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Fast Garment Drape Simulation Using Geometrically Constrained Particle System

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Abstract: A simulation system for versatile garment drape has been developed. Using this system, the shape of a garment can be simulated in consideration of fabric physical properties as well as the interaction between fabrics and other objects. Each fabric piece in a garment is modeled using a geometrically constrained particle system and its behavior is calculated from an implicit numerical integration algorithm in a relatively short time. The system consists of three modules including a preprocessor for the preparation of fabric patterns and external objects, a postprocessor for the results of three-dimensional visualization, and a drape simulation engine. It can be used for the design process of textile goods, garments, furniture, or upholsteries.

Keywords: Particle system, Human body model, Drape simulation, Garment visualization, Three-dimensional garment CAD

Introduction

Simulation for garment drape has become one of the most famous issues not only in computer graphics but also in textile and garment industries and a considerable amount of researches has been reported on this field recently [1-4]. Fabrics behave in a different way from those of other continuous materials such as metals or papers. For example, a fabric shows small in-plane deformation due to its large tensile modulus, while it shows large out-of-plane bending deformation against relatively small bending moment. Therefore, conventional finite element analysis methods, which mainly deal with small deformation, have been considered to be inappropriate for this kind of material and two alternative methods are widely used for fabric drape simulation.

One is the geometry-based method and the other is the particle-based physical approach. Geometry-based methods are very fast but they do not seem to be a suitable way for a versatile simulation because there is not any consideration of fabric physical properties. Therefore, they are limited to some specific graphical uses where the desired final results are already predictable. For example, Hinds and McCarteney tried to visualize three-dimensional garments for the development of a three-dimensional garment CAD system [5]. Weil also simulated the realistic draped shapes of various garments incorporating realistic wrinkles using spline curves without any consideration of fabric physical properties [6]. Particle-based methods have a physical meaning because they take into account of the physical properties of fabric when calculating the force or energy acting on each particle. However, there are also some problems in these methods such as long calculation time, possible numerical instabilities caused by the incorporation of various boundary conditions, and difficulties in the formation of homogeneous particle systems over complex-shaped fabric pieces as shown in the works of Plath [7], Eberhardt and Weber [8], Volino *et al.* [9], Breen *et al.* [10], and Carignan *et al.* [11]. For example, as a fabric has a very large tensile modulus that a serious numerical error might be caused in the calculation of force or energy of each particle, if an undesired large deformation should be induced during the simulation. In addition, it is an ambiguous issue for a physically based particle system how to define various boundary conditions in only force or energy terms such as the collision of a particle with external objects, sewing conditions between two particle systems, or the attachment of a particle to a specific position. Another problem is that as the particle system is usually formed in the shape of a rectangular grid, it may be difficult to form a homogeneous particle system over complex- shaped fabric pieces.

In this study, a geometrically constrained particle system has been developed as a hybrid method of the two methods described above. Using this method, fabric behavior is calculated from an implicit integration algorithm based on a triangular mesh based particle system. The various boundary conditions are solved with a geometry-based algorithm, which even takes into account of the anisotripic nature of fabric physical properties. The drape simulation algorithm is designed for a consistent and fast results through the minimization of possible numerical errors as well as the simplification of mechanical calculation. The system consists of three modules including a preprocessor to define simulation environment for the preparation of garment pattern pieces and external objects, a main engine for drape simulation, a post processor for the visualization of simulated results.

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Preprocessor and Postprocessor

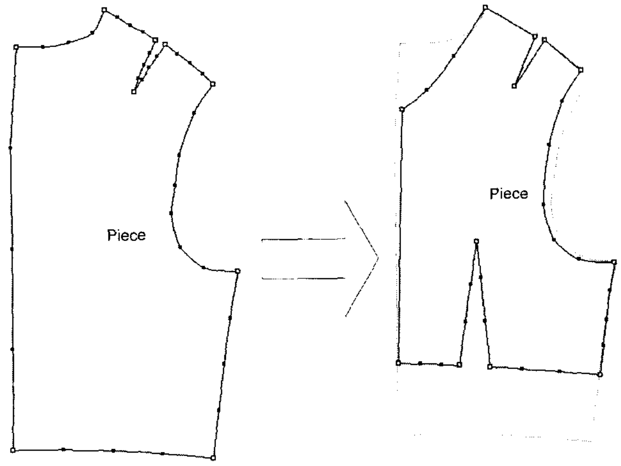
Preparation of 2D Patterns and Human Body Model

