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# Sketch-Based Garment Design with Quad Meshes

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## Abstract

Garment creation continues to be the most tedious part of the virtual clothing process. In this paper, we present an easy to use sketch-based cloth modeling approach. Contours can be easily sketched on a mannequin to generate quad meshes to represent pieces of cloth already fit and draped. Typically, the clothing process depends highly on the meshing scheme that has to infer its geometry from the input boundary. Our quad meshing scheme is based on discrete Coons patches but with arbitrary boundary input. We also apply the permanence principle to our topological solution to allow more control over the influence of the input boundary polyline on the interior output polygonal mesh. This facilitates the creation of folds that are strongest in curvature at the boundary and which diminish towards the interior. The generated garments can then be easily animated in a simulation system based on Finite Elements, using a rediscretization of the generated mesh and a reconstructed metric of the cloth surface.

*Key words:* garment design, sketch-based modeling, quad meshing, extra-ordinary vertices, discrete Coons, permanence patches, physical simulation, Finite Elements

## 1. Introduction

Modeling cloth without having to design pieces of garment and their seaming associations is a major attraction in cloth modeling and animation. In this paper, we present a sketch-based approach for modeling cloth described by a network of polylines input by the user from different 2D views in a virtual 3D environment. We start by setting a 3D mannequin and some auxiliary planes, to sketch the outlines of the cloth. Out of a network of boundary polylines, we construct high quality quad meshes representing cloth pieces. Every piece of the generated cloth is then associated to an underlying body part or a corresponding sub-mesh.

The contribution of our work lies in the design of quad meshes from sketched contours of the desired garments. The literature presents us with criteria to compare the results of various meshing schemes. The authors in [1] quantified this criteria by the *distortion* of the mesh<sup>3</sup> and limited their

quad meshing scheme to instances of the problem where the minimum of this *distortion* is attainable. Their work is mainly concerned with finding a topological solution – the vertices and their connectivity – where the geometry of the resulting mesh is an assembly of rectangular Discrete Coons Patches [7]. In this paper, we extend their work to fill a larger variety of  $n$ -sided regions by introducing additional dislocations and allowing an increase in the distortion but with the least possible amount. Moreover, we generalized the permanence principle [7] to quad mesh a region with an *arbitrary* topological input to allow more control over the weight of the boundary vertices propagated towards the interior of the mesh.

For the purpose of visualization, we implement a fast Finite-Element simulation system which combines the ability of representing accurately the nonlinear anisotropic behavior of cloth materials along a particle-system representation allowing the use of efficient numerical integration methods along the possibility of handling collisions and geometrical constraints efficiently [20]. Thanks to a dedicated collision processing, the cloth respond appropriately to the motion of the body, which can set to various poses or perform various animations.

The remainder of this paper is organized as follows. Section 2 gives an overview of related work. The cloth modeling application along with its three main phases, namely

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<sup>3</sup> The *distortion* of a mesh is the sum of distortion on all the vertices of the mesh. The distortion on a vertex is, in turn, the deviation of its valence from the regular setting (4 for interior, 3 for boundary, and 2 for corner vertices).

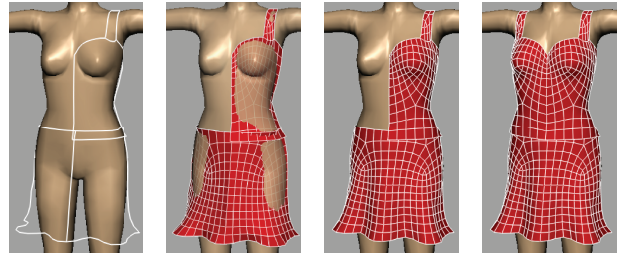
sketching, meshing, and refitting, are detailed out in section 3. We describe the mechanical simulation system in Section 4. Section 5 outlines the conclusion and future work.

