Realistic and Efficient Rendering of Free-form Knitwear

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Abstract

We present a method for rendering knitwear on free-form surfaces. Starting from a parametric surface, a stitch pattern, and optionally a color pattern, we can produce highly realistic rendering of knitwear efficiently. Our method draws its realism from two sources. First, we have developed a novel and sophisticated model for free-form knitwear that takes into consideration the interactions between neighboring loops and the subtle irregularities in the position of the loops. Second, we have derived a method for rendering yarn microstructure with user control of the fluffiness of the yarn. The efficiency of our method comes from the fact that it displays free-form knitwear as Gouraud-shaded polygons, which current graphics hardware is optimized to draw. In contrast, previous technique for rendering free-form knitwear requires tracing curved rays and therefore cannot benefit from mass-market graphics hardware.

Keywords: Knitwear, Textile Rendering, Parametric Surfaces, Computer Animation, E-Commerce.

1 Introduction

We see knitwear frequently in our everyday life. Yet, in computer graphics there is little work on modeling and rendering knitwear. This is partly due to the fact that modeling and rendering knitwear is a challenging task. Realistic modeling of knitwear is difficult for three reasons:

- First, the size of individual stitches of knitwear is much larger than thread structure of woven fabric. While woven fabric can be represented quite well by specialized BRDF models [YYiT92, WAT92, DvGNK99], a realistic display of knitwear needs an explicit model of the knitting pattern. This requirement becomes evident when knitted fabric is stretched and the shapes of individual loops become clearly visible (see Fig. 5).

- Second, knitwear is a complex elastic structure held together by interlocking loops. The interactions between the loops have a big effect on the visual appearance of knitwear. It is difficult to capture this effect with a volumetric texture [KK89, GRS95, Ney98] because its texels do not interact.

- Third, the vast amount of down around the main structure of knitted yarn is an integrated part of knitwear appearance. It is cumbersome, if not impossible, to render this down with existing techniques for hair [iAUK92, WS92, TCC^{+}96] and fur [KK89, Gol97].

To address the above difficulties, we have developed a method for rendering knitwear on free-form surfaces. Starting from a parametric surface, a stitch pattern, and optionally a color pattern, we can efficiently produce highly realistic rendering of knitwear. Fig. 1 provides some examples produced by our system.

Our method draws its realism from two sources. First, we have developed a novel and sophisticated model for knitwear that takes into consideration the interactions between neighboring loops and the subtle irregularities of the loop positions. Second, we have derived a method for rendering yarn microstructure with user control of the fluffiness of the yarn. The efficiency of our method comes from the fact that it displays free-form knitwear as Gouraud-shaded polygons, which current graphics hardware are optimized to draw. In contrast, previous technique for rendering free-form knitwear requires tracing curved rays [GRS96] and therefore cannot benefit from mass-market graphics hardware. By producing realistic rendering of knitwear from the input of a surface, a stitch pattern, and a color pattern, our method is well-suited for a variety of applications including character animation [TCC^{+}96], knitted fabric design, and knitwear shopping over the internet.

In the spirit of Kajiya's work on fur rendering [KK89], Gröller has derived a volume rendering technique for display knitwear [GRS95]. Gröller's volumetric representation of the knitwear consists of two types of basic volume elements, obtained by sweeping a 2D density distribution along the yarn. Gröller's work was an important step beyond rendering knitwear by texture mapping scanned knitwear images. Even so, his model is still too simple to account for important factors such as the interactions between neighboring loops, the subtle irregularities in the loop positions, and advanced stitch patterns.

The rest of the paper is organized as follows. In Section 2, we detail various aspects of our method including how to model interactions between neighboring loops, the subtle irregularities in the loop posi-

