3.21)$$

$$M(t, \omega_r) = \max(\cos \phi_r, 0), \quad (3.22)$$

which accounts for azimuthal shadowing and masking between parallel threads. Equations (3.21) and (3.22) describe the shadowing and masking, respectively, between parallel cylinders, as derived by Poulin et al. [28]. The combined term in Equation (3.20) approximates the combined attenuation due to both shadowing and masking, as described by Ashikhmin et al. [2]. This term is needed to account for the overlap in shadowing and masking where the azimuthal angles of the camera and light are nearly equal, weighted by a unit height gaussian, u , of the difference angle.

The projection term is

$$P(t, \omega_i, \omega_r) = (1 - u(\psi_d)) P(t, \omega_i) \times P(t, \omega_r) + u(\psi_d) \min(P(t, \omega_i), P(t, \omega_r)), \quad (3.23)$$

where,

$$P(t, \omega_i) = \max(\cos \psi_i, 0) \quad (3.24)$$

$$P(t, \omega_r) = \max(\cos \psi_r, 0), \quad (3.25)$$

which accounts for the foreshortening of the length of cylinders by the angle ψ . This foreshortening causes attenuation of light energy, both from the light and to the eye, so the projection term must account for both projections. The light and eye terms are combined just as the shadowing and masking terms.

The projection normalization term is

$$Q = \frac{a_1}{N_1} \sum_t P(t) + \frac{a_2}{N_2} \sum_t P(t) + (1 - a_1 - a_2)(\omega_r \cdot \mathbf{n}), \quad (3.26)$$

which accounts for the total projected length occupied by the smallest patch of both directions. This is used to adjust the ratio of the contribution based on the relative foreshortening of each thread segments' length.¹

This model takes two sets of parameters (one for each thread direction) in order to control the appearance of the rendered cloth. These parameters are summarized in Table 3.2.

This chapter contains several images which are reproduced from a published paper, in which the thesis author contributed significantly to the comparison of the proposed model and a previous model by Irawan et al. [15].

Iman Sadeghi, Oleg Bisker, Joachim De Deken, and Henrik Wann Jensen. A practical microcylinder appearance model for cloth rendering. *ACM Trans. Graph.*, 32(2):14:1–14:12, April 2013.

¹The projection reweighting term is partially the contribution of the thesis author.

Table 3.2: Sadeghi parameters.

Parameter	Type	Meaning
A	color	Albedo of thread
η	float	Index of refraction
k_d	float	Diffuse coefficient. Fraction of volume scattering which is treated as diffuse
γ_s	float	Width of surface scattering lobe (in degrees)
γ_v	float	Width of volume scattering lobe (in degrees)
a	float	Thread coverage ratio
tangent offsets	float array	Offsets from surface tangent (in degrees) of the tangent curve.
tangent lengths	float array	Lengths of tangent curve segments

Chapter 4

Comparison of Irawan’s and Sadeghi’s Models

Irawan’s and Sadeghi’s models represent the state of the art in cloth appearance modeling. There are clear similarities in their approaches to the problem, as both treat threads as curved microcylinders. However, key differences distinguish them in practice. This chapter provides a side-by-side comparison of rendered results from these two models, in the hopes to better understand the implications of these differences.

4.1 Method

4.1.1 Implementation Details

For this chapter, both Irawan’s and Sadeghi’s models have been implemented using Pharr’s Physically Based Ray Tracer (pbrt) [26]. The implementation for Irawan’s model was based on a project by Yang [39]. Yang implemented the small-scale textured model, with an additional self-shadowing term, so the code was modified to match Irawan’s proposed model for large-scale reflectance.

Both Irawan’s model and Sadeghi’s model require integrating along each thread segment. For both of these implementations this integration was performed numerically, using the midpoint rule with 50 uniform samples.

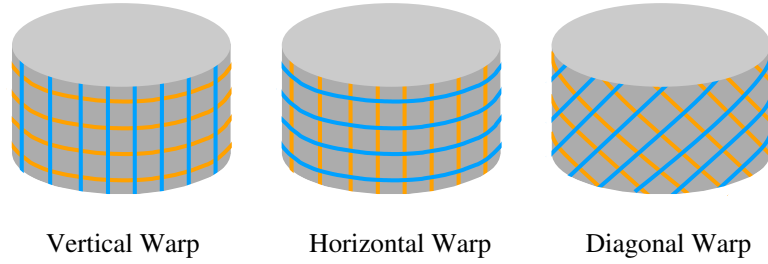


Figure 4.1: Cylinders setup used by Sadeghi et al. to validate their model. We use this same setup to compare Sadeghi’s and Irawan’s models. We refer to the orientation of the warp threads in describing each of these cylinders.

4.1.2 Comparison Method

An image-based approach to measuring the BRDF of cloth involves wrapping samples around a cylinder, at various rotations about the surface normal [19, 21]. A few simple photographs of this setup are able to demonstrate much of the reflectance behavior of a cloth sample. Sadeghi included such photographs for several cloth samples in order to validate the model. The setup for these images is illustrated in Figure 5.1. In this section, Sadeghi’s and Irawan’s models are compared by fitting each model to the cloth samples in Sadeghi’s paper. The materials are Plain Linen, Silk Crepe de Chine, Polyester Satin Charmeuse, Silk Shot Fabric, and Velvet.

Because Sadeghi included parameters for fitting the model to the provided samples, we use those parameters in our rendered results. In order to match the fabric samples using the Irawan implementation, these Sadeghi parameters were methodically translated to Irawan parameters, as described in Table 4.1. This method provided a starting point for matching, although a fair bit of manual tuning was also required. It should be noted that the photographed samples contain a high-frequency component, caused by thread-level detail. However, as the models in this section do not account for thread-level detail, this component will be ignored.

Table 4.1: Method used for matching Irawan parameters from Sadeghi parameters.

Irawan parameter	Value relative to Sadeghi parameters	Comments
α	0.01	
β	if $\gamma_s > 10 \rightarrow 4$ else $\rightarrow 8$	
δ	0.1	For filament threads only. Effect is very dependent on highlight location.
ψ	35	For staple threads only.
$u_{\max}$	Largest angle in Tangent Offsets	For larger δ values, this must be increased.
κ	Match shape of Tangent Curve	Refer to Figure 3.2, and choose κ which most closely matches shape of Tangent Curve.
w	1	
l	$a_j / \min(a_1, a_2)$	Shorter direction thread has unit area. Relative lengths between threads is preserved.
k_s	$(1 - k_d) \times \text{white}$	For some fabrics, especially those with lower η , like silk, this must be tinted by A .
k_d	$k_d \times A$	

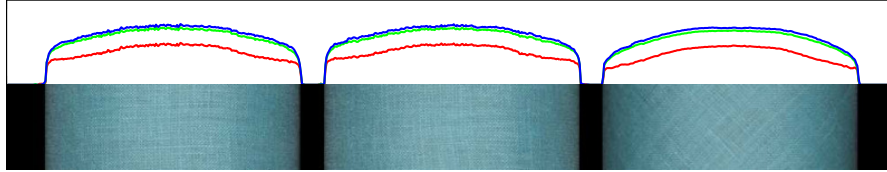
4.2 Results

All photographs and renders in this section are accompanied by plots of the RGB values averaged vertically. This helps us to visualize subtle differences in the reflection behavior of each model. Also, it should be noted that all rendered results have been gamma corrected with an exponent of $\frac{1}{2.2}$.

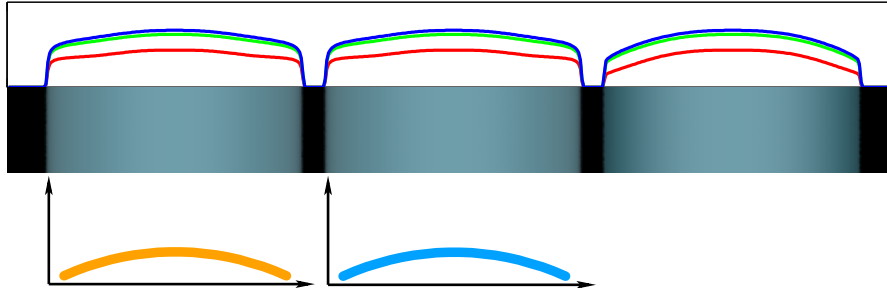
Figure 4.2 shows the results for Linen. Both Sadeghi’s and Irawan’s models are quite successful at reproducing the appearance. The results for Silk Crepe de Chine are shown in Figure 4.3. Note that the reference possesses subtle grazing highlights on the vertical cylinder. This effect is captured by Sadeghi’s model, but not by Irawan’s model. Figures 4.4 and 4.5 show the results for Polyester Satin Charmeuse, front and back face, respectively. Sadeghi’s model is able to reproduce all three highlights on the front face, and all four on the back. Irawan’s model is unable to produce any more than two at a time. Two separate renders are provided to demonstrate the Irawan shading which reproduces either the inner or outer highlights. Figure 4.6 shows the results for Silk Shot Fabric. The results on the vertical and horizontal cylinders are comparable. At grazing angles on the diagonal cylinder, the two models differ, but without any ground truth photos for that angle, it is not possible to verify which model is more correct. Figure 4.7 shows the results for Velvet. Sadeghi’s model successfully reproduces asymmetric grazing highlights. Irawan’s model, however, is unable to reproduce the asymmetry, and produces unrealistic grazing reflection behavior. In the next section, we will address all of these differencing results, and explain the theoretical differences which are responsible.

4.3 Analysis

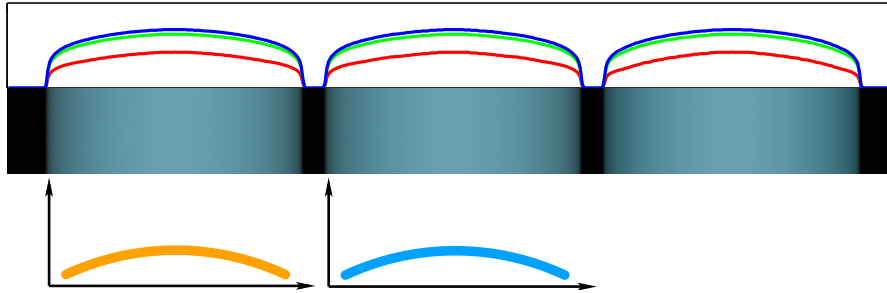
A major difference in the results using Irawan’s and Sadeghi’s models is the number of the highlights each is able to produce. That Sadeghi’s model may produce an arbitrary number of highlights is a key strength of the model. To understand why Sadeghi’s model has this flexibility, while Irawan’s model is unable to produce more than two, we must examine precisely how the curve of thread



(a) Reference photograph. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

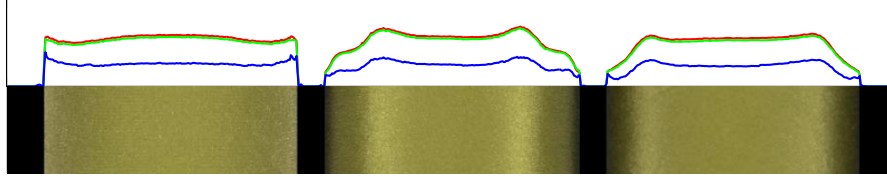


(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.

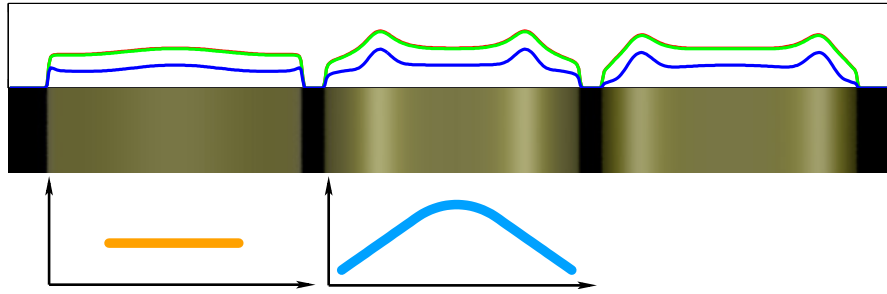


(c) Rendered result using Irawan's model and thread spine curves of weft(left) and warp(right) threads.

