

Visualization of woven cloth

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Abstract

A technique for visualizing clothes is proposed that can handle rendering of complex weave patterns. An industrial standard of weave representation is used to derive the weave pattern and a detailed model of light interaction with the pattern is developed. The proposed visualization technique supports viewing of cloth at various levels of detail, and provides a solution for rendering both back and front surfaces of cloth. The technique works for a wide variation in colors of threads, ranging from a single color for both warps and wefts to several colors of threads, woven into a single fabric. The inhomogeneous nature of transparency of woven materials is also captured. To date no technique for visualizing woven clothes has addressed the problem of visualizing complex weave patterns and therefore the above mentioned features are difficult and often impossible to capture with existing techniques. The capabilities of the proposed approach are demonstrated with rendered examples.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism.

1. Introduction

The need for rendering cloth arises frequently in computer graphics generated scenes. Typical cases include indoor scenes with furnishing like curtains, sofas, etc and scenarios with virtual characters. In this paper we focus on visualizing woven clothes that exhibit rich weave patterns. The ubiquity and richness of patterns in woven clothing is well brought out in the recent series of three articles by Glassner^{7,8,9}.

Woven clothes exhibit micro and milli geometric details. Here micro-geometry refers to the fibers that constitute the threads and milli-geometry refers to the interweaving of threads. It has been proved time and again in computer graphics that the realism of an image is dependent on the ability of the illumination model to capture the light interaction with such geometric details.

1.1. Our approach and contribution

In our approach the weave pattern is defined in a Weave Information File (WIF)¹⁸ format. The file is parsed to obtain

the weave pattern that is used to generate color maps. As the fabric can be viewed from different distances a level of detail representation is created for the weave pattern from the color maps. For distant viewing a mipmapping of the weave pattern is used to define the properties of the fabric that occurs at a pixel and the illumination model is evaluated accordingly. For close-up viewing the constitution of the cloth at a particular pixel (i.e. single thread, both warp and weft or gap) is identified using the weave pattern representation and the illumination is evaluated accordingly.

The main contributions of our approach are:

1. rendering of cloth with a variety of weave patterns, without placing any limits on the complexity of patterns.
2. visualization of cloth at various levels of detail.
3. capturing the difference in appearance of the back and front surfaces of cloth based on the weave pattern.
4. capturing the appearance of cloth when threads of very different colors are woven together.
5. visualization of clothes woven from the same color warp and weft threads, such that 'self-design' is perceivable when a complex weave pattern is employed.
6. capturing the inhomogeneous nature of light transmission through cloth.

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We demonstrate these capabilities by applying the technique to visualize clothing on virtual characters. Except for feature 4 and to some extent feature 6 which are captured in the work of Daubert et al. ⁵, all the other features cannot be captured within the framework of existing approaches to visualize woven clothes.

The rest of the paper is organized as follows. We discuss related work in the following section. Section 3 presents some of our observation on light interaction with woven fabrics. Section 4 describes details of weave pattern representation and its application to define the light interaction with weave. Section 5 summarizes our algorithm. Results that demonstrate the capabilities of our approach are presented in section 6. We conclude in section 7.

2. Related work

There are two main types of clothes namely, knitwear and woven clothes. Impressive results have been reported in visualization of knitwear ^{10, 11, 17, 24, 5, 22, 4}. Techniques to represent complex knit patterns have been developed ^{17, 24}. Visualization of knitwear focus on capturing the fluffy nature of wool and the resulting self-shadowing due to the volume occupied by thick woolen yarn. Due to the different nature of threads and weave pattern these techniques cannot be applied to woven clothes. The main issues that have to be addressed when developing a technique for visualizing such clothes are: representation of interwoven thread patterns and modelling of light interaction with the weave pattern.

No work has been done in the context of representing complex weave patterns for visualization of woven clothes. Only recently the series of three articles by Glassner ^{7, 8, 9} describe methods of creating interesting patterns based on weaving techniques.

