An Evaluation on Woven Cloth Rendering Techniques

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***Abstract*—Advances in graphics hardware have led to large number of new technologies for cloth rendering. However, it is not clear what technology is suitable for what types of applications. While computer games need compact representation and high efficiency in cloth rendering techniques, fashion related applications often need high flexibility for rendering different fabrics. So far no research exists comparing digital representations of fabric rendering techniques. This paper reviews different parameters that contribute to the appearance of fabrics such as fiber types, yarn types, and weaving patterns. Several existing methods are discussed and we analyze their advantages and disadvantages in rendering realistic woven clothes. We categorized these techniques into example-based and procedural-based methods. Our analysis shows that example-based methods generally result in more realistic renderings than procedural-based methods. However, realism comes with the cost of expensive capturing and storage of data, coupled with long processing time for rendering these results. Procedural-based methods tend to be more flexible in supporting different fabric types, and are more suitable for interactive applications.**

I. Introduction

Woven cloth rendering is a vigorously researched area which addresses issues for various industries and applications involving computer graphics and fashion design. While a lot of existing researches have been done for physical simulation of cloth, areas concerning with cloth appearances are still largely unexplored. Moreover, realistic cloth rendering is difficult to achieve due to the complicated fiber structure and its light interaction behavior at the micro-level. The appearance of different fabrics varies greatly, and they are controlled by various parameters including the fiber types, yarn types, and their underlying weaving patterns. These fabric properties are discussed in this paper to find out the main contributing factors that determine the different appearances in different fabrics.

Also, in this paper we look at different approaches for rendering realistic fabrics. We compare and analyze these techniques in order to understand their advantages and disadvantages, to see which models are applied in satisfying different requirements.

II. Background

In cloth manufacturing, fibers are initially extracted or produced synthetically. They are then twisted or grouped into yarns. Yarns are then weaved into fabrics through the weaving machine, and different weaving construct would produce fabrics with distinct appearances.

Therefore, weaving patterns and different types of yarns would be the main contributing factors to the resulting fabric's reflectance behavior. Since yarns are produced from fibers, therefore the reflectance properties of fiber materials are important, to help understand the reflectance properties of yarns. In this section, we analyze the physical characteristics of common fiber types, yarn types, and types of weaving patterns, and we identify parameters that influence the light interaction of the resulting fabric.

A. Fiber Types

As mentioned in Section I, fibers can be extracted naturally from animals, minerals, and plants (natural fibers), or they can be produced chemically (synthetic fibers). Different types of fibers control the appearance of the resulting yarn and fabric due to their difference in density and index of refraction, therefore it is necessary to investigate different types of common fibers and how their surface interacts with light.

There are generally three classes of fiber and they are listed with some examples in the following list:

- Natural fiber from animals: Angora, Cashmere, Mohair, Silk, Wool
- Natural fiber from plants: Cotton, Flax, Jute, Hemp, Modal
- Synthetic fiber: Acetate, Acrylic, Nylon, Polyester

Amongst these fibers, cotton is one of the most widely used fiber in clothing. It is used in approximately 40% of total world fiber production (Welford 1933). It is a naturally short fiber and is often produced into yarns by twisting around other fibers. Yarns that are made up of short fibers consist of many fibers twisting around each other, therefore these yarns tend to have a rougher surface than those produced using longer fibers. This is because longer fibers do not have to be twisted around each other to be grouped into a yarn, therefore they can be arranged along the same direction, thus the resulting yarn would exhibit a smoother surface overall (De Deken 2010).

Synthetic fibers are man-made fibers where the appearance and physical properties can be manipulated during the process of production. The four synthetic fibers - nylon, polyester, acrylic, and polyolefin dominate the synthetic fiber production market, and account for around 98% by production, with polyester having the majority of 60% (McIntyre & Textile Institute Manchester(2005).

B. Yarn Types

As mentioned, the use of different yarns would result in different visual properties of the resulting fabrics. Yarns are generally classified into two categories:

- Staple yarns
- Filament yarns

Yarns tend to give different reflection behavior due to the length of fibers used to produce these yarns. Staple yarns are generally very short, their underlying fibers have to be twisted around one another to make the yarns more cohesive. Short fibers tend to come off loose from the yarns, therefore the resulting fabrics produced by staple yarns tend to look rougher on its surface than fabrics produced by filament yarns(De Deken 2010). Filament yarns contain long and continuous fibers that are grouped together without twisting the fibers around other fibers (De Deken 2010). In general, the length of fibers determines the types of yarns that are produced, which ultimately determines the reflectance properties of the produced fabrics.