## 2. Related Work

The dominating method that is adopted in virtual clothing is the 2D pattern construction and draping of the constituting pieces of cloth. However, sketch-based cloth modeling has received some attention. Turquin et al. [18] developed a sketch-based interface that would let users construct 3D virtual garments on a character model. Their system computes distance-to-the-body for the silhouette lines and point-to-body distances for the borderlines. It then propagates this distance information in 2D to find desired point-to-body distances, which it uses to determine the garment’s 3D position. Folds are incorporated by strokes that mark the presence of either ridges or valleys. Wang et al. [6] model a 3D garment around a 3D human model by 2D sketches input. A feature template for creating a customized 3D garment is defined according to the features on a human model. Then the profiles of the 3D garment are specified through 2D sketches. The smooth mesh surface interpolating the specified profiles is constructed by a modified variational subdivision scheme.

In a somewhat different context, Han et al. [8] computed the 3D shape of cloth from a single image. They present an algorithm that finds the shading primitives on a cloth image and simultaneously recovers their 3D shape by fitting to the 3D fold primitives obtained through photometric stereo. Chen et al. [5] reconstruct generic images by using an attributed graph representation for clothes with a dictionary of image primitives where each stroke may correspond to folds, sewing lines, occluding boundaries, and shape outlines.

Our approach reduces the problem to finding a good meshing algorithm to construct cloth pieces from an input net of polylines entered by the user as outlined in [22]. In general, there are four approaches towards a solution: advancing front, node placement, parametric curves, and the topological approach. In the advancing front technique [3,21,15,16], a set of fronts are defined consisting of the edges at the boundary of the domain. Quads are systematically combined at the front, advancing towards the interior of the area. The node placement process [17,14,10] is made of two stages the positions of the nodes are computed first and their connectivity is decided next. The third approach uses subdivision surfaces and differs in the nature of data input. Given an  $n$ -sided region bounded by  $n$  parametric curves and a user defined vertex  $G$ , connect  $G$  with the middle parameter point on each side constructing an initial quad-based control net [2,19,4,9,11]. The topological approach [1,12] aims at generating the quad mesh topology regardless of the geometric conditions at the boundary. In an afterward phase, the locations of the vertices are determined.



(a) Boundary lines sketched on the mannequin. (b) The generated quad mesh on the man-mesh. (c) The garment mesh refitted to the underlying body part. (d) The garment mesh combined using a mirror operation.

Fig. 1. Cloth generation from boundary lines sketched on a mannequin.

## 3. The Sketch-Based Cloth Modeling Approach

The sketch-based cloth modeling approach allows cloth design in a triple-phase process (see Fig. 1 and Fig. 12). First, the user draws the nets of polylines that represent the descriptive outline of the cloth (Fig. 1(a)). Then, the closed regions in the net of polylines are filled with quad meshes (Fig. 1(b)). In the last phase cloth-body associations are established so that every piece of cloth has a corresponding underlying body part (Fig. 1(c)). This is done either automatically by computing the enclosed submesh or by manually selecting the polygonal faces comprising the submesh of the mannequin when the cloth is loose. We use these associations to resolve cloth-body interpenetration as well as for collision detection and handling at animation time. Simple operations such as mirror and join can be applied later on the resulting mesh (Fig. 1(d)).

### 3.1. Sketching in a 3D Environment

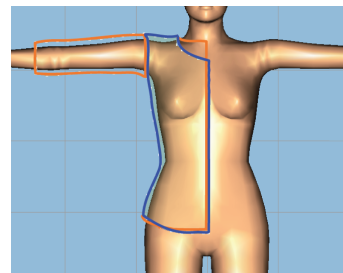


Fig. 2. The outlines of a jacket sketched in the front and back view.

The sketching environment is a multi-view (orthographic and perspective) paneled window. The mannequin –aligned along the y-axis in a standing position– is the basic element in the scene. When the user draws in the front view, the input lines either lie in the xy plane or on the mesh of the model with a user defined offset (see Fig. 2).

It is possible that the system planes (xy, xz, and yz) may not be enough to include all parts of the input outlines.