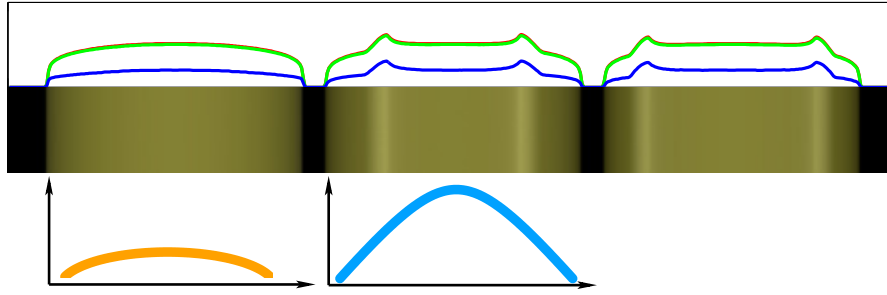
Figure 4.2: Comparison results for Plain Linen.



(a) Reference photograph. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.

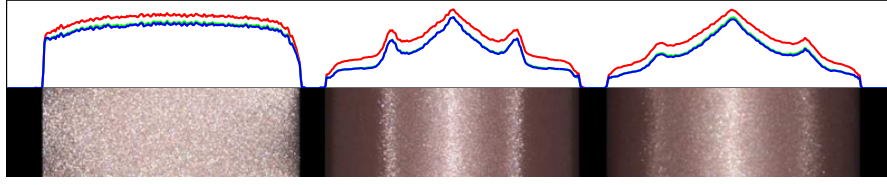


(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.

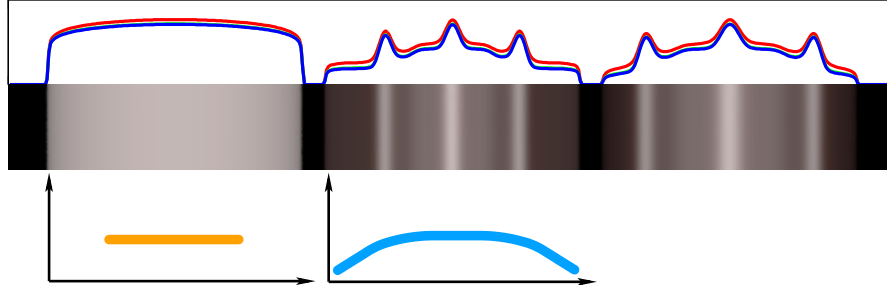


(c) Rendered result using Irawan's model and thread spine curves of weft(left) and warp(right) threads.

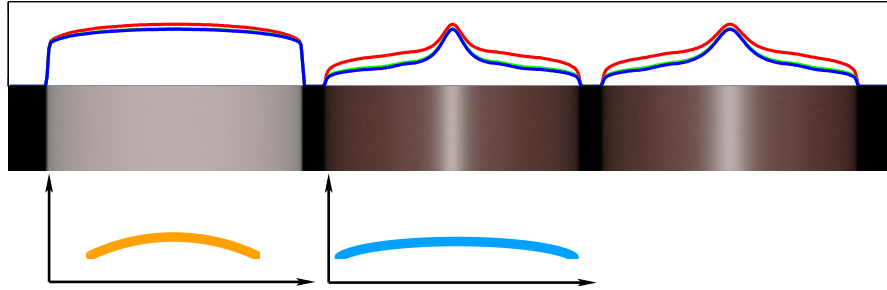
Figure 4.3: Comparison results for Silk Crepe de Chine.



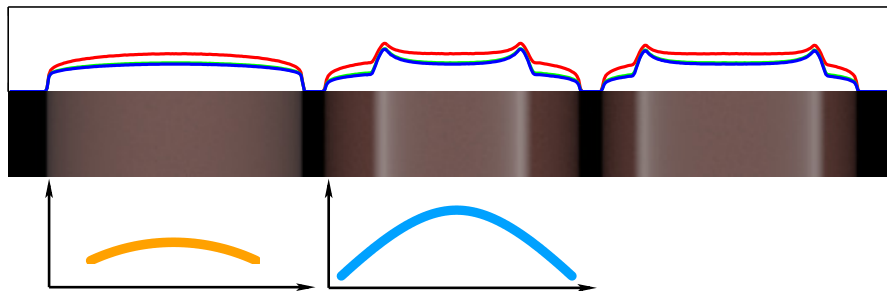
(a) Reference photograph. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.



(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.

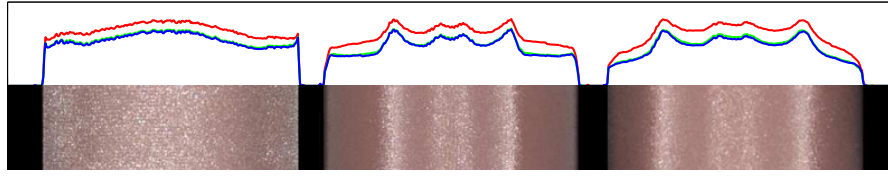


(c) Rendered result using Irawan's model, which captures only the inner highlight, and thread spine curves of weft(left) and warp(right) threads.

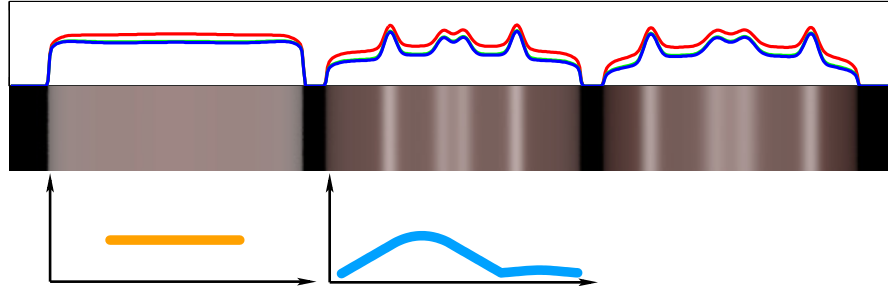


(d) Rendered result using Irawan's model, which captures only the outer highlight, and thread spine curves of weft(left) and warp(right) threads.

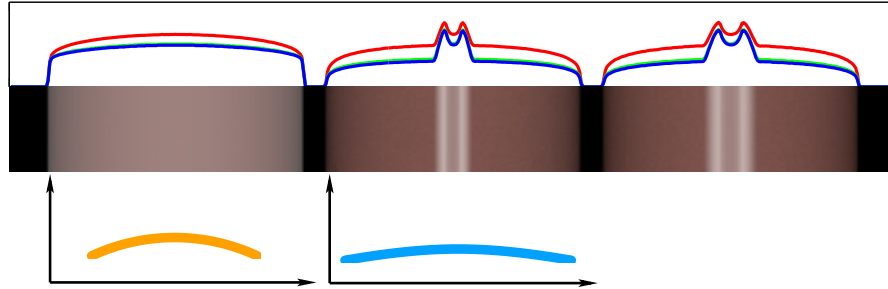
Figure 4.4: Comparison results for Polyester Satin Charmeuse, front face.



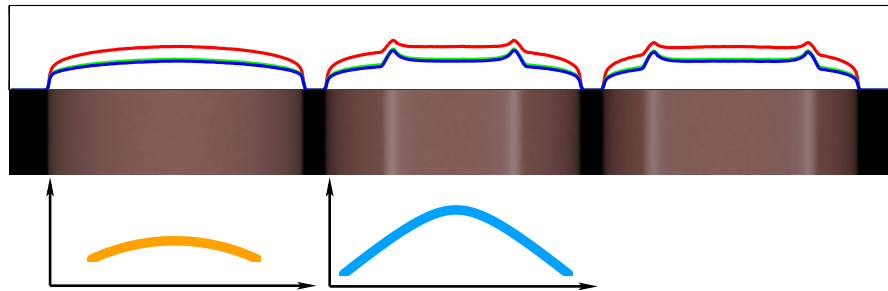
(a) Reference photograph. [30] ©2013 Association for Computing Machinery, Inc. Reprinted by permission.



(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.

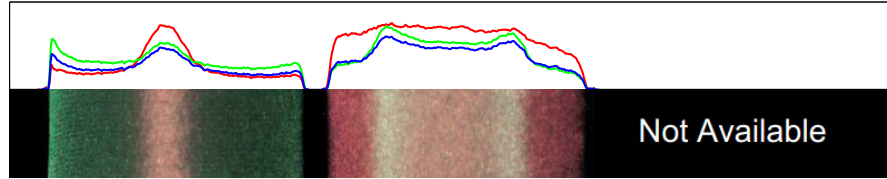


(c) Rendered result using Irawan's model, which captures only the inner highlight, and thread spine curves of weft(left) and warp(right) threads.

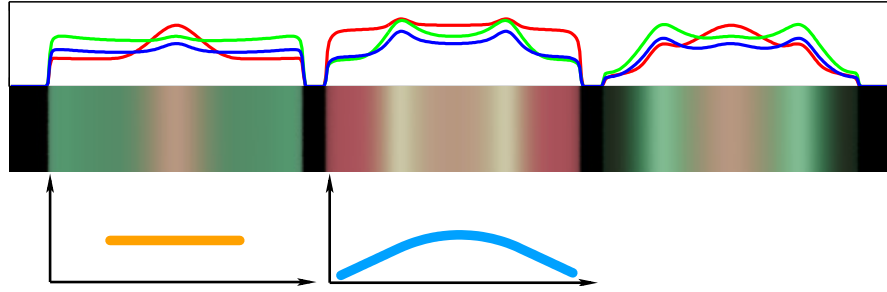


(d) Rendered result using Irawan's model, which captures only the outer highlight, and thread spine curves of weft(left) and warp(right) threads.

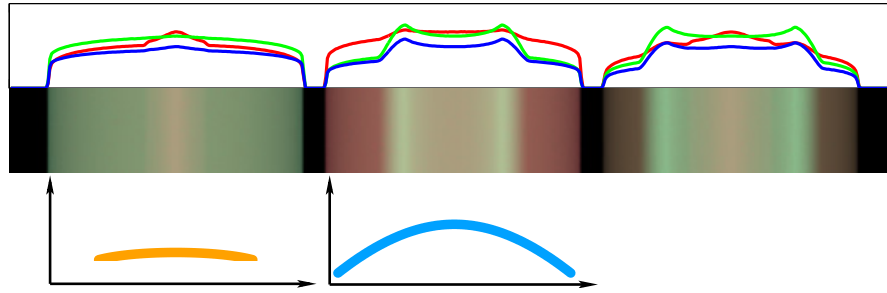
Figure 4.5: Comparison results for Polyester Satin Charmeuse, back face.



(a) Reference photograph. [27] Reprinted by permission.

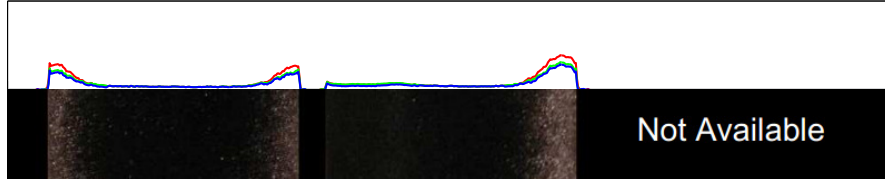


(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.

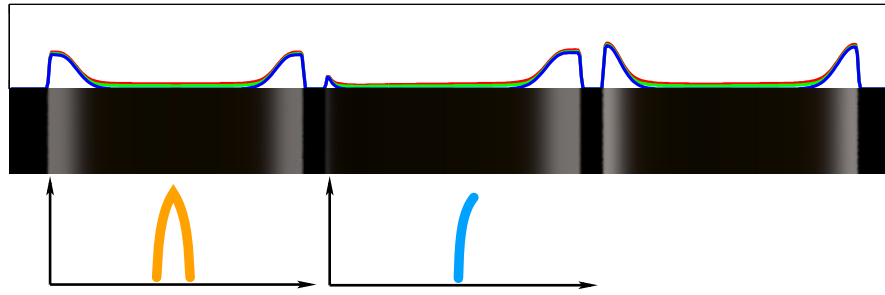


(c) Rendered result using Irawan's model and thread spine curves of weft(left) and warp(right) threads.