In this study, DXF (drawing exchange format) data, which are widely used for most commercial CAD systems, are used for flat garment pattern pieces. The POLYLINE entities of DXF data are approximated using a series of closed-loop Bezier curves to facilitate subsequent manipulation on the geometry and topology of each pattern as shown in Figure 1.

Especially for the garment drape simulation, a human body model is used, which can be generated by a parametric body model generator developed by Kang and Kim [12]. Of course, any kinds of three-dimensional objects can be used as long as it has a triangular faceted surface structure as shown in Figure 2.

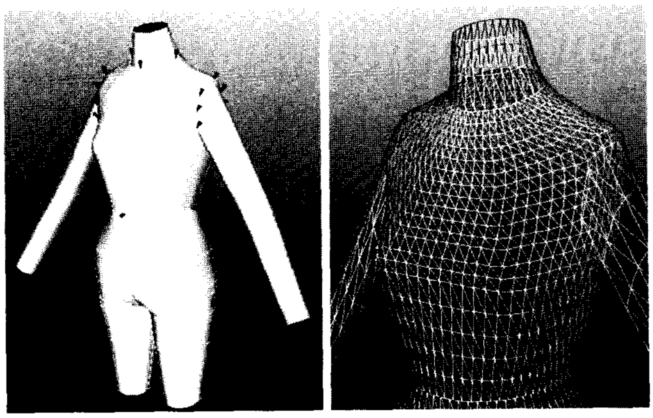
Definition of Geometric Constraints

Various factors must be considered for the versatile simulation of fabric drape such as gravitational effect, anisotropic fabric mechanical properties, sewing between fabric pieces, attachment of a fabric piece onto a specific position, collision between fabric and external objects, and so on. However, the nondescript properties such as sewing, attachment, and collision are difficult to be quantified with only force or energy terms in a physically based particle system. Therefore, a geometry-based constraint solver was developed to deal with such nondescript boundary conditions, which will be discussed later in this paper. In this study, only the mass of unit area is used as the physical property of actual fabric. Other properties including elasticity and bending rigidity are defined as coefficients ranging from 0 to 1 to be used for the geometric constraint solver. A sewing condition is defined through selecting a series of segments from both fabric pieces to be sewn together. User can define landmarks on the surface of an external object and can attach a fabric piece onto them. As the number of particles on each sewing line pair must be the same to form a valid sewing condition as shown in Figure 3, an automatic segment subdivision algorithm was developed to guarantee this condition even the total length of each segment set differs largely.



Original Pattern from DXF Manipulated Pattern

Figure 1. Preparation and manipulation of a flat fabric piece.



Full body model Triangular faceted surface model

Figure 2. Preparation of human body model.

Formation of Particle System

In this study, a fast and consistent automatic triangulation algorithm was developed to make a triangular grid based particle system as shown in Figure 3, which can deal with the anisotropic nature of fabric physical properties such as elasticity and bending rigidity. In this system, the concentrated mass of a particle is calculated in proportion to the total area of its neighboring triangular elements. Other fabric properties