Relatively less work has been done in the area the light interaction with woven cloth. Yasuda et al. ²³ describe a shading model for clothes that emphasizes the interaction of light with individual threads of the cloth. Gröller et al. ¹¹ use a technique based on three-dimensional textures to model textiles. Daubert et al. ⁵ have presented an efficient technique for modelling and rendering clothes, their approach is applicable especially for coarsely woven fabric and knitted fabric where the threads occupy a volume and the shadowed regions of the milli-geometry have a significant contribution to the Bi-directional Reflectance Distribution Function (BRDF) of the material. Their approach relies on performing a pre-rendering step in which a BRDF is fit into data captured from explicit light interaction with a model of weave milli-geometry.

Apart from the work that directly addresses the problems of rendering clothes there is a class of work based on light interaction with surfaces that exhibit micro-geometry that can be applied to address problems in rendering of cloth. These include the work of Westin et al. ²¹ that obtains a realistic

rendering of cloth, with the plain weave pattern ⁷, for distant viewing. Fournier ⁶ discusses techniques of modelling light interaction with micro-geometry especially in the context of cloth. Ashikhmin et al. ¹ develop a micro-facet based technique for modelling light interaction with surfaces and apply it effectively to simulate the appearance of velvet and satin. Also the techniques of illuminating micro-geometry described in Heidrich et al. ¹² and the work done in horizon maps by Max ¹⁶, Sloan et al. ²⁰ Rushmeier et al. ¹⁹ find application to visualization of cloth.

What is clearly absent is a technique that harnesses the rich possibilities of weave pattern ^{7, 8, 9} and combines it with an approach to render woven cloth. This gap in existing techniques is eliminated by this work.

3. Observations on appearance of woven cloth

In this section we highlight some of our observations of light interaction with cloth that are not obvious with casual viewing of fabrics. We substantiate our observations with scans and photographs of woven clothes. We later justify some of the light interaction definitions that we develop in the paper based on these observations.

Reflection component

Cloth consists of fibers that are twisted into threads and individual fibers (separated from the twist of the thread) that appear to be scattered on the surface. Figure 7(a) illustrates the light interaction with the fibers that are scattered on surface. Observe that these fibers, though predominantly white, appears to be changing color based on the thread on which they are passing. This happens because the light that is incident (and hence reflected) from the fiber is mainly the direct light from the source and the light reflected from the threads in the background of the fiber.

Transmission component

Apart from reflection, light incident on the cloth also passes through it and undergoes diffused scattering through the fibers of the thread. The scattering results in color bleeding and a new color of the fibers is perceived as shown in figure 7(b). The original color of a thread is often no longer perceivable once it is woven into the cloth as the colors of the warp and weft threads bleed into each other.

Light is also transmitted when it is incident on the gaps in the weave. In this case the light either passes directly through if the gap is big or undergoes diffraction if the size of the gap is comparable to the wavelength of light. Diffraction is perceivable only when the threads are not too permeable to light and the incident light intensity is high. Since it is relatively less frequent that clothes are back-lit with high intensity light we do not cover diffraction in this paper.

4. Implementation details

Our approach defines the illumination model for woven cloth based on the weave pattern. It consists of a representation of the weave pattern that indicates the constitution of the cloth at any point and a suitable definition of light interaction in each case.

For *distant viewing* a region of the fabric contributes to the shading of a pixel. In this case a mipmapping of the weave pattern, that provides information on the constitution of the weave covered by the pixel is used. The light interaction is computed based on this information.

For *close-up viewing* we identify three main regions of woven cloth, namely:

- *two threads* - where both warp and weft are present
- *single thread* - this occurs in regions adjacent to gaps
- *gap* - where no thread is present

The shading in each of these regions is handled by a suitable approach as detailed in the following sections.

4.1. The weave pattern representation

The wide variety of the weave patterns that we see in everyday life prompted us to investigate the possible existence of standard techniques to define weave in the textile industry.

We found that, in CAD of textile, there is a well-established technique for representing the weave pattern known as WIF (Weave Information File) format¹⁸. It is a specification that provides the information required for weaving a fabric in the textile looms. The WIF includes information from which the weave pattern can be derived.

Since WIF format was designed for manufacturing purpose rather than for visualization, it is not directly applicable to computer graphics. The WIF contains the threading information that defines the threading of the warp threads into the heddles of the shafts. It also contains a liftplan which represents the combination of shafts raised for creation of each weft. The weave pattern is obtained by combining the threading and the liftplan information. We parse the WIF format and derive the weave pattern from it. The WIF format also contains color information for each thread that can be directly combined with the pattern matrix to generate the color scheme for the weave pattern. One can also use the approaches described in^{7, 8, 9} to create weave patterns.