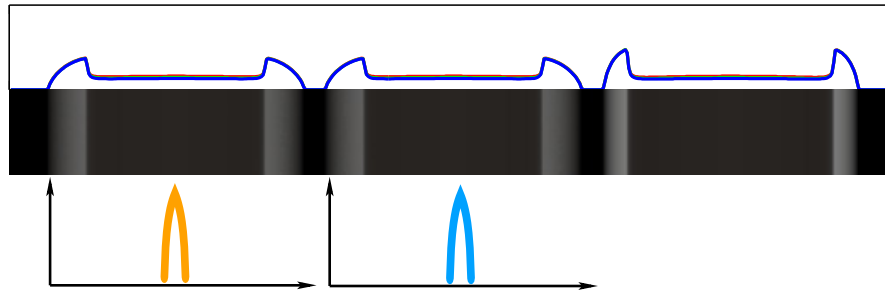
Figure 4.6: Comparison results for Silk Shot Fabric.



(a) Reference photograph. [3] Reprinted by permission.



(b) Rendered result using Sadeghi's model and tangent curves of weft(left) and warp(right) threads.



(c) Rendered result using Irawan's model and thread spine curves of weft(left) and warp(right) threads. Note that the thread spine curves have been stretched horizontally in order to be able to see the shape.

Figure 4.7: Comparison results for Velvet.

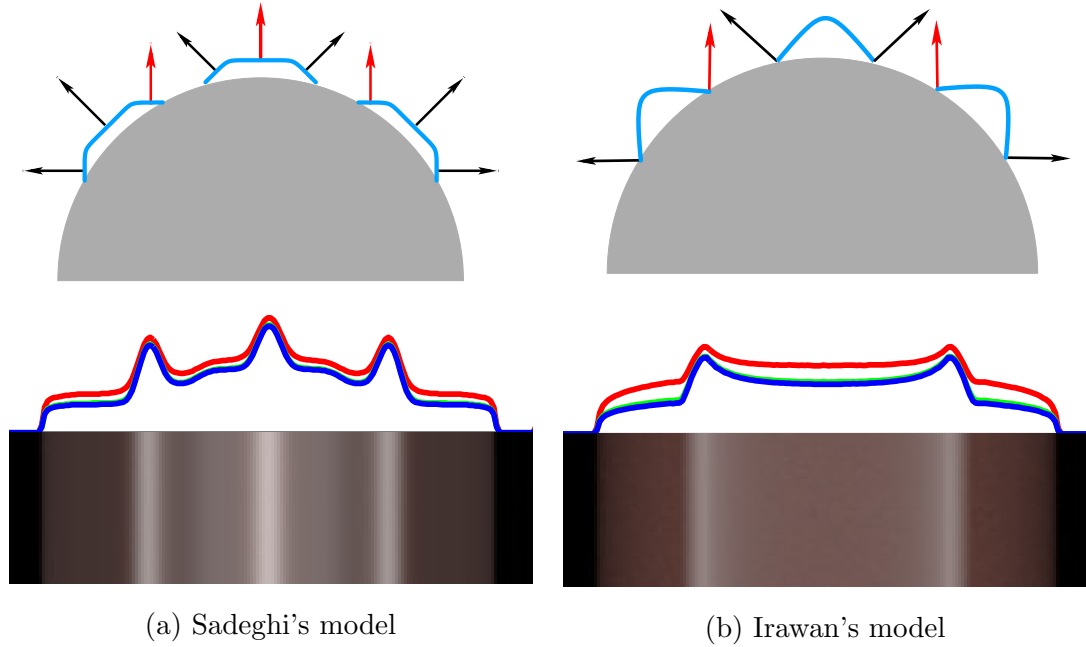


Figure 4.8: Relationship between thread segment shape and highlight location for Sadeghi's model (left) and Irawan's model (right), using results for Polyester Satin Charmeuse. Top: Looking down the length of a cylinder, illustrating how horizontal threads lie on its surface. The arrows indicate the locally flattest regions of the curve. Red arrows indicate regions of curve responsible for front-facing highlights.

segments is expressed in each model. As mentioned in the previous chapter, flat regions of the curve are responsible for highlights on the cylinder. Because Sadeghi's tangent curve may assume an arbitrary shape, threads may produce an arbitrary highlight pattern. To create a highlight at a certain inclination, one must simply create a flat section of the curve at that inclination. Irawan's model, on the other hand, uses a conic section (ellipse, circle, or hyperbola) to describe thread shape. Because conic sections can have at most two nearly flat regions, this model can produce no more than two highlights, as seen in Figures 4.4 and 4.5. Additionally, this forces the spine curve to be symmetric about $\theta = 0$ degrees. Therefore, it is unable to produce the asymmetric highlight in velvet, as shown in Figure 4.7.

In both of these models, the shape of the thread segments is critical for determining at what angles highlights are observed. Figure 4.8 illustrates the relationship between the thread segment shape and the locations of the resulting highlights for each of these models.

Conic sections also have limited ability to control of the appearance of off-specular highlights (those with negative κ parameter, in Irawan's model). Without the use of additional smoothing, such highlights will necessarily be very sharp at $u_{\max}$. Irawan's model uses a cubic smooth-step at the highlight edge in order to soften this highlight. However, this has several negative effects. It pushes the highlight towards the center, smoothing the outside of the highlight, but sharpening the inside (see Figure 4.7). This also changes the location of the highlight, making the parameters harder to tune.

Threads are typically dielectric materials, meaning that surface reflections are untinted, while volume scattering is tinted by the thread albedo. Due to the Fresnel effect, materials with a high index of refraction, like polyester (See Figure 4.4), will have a strong untinted highlight component, while those with lower, such as silk, will have a more prominent tinted component. In Irawan's model, all directional scattering is multiplied by k_s , meaning that to more closely reproduce materials like the Silk Crepe de Chine and Silk Shot Fabric (See Figures 4.3 and 4.6), it is necessary to use a non-physical, non-white k_s . However, the full effect cannot be captured without separate tinted and untinted specular lobes, as

the untinted components should become stronger when the angle between the light and eye is large.

We conclude that for large-scale appearance, Sadeghi’s model is more accurate and flexible than Irawan’s model. So, for the remainder of the thesis we will focus on Sadeghi’s model.

This chapter contains several images which are reproduced from a published paper, in which the thesis author contributed significantly to the comparison of the proposed model and a previous model by Irawan et al. [15].

Iman Sadeghi, Oleg Bisker, Joachim De Deken, and Henrik Wann Jensen. A practical microcylinder appearance model for cloth rendering. *ACM Trans. Graph.*, 32(2):14:1–14:12, April 2013.

Chapter 5

Measurements of New Cloth Types

In this chapter, we present a host of measurements of various fabric types which have not yet been expressed with Sadeghi’s model. We then fit the model according to these measurements and examine the results. The goal of this section is to test how well this model applies to a wider range of physical characteristics, as well as to expand the library of fabrics available for this model.

5.1 Measurements

5.1.1 Setup

All photographs in this section were taken with a Canon EOS-1D Digital SLR camera, with a Canon EF 135mm lens. The aperture was set to 2.8, the ISO was set to 250, and the exposure time varied by sample from 1/10 to 1/400 seconds. The samples were illuminated by a Dolan-Jenner DC950H Machine Vision Illuminator, which uses a 150Watt Tungsten Halogen bulb (Temperature: 3250K). The walls of the room, in which these photographs were taken, were painted black to minimize indirect illumination. There were no other significant sources of light in the room.

These measurements were taken using the setup described by Sadeghi, il-

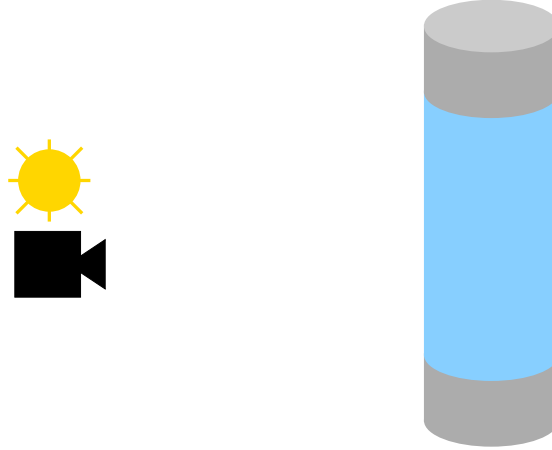


Figure 5.1: Measurement setup. Cloth samples were wrapped around a cylinder and photographed with the light source and camera approximately collocated.

illustrated in Figure 5.1, in which cloth samples are wrapped around a cylinder and photographed with the light source and camera approximately collocated. To minimize reflections through the sample of the cylinder itself, a base layer of black fabric was wrapped around the cylinder, underneath the sample being measured.

5.1.2 Cloth Samples

Table 5.1: Fabric samples.

Cloth	Structure	Material
Denim	Twill weave	100% Cotton
Pink Lining	Satin weave	100% Polyester
Polka-dot Lining	Satin weave	100% Polyester
Swimwear	Warp knit	87% Nylon, 13% Spandex
White T-shirt	Weft knit	100% Cotton
Black T-shirt	Weft knit	50% Cotton, 50% Polyester
Faux Suede	Woven, nap	97% Polyester, 3% Spandex
Corduroy	Woven, pile	100% Cotton

The eight fabric samples, summarized in Table 5.1 and pictured in Figure 5.2, were chosen specifically to test Sadeghi’s model on a broader range of cloth types. Denim and the Pink Lining were selected because they are very com-



(a) Denim



(b) Pink Lining



(c) Polka-dot Lining



(d) Swimwear



(e) White T-shirt



(f) Black T-shirt



(g) Faux Suede



(h) Corduroy

Figure 5.2: Fabric samples

mon woven fabrics, which had not yet been expressed using Sadeghi’s model. The Polka-dot Lining was chosen for its multi-colored pattern. The three knitted fabrics (Swimwear, White T-shirt and Black T-shirt) were selected to test how well Sadeghi’s model applies to a knitted structure, although the model makes no claim to support it. The threads in these three fabrics exhibit varying degrees of specularly. Faux Suede was chosen to see how the model handled a strong nap. Finally, Corduroy was selected for its mixed structure of woven and pile fabric.

5.2 Fitting to Sadeghi’s model

In the process of fitting each of the samples, only the vertical and horizontal cylinder photographs were considered. The accuracy of the diagonal cylinders can be used to gauge the success of the model for predicting non-perpendicular cloth orientations.

These measurements were taken using a range of exposures. In order to account for this, the intensity of the light source used in rendered images was adjusted accordingly.

5.3 Results

All photographs and rendered results in this section are accompanied by plots of the RGB values averaged vertically. This helps us to visualize subtle differences in the reflection behavior of the reference and each model. Also, it should be noted that all rendered results have been gamma corrected with an exponent of $\frac{1}{2.2}$.

Figure 5.3 shows the results for Denim. Sadeghi’s model successfully reproduces the appearance caused by a twill weave of blue and white staple threads.

Figure 5.4 shows the results for the Pink Lining fabric. A satin weave of filament threads causes strong near-specular highlights. The vertical and diagonal cylinders display bright grazing-angle highlights, while the diagonal cylinder possesses dark grazing reflections. The bright grazing reflections observed on a

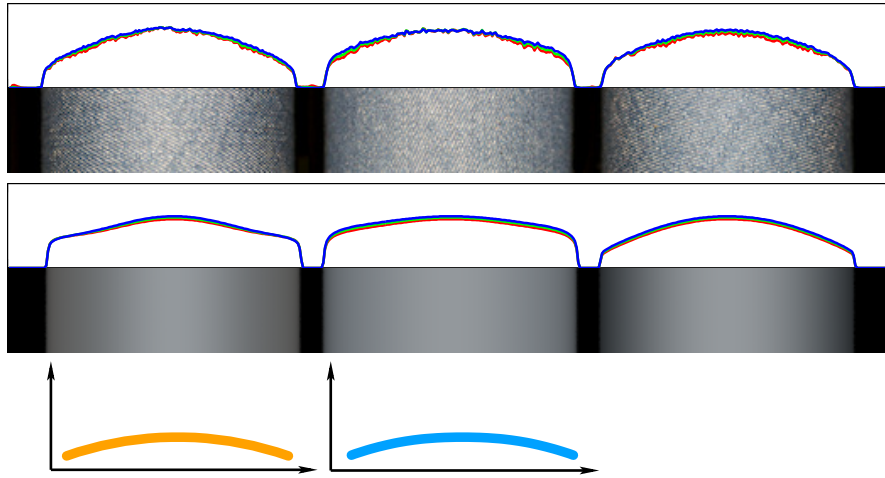


Figure 5.3: Denim. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.