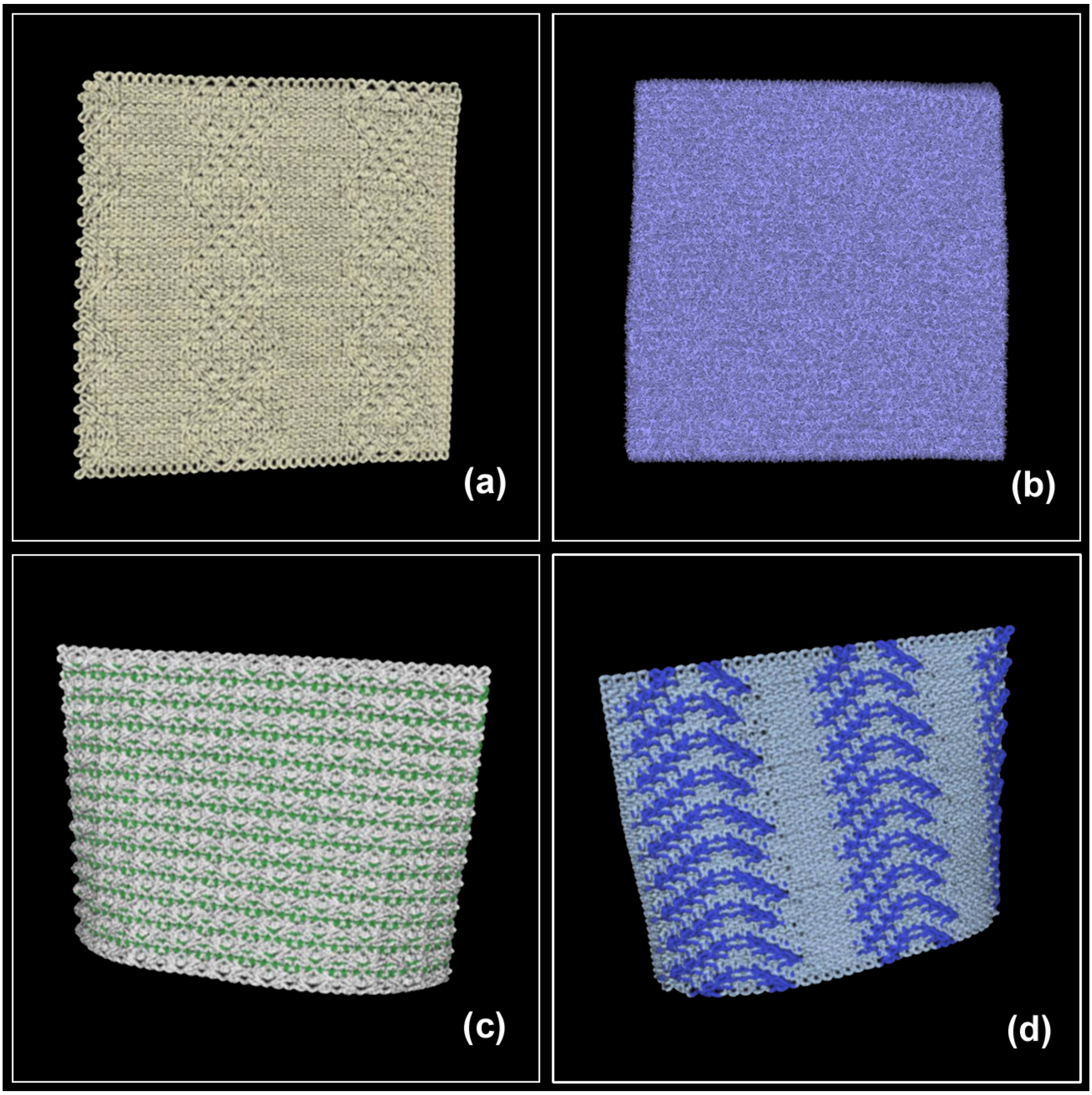

Figure 1: Sample knitwear produced by our system. (a) Knitwear with advanced stitch pattern of cables and twists. (b) Our system allows user control of the fluffiness of the yarn. Here we show a knitwear with very fluffy yarn. (c) Knitwear with colored yarn and advanced stitch pattern “Diamond”. (d) Knitwear with colored yarn and advanced stitch pattern “Chevrons”. The advanced stitch patterns are taken from knitting books.

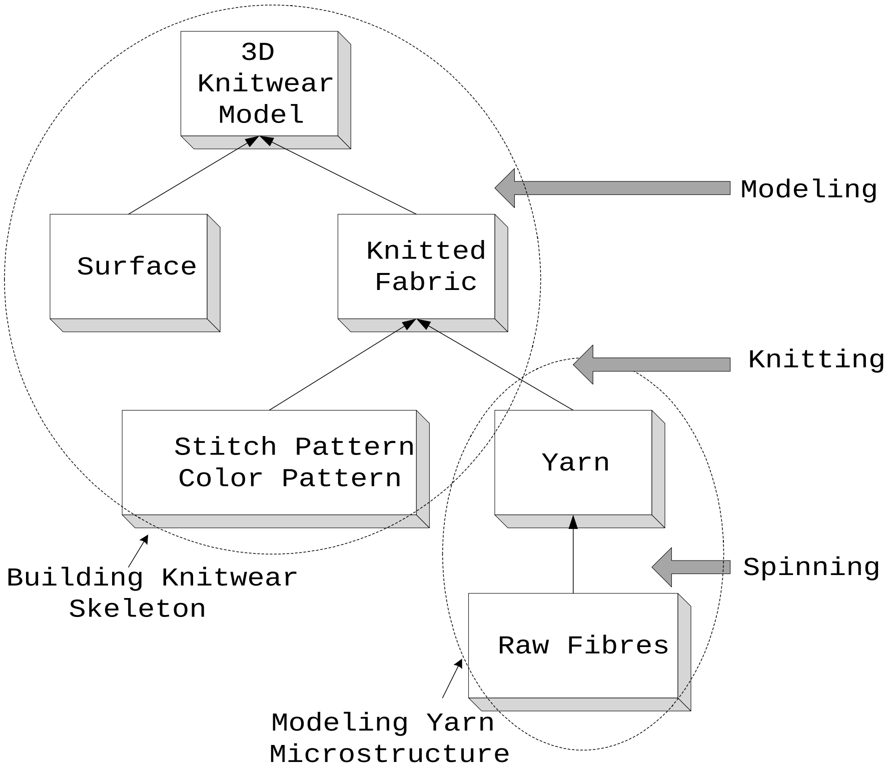

Figure 2: The process of making knitwear in the physical world. First, the spinning process turns raw fibres into yarn. Then, the knitting process produces a piece of knitted fabric base on a stitch pattern and optionally a color pattern. Finally, the modeling process puts the knitted fabric on a given surface in 3D. Our method consists of two parts: building a knitwear skeleton and modeling yarn microstructure.

tions, and yarn microstrucure. Section 3 presents results. In Section 4, we conclude with some suggestions for future work.

2 Modeling Knitwear on Free-form Surface

2.1 Conceptual Overview

Fig. 2 summarizes the process of knitwear making in the physical world. First, the spinning process turns raw fibres into yarn. Then, the knitting process produces a piece of knitted fabric base on a stitch pattern and optionally a color pattern. Finally, the modeling process puts the knitted fabric on a given surface in 3D .