Since the weave pattern indicates which thread is visible at each point on the face of a cloth, the texture of the other side of the cloth is obtained by reversing the visibility of the threads.

We represent the weave pattern in three maps, one is as a gray scale map that we refer to as a grammar-map and the other two are color maps. The gray scale map defines the fraction of warps present at a location, while the two color maps are for storing the color scheme of the front and back

surfaces of the cloth. In the case when the size of gaps is significant, i.e. more than 0.2 times the width of the interwoven threads, we maintain an additional gray scale gaps map.

All these maps are mipmapped to enable level-of-detail representation. In the high-detail maps a single pixel represents a single thread, while at lower levels a single pixel in the maps represents several adjacent threads. In the case of the grammar-map, locations where warps occur are assigned white(1.0) and locations where they do not occur (namely where there are wefts) are assigned black (0.0). Thus, the high detailed maps are black and white as single pixels represent presence of a warp or weft thread while lower detailed maps become gray valued and represents the fraction of warp threads at a location. A similar approach is adopted for the gaps map, we store white when a gap is present and black otherwise.

Figure 8 shows the three maps for a weave pattern of a snow flake generated from a WIF.

In the following subsections we define light interaction with weave patterns.

4.2. Reflection model

The appearance of the cloth is dictated by the optical properties of the threads and the light interaction with the weave patterns. The first problem can be addressed only by direct measurements of the optical properties of the various kinds of yarns, and is outside the scope of this paper. The latter aspect, namely light interaction with weave patterns, is addressed in detail here.

We have separate models for the distant and close-up viewing of the material. This is necessary as the features perceivable in the two cases and hence the light interaction that is modelled in the two cases differ significantly. For distant viewing typically a single pixel represents a region of the cloth, and the light interaction with the weave pattern in this region is captured. While for close-up viewing the fibers on the surface of the cloth (i.e. the fibers that come loose from the threads and appear to be scattered on the surface of the cloth) and the twist of the fibers of the threads are captured.

Distant viewing

We use the micro-facets based approach to model the light reflected from the woven cloth, as this approach enables us to define a formulation that works elegantly with the grammar representation defined above. The micro-facet based BRDF¹ is given by the equation:

$$\Psi(\vec{w}_{in}, \vec{w}_{out}) = \frac{p(\vec{h}) \langle \vec{h} \cdot \vec{n} \rangle F(\langle \vec{h} \cdot \vec{w}_{in} \rangle, \lambda)}{4g(\vec{w}_{in})g(\vec{w}_{out})} \quad (1)$$

where \vec{w}_{in} is the in coming light direction, \vec{w}_{out} is the viewing direction, \vec{h} is the half way vector given by $\vec{w}_{in} + \vec{w}_{out}$,

$p(\vec{h})$ is the probability distribution of micro-facets in the direction of the half way vector \vec{h} . The term $\langle(\vec{h} \cdot \vec{n})\rangle$ is the ensemble average of the half-way vectors in the hemisphere containing the normal to the surface this term accounts for the projected area of the micro-facets. $F((\vec{h} \cdot \vec{w}_{in}), \lambda)$ is the Fresnel coefficient given by the standard Fresnel equation used in graphics. At near perpendicular angles of incidence influence of warp color is incorporated in defining the λ s while at grazing angles the weft color is made to dominate the definition of the λ s in the Fresnel equation. This is achieved by weighting the color influence based on the viewing and light incidence directions. This approach is needed as warps are less visible at grazing angles, because they usually occupy a slightly lower plane than the wefts due to the nature of the weaving process. The functions $g(\vec{w}_{in})$ and $g(\vec{w}_{out})$ are the shadowing functions that account for the obstruction of some of the micro-facets in the light and viewing directions. They are defined ¹ by the following equation:

$$g(\vec{w}) = \int_{W_+} (\vec{h} \cdot \vec{w}) p(\vec{h}) dW_+ \quad (2)$$

where the integral is over W_+ the hemisphere over the directions in which $(\vec{h} \cdot \vec{w})$ are positive.