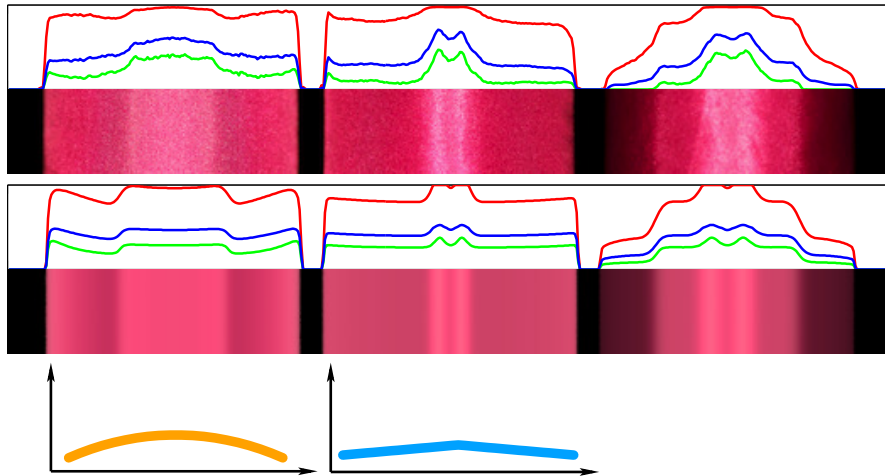


Figure 5.4: Pink Lining. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.

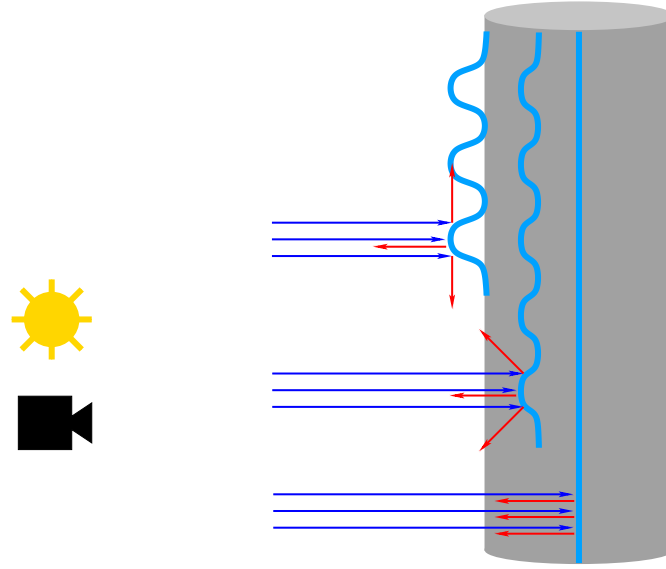
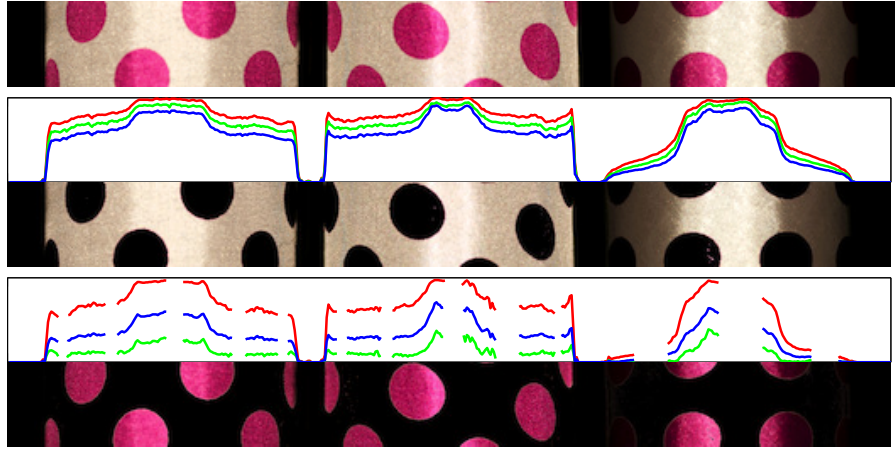


Figure 5.5: A side-view of the measurement scene, illustrating reflections on vertical threads as they lie on the cylinder. At grazing angles, vertical threads reflect all incoming light back towards the camera, causing a highlight.

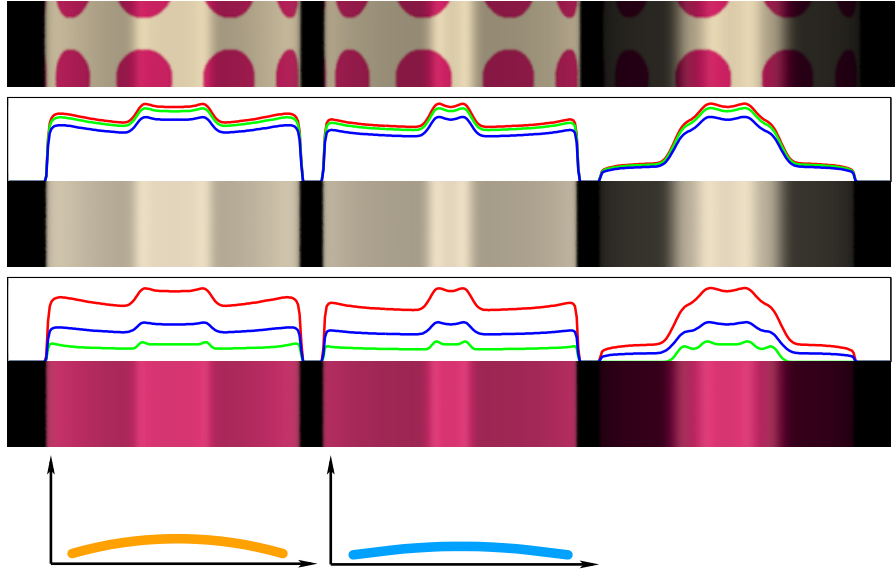
cylinder are caused, in part, by the threads which lie vertical on that cylinder. The reason for this behavior is illustrated in Figure 5.5. However, on the diagonal cylinder, no thread direction is vertical, so we observe the dark regions at grazing angles.

The Polka-dot Lining was chosen to determine how best to accommodate a dyed pattern within Sadeghi’s model. The pattern for this sample is two-colored, so we’ve separated each color for the plots in Figure 5.6. From the measurements, the graphs for each color appear to have the same general shape, so we hypothesized that having a separate albedo for the two colors would be sufficient to capture the full behavior. The rendered results match well, supporting this hypothesis.

The Swimwear was perhaps the most interesting of the fabric samples. The fact that the base color was green and the highlights were yellow suggested that using differently colored warp and weft threads would best be able to reproduce the appearance. This approach was used to produce the results in Figure 5.7. However, because knitted fabric is made from a single continuous strand, there should be only a single color for all directions. A closer inspection of the threads reveals that the

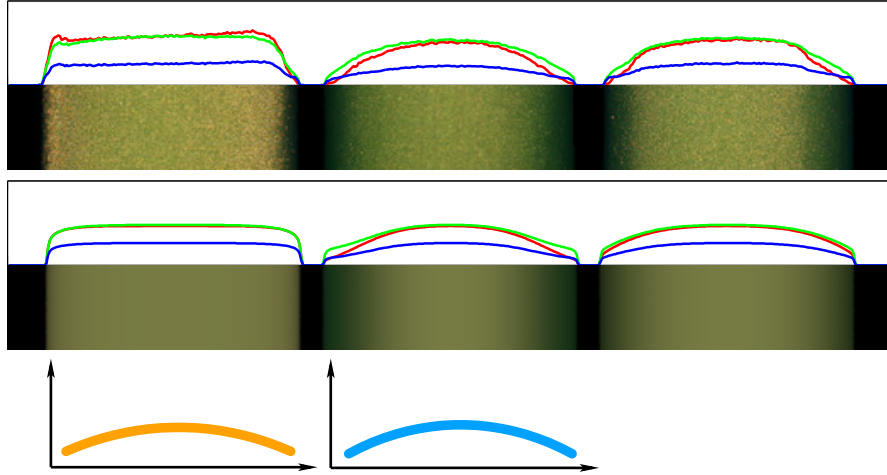


(a) Reference photo (top) with white (middle) and pink (bottom) components separated. The RGB curve for the pink component has gaps where no color information was available.

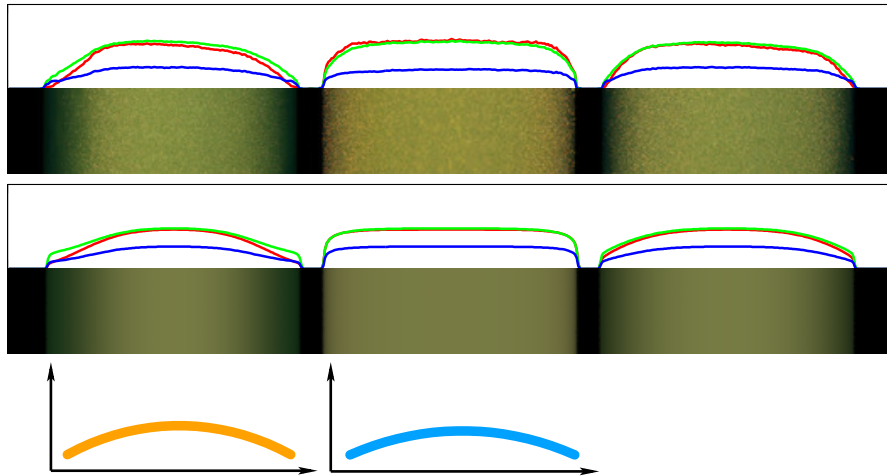


(b) Rendered result using Sadeghi's model (top), with white (middle) and pink (bottom) components separated.

Figure 5.6: Polka-dot Lining.



(a) Swimwear, front face. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.



(b) Swimwear, back face. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.

Figure 5.7: Swimwear.