C. Weave Structure

Yarns are weaved into fabrics using a particular weaving pattern. Many types of weaving patterns exist, their structures produce different appearances in resulting fabrics. The three most fundamental weaving patterns are shown in the following list:

- Plain Weave
- Twill Weave
- Satin Weave

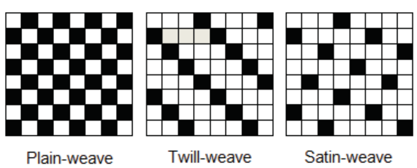

Fig. 1: Examples of different weaving patterns. White squares represent weft yarn and black squares represent warp yarn.

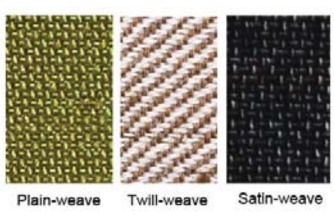

Fig. 2: Examples of different weaving pattern on actual fabrics at micro-level.

As shown in Figure 1, plain-weave has a regular pattern, for each weft yarn, there is a warp yarn located next to it. Twill-weave has a regular diagonal pattern, with a longer weft yarn going across multiple warp yarns, forming a diagonal line visible on resulting fabrics. Satin-weave has even longer weft yarns going across warp yarns, where either weft or warp yarn dominates the fabric surface, causing it to look the smoothest out of the three patterns.

The pattern that yarns are weaved into is critical to fabrics' reflectance properties, as the weaving pattern is still clearly visible from a distant view. Thus, it acts as a texture on the fabric surface. The weaving pattern also alters the light interaction of the fabric surface, producing self-shadowing and inter-reflection effects affecting the micro and macro-level (De Deken 2010).

III. Bidirectional Texture Function

Bidirectional Texture Function (BTF) is a function proposed by Dana, et al. (1999). It represents the structural geometry on any real-world surfaces in terms of viewing and illumination direction, capturing different textures of a surface under varying viewing and illumination direction (Dana et al. 1999). BTF data is the most accurate and realistic virtual material representing real-world material, and is often used in rendering photorealistic objects in virtual environments. Due to the complicated microstructure on fabrics, simple BRDF and texture mapping methods are not sufficient in capturing the inter-reflections and occlusions of yarns. Therefore, BTF is often used in cloth rendering to capture those missing visual aspects of fabrics rendered in those techniques.

BTF is able to capture all of the local and non-local visual properties of the fabrics by capturing textures of the surface under all combinations of illumination and viewing direction, thus it is more visually realistic than simple texture mapping and general BRDF models. However, in practice this is a tedious data acquisition process with high storage requirement for over thousands of images for each object surface (Filip & Haindl 2008).

IV. Methods for Cloth Rendering

There are two categories of methods that are currently used for fabric rendering:

- Example-Based Models
- Procedural-Based Models

A. Example-Based Models

Example-based fabric rendering techniques focus on collecting reflectance information of materials for rendering. Existing researches are focused on texture-based models using variants of BTF, with various data compression techniques. Recently, Zhao, et al. (2011) proposed a volumetric approach that enabled the capturing of volumetric data of fabrics and uses the data along with some appearance data captured by a camera to render photorealistic fabrics with great detail.

1) Acquisition Techniques: The main setup for capturing the material reflectance information requires lighting, sensor, and a planar example of the corresponding materials. A common tool that is used for capturing such BRDF measurements is gonioreflectometer, which consists of a light source and a light sensor for capturing material reflections (Ward 1992). For the BTF model, the reflectance sensor captures many textures of the material with varying the illumination direction and the viewing direction.

2) Texture-Based Models: When fabrics are being viewed closely, individual knits and weaving patterns are clearly visible. However, simple texture mapping methods cannot capture both illumination effect at the macro-level and complex reflectance behavior of weaving patterns at the micro-level. Hence, by capturing textures of the material in varying illumination and viewing direction, the exact light interaction of the material is captured, including inter-reflections and occlusions effects of the microfacets on the fabric surface.

$$f_r(\vec{l}, v) = T(v) \cdot f_1(\vec{l}, v) \quad (1)$$

Daubert, K., et al, (2001) proposed a Spatially-Varying Bi-directional Reflection Distribution Function (SVBRDF) method specifically for cloth rendering using the Lafortune reflection model, which aimed to render fabrics with different knitting and weaving patterns. A texture map T(v) is computed for each different illumination and viewing direction and modified using the Lafortune reflection model $f_1(\vec{l}, v)$ during render time, setting up the texture for look-ups, as shown in Equation 1. A similar approach is Bidirectional Texture function (BTF), which aimed to capture the reflectance variation on the fabric surface with different illumination and direction as a texture. BTF extended the SVBRDF by capturing non-local effects such as self-shadowing, occlusion, and inter-reflections by acquiring reflectance data relative to different illumination and viewing directions.