The probability distribution of the micro-facets $p(\vec{h})$ is the most crucial element of the above definition as it is responsible for modelling the appearance of the material. We define $p(\vec{h})$ for a cloth as follows:

$$p(\vec{h}) = f_{warp} * p_{warp}(\vec{h}) + f_{weft} * p_{weft}(\vec{h}) \quad (3)$$

where $p(\vec{h})$ represents the probability distribution of the normals of the micro-facet, f_{warp} and f_{weft} are respectively the fractions of the surface occupied by the warp and weft threads. The probability distributions of facets on individual warp and weft threads are given by the $p_{warp}(\vec{h})$ and $p_{weft}(\vec{h})$ respectively. The above equation (3) is a generalization of the probability distribution used in Ashikhmin et al. ¹ for satin.

This definition enables effective exploitation of the grammar representation, presented in the previous section, as the values of the parameters f_{warp} can be directly read out from the gray scale grammar map. The the value of f_{weft} is $1 - f_{warp}$. When the gaps are large (i.e. gap size is more than 0.2 times the thread width) we reduce the values of f_{warp} and f_{weft} proportionally based on the gap size. We are thus able to define a spatially varying BRDF based on the weave grammar. This is similar to Daubert et al. ⁵, however in their case they employ a detailed acquisition and fitting phase and use the approach of LaFortune et al. ¹⁵ to represent the BRDF. An added advantage of our method is that we can exploit the knowledge that the back face of a cloth is a complement of its front face. This gives an efficient and straightforward solution for the BRDF of the back face, which is obtained by exchanging the values of f_{warp} and f_{weft} .

The probability distributions of the micro-facets on individual threads in the warp and weft directions, namely the functions for $p_{warp}(\vec{h})$ and $p_{weft}(\vec{h})$ are defined as *cylindrical* Gaussian with $\sigma_y = \infty$ similar to the one described in Ashikhmin et al. ¹ for this purpose. The width of the thread is used to choose the σ_x of the cylindrical Gaussian.

Close-up and magnified viewing

When the cloth is magnified or viewed in close-up we consider the presence of fibers on the surface of the cloth and the twist of the fibers that constitute the thread.

We use a procedural function with random parameters that tile over the regions of the cloth to define fibers on the surface of the cloth. The random parameters include starting and ending locations of curves and parameters to introduce randomness into the shape of the fibers. Any function can be chosen to define the shape of the fibers, in our case we use trigonometric functions.

The illumination model for the fibers on the surface of the cloth is given by:

$$I_{fiber} = k_r * (I_L + I_{thread}) \quad (4)$$

where I_{fibers} is the light intensity reflected of the fibers, $k_r \in [0, 1]$ is a coefficient of reflection of the fibers, I_L is light source intensity and I_{thread} is the intensity of light reflected of the surface of the thread onto the fiber. It basically states that the light intensity reflected of the fibers is a fraction of the total light incident on the fibers. This total incident light includes the component of the light reflected from the threads onto the fiber. We assume all the interactions are non-specular. This assumption is based on our observations from the scans of cloth (sample given in figure 7(a)) as explained in section 3.

We employ a BRDF based on the Cook-Torrance micro-facet BRDF model for light interaction with threads ³. This approach keeps the conceptual consistency in that both the distant and close-up models of light interaction are based on the micro-facet distribution. The details of the twisting of fibers are modelled as a function and used to define the probability distribution of the micro-facets $p(\vec{h})$. The Cook-Torrance BRDF is given by:

$$\Psi(\vec{w}_{in}, \vec{w}_{out}) = \frac{p(\vec{h})F((\vec{h} \cdot \vec{w}_{in}), \lambda)}{4(\vec{n} \cdot \vec{w}_{in})(\vec{n} \cdot \vec{w}_{out})} * \min(2 \frac{(\vec{n} \cdot \vec{h})(\vec{n} \cdot \vec{w}_{out})}{(\vec{w}_{out} \cdot \vec{h})}, 2 \frac{(\vec{n} \cdot \vec{h})(\vec{n} \cdot \vec{w}_{in})}{(\vec{w}_{in} \cdot \vec{h})}, 1) \quad (5)$$

where the notation is similar to the equation 1. The vector \vec{n} is the local normal on the thread and is defined by considering the thread to be cylindrical. We also use a shadow mask as a multiplicative factor on the $p(\vec{h})$ that takes into account the details of shadows that result from the weave grammar.