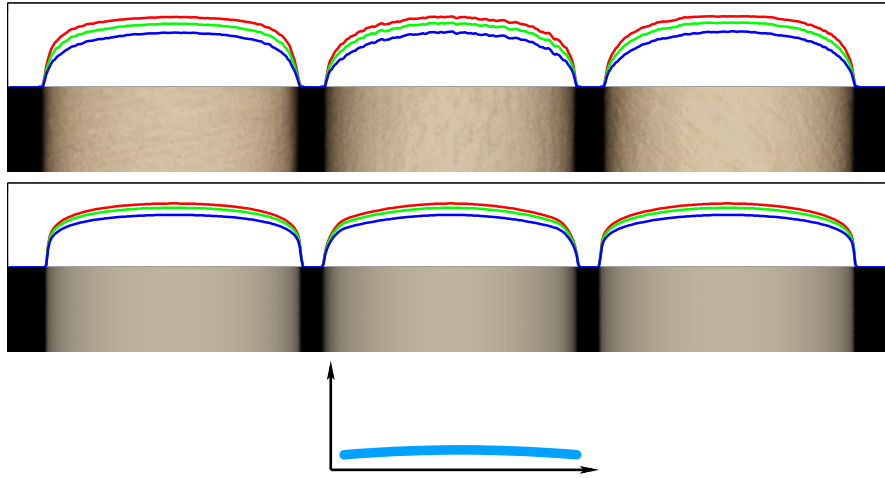
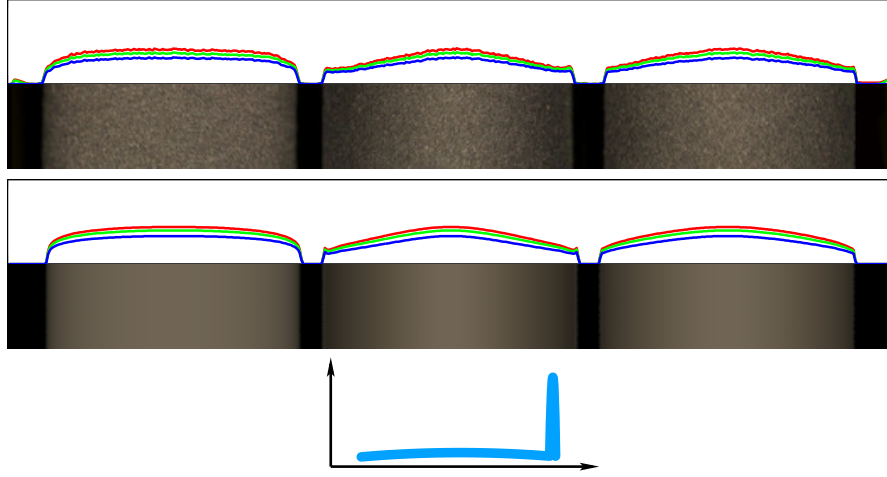


Figure 5.8: T-shirt, white. Top: Reference photo. Bottom: Rendered using Sadeghi's model.

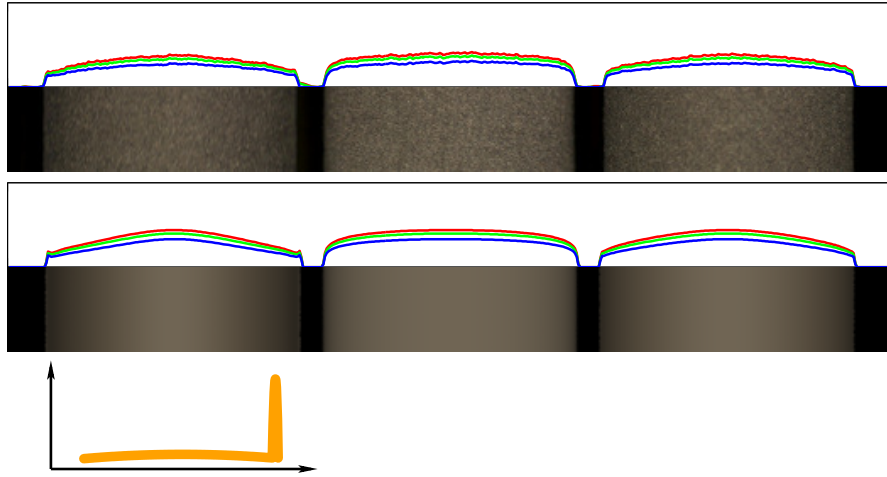
fibers themselves exhibit yellow surface scattering, and green volume scattering. There are two possible explanations. We could be observing a color shift resulting from dispersion in higher order volume scattering. However, it is perhaps more likely that a metallic coating was applied to the threads in the production of the fabric, which is causing the yellow reflection. It should also be noted that on the vertical front face and horizontal back face cylinders, the model predicts yellow highlights which extend to the edge of the cylinder. However, this is not observed in the measurements. This is discussed in the next chapter.

Figure 5.8 shows the results for the White T-shirt sample, and Figure 5.9 shows the results for the Black T-shirt sample, front and back, respectively. In all of these fittings, only a single thread direction was needed, which was achieved by setting the area ratio to 1 for the dominant direction, and 0 for the other. In these samples, we observed that the front face was warp-dominant, and that the back-face was weft-dominant. Also, we found that the Black T-shirt sample exhibited small grazing highlights when the dominant thread was horizontal. We reproduced these by adding a high-angle section to the tangent curve, like that found in velvet.

Figure 5.10 shows the fit results for Faux Suede. This is a woven fabric which has been brushed to create a stronger nap. Sadeghi's model is able to



(a) T-shirt, black, front face. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.



(b) T-shirt, black, back face. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.

Figure 5.9: Black T-shirt.

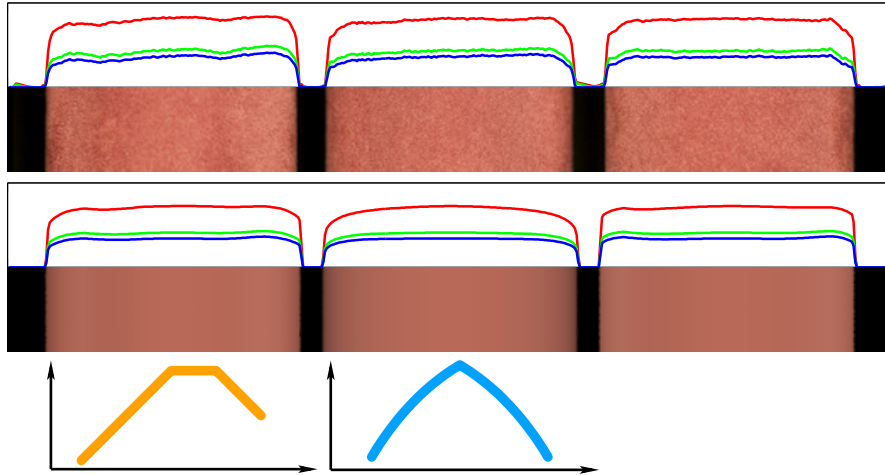


Figure 5.10: Faux suede. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.

reproduce this material's relatively flat, yet slightly asymmetric appearance, which is comprised of a soft specular highlight as well as soft grazing highlights. Using high γ values widen the scattering lobes, creating softer highlights.

Corduroy, pictured in Figure 5.11, is a more complex material. It is composed of alternating stripes of woven and pile fabric. Because this fabric is made of two different types of cloth, it may seem natural to model it as a weighted sum of two Sadeghi cloths, each with their own set of parameters. However, by simply choosing our parameters based on the overall shape of the RGB curves, we are still able to capture the general appearance with only a single Sadeghi cloth. The alternating stripes, however, do strongly affect the recognizability of Corduroy. A possible approach for addressing this is discussed in the next chapter.

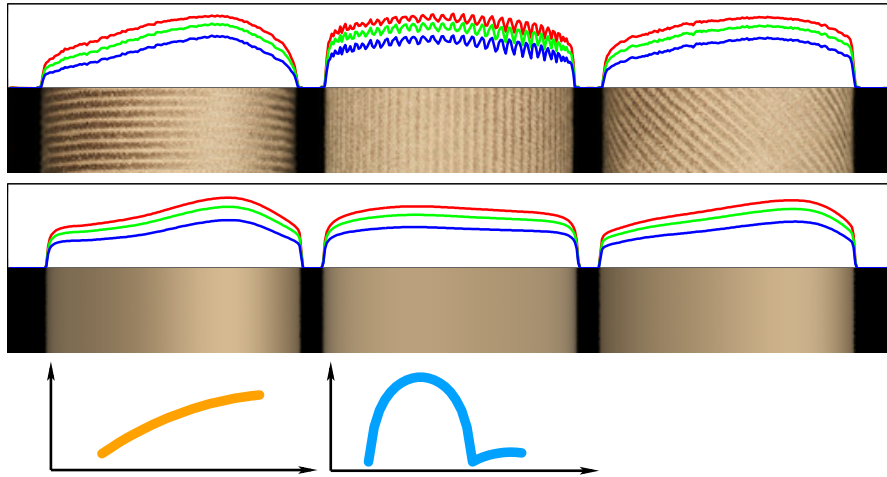
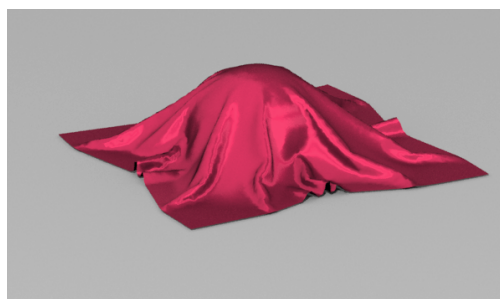


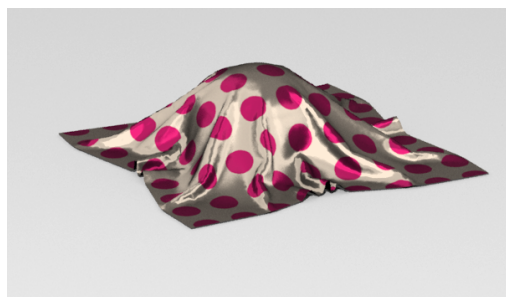
Figure 5.11: Corduroy. Top: Reference photo. Bottom: Rendered result using Sadeghi's model.



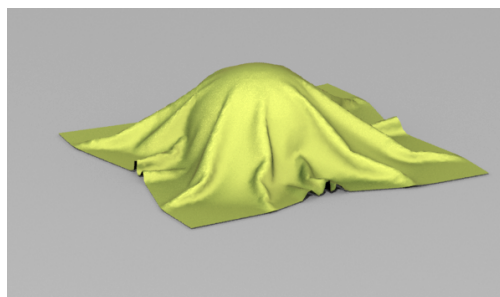
(a) Denim



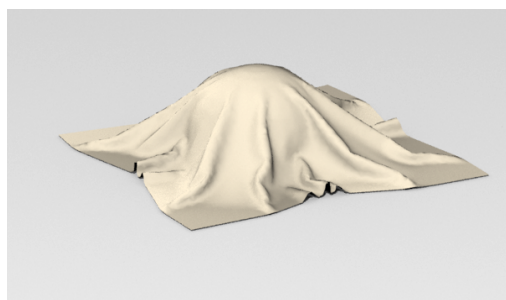
(b) Pink Lining



(c) Polka-dot Lining



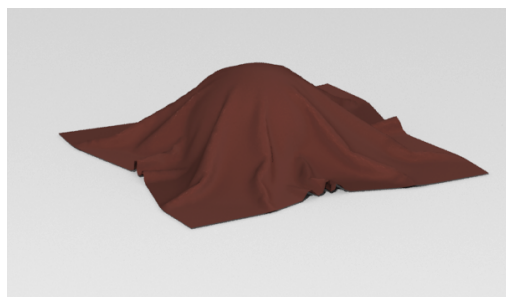
(d) Swimwear



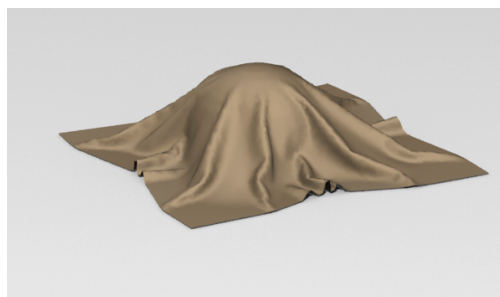
(e) White T-shirt



(f) Black T-shirt



(g) Faux Suede



(h) Corduroy

Figure 5.12: Rendered fabric samples. The Pink Lining and Swimwear samples were rendered under lower light intensity to avoid saturating the image.

Chapter 6

Discussion and Future Work

In all, Sadeghi’s model was quite successful in reproducing the appearance of a wide range of cloth types. In this section, we address each new type of fabrics which was investigated, and discuss both strengths and weaknesses. For the limitations discovered, we suggest extensions to the model that would address them.

6.1 Knitted Fabrics

For the Swimwear fabric, Sadeghi’s model predicted grazing highlights when the true highlights were just inside grazing. This suggests that a woven model may not necessarily be completely appropriate for knitted fabric, especially when a high level of accuracy is required.

Additional measurements of the Swimwear sample reveal more interesting properties about this particular fabric. Because there were no grazing highlights found in the original measurements, we took additional measurements to see whether there were grazing highlights at any other cloth orientation. We found grazing highlights at off-perpendicular orientations, which are pictured in Figure 6.1. The model, as fit in the previous chapter, does not reproduce these grazing highlights.