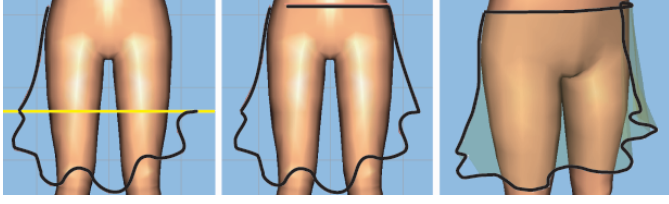


Fig. 3. The virtual mode that helps draw the loose parts that are not directly attached to the body.

For example, consider the lower part of the skirt that may be described by a closed contour drawn around the knees and lying in a plane parallel to the  $xz$  plane (see Fig. 3). In order to draw the loose parts that are not directly connected to the body, the user may switch to a temporary drawing mode where the sketches are rotated to lie in the plane perpendicular to the current viewing plane and passing through the last point drawn in the normal mode.

As the user creates the outlines of the pieces of cloth, different tools such as cut and add are needed. Figs. 4, 5, and 6 demonstrate the process.

### 3.2. The Quad Meshing Scheme

The quad meshing algorithm in [1] is based on the criteria of the existence of at least one  $n$ -valent dislocation (an extraordinary vertex or a non-quadrilateral facet) in an  $n$ -sided region. Starting from this criteria, a partitioning to rectangular regions is inferred from the flow of lines around and through this dislocation (see Fig. 7). Thus, given the lengths  $l_i$  of the sides of the region, the topological distances  $d_i$ , that define the dimensions of the rectangular subregions, are computed using the designed formulae.

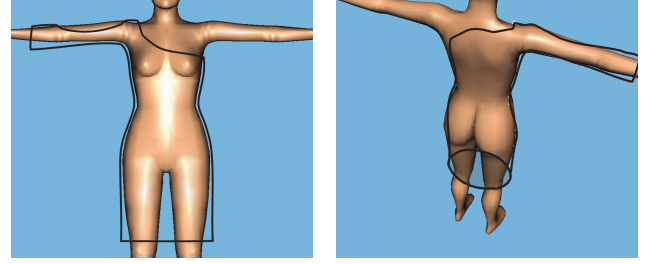
However, there are instances where the topology of the boundary lines does not permit the construction of strictly rectangular regions. In what follows, we present a simple method to deal with such cases. We also extend what was previously proposed in the context of discrete Coons to the permanence patches [7].

#### 3.2.1. Quad Meshes with Higher Distortion

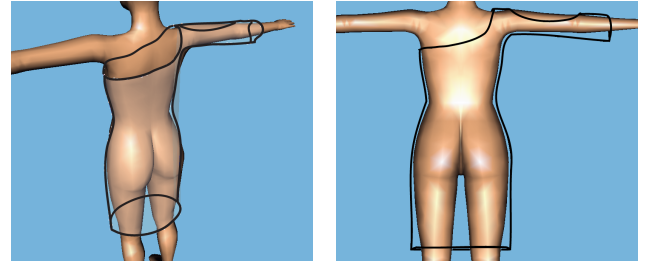
For certain topological configurations, the system that computes the distances  $d_i (1 \leq i \leq n)$  from the dislocation to the sides yields one or more negative values. The basic idea of our algorithm (see Fig. 9) is to isolate sides that are relatively *large* in 4-sided distorted sub-regions. All cases of such regions are guaranteed to be filled by a quad mesh in [1] with maximal total distortion equal to 4. In what follows, we show how to distinguish '*large*' sides, mark distorted subregions, and iterate over the distances  $d_i$  to recalculate the new dimensions of the remaining rectangular sub-regions only from the lengths of not '*large*' sides.

The formula that evaluates the distance is:

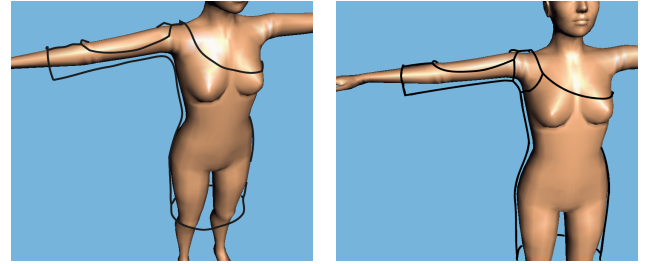
$$d_i = \frac{1}{2} \times \left[ \sum_{k=1}^{\lfloor p \rfloor} l_{i+4k-3} - \sum_{k=1}^{\lfloor p \rfloor} l_{i+4k-1} \right]$$



(a) The user starts by drawing the boundary of the front part as one region. (b) The back part is added to the front one by drawing the lower-back boundary of the dress.