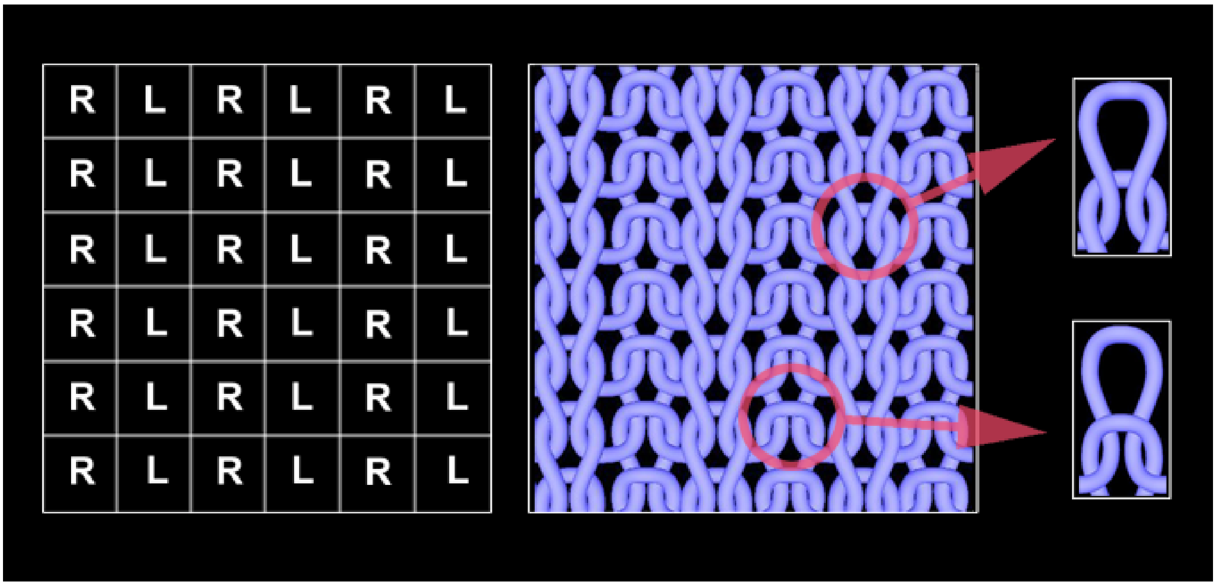

Figure 3: A simple stitch pattern consists of plain stitch (R-loop) and reverse stitch (L-loop) with the corresponding knitted fabric. The two basic stitches are shown on the right.

The process of making knitwear in physical world provides a reference frame for describing our method, which consists of two parts. First, we build a knitwear skeleton according to the given object surface and stitch pattern. The knitwear skeleton is a network of interlocking mathematical curves in 3D. If a color pattern is also given, then the curves in the knitwear skeleton also contains color information. Second, we model the yarn microstructure along the curves in the knitwear skeleton. Our method produces a free-form knitwear model consisting of Gouraud-shaded triangles for displaying through the standard graphics pipeline.

2.2 Stitch Pattern

There are two basic stitches, plain stitch (R-loop) and reverse stitch (L-loop), which provide the basis of most knitted fabrics [Har92, GRS95]. The two basic stitches are the reverse of each other. Fig. 3 is a simple stitch pattern showing which type of loop should be knitted at each location. Our method is more flexible than [GRS95] and can create knitwear from simple stitch patterns like this one as well as advanced stitch patterns commonly seen in knitting books [Har92].

2.3 Knitwear Skeleton

Suppose that the parametric domain of the surface patch $\mathbf{s}(u, v)$ is the rectangle Q and that Q is partitioned into tiles, each being a quadrilateral corresponding to a stitch in the stitch pattern. If we do not consider the irregularities of the stitch positions, this partition is simply an equal partition of the rectangle Q into rectangular tiles based on the stitch pattern. When we do consider the irregularities of the stitch positions, each tile of Q is a general quadrilateral. This is the case in this work. As we shall see, the corners of each tile of Q have been jittered by the recursive random perturbation described in Section 2.4.

Basic Method: As shown in Fig. 4, for every loop L (stitch) we first specify six points $\{\hat{k}_i = (u_i, v_i) \mid 0 \leq i \leq 5\}$ in Q and thus obtain six key points $\{\mathbf{s}(u_i, v_i) \mid 0 \leq i \leq 5\}$ in 3D. If the loop L resides in the tile defined by its four corner points $\hat{n}_0$, $\hat{n}_1$, $\hat{n}_2$, and $\hat{n}_3$, then the points $\{\hat{k}_i = (u_i, v_i) \mid 0 \leq i \leq 5\}$ are defined as follows:

$$\hat{k}_0 = 0.35(\hat{n}_3 - \hat{n}_0) + \hat{n}_3,\ \hat{k}_1 = 0.375(\hat{n}_2 - \hat{n}_3) + \hat{n}_3$$

$$\hat{k}_2 = 0.125(\hat{n}_1 - \hat{n}_0) + \hat{n}_0,\ \hat{k}_3 = 0.35(\hat{n}_4 - \hat{n}_0) + 0.5(\hat{n}_0 + \hat{n}_1),$$

$$\hat{k}_4 = 0.875(\hat{n}_1 - \hat{n}_0) + \hat{n}_0,\ \hat{k}_5 = 0.625(\hat{n}_2 - \hat{n}_3) + \hat{n}_3,$$

where $\hat{n}_4$ is the northern neighbor of $\hat{n}_0$, as is shown in Fig. 4. The points $\{\hat{k}_i = (u_i, v_i) \mid 0 \leq i \leq 5\}$ are chosen so that they can be connected into a loop in the parameter space and this loop is mapped into our desired loop L in 3D by the mapping $\mathbf{s}(u, v)$.