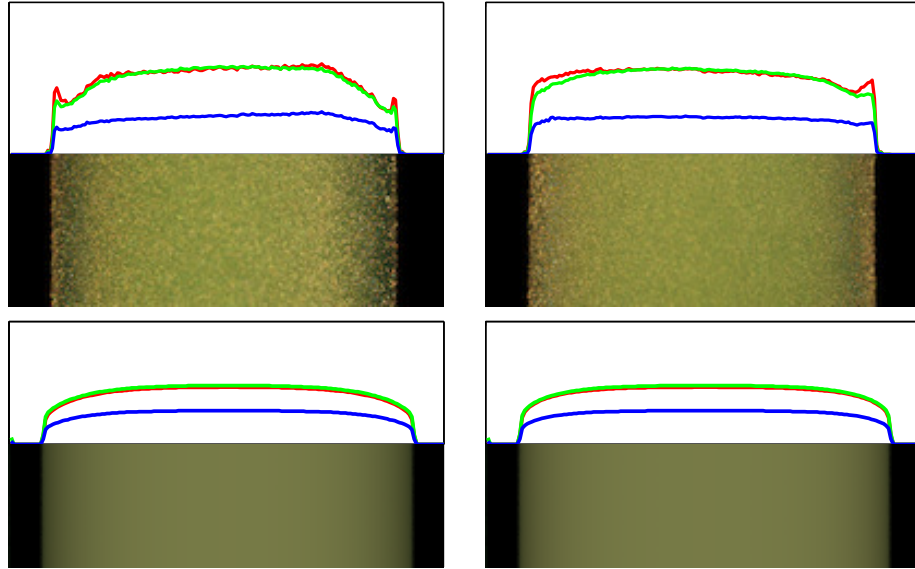


Figure 6.1: Additional photographs (top) and corresponding rendered results using Sadeghi's model (bottom) of the Swimwear sample. Note the absence of the grazing angle highlights in the rendered images. Left: Front face of fabric, oriented 65 degrees about the normal. Right: Back face of fabric, oriented 20 degrees about the normal.

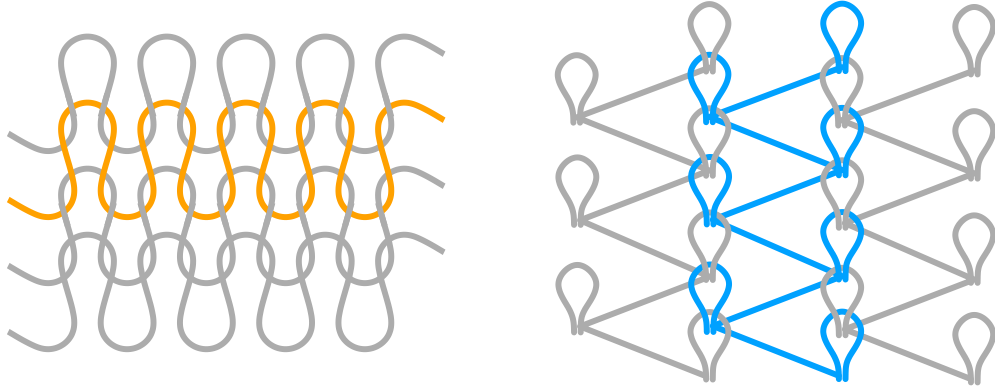


Figure 6.2: Knitted structure. Left: Simple weft knit. Right: Simple warp knit.

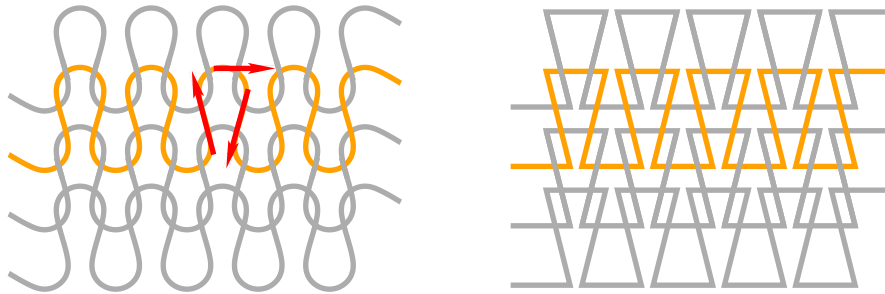


Figure 6.3: Weft knit simplified into the three dominant thread directions.

6.1.1 Knitted Structure

Before speculating on the reasons for these shortcomings, it's important to first understand the structure of knitted materials and how it differs from that of woven materials. There are hundreds, if not thousands of distinct knits, though the two main categories are weft and warp knits. The structure of the knitted samples in the previous section are some of the simplest examples of each weft and warp knits, which are illustrated in Figure 6.2. Weft knits, like those found in the T-shirt samples, involve a single strand of yarn or thread, looping around itself across the weft of the material. In a warp knitted fabric like the Swimwear sample, separate strands loop around each other down the warp of the material.

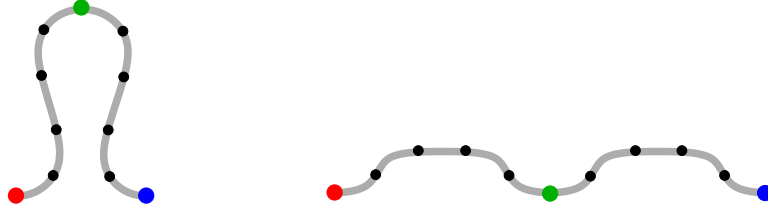


Figure 6.4: Thread direction curve (left) and thread tangent curve (right) for weft knit. The red, blue and green markers each indicate corresponding locations on the two curves.

6.1.2 Non-Perpendicular Thread Directions

The key difference between woven and knitted fabric is that in woven fabric, there are exactly two perpendicular thread directions. However, in knitted materials, there are usually more than two dominant thread directions, which are not necessarily perpendicular. This would suggest that Sadeghi’s model could be extended to more fully support knitted materials by allowing a variable number of thread directions, which can be in any specified direction. Figure 6.3 illustrates how thread directions in a simplified model for weft knitted fabric, like the T-shirt samples, might be broken down into its three dominant directions.

If this coarse approximation is insufficient, the model could further be extended to support a continuous curve of thread directions. Much like the thread tangent curve can be thought of as a side-view of the thread, a *thread direction curve* would be the top-view of the thread. If the tangent and the direction curves were aligned, as illustrated in Figure 6.4, this direction curve could then be sampled along with the tangent curve. Because the combination of a tangent and a direction can specify any possible 3D orientation of a cylinder, this modification should allow Sadeghi’s model to describe *any possible fabric* composed of dielectric microcylinders, regardless of the thread structure.

6.1.3 Improved Reflectance Visualization

The three-cylinders model works very well for producing test renders of woven fabric. Because the thread directions are always perpendicular on the ver-

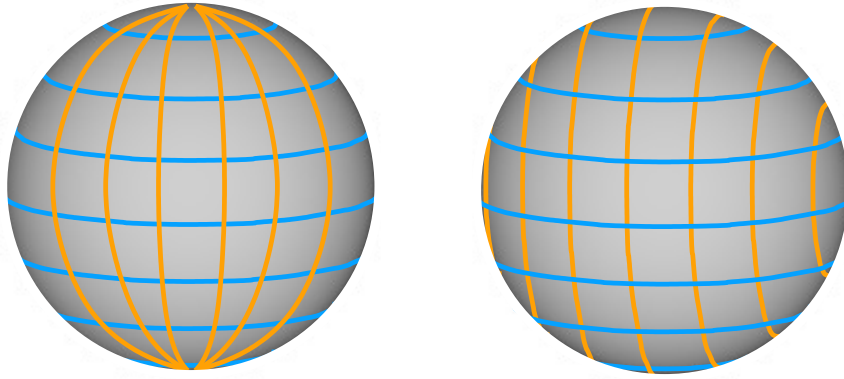


Figure 6.5: Left: Typical sphere mapping. Right: Proposed mapping of cloth on a sphere for test renders. Blue lines indicate the warp direction, and orange lines indicate the weft. In the proposed mapping, the material wraps away from the center of the sphere towards all grazing angles.

tical and horizontal cylinders, the dominant components of the appearance are captured with just those orientations. However, with any non-woven fabrics, this will be insufficient to visualize the full behavior. Instead, we propose rendering the material on a sphere as illustrated in Figure 6.5. In this mapping, as opposed to traditional spherical mapping, the material wraps away from the center of the sphere towards all grazing angles. The benefit of this mapping is that each slice across the diameter corresponds to a single cylinder orientation, as illustrated in Figure 6.6. Therefore the sphere effectively captures all cylinder orientations in a single view.

The down-side of this approach, however, is that no planar cloth can actually be wrapped flat around a sphere. This means that this is not an accurate method for measuring physical cloth samples. For fabrics which can stretch in all directions, one can stretch the material around a sphere, as we’ve done in Figure 6.7, in order to get a general feel for the appearance behavior. But this should not be considered an accurate measurement, as stretching the cloth changes the underlying structure - and thus the reflective properties - of the material. However, even this rough measurement demonstrates the grazing angle highlights we observed in the non-perpendicular orientations from Figure 6.1.

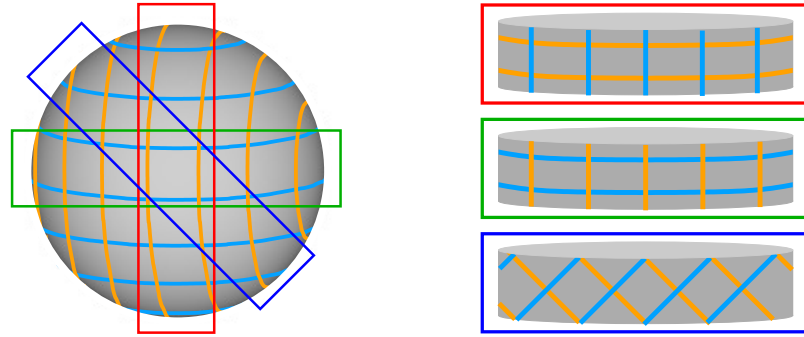


Figure 6.6: The proposed sphere mapping captures all cylinder orientations in a single view. To illustrate this point we've outlined the vertical (red), horizontal (green), and diagonal (blue) cylinders on the sphere.

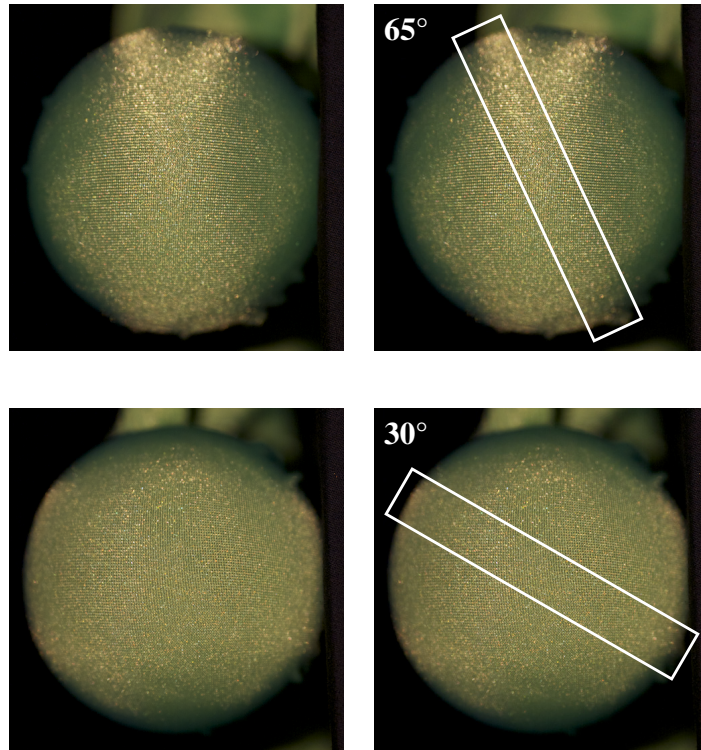


Figure 6.7: Swimwear sample stretched around a sphere to visualize highlight behavior at all orientations simultaneously. Top: Front face. Bottom: Back face.