(c) The second region constructed needs to be cut in two allows the creation of a stylish places for the general outline of hole in the garment. (d) One last stroke on the sleeve to be completed .



(e) The network of outer boundaries that depict the general non-convex regions. (f) sketches added to partition shape of the garment.

Fig. 4. Sketching the network of boundaries representing the dress.

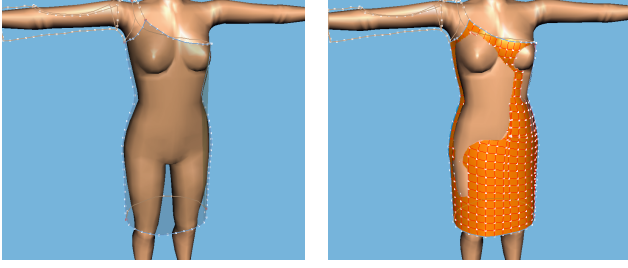
where  $i = 0 : n - 1$

$$\text{and } p = \begin{cases} n/2, & \text{if } n \text{ is odd;} \\ n/4, & \text{if } n \text{ is even and } n/2 \text{ is odd.} \end{cases}$$

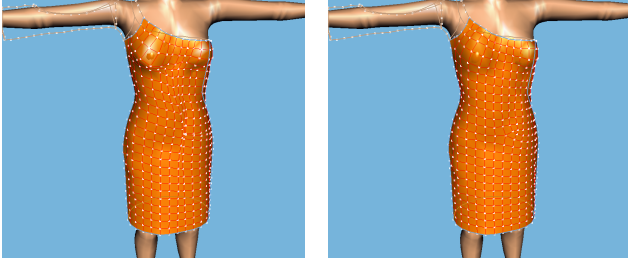
For every negative distance with index  $i$ , the sides that contribute to the summation with the negative coefficients are identified by the indices:

$$i + 4k - 1 \quad \text{where } 1 \leq k \leq \lfloor \frac{n}{2} \rfloor$$

These lengths are marked as *large* lengths. For every *large* length  $l_i$ , regions  $i$  and  $i + 1$  are marked as distorted if neither  $l_{i-1}$  nor  $l_{i+1}$  is large or both  $l_{i-1}$  and  $l_{i+1}$  are large. Otherwise, only region  $i+1$  is marked as distorted if  $l_{i+1}$  is *large* and  $l_{i-1}$  is not. To recalculate the distances, for every negative distance,  $d_i$ , if length  $i$  is large, set it to 2, otherwise set it to 1. Then, while there are still distances being modified or set, for each distance where length  $i$  is not *large*:

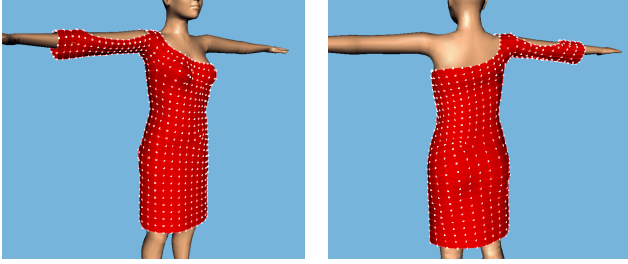


(a) For each closed region, corners are identified by the system and verified by the user. (b) Filled with a quad mesh (corners are identified by the system scribed in the next section).