Both SVBRDF and BTF have long acquisition time and high storage requirements for multiple images using expensive capturing devices (Kautz 2005). Recent researches focus on BTF data compression, such as the compression method proposed by Kautz, J., (2005), so that fewer images are captured at some specific illumination and viewing directions (Kautz 2005).

3) Volumetric Approach: Recently, a volumetric approach that used the microflake model was proposed by Zhao, et al. (2011). This approach captures the volume model of the fabric using a X-ray computed tomography (CT) scanner (Zhao et al. 2011). The volumetric data acquired are then post-processed for orientation extraction and noise removal, and are matched to images of the same material captured to obtain the optical properties to render realistic fabric appearance(Zhao et al. 2011).

4) Reflectance Data Availability: BRDF measurements of fabrics are available on some online public BRDF database. An example is the MERL BRDF Database, which contains reflectance functions of 100 different materials (Matusik et al. 2003). However, the focus of this database is not on fabrics, this database does not categorize its data into different types of fabrics.

Another publicly available BRDF database is CUReT under the CAVE project in University of Columbia. This database consists of several different common types of fabrics in 205 different viewing and illumination directions. It contains several materials such as polyester, terrycloth, velvet, corduroy, linen, and cotton (Dana et al. 1999). Other than BRDF, this database also has BTF textures available for these materials, with over 200 images available per material.

B. Procedural-Based Models

Procedural-based cloth rendering techniques mainly focus on adopting and extending existing BRDF models to control different physical properties of woven clothes for rendering realistic fabrics. Some researches chose to focus on realism in rendering quality, while others focused on achieving high quality rendering in real-time.

Yasuda, et al (1992) was one of the first researches that developed physical models for cloth through analyzing the fiber structure and fabric patterns to render realistic woven clothes. They proposed a tiny facet model for fabric materials, and analyzed the scattering effects of light on fabrics with no real considerations in complicated weaving structure (Yasuda et al. 1992).

1) General BRDF Model: Ashikhmin, et al. (2000) developed a microfacet-based anisotropic model that can be used for any materials and tested it by modelling several different materials including two types of fabrics: satin and velvet. Ashikmin, et al. (2000) also took into account the weaving pattern of satin and velvet, where the satin weave was modelled using the simple approach of weighting the values of reflectance of weft and warp yarns. However, this approach cannot clearly represent more complicated weaving patterns and show individual weave and weft yarns.

2) Weaving Pattern Modelling: Another approach for woven cloth rendering was done by Adabala, N., et al. (2003). This model uses Weaving Information File (WIF) for inputting weaving patterns, and generates the corresponding BRDF, color texture, and horizontal map for the clothing material. Contrary to many approaches that construct different lighting models by analyzing yarn structures and their reflectance properties with simple weaving patterns, Adabala, N., et al. (2003) focused on modelling light interaction with the physical structure of weft and warp yarns in weaving patterns (Adabala et al. 2003), thus giving greater flexibility and robustness in rendering a wider range of weaving patterns.

3) Parameterized Cloth Models: Kang, Y. M. (2010) later proposed a procedural method that models the reflectance properties of woven fabric using alternating anisotropy and deformed microfacet distribution function. The proposed method is based on the microfacet distribution function (MDF) along with the anisotropic reflectance mode called Ashikhmin-Shirley anisotropic shading model (Ashikhmin & Shirley 2000). Each fabric fragment is determined to be weft or warp yarned depending on the weaving pattern, and a weft or warp anisotropic function is applied on it correspondingly (Kang 2010). This algorithm was implemented on the GPU, it achieved real-time interactive frame-rates, and also produced realistic results.

Irawan, P., (2007) developed a reflectance model and a texture model for rendering cloth viewing from distant and close view. The reflectance model depends on the scattering effect of the fabric surface overall, while the texture model depends on the reflection and highlight at yarn level (Irawan 2008). The texture model (BTF) is generated on the fly using parameters to control the fiber and yarn properties, and it also supports weaving structure input from user.