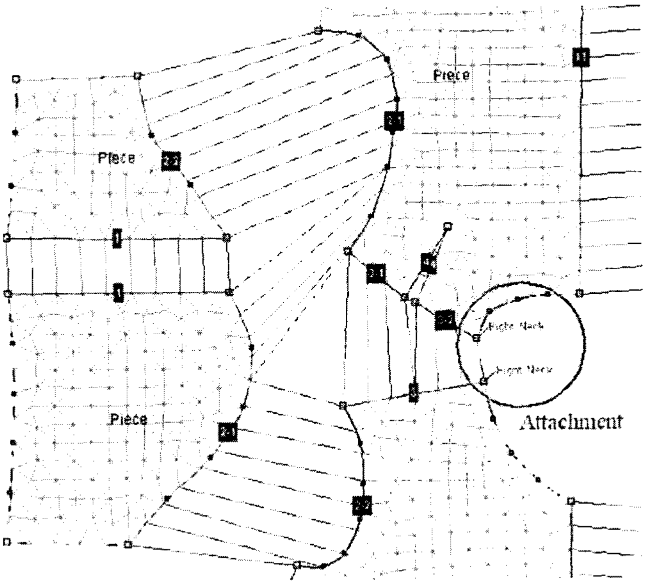


Figure 3. Definition of sewing and attachment condition.

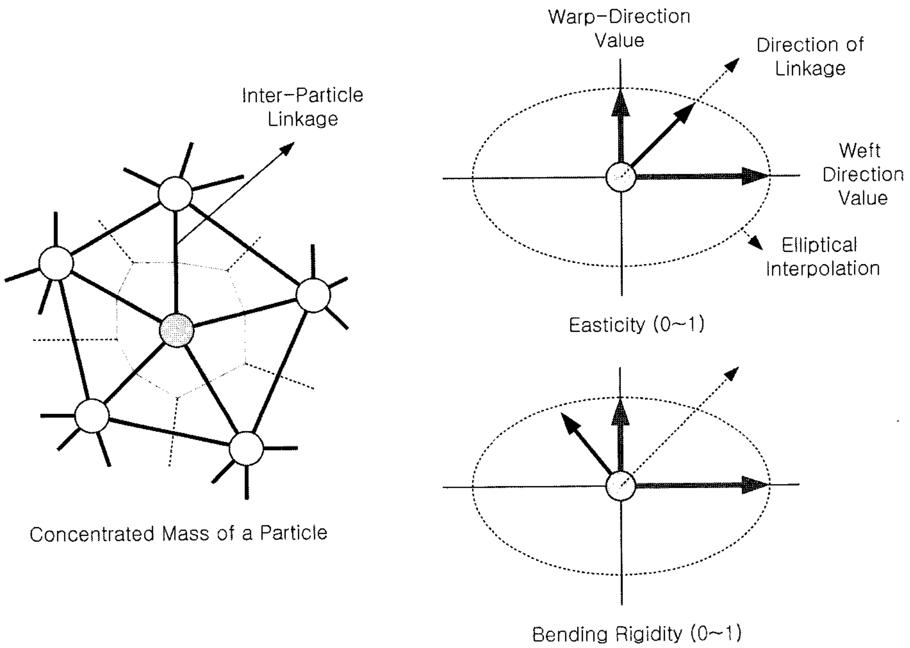


Figure 4. Formation of particle system.