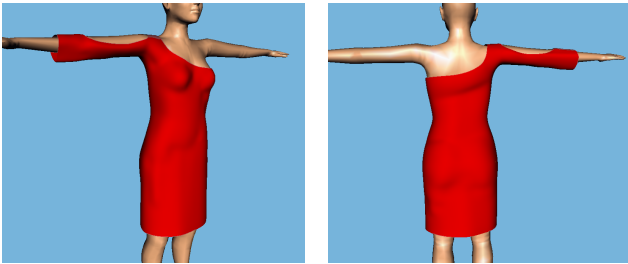


(c) Resolve body-garment interpenetration. (d) Mesh beautified using either an optimization technique or a particle system.

Fig. 5. Quad mesh generation.



(a) The front polygonal mesh. (b) The back polygonal mesh.



(c) The Catmull-Clark surface. (d) The Catmull-Clark surface.

Fig. 6. The resultant dress after quadrangulating all closed regions.

a) if  $d_{i-1}$  is known,

$$d_{i+1} = \begin{cases} \min(l_i - d_{i-1}, d_{i+1}), & \text{if } d_{i+1} \text{ is known;} \\ l_i - d_{i-1}, & \text{otherwise.} \end{cases}$$

b) else if  $d_{i+1}$  is known,

$$d_{i-1} = \begin{cases} \min(l_i - d_{i+1}, d_{i-1}), & \text{if } d_{i-1} \text{ is known;} \\ l_i - d_{i+1}, & \text{otherwise.} \end{cases}$$

c) else,  $d_{i-1} = \lfloor \frac{l_i}{2} \rfloor$  and  $d_{i+1} = \lceil \frac{l_i}{2} \rceil$

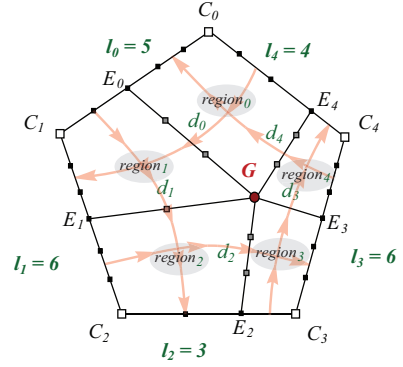


Fig. 7. The flow of lines (in light red) infer the partitioning to rectangular subregions. Regions  $i$  and  $i+1$  are associated with side  $i$ .

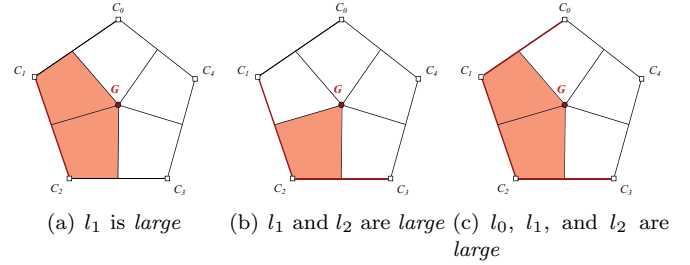
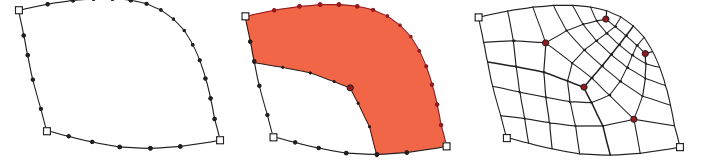
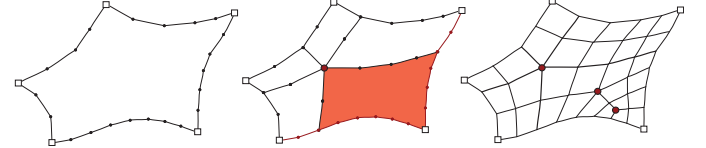


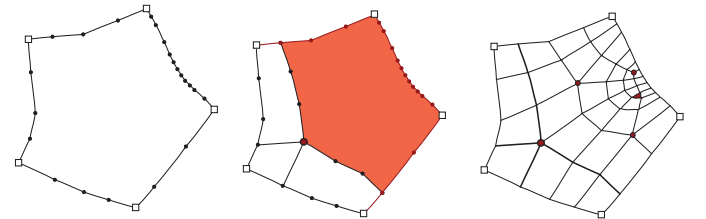
Fig. 8. Distorted regions (light red) are identified according to large lengths (dark red).