4.3. Transmission model

The light transmission model has to address the problems of light transmission through the fibers of the threads and through the gaps in the weave.

Transmission and color bleeding through fibres

The interaction of light that is incident on the thread is illustrated in figure 1. The light interaction in this case can be

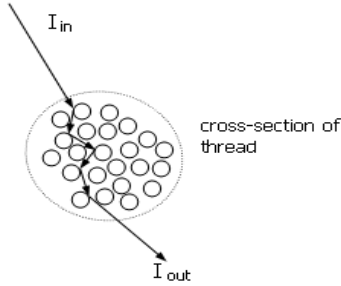


Figure 1: Light transmitted through the fibers, cross-sectional view that shows that we can apply the scattering-absorption formula used for participating media.

represented by the scattering-absorption model of volume illumination². The relationship between the intensities I_{in} and I_{out} is given by:

$$I_{out} = I_{in} e^{-\tau \sum_{r=p_{in}}^{p_{out}} \rho_r} ph(\cos\theta) \rho_{out} \quad (6)$$

where τ is the optical thickness of the material, p_{in} is the point of entry of the light into the fiber, p_{out} is point of exit and ρ_r is the density of the fibers at location r . This is similar to the standard equation used for rendering participating media in computer graphics¹⁴. Since the cloth is thin we do not consider stepping along the path of the ray within the fiber, therefore the outer integral is absent. We replace the summation term by ρ_{out} that represents the effective density perceived by the ray that exists the thread at point p_{out} . The value of ρ_{out} is defined by the twist of the fibers at that point. This twist function is the same as the procedural function that we employ to define the distribution of micro-facets for the Cook-Torrence BRDF. $ph(\cos\theta)$ is the phase function that defines the scattering of light. As the fibers are large compared to the wavelength of light, Mie scattering occurs. Therefore we use the empirical Henyey-Greenstein function with two lobes given by:

$$f(\cos\theta, g_1, g_2, w) = w \frac{1 - g_1^2}{(1 - 2g_1 \cos\theta + g_1^2)^{\frac{3}{2}}} + (1 - w) \frac{1 - g_2^2}{(1 - 2g_2 \cos\theta + g_2^2)^{\frac{3}{2}}} \quad (7)$$

where for forward scattering is controlled by parameter $g_1 \in [1, 0]$ and backward scattering by $g_2 \in [-1, 0]$. The parameter w can be used to control the relative weight of forward and backward scattering, forward scattering

is higher for larger values of w . Plots of the behavior of this function can be found in¹³. We use the values $g_1 = 0.05, g_2 = -0.05$ and $w = 0.2$ in our work, these are the values used for dry material in¹³.

Transmission of light through gaps

In the case when the gaps are large the light is directly transmitted through the gap. For distant viewing when a pixel represents a region of the cloth, the fraction of this region that is occupied by the gaps is obtained from the gaps map. Light is transmitted through the region based on this value.

At graze angles of viewing the gaps are occluded by the threads resulting in reduced transparency. This property is implemented by considering the gap size and the angle between the surface normal and viewing direction. The cloth is opaque when the view direction is perpendicular to the surface normal. The transparency increases as the angle of viewing coincides with the surface normal. The extent to which the material is transparent is dictated by the size of the gaps that is captured in the gaps map.

5. Summary of the visualization approach

The algorithm for visualizing cloth using the techniques described so far can be summarized as follows:

1. Obtain the weave pattern (in our case by parsing the weave file). Build the grammar and color mipmaps. (details in section 4.1)
2. For each point on the cloth that is to be rendered check whether it is front or back face and find the detail at which it is to be rendered based on its distance from view point.
3. **Close-up/Magnified view**
 - a. Check if fibre occurs on the surface, if so do the shading for fibre.(equation (4))
 - b. Look up the constitution of the cloth at that point, two threads, single thread or gap. Depending on the type do step
 - i. If *two threads* evaluate per thread BRDF and color bleeding by considering light scattering through the fibers.(equation (6))
 - ii. If *single thread* evaluate per thread BRDF. (equation (5))
 - iii. If *gap* transmit light.
4. **Normal viewing**
 - a. Read the grammar from the suitable level of detail of the grammar mipmap.
 - b. Evaluate the BRDF based on the parameters at this point. (equations (1-3))
 - c. Evaluate diffused light interaction that accounts for transmission of light through the threads.(Equation (6) assuming a density for the cloth based on thread thickness/opacity).