Next we connect these key points specified in the previous step using curve segments to get our desired loop L. The points $\{\mathbf{s}(u_i, v_i) \mid 0 \leq i \leq 5\}$ are by definition on the surface $\mathbf{s}(u, v)$. A loop in a knitwear, on the other hand, has slight deviations from the underlying surface $\mathbf{s}(u, v)$ due to the physical thickness of the yarn. In different parts of the loop the deviations are different. As shown in Fig. 4 (top right), we model these deviations by giving each key point $\mathbf{s}(u_i, v_i)$ an offset $\lambda_i \mathbf{n}(u_i, v_i)$ where $\mathbf{n}(u_i, v_i)$ is the surface normal at $\mathbf{s}(u_i, v_i)$. The sign and magnitude of every one of $\{\lambda_i \mid 0 \leq i \leq 5\}$ is chosen so that the resulting loop is knitted into the knitwear skeleton according to the stitch pattern and there is no intersection with neighboring loops even if the curves of all loops are replaced by cylindrical pipes of the diameter of the yarn. After offsetting the key points, we connect them using cubic cardinal splines to interpolate the key points $\mathbf{s}(u_0, v_0)$ through $\mathbf{s}(u_5, v_5)$.

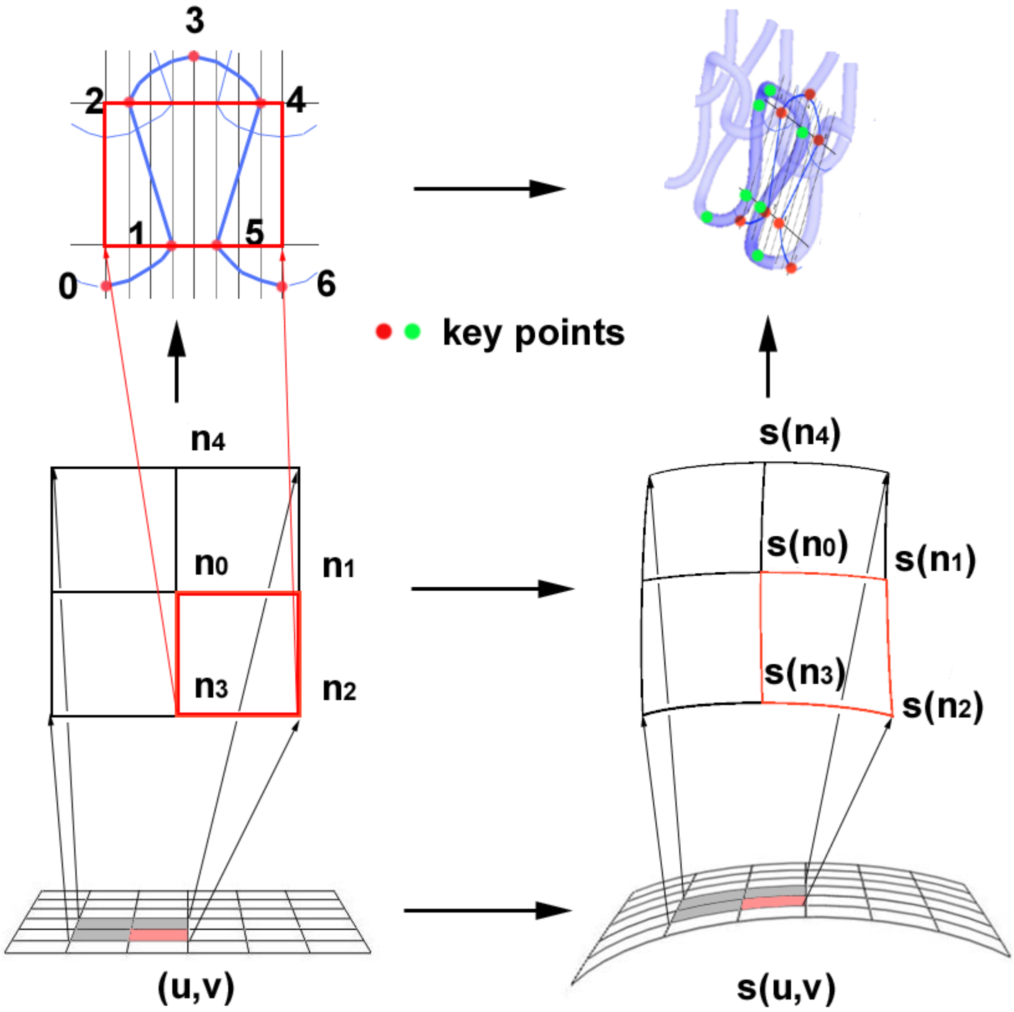

Figure 4: The construction of knitwear skeleton. Loop L is shown in the parameter space on the left and in 3D on the right. For $0 \leq i \leq 5$, the key point $\hat{k}_i$ is marked by i on the loop L in the parameter space. In 3D, the key points before offsetting are marked by red dots and after by green dots.