(a) a 3-sided region where only one length is large



(b) a 5-sided region where two adjacent lengths are large



(c) a 5-sided region where three adjacent lengths are large

Fig. 9. Examples of regions filled by quad meshes of non-minimal distortion. From left to right: the region defined by boundary poly-lines, distorted subregions (light red) and large lengths (dark red), and the resulting quad mesh.

### 3.2.2. Permanence Patches

The generalized approach that is proposed in this paper introduces slight complications to this boundary-interior polyline associations. Using strictly discrete Coons may re-

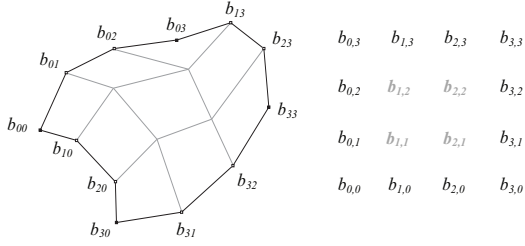


Fig. 10. A configuration where  $m = n = 3$ . The gray colored vertices are the unknown interior vertices.

sult in geometrically distorted meshes.

According to the permanence principal [7], the relation between every interior vertex and its immediate neighbors:  

$$b_{i,j} = -\frac{1}{4} (b_{i-1,j+1} + b_{i+1,j+1} + b_{i-1,j-1} + b_{i+1,j-1}) + \frac{1}{4} (b_{i,j+1} + b_{i+1,j} + b_{i,j-1} + b_{i-1,j})$$
A neater way of writing this is using a mask as shown in Eq. 1.

$$b_{i,j} = \frac{1}{4} \times \begin{matrix} -1 & 2 & -1 \\ 2 & \bullet & 2 \\ -1 & 2 & -1 \end{matrix} \quad (1) \quad b_{i,j} = \begin{matrix} \alpha & \beta & \alpha \\ \beta & \bullet & \beta \\ \alpha & \beta & \alpha \end{matrix} \quad (2)$$

The discrete Coons patch has  $m + 1 \times n + 1$  vertices; of these,  $m - 1 \times n - 1$  are unknown. Eq. 1 gives one equation for each unknown. Thus we may find the discrete Coons patch as the solution of a linear system with  $m - 1 \times n - 1$  equations in as many unknowns.

So far, solving  $m - 1 \times n - 1$  equations has given what was already available with much less computation in the discrete Coons. However, the mask in Eq. 1 gives a new insight towards relating vertices to their neighbors and thus establishing a global linear system that describes the patch. By preserving relative values, the mask may be written as given by Eq. 2. As such, different choices for  $\alpha$  and  $\beta$  could be used. Note that we always need  $4\alpha + 4\beta = 1$  in order for 2 to utilize barycentric (or affine) combinations. It is evident that these patches are defined in regular topology where the quad mesh is a grid of 4-valent vertices. Thus, for us to use permanence patches in arbitrary topology we need to generalize the mask to facilitate adding dislocations and vertices on facets to the system of linear equations. The approach is rather simple. The condition is to satisfy the following equation as we calculate  $\alpha_n$  for an  $n$ -valent vertex:

$$4\alpha_4 + 4\beta_4 = 1$$

where  $\alpha_4$  is the value of the mask for a 4-valent vertex [7]. Thus:

$$\alpha_n = \alpha_4 \times \frac{4}{n} \quad \text{and} \quad \beta_n = \frac{1}{n} - \alpha_n$$

As for the vertex which belongs to a non-quadrilateral facet, its diagonal opposite vertex on this facet is the centroid of this facet. After defining the mask of every vertex, a linear equation is added to the system. We base this generalization on the general way Farin et al. [7] followed to

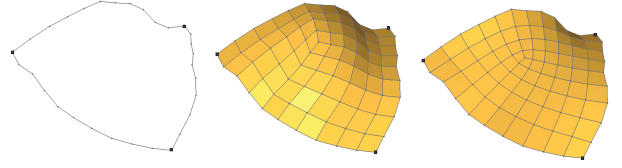


Fig. 11. A three sided region filled by a permanence patch with values  $-0.25$  (middle) and  $0.0$  (right) for  $\alpha$ .