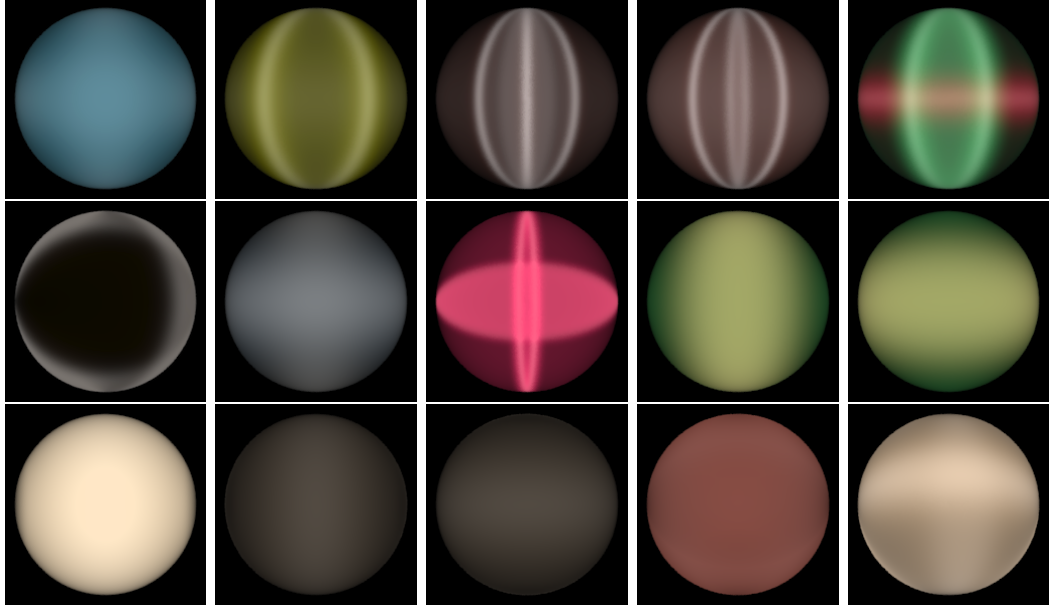


Figure 6.8: All non-textured cloths from this paper rendered on a sphere as described. First row: Linen, Silk Crepe de Chine, Polyester Satin Charmeuse (front), Polyester Satin Charmeuse (back), Silk Shot Fabric. Second row: Velvet, Denim, Polyester Lining, Swimwear (front), Swimwear (back). Third row: White T-shirt, Black T-shirt (front), Black T-shirt (back), Faux Suede, Corduroy.

Figure 6.8 shows all cloths used in this paper, rendered in the fashion described above. The actual model in these images is composed of 180 very short cylinders, rotated about the z-axis from 0 to 179 degrees. These images capture all cloth orientations in a single shot. A clear result of using a woven model with perpendicular threads is that the highlights are oriented in on-perpendicular directions.

6.2 Texture

6.2.1 Large-Scale: Dyed Cloth

We’ve demonstrated, with the Polka-dot Lining sample, that it is sufficient to assume that dying a fabric only affects its albedo. Therefore, a piece of cloth with a dyed pattern can be reproduced simply by using a texture for the albedo

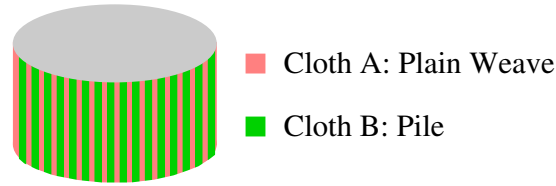


Figure 6.9: Proposed pattern of two cloth types for corduroy.



Figure 6.10: Rendered corduroy using alternating stripes of different materials.

parameter. It should be noted that this would not apply to any coating applied to the cloth surface, such as opaque paint on a silk-screened t-shirt.

6.2.2 Medium-Scale: Mixed Cloth Types

The appearance of some materials, like corduroy, are dominated by medium-scale features from a pattern of different cloth types. This can likely be addressed by modeling corduroy as a striped pattern of two different cloths, with two separate sets of parameters, as illustrated in Figure 6.9. This would produce the familiar striped pattern, as in Figure 6.10, while allowing each separate material to behave correctly.

6.3 Fuzz

The sphere render of velvet exposes a potential problem with using a woven model for fuzzy fabrics. The highlights in velvet end up with a rather square appearance, which does not match the smooth appearance typically associated with velvet. A photo of a different velvet sample stretched around a sphere, as in Figure 6.11, demonstrates the expected smooth reflection shape. Because the microcylinders in fuzz are typically oriented in a broad distribution of directions, it seems that an approach like the thread direction curve could be a natural fit for describing grazing angle highlights from fuzz.

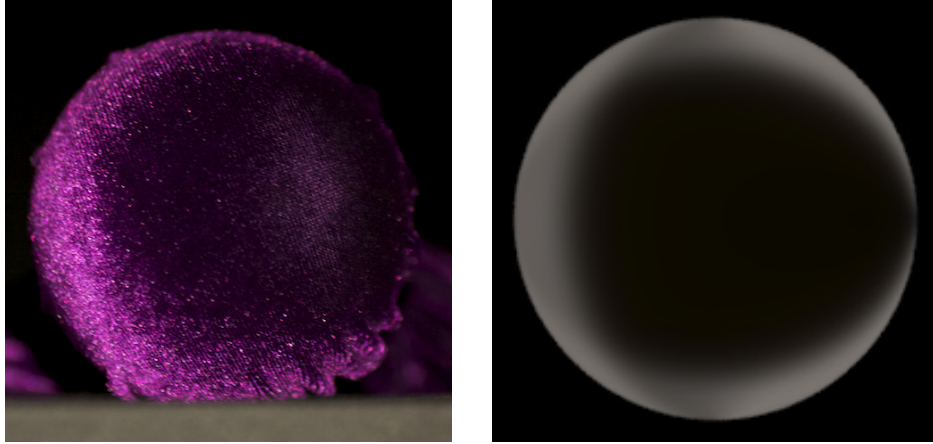


Figure 6.11: Left: Photograph of velvet stretched around a sphere. Right: Rendered sphere using Sadeghi velvet model from Chapter 4.

6.4 Tailoring the model for artists

In computer graphics research, it is a common problem that the workflow of artists is given insufficient consideration. With any new advancement, particularly in appearance modeling, if it is not intuitive for an artist to control, it will never see the light of day. Sadeghi’s work on hair rendering incorporated input from artists [31], resulting in a significant improvement in the physical accuracy in hair shading used in film. Similarly, it would be informative to learn what qualities artists want to control when shading a piece of cloth, and how this model might be modified and parameterized to best suit their workflow.

Chapter 7

Conclusion

7.1 Contributions

This thesis has helped to clarify the state of the art of cloth rendering by comparing and analyzing Irawan’s and Sadeghi’s appearance models. These two models, which are based on BRDF measurements of cloth, represent the forefront of cloth appearance modeling research. We have determined that Sadeghi’s model both has a stronger physical basis, and is better able to express a wide range of cloth appearances.

We also have provided a host of measurements which can be used to gauge the success of a cloth model. These measured cloth samples have been reproduced using Sadeghi’s model, accomplishing two things. First, we have expanded the library of parameterized cloth types available for this model. Secondly, we have used these results to further evaluate the flexibility and accuracy of Sadeghi model, by comparing the results to the measurements. This evaluation brings to light an inherent limitation of woven cloth models, for which we suggest the addition of a *thread direction curve*.

7.2 Future Work

Because of its physical basis and its flexibility, Sadeghi’s model holds much promise for cloth appearance modeling. With the addition of a thread direction

curve, it is likely this model can be generalized to describe a much wider range of cloth types. With this added complexity, however, it will be important to address the model’s usability. Therefore, further research should be invested in tailoring the model to better suit artists’ workflow, and improving its ability to be intuitively controlled.

The medium and small scale appearance of cloth often contributes significantly to its overall appearance. Yet Sadeghi’s model only addresses the large-scale appearance of cloth. An approach which incorporates thread-level detail, like Bisker’s model [4], or even simply physically plausible noise, would greatly improve the flexibility of the model to support a wider range of zoom levels. The physical accuracy of texturing models like this, however, tend to break down at grazing angles. So it would be informative to evaluate any small-scale model with comparisons against the large-scale model. Additionally, it would be interesting to investigate the transmission of light through various fabrics.

We believe these directions for future research are the most important in order to realize the full potential of Sadeghi’s model. With these areas addressed, we would finally have the ability to describe all cloth types, for all levels of detail, with a single, unifying model.

Appendix A

Sadeghi Parameters

This Appendix contains the Sadeghi parameters for all new cloth types introduced in this thesis.

Table A.1: Sadeghi parameters for Denim.

Parameter	Warp	Weft
A	$(0.5, 0.75, 1) \times 0.07$	$(0.9, 0.85, 0.07) \times 0.1$
η	1.4	1.4
k_d	0	0
γ_s	15	15
γ_v	30	30
a	0.7	0.3
Tangent Offsets	-20, -5, 5, 20	-20, 20
Tangent Lengths	1, 1, 1	1

Table A.2: Sadeghi parameters for Polyester Lining.

Parameter	Warp	Weft
A	$(1, 0.04, 0.18) \times 0.7$	$(1, 0.04, 0.18) \times 0.7$
η	1.3	1.3
k_d	0.2	0.2
γ_s	1.5	1.5
γ_v	3	3
a	0.7	0.3
Tangent Offsets	-25, 25	-5, -5, 5, 5
Tangent Lengths	1	1, 0, 1

Table A.3: Sadeghi parameters for Polka-dot Polyester Lining.

Parameter	Warp	Weft
A_{white}	$(0.8, 0.7, 0.6) \times 0.5$	$(0.8, 0.7, 0.6) \times 0.5$
A_{pink}	$(1, 0, 0.25) \times 0.35$	$(1, 0, 0.25) \times 0.35$
η	1.2	1.2
k_d	0.1	0.1
γ_s	1.5	1.5
γ_v	3	3
a	0.6	0.4
Tangent Offsets	-15, -15, 15, 15	-7, -7, 7, 7
Tangent Lengths	0.1, 0.8, 0.1	0.2, 0.6, 0.2

Table A.4: Sadeghi parameters for Swimwear, front.

Parameter	Warp	Weft
A	$(1, 0.9, 0.3) \times 1$	$(0.1, 1, 0.2) \times 0.7$
η	1.3	1.3
k_d	0	1
γ_s	8	32
γ_v	16	64
a	0.8	0.2
Tangent Offsets	-30, 30	-25, 25
Tangent Lengths	1	1

Table A.5: Sadeghi parameters for Swimwear, back.

Parameter	Warp	Weft
A	$(0.1, 1, 0.2) \times 0.7$	$(1, 0.9, 0.3) \times 1$
η	1.3	1.3
k_d	1	0
γ_s	32	8
γ_v	64	16
a	0.2	0.8
Tangent Offsets	-25, 25	-30, 30
Tangent Lengths	1	1

Table A.6: Sadeghi parameters for White T-shirt.

Parameter	Warp	Weft
A	$(1, 0.9, 0.75) \times 1$	—
η	1.3	—
k_d	1	—
γ_s	24	—
γ_v	48	—
a	1	0
Tangent Offsets	-5, 5	—
Tangent Lengths	1	—

Table A.7: Sadeghi parameters for Black T-shirt, front.

Parameter	Warp	Weft
A	$(0.89, 0.68, 0.48) \times 0.05$	—
η	1.1	—
k_d	0.1	—
γ_s	15	—
γ_v	30	—
a	1	0
Tangent Offsets	-5, 5, -90, -90, 90, 90	—
Tangent Lengths	10, 0, 0.2, 0, 0.2	—

Table A.8: Sadeghi parameters for Black T-shirt, back.

Parameter	Warp	Weft
A	—	$(0.89, 0.68, 0.48) \times 0.05$
η	—	1.1
k_d	—	0.1
γ_s	—	15
γ_v	—	30
a	0	1
Tangent Offsets	—	-5, 5, -90, -90, 90, 90
Tangent Lengths	—	10, 0, 0.2, 0, 0.2

Table A.9: Sadeghi parameters for Faux Suede.