- d. Evaluate light transmission through gap using gap map.
5. Combine the components of light intensities computed for specular interaction, diffused interaction and transmission.

Thus the algorithm gives the way in which the weave grammar creates a global illumination model for the cloth by employing local specialized illumination models that are generated by assigning the appropriate parameters depending on color and composition of the cloth at that particular location.

6. Results and discussion

In this section we present the images synthesized by our algorithm. The algorithm was implemented as a shader plug-in for 3DS Max. The program was run on a PC with a pentium 4 processor (2 GHz), with an nVIDIA graphics card. A vanilla raytracer implemented by us for 3DS Max was used as the renderer. The implementation was not optimized for speed.

Figures 2 and 5 give a comparison of the images generated by our method and scanned images. The scans of the cloth were done at 1200 dpi and 600dpi in figure 2, in the case of the second cloth sample the threads were thicker and the scan was done at 600 dpi and 300dpi. There is a larger divergence in appearance of the colored cloth because of the difficulty to reproduce the same colors of threads.

Figure 3 shows the appearance of a cloth from various viewing distances. The capability to handle the back and front surfaces of the cloth based on the weave pattern is also demonstrated. A smooth transition between distant and close-up viewing is realized by blending. These images are created with the snowflake weave pattern shown in figure 8.

The images in figure 6 show the application of our technique to visualize clothing on virtual characters. Figure 6(a) shows the appearance of double colored cloth. This image was generated by considering red and blue color threads woven together with satin weave grammar.

Figures 6(b)-(e) illustrate the richness of details that can be captured by our algorithm. Figure 6(b) gives the image of dress made of a material that is woven with threads of eight different colors. The ability of the technique to handle more than two color threads, which is difficult for approaches that require BRDF fitting, in the weave is demonstrated here.

Figure 6(e) gives the image of a "self-designed" cloth where both the warp and weft threads are white. The appearance of the pattern on the clothes is the result of the detailed light interaction that we are able to define in our technique. Notice the variation in appearance of the weave depending on the light and view direction especially in the folds of the cloth.

Figure 4(a) illustrates the appearance of the clothes when

the gaps in the weave are large. An image of the same model created with suitable opacity assigned to the cloth material is shown in figure 4(b) for comparison. As can be seen the inhomogeneous composition of the cloth is captured well in our approach.

The rendering time for images of PAL resolution (720x576) for close up view of cloth, when the whole image consists of the cloth, is 2 minutes with super-sampling. For the clothed virtual character animations the rendering time is dependent on the number of polygons in the model. For the character in figure 6 (8000 polygons) the time taken is 12 seconds and figure 4 (51000 polygons) the timing is about 42 seconds. Both these timings do not consider super-sampling as the use of mipmaps to represent the weave pattern and evaluate the illumination solves the problem of aliasing inherently.

While it can be said that the results of the technique presented are comparable to texturing techniques, it should be noted that it is impossible to generate cloth with "self design" (the image in figure 6(e)) with any texturing technique. It is only the distributed BRDF that we defined that enables this visualization. The texture based techniques are limited by the prerequisite of an image of the desired texture. The superiority of the realism resulting from our detailed illumination model is also obvious in the animations submitted along with this paper.

7. Conclusions

We have presented an algorithm that exploits the weave pattern to create a global illumination model for cloth. This is achieved by using local specialized illumination models that are generated by assigning the appropriate parameters depending on color and composition of the cloth at that particular location.