V. Comparisons of Methods for Cloth Rendering

Table I shows the comparisons of different algorithms discussed in the following sections. The following sections discuss and compare the algorithms in terms of data acquisition requirement, storage requirement, speed performance, rendering quality, and flexibility. Different algorithms were proposed to satisfy requirements such as realism and real-timeness in fabrics rendering. Table I is used to summarize the realization of suitable methods for different requirements.

A. Data acquisition

Data acquisition is only required for example-based methods where the reflectance data is captured, such as the BTF and SVBRDF models. The data acquisition steps are complicated due to a high number of images of each material have to be captured in varying illumination and viewing direction, and they have to be post-processed so that the textures are aligned with each other for 3D texture mapping onto a virtual object. On the other hand, the volumetric approach proposed by Zhao, et al. (2011) requires the capturing of volumetric data using a CT scanner along with the capturing of appearance data using an image capturing device. These data are then used in conjunction to render the resulting fabric. The data acquisition process for this method is particularly hard to capture, due to the difficulty in obtaining the expensive device to capture volumetric data.

There is no data capturing required for procedural-based methods as the calculations have to be done using input parameters. For some approaches such as Adabala, N., et al. (2003), alternative inputs such as weaving pattern in WIF format have to be obtained to render the fabric. Parameterized models require only parameters as inputs, such as the model proposed by Irawan, P. (2007), where parameters are intuitive and physically meaningful, thus it would be easy to obtain parameters for a particular fabric. However, if parameters are difficult to understand, such as the model proposed by Kang, Y. M. (2010), then parameters have to be obtained empirically and experimentally.

B. Storage

The storage requirements for example-based cloth rendering methods are much higher than procedural-based methods. SVBRDF and BTF require a high number of images captured with varying illumination and viewing direction. Hence, both the hard-disk storage and the memory requirement are high for these approaches. For example, the CUReT database has a set of 205 BTF images captured for each material, which sum up to over 100mb in size for each material. This is impractical for rendering many different types of materials, and especially for GPU implementations where there is limited memory available for storing these images in 3D textures. The volumetric model by Zhao, et al. (2011) generally consumes a lot of memory and storage for storing volumetric data. This was shown in their tests, where the data size went up to approximately 7.26gb for the felt fabric (Zhao et al. 2011). Contrarily, the procedural-base approaches require little to no storage due to the use of parameters to control the computation of reflectance and textures.

C. Speed

The speed of example-based methods are often very fast and these methods can often be implemented with GPU shaders for real-time applications. The downside of these methods is their loading time in loading a large number of images into the memory. However, using compression methods, algorithms such as BTF are capable of achieving interactive frame rates. A variation of BTF developed by Sattler, et al. (2003). The model uses Principal Components Analysis to compression the number of textures required (Sattler et al. 2003). On the other hand, methods that require extra computation along with the captured reflectance data would require more computation time, such as the SVBRDF model proposed by Daubert, K., et al. (2001), where its computation of the entire model has to be done in several passes. Similarly, the volumetric model by Zhao, et al. (2011) requires a lengthy pre-processing process due to the size of the volumetric data.

The general purpose BRDF model with anisotropy proposed by Ashikhmin, et al. (2000) can be implemented with GPU shaders for real-time applications, albeit with sacrifices in the level of details of the rendered fabrics. The model proposed by Adabala, et al. (2003) is also a real-time cloth rendering approach where complex weaving patterns can be rendered on the fabric surface. Similarly, the model by Kang, Y. M. (2010) is also a real-time rendering model in which the time requirement of the model is only slightly higher than OpenGL Gouraud Shading. The model's performance results can be referred directly from the paper (Kang 2010).

Irawan, P., (2007) developed a reflectance and texture model for rendering woven fabrics. Although the algorithm's performance was not evaluated and the algorithm was not implemented in GPU programs for performance applications, the model proposed is in general very simple and only requires a single pass computation in render time (Irawan 2008).