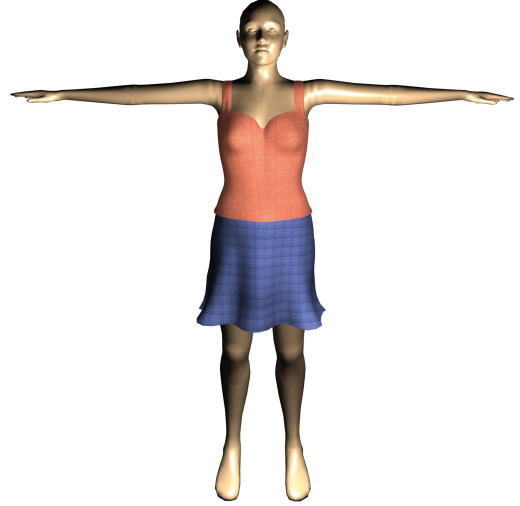


Fig. 12. Textured cloth designed using a quad mesh generation scheme.

set up the permanence patches. The value of  $\alpha$ , and consequently  $\beta$ , is a user choice. The feasible range of  $\alpha$  values is between  $0.0$  and  $-0.25$  (see Fig 11). Other values may produce noisy meshes. The maximal value ( $0.0$ ) yields geometries that tend to look flat, a feature which diminishes as  $\alpha$  decreases towards  $-0.25$ .

#### 4. Mechanical Garment Simulation

The first task of mechanical simulation is the construction of a suitable geometric representation of the garment object, fitting the requirement of the mechanical simulator. The mechanical simulator uses triangle elements, which is suitable to a precise computation of weft, warp and shear strains and stresses of the cloth material [Volino and Magnat-Thalmann, 2009]. Thanks to a lumped-mass approximation, the model can be formulated as interaction forces relating particles belonging to the same triangle, depending on their relative position. It is therefore essential for the simulation mesh to offer suitable geometric properties for efficient mechanical simulation (regularity of the mesh, no degenerate (flat) mesh elements...). Hence, rather than using the generated patch mesh directly, we perform an adaptive rediscrretization of the mesh into triangle elements according to size limits and the Delaunay criteria. To this mesh is then associated a set of "material coordinates" representing the metric (rest shape) of the cloth elements. Assuming the initial design roughly represents the tensile



Fig. 13. Mechanical garment simulation using various postures and animation of the character.

cloth deformation at rest, these material coordinates are extracted from the initial shape of the element mapped on its patch. Our mechanical simulation animates the garment according to the following factors:

- (i) The internal elasticity of the cloth material, represented by weft, warp and shear strain-stress curves.
- (ii) Gravity, which pulls the garment downward.
- (iii) Collision forces, which prevent the penetration of the garment inside the surface representing the body.

Cloth materials are properly represented through nonlinear strain-stress curves extracted from tensile tests performed on actual materials, or extracted from standard fabric characterization procedures [13]. Collisions are detected using a Bounding Volume Hierarchy algorithm, which detects proximities between cloth vertices and body polygons. These collisions are integrated into the simulation system as geometrical constraints.

## 5. Conclusion and Future Work

Designing garments from sketched outlines in a 3D environment alleviates some of the difficulties involved in cloth modeling. Our approach utilizes the enhanced version of a quad meshing algorithm proposed in [1] to construct pieces of cloth from the outlines drawn by the user. For more control over the geometry of the resulting mesh, we propose a generalized version of permanence patches and introduce weights to the boundary vertices to compute interior vertex positions. Garment animation also offers interesting perspectives of the designer, who should be able to assess the dynamic behavior, the fitting and the garment style according to body poses and motion.

An important future topic to be addressed is the extraction of high-accuracy garment patterns from the obtained 3D garment surface. Essentially based on surface unwrapping and dart insertion techniques, these should be able to produce 2D garment patterns which follow basic design rules currently used in the garment industry.

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