Parameter	Warp	Weft
A	$(1, 0.27, 0.2) \times 0.15$	$(1, 0.27, 0.2) \times 0.15$
η	1.15	1.15
k_d	0.7	0.7
γ_s	15	15
γ_v	30	30
a	0	1
Tangent Offsets	-60, -30, 30, 60	-45, -45, 0, 0, 45, 45
Tangent Lengths	1, 0, 1	2, 0, 1, 0, 1

Table A.10: Sadeghi parameters for Corduroy.

Parameter	Warp	Weft
A	$(0.83, 0.58, 0.35) \times 0.4$	$(0.83, 0.58, 0.35) \times 0.4$
η	1.5	1.4
k_d	0.3	0.3
γ_s	8	8
γ_v	16	16
a	0.5	0.5
Tangent Offsets	-90, 90, -30, 10	-35, -5
Tangent Lengths	1, 0, 0.5	1

Appendix A

Additional Rendered Images

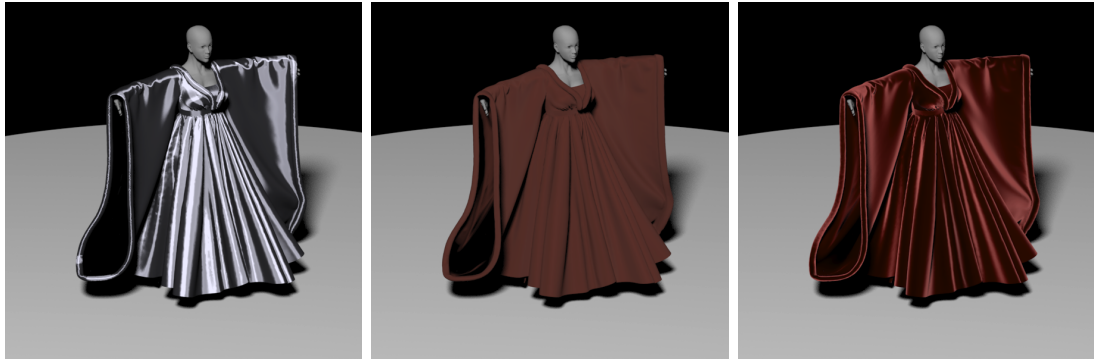


Figure A.1: Sadeghi’s model is able to reproduce a wide range of cloth appearances, including the strong specular highlights found in polyester lining (left), the matte appearance of faux suede (center), and the asymmetric grazing highlights found in velvet (right).



Figure A.2: A curtain made of the Polka-dot Lining fabric, rendered using Sadeghi's model.



Figure A.3: A curtain made from two orientations of the same Lining fabric, rendered using Sadeghi's model.

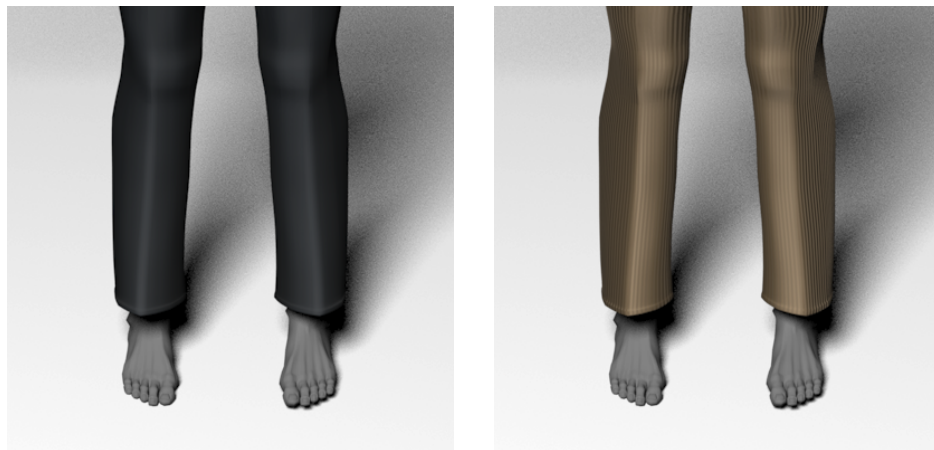


Figure A.4: Pant fabrics, rendered using Sadeghi's model. Left: Denim, Right: Corduroy

Bibliography

- [1] Neeharika Adabala, Nadia Magnenat-Thalmann, and Guangzheng Fei. Visualization of woven cloth. In *Proceedings of the 14th Eurographics workshop on Rendering*, EGRW '03, pages 178–185, Aire-la-Ville, Switzerland, Switzerland, 2003. Eurographics Association.
- [2] Michael Ashikhmin, Simon Premože, and Peter Shirley. A microfacet-based brdf generator. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '00, pages 65–74, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.
- [3] Michael Victor Ashikhmin. *Approximate methods for improving surface appearance*. PhD thesis, 2001. AAI3012256.
- [4] Oleg Bisker. *A Measurement-Based Appearance Model for Fabrics*. PhD thesis, University of California, San Diego, 2011.
- [5] James F. Blinn. Models of light reflection for computer synthesized pictures. *SIGGRAPH Comput. Graph.*, 11(2):192–198, July 1977.
- [6] Yanyun Chen, Stephen Lin, Hua Zhong, Ying-Qing Xu, Baining Guo, and Heung-Yeung Shum. Realistic rendering and animation of knitwear. *IEEE Transactions on Visualization and Computer Graphics*, 9(1):43–55, January 2003.
- [7] R. L. Cook and K. E. Torrance. A reflectance model for computer graphics. *ACM Trans. Graph.*, 1(1):7–24, January 1982.
- [8] Kristin J. Dana, Bram van Ginneken, Shree K. Nayar, and Jan J. Koenderink. Reflectance and texture of real-world surfaces. *ACM Trans. Graph.*, 18(1):1–34, January 1999.
- [9] Katja Daubert, Hendrik P. A. Lensch, Wolfgang Heidrich, and Hans-Peter Seidel. Efficient cloth modeling and rendering. In *Proceedings of the 12th Eurographics Workshop on Rendering Techniques*, pages 63–70, London, UK, UK, 2001. Springer-Verlag.

- [10] Joachim De Deken. *A BRDF analysis of cloth*. PhD thesis, University of California, San Diego, 2010.
- [11] Frédéric Drago and Norishige Chiba. Painting canvas synthesis. *Vis. Comput.*, 20(5):314–328, July 2004.
- [12] Rick Glumac and David Doepp. Generalized approach to rendering fabric. In *ACM SIGGRAPH 2004 Sketches*, SIGGRAPH '04, pages 120–, New York, NY, USA, 2004. ACM.
- [13] P. Irawan and SR Marschner. A simple, accurate texture model for woven cotton cloth. Technical report, Tech. Rep. PCG-06-01, Cornell University, Department of Computer Science, 2006.
- [14] Piti Irawan. *Appearance of woven cloth*. PhD thesis, Ithaca, NY, USA, 2008. AAI3295837.
- [15] Piti Irawan and Steve Marschner. Specular reflection from woven cloth. *ACM Trans. Graph.*, 31(1):11:1–11:20, February 2012.
- [16] J. T. Kajiya and T. L. Kay. Rendering fur with three dimensional textures. *SIGGRAPH Comput. Graph.*, 23(3):271–280, July 1989.
- [17] JH Lambert. Photometria sive de mensura et gradibus luminus colorum et umbrae. *Colorum et Umbrae (Eberhard Klett, 1760)*, 1760.
- [18] Robert R. Lewis. Making shaders more physically plausible. *Computer Graphics Forum*, 13(2):109–120, 1994.
- [19] Rong Lu, Jan J. Koenderink, and Astrid M. L. Kappers. Optical properties (bidirectional reflection distribution functions) of velvet. *Appl. Opt.*, 37(25):5974–5984, Sep 1998.
- [20] Stephen R. Marschner, Henrik Wann Jensen, Mike Cammarano, Steve Worley, and Pat Hanrahan. Light scattering from human hair fibers. *ACM Trans. Graph.*, 22(3):780–791, July 2003.
- [21] Stephen R. Marschner, Stephen H. Westin, Eric P. F. Lafortune, and Kenneth E. Torrance. Image-based bidirectional reflectance distribution function measurement. *Appl. Opt.*, 39(16):2592–2600, Jun 2000.
- [22] Jan Meseth, Gero Müller, and Reinhard Klein. Reflectance field based real-time, high-quality rendering of bidirectional texture functions. *Computers & Graphics*, 28(1):105 – 112, 2004.
- [23] G. Müller, J. Meseth, M. Sattler, R. Sarlette, and R. Klein. Acquisition, synthesis, and rendering of bidirectional texture functions. *Computer Graphics Forum*, 24(1):83–109, 2005.

- [24] Addy Ngan, Frédo Durand, and Wojciech Matusik. Experimental analysis of brdf models. In *Proceedings of the Eurographics Symposium on Rendering*, pages 117–226. Eurographics Association, 2005.
- [25] Michael Oren and Shree K. Nayar. Generalization of lambert’s reflectance model. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, SIGGRAPH ’94, pages 239–246, New York, NY, USA, 1994. ACM.
- [26] M. Pharr and G. Humphreys. *Physically based rendering: From theory to implementation*. Morgan Kaufmann, 2004.
- [27] Sylvia C. Pont and Jan J. Koenderink. Split off-specular reflection and surface scattering from woven materials. *Appl. Opt.*, 42(8):1526–1533, Mar 2003.
- [28] Pierre Poulin and Alain Fournier. A model for anisotropic reflection. *SIGGRAPH Comput. Graph.*, 24(4):273–282, September 1990.
- [29] I. Sadeghi. *Controlling the Appearance of Specular Microstructures*. PhD thesis, University of California, San Diego, 2011.
- [30] Iman Sadeghi, Oleg Bisker, Joachim De Deken, and Henrik Wann Jensen. A practical microcylinder appearance model for cloth rendering. *ACM Trans. Graph.*, 32(2):14:1–14:12, April 2013.
- [31] Iman Sadeghi, Heather Pritchett, Henrik Wann Jensen, and Rasmus Tamstorf. An artist friendly hair shading system. *ACM Trans. Graph.*, 29(4):56:1–56:10, July 2010.
- [32] Hans Holbein the Younger. Sir thomas more, 1527. Oil on oak panel.
- [33] K.E. Torrance and E.M. Sparrow. Theory for off-specular reflection from roughened surfaces. *JOSA*, 57(9):1105–1112, 1967.
- [34] Unknown. Woman in satin dress holding mirror, ca. 1915. George Eastman House Collection.
- [35] Gregory J. Ward. Measuring and modeling anisotropic reflection. *SIGGRAPH Comput. Graph.*, 26(2):265–272, July 1992.
- [36] Jerry Weil. The synthesis of cloth objects. *SIGGRAPH Comput. Graph.*, 20(4):49–54, August 1986.
- [37] Stephen H. Westin, James R. Arvo, and Kenneth E. Torrance. Predicting reflectance functions from complex surfaces. In *Proceedings of the 19th annual conference on Computer graphics and interactive techniques*, SIGGRAPH ’92, pages 255–264, New York, NY, USA, 1992. ACM.

- [38] Ying-Qing Xu, Yanyun Chen, Stephen Lin, Hua Zhong, Enhua Wu, Baining Guo, and Heung-Yeung Shum. Photorealistic rendering of knitwear using the lumislice. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '01, pages 391–398, New York, NY, USA, 2001. ACM.
- [39] Lingfeng Yang. Cse 348b final project: Cloth rendering, 2009.
- [40] W. Yuen and B. Wünsche. An evaluation on woven cloth rendering techniques. In *Proceedings of Image and Vision Computing New Zealand 2011*, pages 7–12, Auckland, New Zealand, 2011.
- [41] Shuang Zhao, Wenzel Jakob, Steve Marschner, and Kavita Bala. Building volumetric appearance models of fabric using micro ct imaging. *ACM Trans. Graph.*, 30(4):44:1–44:10, July 2011.