D. Quality

The general BRDF generator proposed by Ashikhmin, et al. (2000) showed decent quality in rendering satin fabric from distant view. Due to the simple approach used to account for weaving pattern, there is a lack of description for more complex weaving patterns such as velvet. Furthermore, due to a lack of BTF or any use of texturing methods, there is a lack of detail present on the surface of the rendered fabric. Therefore, the fabric also does not look very realistic when

Cloth Rendering Methods							
	BTF	**Daubert, et al.**	**Zhao, et al.**	**Ashikhmin, et al.**	**Adabala, et al.**	**Irawan**	**Kang**
Data							
Data Requirement	Images	Images	Image CT Scans	-	Weaving Pattern file - WIF	-	-
Acquisition Device	Reflectometer	Reflectometer	Camera CT Scanner	-	-	-	-
Storage Requirements	High	High	Very High	None	Low	None	None
Paramters	No	No	No	Yes	No	Yes	Yes
Performance							
Speed	Slow	Slow	Slow	Real-Time	Real-Time	Fast	Real-Time
Preprocessing	Yes	Yes	Yes	No	Yes	No	No
Quality							
Rendering Quality	High	High	Very High	Low	Low	High	High
Model							
Fabric Analytical Model	No	No	Yes	No	Yes	Yes	Yes
Rendering Model	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Model Flexibility	Low	Low	Low	Medium	Very High	High	High

TABLE I: Table summary of properties of all woven cloth rendering methods

fabric is viewed closely, as the weaving pattern is completely invisible in close range. Contrarily, the volumetric model by Zhao, et al. (2011) is able to render fabrics in high quality even when the view is magnified into the fabric, where individual fibers are clearly visible on screen.

The model by Adabala, et al. (2003) is based on Ashikhmin, et al. (2000), with a strong focus in rendering any weaving patterns. Despite different weaving patterns are rendered on screen clearly, because there is a lack of modelling of light interaction at the yarn level in the model, therefore the resulting fabric does not look very realistic overall when being viewed from a distant view.In their results, rendered fabrics such as satin and plain-weaved fabrics could still easily be distinguished, but their rendering results did not exhibit close enough optical properties to their corresponding fabrics.

The quality of BTF related models are generally high for fabric rendering due to the texturing of weaving pattern. When the fabric is being viewed from distant, the render quality is high. This is the case for the example-based BTF method and also the method proposed by Irawan, P., (2007) due to the capturing of mesostructures of the fabric. However, the approach proposed by Irawan, P., (2007) renders a uniform textured fabric unless noise is added in post-processing steps, which is less realistic than the noise captured in example-based BTF models. The self-shadowing and occlusion properties of the fabrics caused by the microfacets in the weaving pattern are also captured by exampled-based methods, whereas Irawan, P., (2007) completely ignored inter-yarn interactions, thus lacking shadowing and masking effects caused by the yarns. However, this problem was shown to be not very detrimental to the model, as results showed that the rendered fabrics closely resembled realistic fabrics (Irawan 2008).

Kang, Y. M. (2010) also renders woven fabrics realistically with both online and offline renderers. The quality is comparable to the model of Irawan, P., (2007) and supports a wide range of weaving patterns. However, similar to the BTF approaches, this approach also renders fabric less realistically as the view is magnified towards the fabric as the weaving pattern is rendered larger and larger. Despite this problem, this model renders fabrics very realistically when viewed from a distant position.

E. Flexibility

The flexibility of these algorithms is their capability to render many different types of fabrics. In general, example-based models do not have the flexibility to render many different types of fabrics with ease. This is because reflectance data has to be reacquired to render another fabric. On the other hand, the volumetric model proposed by Zhao, et al. (2011) allows for some flexibility such as changing the fiber color, opacity, and material thickness as volume data can be modified. However, there is not currently a way to change the volume data structure to allow for changing between different weaving patterns and fiber types.

The model proposed by Adabala, et al. (2003) is capable of handling any type of weaving pattern that is passed as an input from the user. The focus of this model is to handle complex weaving pattern, ranging from simple patterns such as plain, twill, and satin to any complex patterns that can be drawn by the user. Furthermore, the visual aspects resulted from these weaving patterns were clearly shown in the paper's results, such as the satin weaves clearly display much smoother surface and more shininess than twill weaves and plain weaves.

The model developed by Irawan, P., (2007) is a parameterized model using physically meaningful parameters such as fiber properties, yarn geometry, and weave pattern parameters including yarn curvature to describe the fabric's construct. This parameterized model is highly flexible and allows description of a high number of fabrics such as denim, charmeuse, gabardine, shantung, with varying weaving pattern and yarn geometry.

The alternating deformable anisotropy model proposed by Kang, Y. M. (2010) is also capable of handling a large variety of weaving pattern. This model allows weave control using alternating anisotropy for weft and warp yarn. However, the paper was not very clear on how the parameters n_w and n_q are used to define the weaving pattern, as theses parameters were not defined in the paper and were just briefly mentioned that they were used in the results section. These parameters used are not very intuitive and they are not physically meaningful enough for people to adopt without understanding the underlying anisotropic reflectance model.