Our technique:

- Enables visualization of cloth with rich weave patterns, by harnessing the benefit of the WIF standard from textile CAD. It also bridges the gap between the textile and graphics industry.
- Supports rendering of both front and back surfaces of cloth based on weave pattern. This was not possible with existing approaches.
- Enables rendering clothes with a wide range of weave thread colors. We are able to capture the color shift when contrasting threads are interwoven.
- Has the ability to visualize 'self-design' in clothing that results when warps and wefts of complex weave patterns are the same color. This is impossible to capture in texture based approaches.
- Captures the inhomogeneous transparency of woven cloth.
- Enables visualization of clothes at various distances and levels of detail by exploiting mipmap representations of

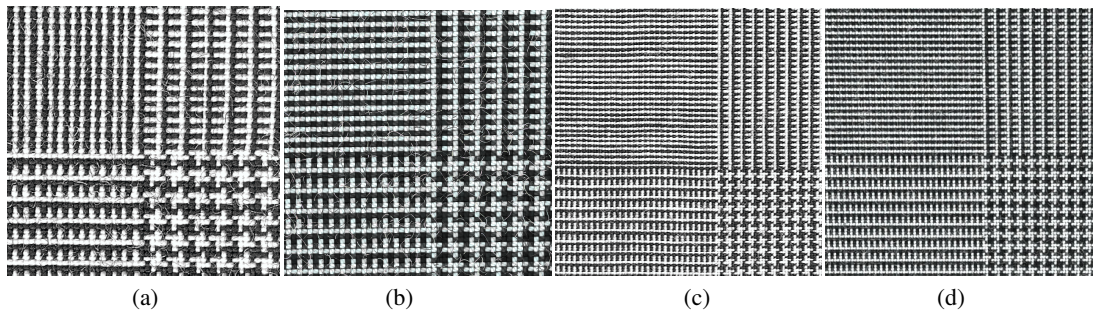


Figure 2: Comparison of scanned and generated images of black and white cloth at different levels of detail. (a) and (c) are scanned images while (b) and (d) are synthesized by our technique.

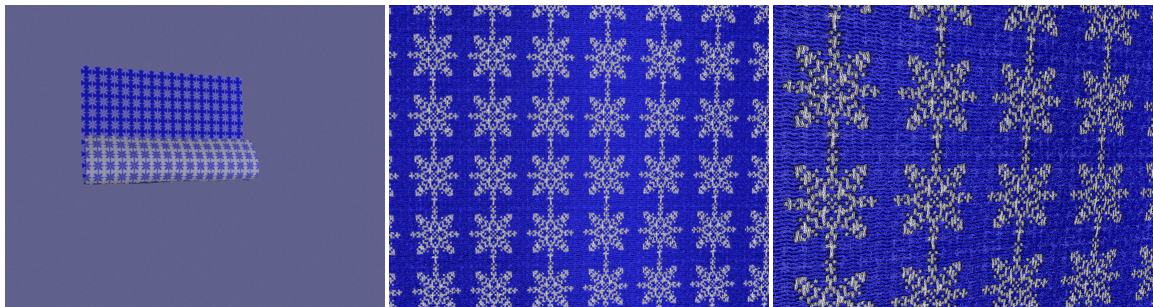


Figure 3: The ability of the technique to create images of the cloth at various levels of detail is demonstrated. In the close-up view the fibres on the surface of the cloth are also visualized. The white colored threads appear bluish due to color bleeding that results from the light transmission through the threads.

weave patterns. This approach implicitly solves the problem of aliasing. It results in scalability of our approach for both high and low resolution renderings. This is an attractive feature in the context of creating images for hand held portable devices.

We are currently investigating approaches to modify the technique for real-time rendering.

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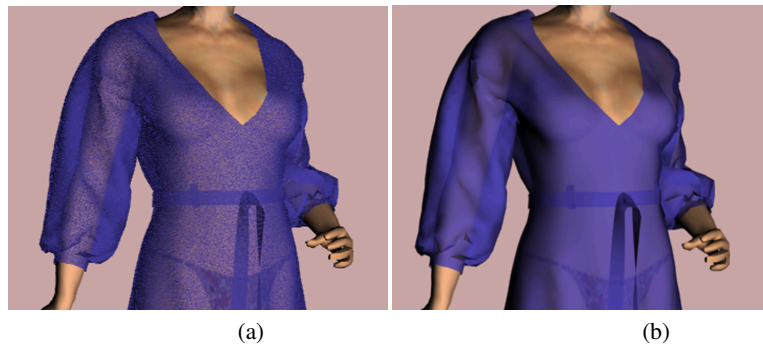


Figure 4: (a) Appearance of cloth with large gaps. (b) Comparison with implementing it as a transparency of polygons.