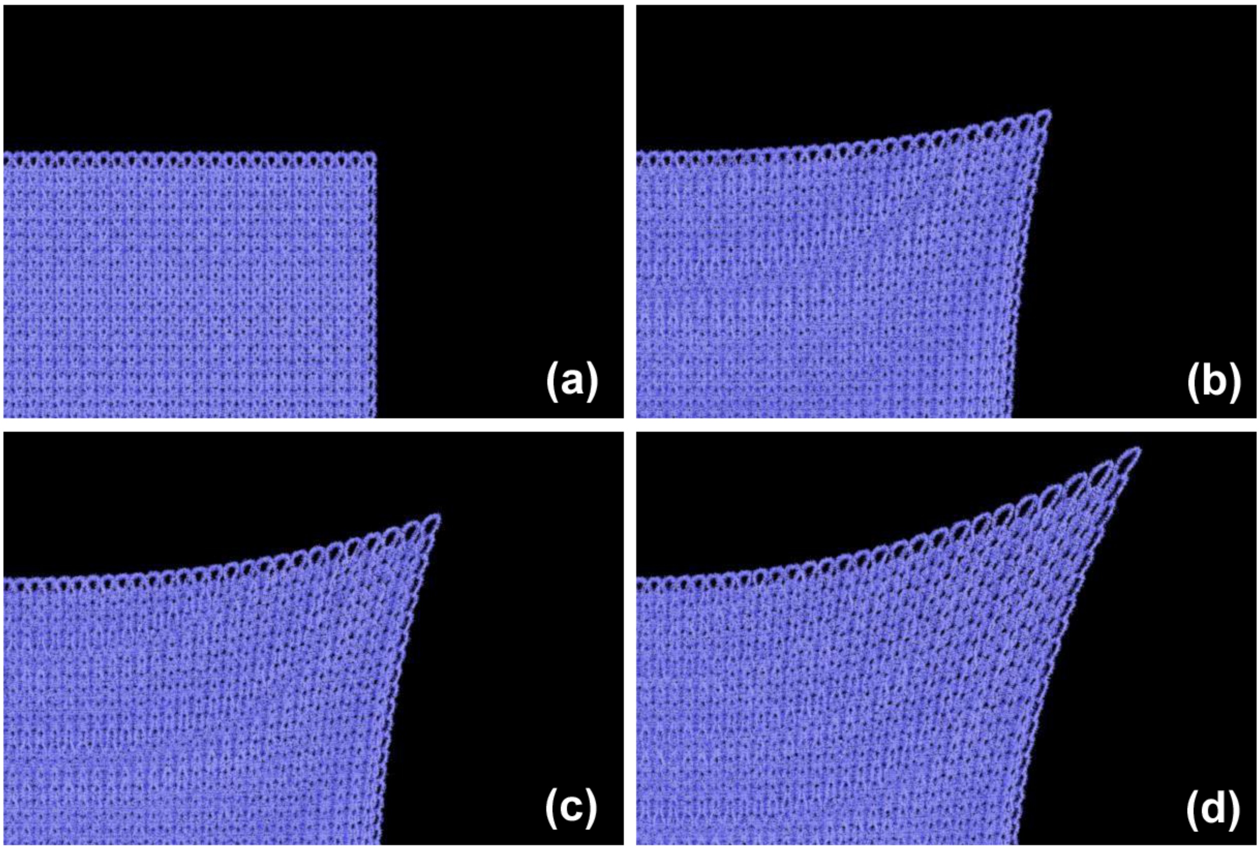

Figure 5: The loops in the knitwear change shapes while remaining correctly interlocked when we move a control point of the underlying surface.

Interactions Among Stitches: If we collect the key points of all loops, then we have the key points of the knitwear skeleton. These key points determine the overall shape of the knitwear. From the above construction of the key points, we observe that the key points of every loop are tied together with the key points of the neighboring loops. For example, in Fig. 4 the key point $\hat{k}_2$ is related to the upper left neighboring loop through the tile corner $\hat{n}_0$. Because of such relations among the key points, the knitwear can preserve its topological connections during stretch and deformation. As the underlying surface $\mathbf{s}(u, v)$ changes shape, each loop will also change shape depending on its location in the knitwear. At the same time, each loop will remain correctly interlocked with neighboring loops. Fig. 5 shows how the loops in the knitwear change shapes while remaining correctly interlocked when the underlying surface deforms. Note that neither specialized BRDF [YYiT92, WAT92, DvGNK99] nor volumetric texture [KK89, GRS95, Ney98] can capture this kind of effect.

Advanced Stitch Patterns: An important feature of the key points is that they allow us to model basic stitch patterns as well as advanced stitch patterns [Har92]. In Fig. 4, a cardinal splines curve connects the key points $\mathbf{s}(u_0, v_0)$ through $\mathbf{s}(u_5, v_5)$. This is the connection for simple stitch pattern. For advanced stitch patterns, we need to connect key points according to the given stitch pattern.

2.4 Irregularity of Stitch Positions

Although knitted fabric has a regular structure, the position of each stitch has some randomness. This randomness presents even when the knitted fabric is on a flat surface and subject to no external force. A piece of knitted fabric consists of interconnected loops with elastic properties determined by the yarn. Because of the empty space between the loops, an individual loop may be free to move within a small range without being affected by the tension forces of neighboring loops. As a result, the position of the loop is random within that small range. If we think of a piece of knitted fabric as a spring net, then the balance point of each node of the net is not a point but a small region in 3D.

We have developed a recursive perturbation technique for modeling the randomness of stitch positions. This is an empirical technique based on a multiscale model of the parameter domain of the underlying surface patch. At the global scale, the parameter domain is regarded as an elastic sheet. At local scale, each stitch is subject to a small random perturbation in the parameter space. The perturbation is done in