VI. Conclusion

For real-time rendering, the alternating anisotropy model proposed by Kang, Y. M. (2010) is the recommended due to the proposed algorithm's real-timeness and the realistic results of fabrics. For high flexibility, the model proposed by Adabala, et al. (2003) is capable of handling very complicated weaving patterns, while the woven cloth rendering model proposed by Irawan, P., (2007) provides intuitive and physically meaningful parameters to render different fabrics, though with less variety than Adabala, et al. (2003), but is able to provide better quality in rendering results.

A promising area for future research is improving the accuracy of existing procedural-based models such as Irawan, P., (2007), by improving the self-shadowing and masking effects of microfacets. Example-based model such as BTF can be improved by introducing parameters for changing the texture model to allow weave control to improve the flexibility in supporting different types of fabrics. Furthermore, the volumetric model proposed by Zhao, et al. (2011) is promising in rendering quality, but methods of compressing the volumetric data has to be investigated to put it into practical use.

References

Adabala, N., Magnenat-Thalmann, N. & Fei, G. (2003), Real-time rendering of woven clothes, *in* 'Proceedings of the ACM symposium on Virtual reality software and technology', ACM, pp. 41–47.

Ashikhmin, M. & Shirley, P. (2000), 'An anisotropic phong brdf model', *Journal of graphics tools* **5**(2), 25–32.

Ashikmin, M., Premože, S. & Shirley, P. (2000), A microfacet-based brdf generator, *in* 'Proceedings of the 27th annual conference on Computer graphics and interactive techniques', ACM Press/Addison-Wesley Publishing Co., pp. 65–74.

Dana, K., Van Ginneken, B., Nayar, S. & Koenderink, J. (1999), 'Reflectance and texture of real-world surfaces', *ACM Transactions on Graphics (TOG)* **18**(1), 1–34.

Daubert, K., Lensch, H. & Heidrich, W. (2001), Efficient cloth modeling and rendering, *in* 'Rendering techniques 2001: proceedings of the Eurographics workshop in London, United Kingdom, June 25-27, 2001', Springer Verlag Wien, p. 63.

De Deken, J. (2010), A BRDF analysis of cloth, PhD thesis, University of California, San Diego.

Durupinar, F. & G"ud"ukbay, U. (2007), 'Procedural visualization of knitwear and woven cloth', *Computers & Graphics* **31**(5), 778–783.

Filip, J. & Haindl, M. (2008), 'Bidirectional texture function modeling: A state of the art survey', — *IEEE Transactions on Pattern Analysis and Machine Intelligence* pp. 1921–1940.

Irawan, P. (2008), Appearance of woven cloth, PhD thesis, Ithaca, NY, USA. AAI3295837.

Irawan, P. & Marschner, S. (2006), A simple, accurate texture model for woven cotton cloth, Technical report, Tech. Rep. PCG-06-01, Cornell University, Department of Computer Science.

Kang, Y. (2010), 'Realtime rendering of realistic fabric with alternation of deformed anisotropy', *Motion in Games* pp. 301–312.

Kautz, J. (2005), 'Approximate bidirectional texture functions', *GPU Gems* **2**, 177–187.

Matusik, W., Pfister, H., Brand, M. & McMillan, L. (2003), 'A data-driven reflectance model', *ACM Transactions on Graphics* **22**(3), 759–769.

McIntyre, J. & Textile Institute (Manchester, E. (2005), *Synthetic fibres: nylon, polyester, acrylic, polyolefin*, CRC Press.

Sattler, M., Sarlette, R. & Klein, R. (2003), Efficient and realistic visualization of cloth, *in* 'Proceedings of the 14th Eurographics workshop on Rendering', Eurographics Association, pp. 167–177.

Ward, G. (1992), 'Measuring and modeling anisotropic reflection', *ACM SIGGRAPH Computer Graphics* **26**(2), 265–272.

Welford, T. (1933), *The textiles student's manual: an outline of all textile processes, from the origin of the fibre to the finished cloth; a handbook to all branches of the textiles industries*, Pitman.

Yasuda, T., Yokoi, S., Toriwaki, J. & Inagaki, K. (1992), 'A shading model for cloth objects', *Computer Graphics and Applications, IEEE* **12**(6), 15–24.

Zhao, S., Jakob, W., Marschner, S. & Bala, K. (2011), 'Building volumetric appearance models of fabric using micro ct imaging', *ACM Trans. Graph.* **30**, 44:1–44:10.
URL: *http://doi.acm.org/10.1145/2010324.1964939*