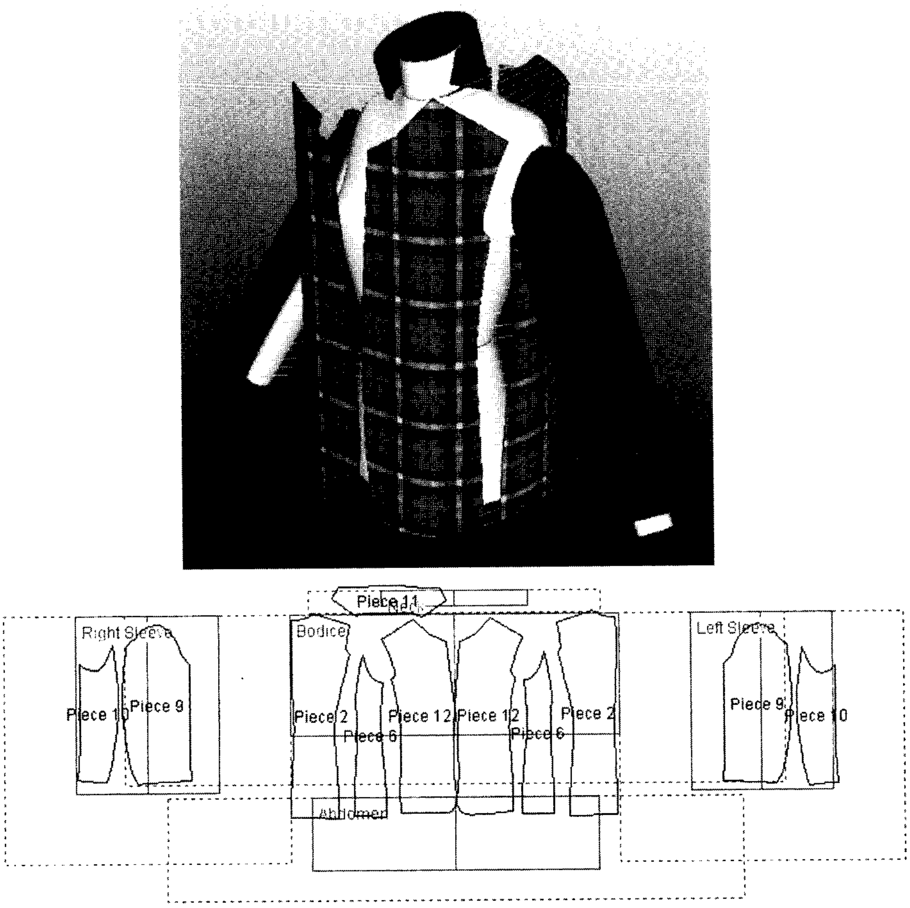


Figure 5. Automatic arrangement based on bounding box algorithm.

are appropriately assigned to each inter-particle linkage using an elliptical interpolation method as shown in Figure 4. For elasticity, interpolated value along the direction of linkage is used in the simulation. However, as out-of-plane bending occurs along the common edge of two neighboring elements, interpolated value perpendicular to the direction of linkage is used for bending rigidity.

Spatial Arrangement of Pattern Pieces

Once all the particle systems are formed, fabric pieces must be placed around the human body model for drape simulation. Because the arrangement of patterns is very difficult when the number of pieces is quite large, the automatic arrangement method is regarded as one of the most famous issues in this field [13]. In this study, automatic pattern arrangement method based on the bounding box algorithm was used, which was developed in our previous research. With this method, fabric pieces can be arranged automatically around the body simply by placing each piece appropriately with respect to the bounding boxes in two-dimensional domain as shown in Figure 5.

As can be seen in this figure, various texture image mapping on the patterns is supported for a realistic visualization. Also the sewing conditions are visualized using virtual sewing threads. Each simulation step can be recorded as a still image and an AVI format movie can be generated automatically by combining those images when the simulation is completed.

Drape Engine

Integration of the Equation of Motion

As a fabric is modeled as a system of particles, its behavior can be predicted by calculating the trajectory of each particle using Newton's equation of motion, $F = ma$. It can be expressed as equation (1) for a particle.

$$F = m\left(\frac{d^2x}{dt^2}\right) \tag{1}$$

where x is its position at a specific time step, and m is its concentrated mass. Therefore, the position of a particle at time t can be calculated by integrating equation (1) into equation (2)

$$x_t = \frac{F}{2m}t^2 + \left(\frac{dx}{dt}\right)_{t=0} t + x_0 \tag{2}$$

Using a numerical integration method with sufficiently small time step, x can be calculated according to time t. However, as the velocity of a particle is required in equation (2), a serious numerical error could occur during the integration if a perturbation should be induced in the velocity when solving the various boundary conditions. Therefore, the Verlet integrator was used in this study where only the position of a particle is required as described in equation (3)

$$x_{new} = 2x - x_{prev} + \frac{F}{m}\Delta t \tag{3}$$

where, x is the position of a particle

In this method, the relationship between the velocity and position of a particle is given implicitly and thus possible numerical error can be prevented. For the time step, an appropriate value should be chosen because too small time step may take too much calculation time, while too large one may cause undesirable oscillation. However, oscillation can be compensated by adjusting the force acting on the particle using a numerical damping method described in equation (4). C is the coefficient that controls the amount of damping.