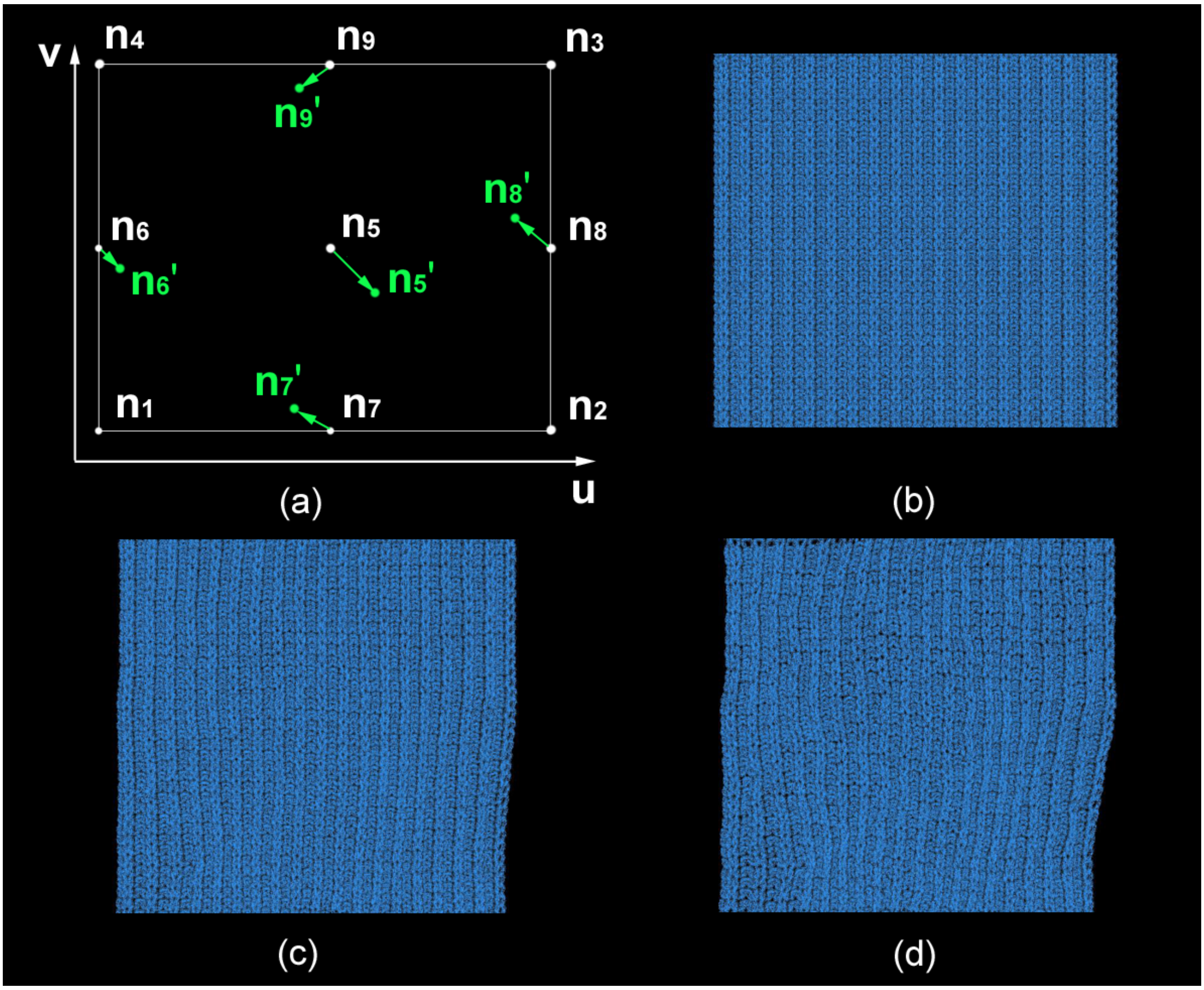

Figure 6: Modeling irregularity of stitch positions using recursive random perturbations. (a) Recursive random perturbation scheme. (b) Knitwear without random perturbations. (c) Knitwear with small random perturbations (d) Knitwear with large random perturbations.

the parameter space means that for a stitch at $\mathbf{s}(u_0, v_0)$, the perturbation moves (u_0, v_0) to (u_0', v_0') and the stitch to $\mathbf{s}(u_0', v_0')$.

Consider a rectangular knitwear skeleton K whose four corner stitches have parameters $\hat{n}_i = (u_i, v_i)$ with $i = 1, 2, 3, 4$ as shown in Fig. 6 (a). We compute parameters for the center stitch of K and the middle stitch of each edge of K. For each one of these, we first compute its regular balance position using the fact that Q is an elastic sheet. Then we add a random perturbation in u- and v-directions. The random perturbation in a direction is proportional to the number of stitches in that direction because the randomness comes from the empty space between stitch loops.

Center stitch We first compute the center point of the quadrilateral Q to be $\hat{n}_5 = (u_5, v_5) = \frac{1}{4}\sum_{i=1}^{4}(u_i, v_i)$. Next, we perturb $\hat{n}_5 = (u_5, v_5)$ to $\hat{n}_5' = (u_5', v_5') = (u_5 + \nabla u_5, v_5 + \nabla v_5)$. The offsets $\nabla u_5 = \kappa n_u$ and $\nabla v_5 = \kappa n_v$ where n_u and n_v are the number of stitches in u- and v-directions respectively, and κ is is a constant determined by the elastic property the parameter space.

Middle stitch of each edge We can compute the parameter of the middle stitch of each edge of K the same way. For example, $\hat{n}_6' = (u_6', v_6') = (u_6 + \nabla_6 u, v_6 + \nabla v_6)$, where $\hat{n}_6 = (u_6, v_6) = 0.5(u_1 + u_4, v_1 + v_4)$ and $\nabla v_6 = \kappa n_v$. However, $\nabla v_6 = \kappa 0 = 0$ because $\hat{n}_1 = (u_1, v_1)$ and $\hat{n}_4 = (u_4, v_4)$ are on the same column of the stitch pattern.

Having obtained the center stitch of K and the middle stitch of each edge of K, we recursively repeat the above procedure for each quarter of K. For example, we repeat the about procedure on the lower left quarter, whose four corner stitches have parameters $\hat{n}_1 = (u_1, v_1)$, $\hat{n}_7' = (u_7', v_7')$, $\hat{n}_5' = (u_5', v_5')$, and $\hat{n}_6' = (u_6', v_6')$.

Fig. 6 (b) through (d) show knitwear with increasing larger random perturbations.

2.5 Yarn Microstructure

Yarn consists of strands of fibre which are twisted together into a continuous thread. A simple model of a yarn is a cylinder. However, a smooth-shaded cylinder does not give the visual impression of a yarn. This is because, even though a single strand of fibre is not perceivable, a collection of fibres and the small down around it give knitwear a unique appearance.

