An Evaluation on Woven Cloth Rendering Techniques

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***Abstract*—Advances in graphics hardware have led to large number new technologies for cloth rendering. However, it is not clear what technology is suitable for what type of applications. Whereas computer games need compact representation and fast speed, fashion related applications often need flexibility to change parameters affecting appearance. So far no research exists comparing digital representations of fabric and techniques for rendering cloth. This paper reviews different parameters that contribute to the appearance of fabrics such as fiber types, yarn types, and different 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 fiber 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 appearance are still largely unexplored. Moreover, realistic cloth rendering is difficult due to the complex procedures in producing clothes, where a lot of variables are involved to contribute to the differences in the look and feel of the clothes, such as the fiber types, yarn types, and types of weaving patterns. These are discussed in this paper to find out the contributing factors of different visual appearance of different fabrics.

In this paper wel look at different approaches in current rendering techniques, compare and analyze these techniques to understand their advantages and disadvantages, to see which model can be used in which circumstances.

II. Background

In cloth manufacturing, initially the fibers are first extracted or produced synthetically. After that, the fibers are twisted or grouped into yarns. Yarns are then weaved into fabrics through the weaving machine, and different weaving structure construct would produce fabrics with distinct look and feel in them.

The main contributing factor to the resulting fabric reflectance consist of notably the weaving patterns and the different types of yarns. Due to the fact that yarns are produced from fibers, therefore the reflection on fibers materials is important to 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 identify parameters that influence the light interaction with the resulting fabric.

A. Fiber Types

As mentioned in Chapter I, fibers can be extracted naturally from animals, minerals, and plants (natural fibers), or they can be produced chemically (synthetic fibers). As different types of fibers controls how 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 are listed with some of their 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, where about 40% of total world fiber production uses cotton fiber (Welford 1933). Cotton is a naturally short fiber and is often produced into yarns by twisting around other fibers. This is an important property of fiber as yarns are made up of short fibers twisting around other fibers tend to have a rougher surface than those exhibited by longer fibers. This is because longer fibers don't have to be twisted to get grouped into a yarn, therefore the fibers would all be arranged along the same direction, making the resulting yarn look much smoother.

Synthetic fibers are man-made fibers where the appearance and physical properties can be manipulated during the process of manufacturing. The four synthetic fibers - nylon, polyester, acrylic, and polyolefin dominates market for synthetic fiber production, 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 classified into two categories:

- Staple yarns, Filament yarns

Yarns tend to give a different reflection off the cloth is due to the length of the fibers used to produce these yarns. Staple yarns are generally very short, thus fibers have to be twisted or bonded around one another to make the yarn cohesive. Due to the short length, fibers might come off loose, thus forming irregularities in patterns, making the resulting fabric look rough on its surface (De Deken 2010). Filament yarns contain long and continuous fibers that are grouped together without twisting the fibers around other fibers (De Deken 2010). The length of fibers determines the type of yarns that is produced, which ultimately determines the resulting reflectance properties of the fabric that uses these yarns.

C. Weave Structure

Yarns are weaved into fabrics using a particular weave structure or pattern. There exists many types of weave structures, and different structures produces different appearance in resulting fabrics. The three most fundamental weave structures that are used are:

- Plain, Twill, Satin

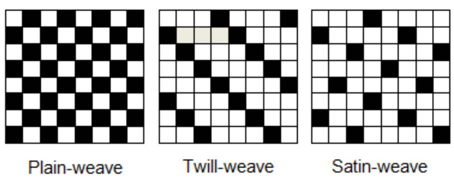

Fig. 1: Examples of different weaving patterns. White squares represent weft yarn and black squares represent warp yarn.

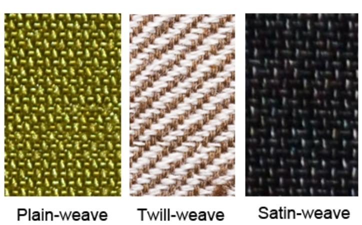

Fig. 2: Examples of different weaving pattern on actual fabrics at micro-level.

As shown in Figure 1, plain-weave has a regular pattern, for each weft yarn, there's a warp yarn next to it. Twill-weave has a somewhat regular pattern, with a longer weft yarn going across multiple warp yarns, and the warp yarns forming a diagonal line visible on fabric. Satin-weave basically has even longer weft yarns going across warp yarns, and it generally look smooth due to the domination of either a warp or weft yarn.

The pattern that yarns are weaved into is highly important to the optical properties of fabrics, as the pattern of a fabric is clearly visible even from a reasonably distant view, creating a texture on the fabric surface.