$$\begin{aligned} F_{damped} &= F_{original} - \left(\frac{dx}{dt}\right)\frac{\Delta t}{m} \cdot C \\ &= F_{original} - \frac{(x - x_{prev})}{m} \cdot C \end{aligned} \tag{4}$$

The overall procedure of drape simulation can be described briefly as follows. First, an initial guess for the position of each particle at next time step is obtained from equations (3) and (4) using its positions at previous and current time steps. Then the final position for each particle at next time step is calculated from this initial guess and predefined geometric constraints. As repeating these procedures, the final shape of draped fabric can be obtained.

Solution of Geometric Constraints

In-plane Stretch

The in-plane deformation of a fabric due to its own weight is usually very small when most fabrics have a very large tensile modulus. In this study, a parameter was used instead of an actual tensile modulus for numerical stability. The parameter can be regarded as the maximum elastic strain of the fabric, which ranges from 0 to 1. The positions of two connected particles are adjusted simultaneously if the distance between them exceeds the tolerable value, which can be determined from the parameter as described in equation (5).

$$l = \overline{x_1x_2}, \quad v = \overrightarrow{x_1x_2}, \quad D = \frac{l - l_{rest}}{l\frac{1}{m_1} + \frac{1}{m_2}} \tag{5}$$

$$x_1' = x_1 + \frac{1}{m_1}vD, \quad x_2' = x_2 + \frac{1}{m_2}vD \quad \left(\frac{l - l_{rest}}{l_{rest}} > \varepsilon_{\max}\right)$$

x_1, x_2 and x_1', x_2' are the current and adjusted positions of mutually connected particles. l is the stretched length of the linkage while l_{rest} is its rest length. The position of each particle is adjusted appropriately considering its mass. Therefore the amount of in-plane deformation can be controlled by repeating this calculation over the entire particle system.

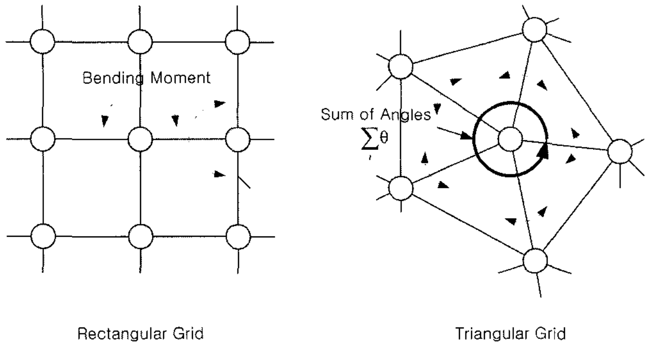


Figure 6. Schematic diagram of out-of-plane bending in particle system.

Out-of-plane Bending

Although a fabric has small in-plane deformation due to large tensile modulus, large bending deformation can easily be observed in fabric drape phenomena due to a relatively small out-of-plane bending rigidity. For most particle-based drape simulation algorithm with a rectangular grid structure, the treatment of bending behavior is rather simple as shown in Figure 6. However, for a triangular grid structure used in this study, a new calculation scheme was required to deal with the bending behavior of the fabric using a geometrical method. For a particle completely surrounded by other particles as shown in Figure 6, the sum of angles between adjacent two links is 2π at initial state. But it may not remain 2π during the simulation because the relative positions of particles may be changed.

As the bending rigidity of the fabric is defined by a parameter ranging from 0 to 1 in this study, the bending behavior of the fabric can be predicted by considering this parameter when calculating the sum of angles for each particle as shown in equation (6).

$$\alpha = 1 +\_ \sqrt{\min\left(\pi, \frac{\sum_i \theta_i C_i}{\pi}\right)}, \quad \vec{v} = \overrightarrow{xx_{prev}}, \quad l = \overrightarrow{xx_{prev}} \tag{6}$$

x_{prev}, x, x_{new} are the position of each particle at previous, current, and next time step, respectively. α controls the amount of deformation recovery if any bending deformation should occur and it can be calculated from the angles formed by two adjacent links. C is the elliptically interpolated bending rigidity parameter. A square root filtering function was also used to simulate the non-linear bending behavior of a fabric through controlling the amount of deformation recovery inverse proportionally to the amount of deformation occurred in a single time step.