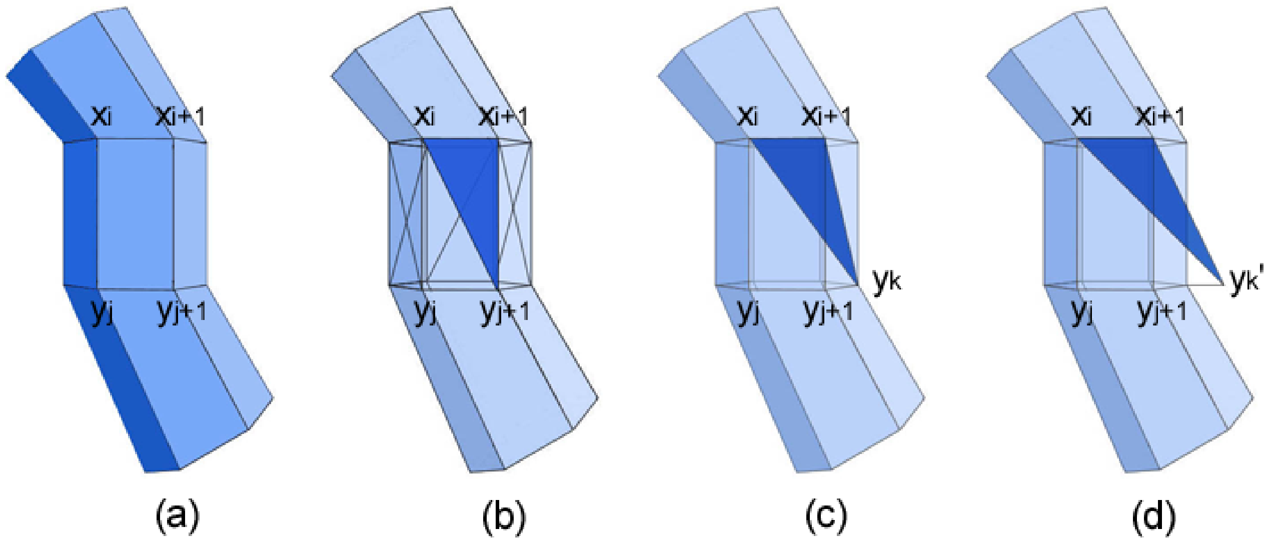

Figure 7: Modeling yarn microstructure. (a) A triangulated cylinder representing a yarn segment. (b) and (c) Vertex $\mathbf{y}_j$ of the dark blue triangle is replaced by a vertex $\mathbf{y}_k$ randomly chosen among $\{\mathbf{y}_i \mid i = 1, \ldots, n\}$. (d) Perturb the vertex $\mathbf{y}_k$ to new location $\mathbf{y}'_k$ along the normal of the cylinder surface to control the fluffiness of the yarn.

We have developed an effective model for rendering yarn microstructure using Gouraud-shaded triangles. This model is based on the following observation: for a short segment of yarn, we can use a Gouraud-shaded triangle to represent a collection of fibre strands. Because of this observation, we can model the yarn segment as a bundle of Gouraud-shaded triangles, each elongated along the direction of the yarn. To construct the triangle bundle, we start with a triangulated cylinder representing the shape of the yarn segment as shown in Fig. 7 (a). In Fig. 7 (b), the cylinder segment surface is bounded by two loops L_1 and L_2. The loop L_1 is discretized as edges $\{[\mathbf{x}_i\mathbf{x}_{i+1}] \mid i = 1, \ldots, m$ and $\mathbf{x}_1 = \mathbf{x}_m\}$, whereas L_2 as edges $\{[\mathbf{y}_i\mathbf{y}_{i+1}] \mid i = 1, \ldots, n$ and $\mathbf{y}_1 = \mathbf{y}_n\}$. The cylinder surface is discretized into $m + n$ triangles. Our triangle bundle also consists of $m + n$ triangles, built as follows. We traverse the loop L_1 and L_2 and generate triangles. For each edge $[\mathbf{x}_i\mathbf{x}_{i+1}]$ of the loop L_1, we form a triangle by randomly choosing a vertex $\mathbf{y}_k$ out of $\{\mathbf{y}_i \mid i = 1, \ldots, n\}$ as shown in Fig. 7 (c). Similarly for each edge $[\mathbf{y}_i\mathbf{y}_{i+1}]$ of the loop L_2, we form a triangle by randomly choosing a vertex out of $\{\mathbf{x}_i \mid i = 1, \ldots, m\}$. The randomized triangles bundle generates a random reflectance similar to that of knitted fabric.

Yarns vary enormously in thickness from very fine to very bulky, each yarn having its own visual characteristics. We have extended the above basic model to allow a variation of yarn microstructure. In the basic model, when we add a triangle to the triangle bundle we do not change the vertex location. To control the fluffiness of the yarn, we perturb the locations of vertices outward in the direction of the normal of the cylinder surface. As shown in Fig. 7 (d), we perturb the vertex $\mathbf{y}_k$ to new location $\mathbf{y}'_k$. By controlling the amount of the perturbation, we can control the fluffiness of the yarn. Fig. 9 shows knitwear examples with the same color and stitch patterns but different fluffiness.

3 Results

Rendering Speed: All the examples reported in this paper have a few millions of Gouraud-shaded polygons. Depending on the performance of the PC graphics card, the rendering time is about one to a few seconds. This rendering time will decrease quickly with the rapid improvement of the PC graphics card performance.

Color Pattern: The color pattern determines the color each stitch. Introducing color pattern to knitting vastly increases the scope for interesting designs. Fig. 8 shows an example.

Stitch Pattern: As mentioned, an important advantage of our method is its ability to use advanced stitch patterns. Most of the knitwear we see in our daily life include some advanced stitch patterns, including cables, twists, bobbles [Har92]. All these can be modeled with our method. Fig. 1 (a), (c), and (d) are some examples.

Yarn Fluffiness: Our method can control the fluffiness of the yarn. Fig. 9 shows knitwear examples with the same color and stitch patterns but different fluffiness. Fig. 1 (b) shows knitwear with very fluffy yarn.