III. Bi-Directional Texture Function

BTF data are 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. Bi-directional Texture Function(BTF) is used in cloth rendering to capture such visual aspects of fabrics missing in those techniques. BTF consists of parameters in relation to light source and camera viewing direction in spherical co-ordinates and texture co-ordinates to represent the fabric surface. BTF captures images of the surface of the fabrics under varying viewing and illumination direction and stores over thousands of these images for rendering a particular fabric surface. 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, this results in a lenghty data acquisition process and high storage requirement for adopting such approach (Filip & Haindl 2008).

IV. Methods for Cloth Rendering

There are two categories of methods that are currently used to render clothes:

- Example-Based Models
- Procedural-Based Models

A. Example-Based Models

Example-based cloth rendering techniques focus on collecting reflectance information of materials for rendering. Most of existing researches are focused on texture-based models using techniques like BTF or similar to BTF, or techniques for compressing and improving the efficiency of BTF. Recently, there is a volumetric approach that captures the volumetric data of the fabric and uses this data along with some appearance data captured by an image capturing device 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 reflection (Ward 1992). By varying the light source position along the same arc with respect to the material's position, and the sensor position at different viewing angles of the material sample, different reflectance data given off by the material are acquired by the reflectance sensor(Ward 1992). This can then be used to render the material using a fabric rendering model.

2) Texture-Based Models: When clothes are being looked at from a relatively close distance, individual knits and weaving patterns can be seen. However, simple texture mapping methods cannot capture both the illumination effect from a larger distance and the complex pattern of the cloth caused by the weaving patterns when viewed upon closely. Hence, by capturing textures of the material in varying illumination and viewing direction, the exact light interaction of the material is captured, such as the inter-reflections and occlusions of the microfacets on the surface of fabric.

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

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 clothes with patterns such as knitting and weaving patterns. In essence, 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. A similar approach is Bidirectional Texture function (BTF), which aims to capture the variation on the surface of the fabric with different illumination and direction as a texture. Unlike SVBRDF, BTF captures non-local effects such as self-shadowing, occlusion, and inter-reflections through acquiring reflectance data relative to different illumination and viewing direction, and is used widely for many cloth rendering applications.

Both SVBRDF and BTF requires high acquisition time and storage for multiple images using expensive devices (Kautz n.d.). More recent researches focus on compressing BTF data such as a compression method proposed by Kautz, (n.d.) for BTF to capture fewer images at some specific positions, and images that are not captured initially in a specific illumination and viewing direction can be interpolated captured images (Kautz n.d.).

3) Volumetric Approach: Recently, a volumetric approach that uses the microflake model was proposed by Zhao, et al. (2011). The approach acquires a volume model of the material that needs to be rendered using a X-ray computed tomography (CT) scanner (Zhao et al. n.d.). The volumetric data acquired is post-processed for orientation extraction and noise removal, and is matched to a photograph of the same material captured to obtain the optical properties to render the resulting fabric (Zhao et al. n.d.).

4) Reflectance Data Availability: BRDF measurements of fabrics can be acquired in some publicly available BRDF database. One example is the MERL BRDF Database, which contains reflectance functions of 100 different materials (Matusik et al. 2003). However, this database's focus is not on cloth rendering, as the database does not distinguish different fabric types nor yarn types.

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 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 materals, and are publicly available for educational purposes.

B. Procedural-Based Models

Procedural-based cloth rendering techniques focus on developing or using existing BRDF models to control different physical properties of woven clothes for rendering different types of fabrics in real-time.

Yasuda, et al (1992) is one of the first researches that developed models for cloth through analyzing their fiber physical properties and fabric patterns for rendering realistic woven clothes. They proposed a tiny facet model for fabric materials analyzing the scattering effects behavior of light with fabrics with a very simplified weaving pattern such as warp and weft in woven clothes yasuda1992shading.

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

2) Weaving Pattern Modelling: Another approach for woven cloth rendering is done by Adabala, N., et al. (2003), which uses a 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 general approaches which attempt to construct different lighting models by analyzing yarn structures and their reflectance properties in simple weaving patterns, Adabala, N., et al. (2003) focuses on modelling the light interaction with weaving pattern (Adabala et al. 2003). This approach gives greater flexibility in rendering different 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), where each of the sample point on the cloth is determined to be weft yarned or warp yarned depending on the weaving pattern, thus a weft or warp anisotropic function is used on it accordingly (Kang 2010). Furthermore, this method uses of parameters to describe the type of weaving structure and the physical property of underlying yarn (i.e. the degree of twist in spurn yarns), and is a real-time rendering algorithm that can be implemented on GPU.