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Figure 5: Comparison of scanned and generated images of colored cloth at different levels of detail. (a) and (c) are scanned images while (b) and (d) are synthesized by our technique.

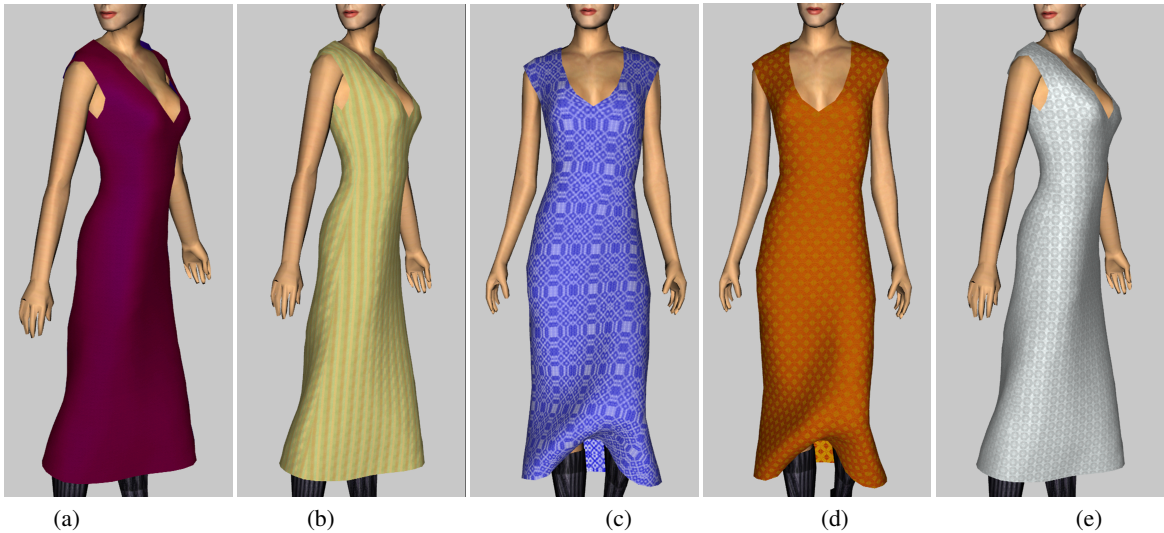


Figure 6: (a) Appearance of cloth woven from two very contrasting colors. (b) Weave created with 8 different colored threads. (c&d) Different weave pattern made possible by WIF. (e) Weave that is created with only white colored threads, Our technique is able to capture the detailed light interaction with the weave pattern and therefore the pattern is highlighted depending on the angle of viewing and light direction.

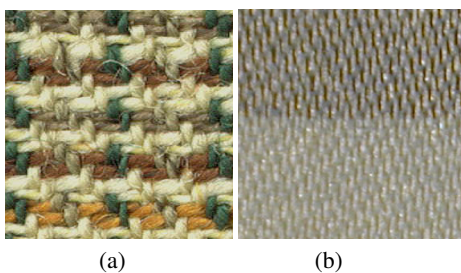


Figure 7: (a) Light reflected by the fibers (scan of cloth). Observe that the fibers above the surface appear to change their color based on the thread color on which they are present. (b) Light transmission through threads. Photograph of satin weave with light source on the same side as the camera. The cloth is woven with dark gray and white threads. One can observe the change in the color of the wefts of white thread due to the presence of the grey thread underneath.

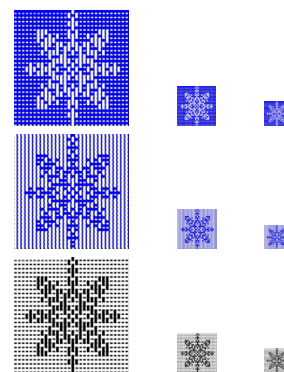


Figure 8: Weave pattern representation, the first row is the front face color scheme, the second is the back face color scheme and the third row is the grammar map.