Knitwear Texture: Instead of a full-blown 3D knitwear modeling, we can just create knitwear skeleton in the parameter space and color the 2D stitches according to a color pattern. The result so obtained is a knitwear texture. A knitwear texture does not have true 3D features such as, detailed silhouette, self occlusions, and self shadows if shadows are cast. As a result, when a knitwear texture is mapped onto a 3D surface, the rendering will be less convincing. On the other hand, knitwear texture is much cheaper to compute and we can still model the randomness of the stitch positions. Fig. 10 shows an example of

Figure 8: Knitwear with color pattern.

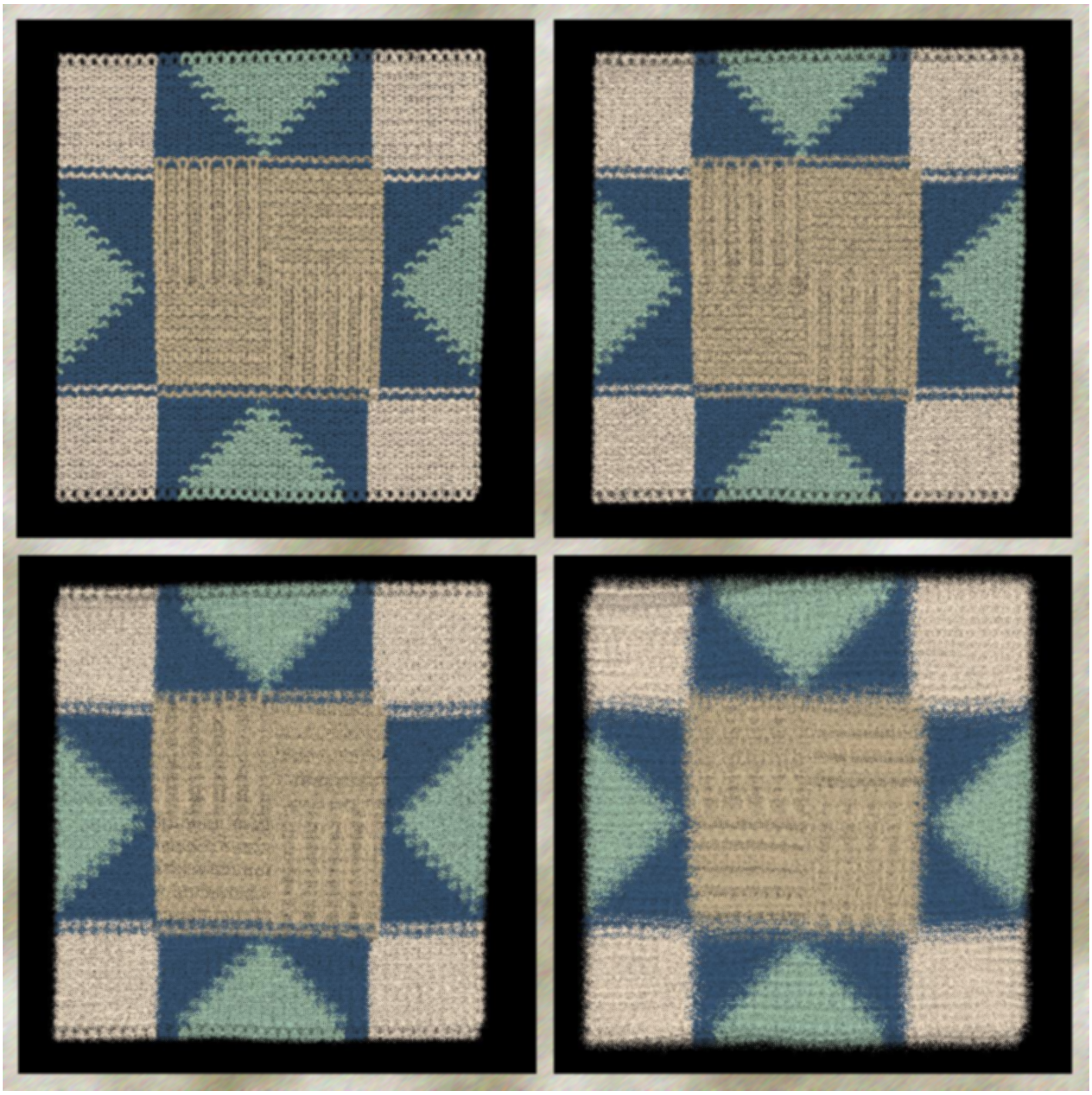

Figure 9: Knitwear of increasing fluffiness.

Figure 10: Knitwear texture. Left: photograph. Right: knitwear texture generated from the photograph. Notice the randomness of stitch positions generated by recursive random perturbation.

knitwear texture.

Finally, Fig. 11 shows that it is easy to apply our method to knitwear commonly seen in our daily life.

4 Conclusions

We have presented a method for realistically rendering knitwear on free-form surfaces. By carefully modeling the interactions between neighboring loops, the subtle irregularities in the position of the loops, and yarn microstructure, our method can produce highly realistic rendering of knitwear. Since our method displays free-form knitwear as Gouraud-shaded polygons, we gains rendering speed by capitalizing on the rapidly improving mass-market graphics hardware.

One of the future directions is building and rendering multiresolution models for knitwear. With rapidly

Figure 11: Modeling knitwear common in our daily life. Notice we see not only the down mass but also some of the individual hairs in the down. This effect is difficult to achieve with existing volumetric method.

improving PC graphics card, we expect our method to become interactive soon. In that scenario, multiresolution modeling and rendering of knitwear will greatly improve the user experience with our method. Other topics of interest include the use of knitwear models in animation and E-commerce applications. Finally, our work provides insight into the difficult problem of hair modeling and we hope to stimulate more work in that important area.

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