Irawan, P., (2007) developed a reflectance model and a texture model for rendering cloth viewing from distant and magnified view. The reflectance model depends on the scattering effect of the fabric, while the texture model is depended on the highlight calculated previously using the reflectance model (Irawan 2007). The texture model (BTF) is generated on the fly using parameters to control the fiber and yarn properties, and allows the definition of weave pattern and its properties.

V. Comparisons of Methods for Cloth Rendering

Table I shows a summary of comparison of the algorithms that is discussed in the following subsections. The following sections discuss and compare the algorithms in terms of data acquisitions required, storage requirements, speed performance, quality of rendering results, and flexibility for different fabrics. As different algorithms are proposed for different purposes such as realistic rendering or real-time rendering, thus the present of Table I enables the realization of suitable methods for different circumstances.

A. Data acquisition

Data acquisition is only required for example-based methods where the reflectance data is captured, such as images of fabric's surface for BTF and SVBRDF. The data acquisition steps are complicated because images of the material have to be captured in varying illumination and viewing direction, thus a high number of images have to be taken for each material, and they have to be rectified so that the textures are aligned with others for 3D texture mapping on the object. On the other hand, the volumetric approach proposed by Zhao, et al. (2011) requires capturing of volumetric data using a CT scanner along with the capturing of appearance data with images of a fabric. These data captured are then combined and used to render the resulting fabric. The data acquisition for this method is particularly hard to capture, as CT scanner is an expensive equipment and it is not often available for use.

There's no capturing of data prior to rendering 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 has to be obtained to render the fabric. Parameterized models only require parameters as inputs, such as the model proposed by Irawan, P. (2007), where parameters are intuitive and physically meaning, 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 through experiments or previous researches.

B. Storage

The storage requirements for example-based cloth rendering methods are much higher than those 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 is high for these approaches. For example, the CUReT database has a set of 205 BTF images captured for each material, which adds 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's limited memory available for storing these images in 3D textures. The storage for the volumetric model by Zhao, et al. (2011) uses a high amount of memory and storage for volumetric data, where the data size goes up to 7.26gb for the felt fabric (Zhao et al. n.d.).

On the other hand, the procedural-base approaches require little to no storage due to the use of parameters to control the computation of reflectance and texture for rendering fabric, with the exception of the model proposed by Adabala, N., et al. (2003), which requires minor storage for storing weaving patterns in the WIF format for reusability.

C. Speed

The speed of exampl-based methods is often very fast and these methods can often be implemented in GPU shaders for real-time applications. The downside of these methods is perhaps the loading time prior to rendering to load the images into the memory. However, using compression methods, algorithms such as BTF achieves interactive frame rates. A variation of BTF developed by Sattler, et al. (2003) uses Principal Components Analysis to generate texture maps for compression (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 time due to the size of the volumetric data of the fabric.

The general purpose BRDF model with anisotropy proposed by Ashikhmin, et al. (2000) can be implemented in modern GPU shaders for real-time applications, albeit with sacrifices in the level of details of the rendered fabrics. Adabala, et al. (2003) is also a real-time cloth rendering approach where complex weaving patterns can be rendered. Similarly, the model by Kang, Y. M. (2010) is also a real-time rendering model which the time cost of the model is only slightly higher than per pixel lighting rendering. 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 was in general very simple and only require a single pass computation in render time (Irawan 2007).

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 by, there's 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

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

a lack of detail present on the surface of the rendered fabric. Therefore, the fabric also does not look very realistic when the view is manigified towards the fabric, as the weaving pattern is completely invisible. Contrarily, the volumetric model by Zhao, et al. (2011) is able to render the fabric in high quality even when the view is manigifed into the fabric, where individual fibers are clearly visible on screen.

Adabala, et al. (2003) is based on Ashikhmin, et al. (2000), with a strong focus on rendering any provided weaving patterns from the user input. Despite that different weaving patterns are rendered on the screen clearly, due to a lack of analysis on light interaction with yarns is involved in the model, the rendered fabric does not look realistic overall when being viewed from a distant view. However, different fabric types such as satin and plain weaved fabrics can still easily be distinguishable, albeit not looking close to their corresponding real fabrics.

The quality of BTF related models is generally high for fabric rendering due to the texturing of the 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 the mesostructure 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, where as Irawan, P., (2007) completely ignored inter-yarn interactions, thus lacking shadowing and masking caused by the yarns. However, this is shown to be not too much of a problem for the model, as results showed Irawan's rendered fabrics closely resembles realistic fabrics (Irawan 2007).

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 isn't 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 are clearly shown when rendered using this model, 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 anistropy 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 anistropy 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 best 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 modell to allow weave control to improve the flexibility in supportin 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.

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