Sewing and Attachment

Nondescript boundary conditions such as sewing and attachment can also be processed stably using geometric method. Sewing of two fabric pieces can be achieved through moving each particle pair on two sewing lines to their midpoint. Similarly, attachment of the fabric to a certain position can be achieved through moving the specified particle to its desired position. Of course, the new deformation on the entire particle system by this motion can be compensated later from iterative constraint solving process.

Collision Detection and Handling

For fabric drape simulation to be realistic, three types of collision should be resolved including the collision between a fabric and an object, inter-fabric collision, and intra-fabric collision. As described above, calculation related to the mechanical properties of fabric is linear and simple so that it does not need much time. However, collision resolution is a very complex problem related to so many numbers of particles and triangular elements so that it can be regarded as a so called non-deterministic polynomial time problem and takes virtually more than 90 % of simulation time. Of course it has been one of the most famous issues in this field as studied by Liu *et al.* [14], Moore and Wilhelms [15]. In this study, an efficient collision detection algorithm was designed by sorting the elements in the body model with respect to their heights to shorten the collision resolution time. Using this algorithm, the collision between a particle and body model is checked only for the elements in the body model that are close enough to the particle for possible collision at each time step. As the fabric and the external object are all composed of triangular elements, collision between a particle and an element can be detected from checking whether the trajectory of a particle during one time step penetrates the element or not as shown in Figure 7. Once a collision is detected, the final position of the reflected particle can be calculated considering its velocity vector and the reflection coefficient of the body model.

However, there is a drawback in this method that some collision may not be detected in case the particle moves very fast for a certain time step. But it can also be observed that such a situation can be avoided by choosing an appropriate time step and numerical damping method.

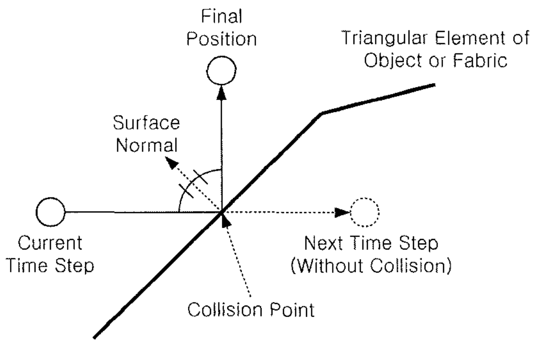


Figure 7. Schematic diagram of collision detection and response.

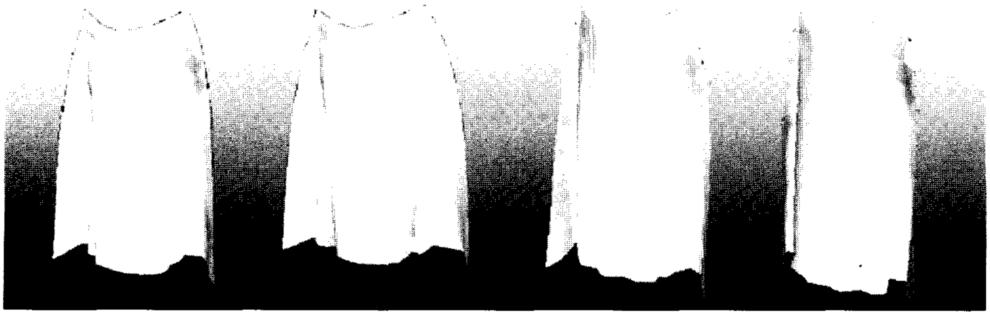


Figure 8. Examples of drape simulation with different fabric properties.

Results and Discussion

System Overview

The entire software modules are created by C++ language with OpenGL library for three-dimensional graphics on a Pentium-IV 1.3 GHz personal computer system. As the software has been designed for multi-thread operation, multiple simulation projects can be performed simultaneously. User can open DXF type garment pattern data and can edit their geometry, topology, physical property, and texture mapping data easily. User can stop the simulation at any time and restart it after making some changes on patterns or external objects for an interactive drape simulation. User can also monitor each step of simulation and can make an AVI type movie after the simulation is completed.

Examples of Drape Simulations

Figure 8 shows the shapes of a series of trapezoidal fabrics with different physical properties, draped from two fixed upper corners. As can be seen in Figure 8, different physical properties result in different final shapes. Therefore, a true-to-life simulation with actual physical fabric properties will be possible if the relationship between actual fabric properties and parameterized ones should be established through carefully controlled physical drape experiments.

Simulation results of various garments are shown in Figure 9 and Table 1. As can be seen in Table 1, each simulation took less than just one minute.

Conclusion

A fast simulation system for garment drape based on a geometrically constrained particle system has been developed. For this system, a hybrid algorithm of geometrical and physical methods was developed to enhance the stability and speed of simulation. The geometrically constrained particle system was developed to solve the problems inherent in a physically based particle systems. In this method, a triangular mesh structure was used instead of a rectangular grid system for more efficient formation of homogeneous particle system

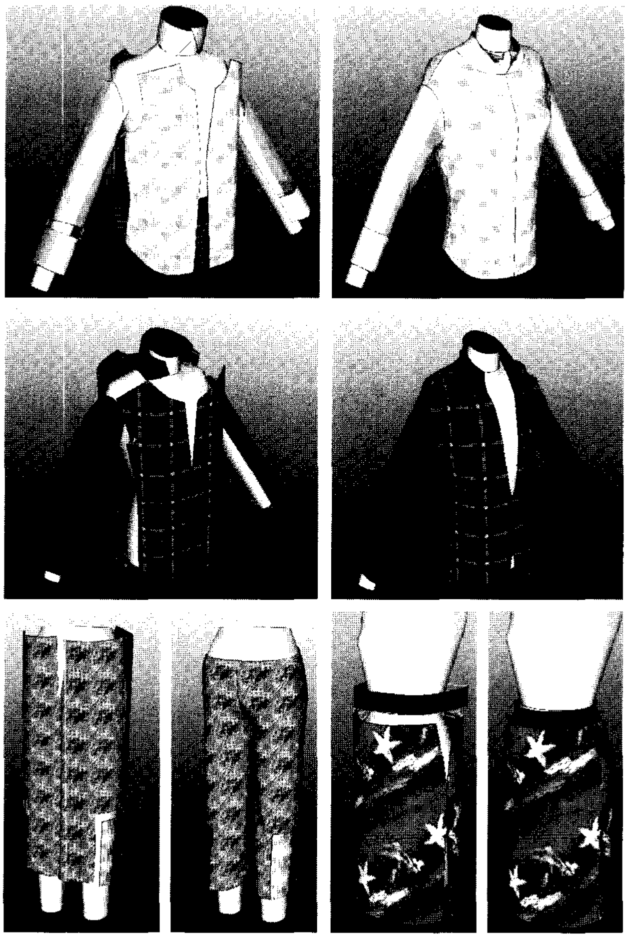


Figure 9. Examples of drape simulation.

Table 1. Simulation results

Garment	No. of particles on fabric	No. of element on body Model	Simulation time (Sec)
Blouse	3581	4562	35
Jacket	4453	5624	47
Slacks	5660	2204	36
Skirt	3130	3304	24

while taking into account of the anisotropic nature of fabric physical properties. The nondescript boundary conditions such as sewing, attachment, and collision are also considered for the simulation and can be treated easily by the geometric constraint solver developed in this study. As this system is designed for a versatile fabric drape simulation of multiple pattern pieces and multiple objects, it can be used for the design process of general textile goods, garments, furniture, or upholsteries through some customization. The reduction in both the development period and the production cost of new items can be realized for textile and garment industries if the system is utilized to substitute the trial-and-error based repetitive physical prototype generation processes.

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