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A Clothing Simulation System for Realistic Clothing and Mannequin

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ABSTRACT

This study adopts a particle systems approach to simulate the non-isotropic properties of fabrics by applying basic geometric methods in deriving separate relationships between geometric coordinates and strain, strain energy and stress. Unlike in previous studies, this approach can be used in irregular triangular mesh models, and can deal with large deformations to simulate a high degree of fabric softness. The simulation process involves loading a digital mannequin along with a digital version of the clothing, a clothing patch grid, simulated stitching, a draping simulation, and collision detection and handling. Finally, we used OpenGL library and C++ coding to simulate different styles of clothing in order to verify the feasibility of the theory.

Keywords: customized mannequin, simulated stitching, draping simulation.
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1 INTRODUCTION

The traditional clothing design process starts with the fashion designer produces sketches, which the pattern designer then renders as 2D patterns, which are then developed as production prototypes. At this point, the prototypes can be compared to the designer's original concept and assessed for marketability. Currently, several software packages are available on the market [1],[9],[13],[16],[18],[24], to assist in the design and manufacture of clothing, each with its own functions including patterning, sizing, marking, etc. The output of these various software packages is in 2D, and a system able to simulate how a piece of clothing drapes offers the potential to replace the current prototyping process and would greatly increase the speed of the overall design process.

Basic fabric simulations come in two categories: finite element method and particle systems [20]. The finite element method is based on a comprehensive umbrella equation which can produce highly accurate simulations [8], [11], [14]. However, the simulation's handling of large variations and large numbers of collisions can result in the entire system transforming into highly non-linear problems, which requires vast processing power. By comparison, particle systems make use of the interactions between discrete particle groups (i.e. spring force) to simulate the physical properties of fabrics, including collision detection and response, striking a balance between the realism of the fabric simulations and computational efficiency [26].

Particle systems were first proposed by Reeves [23] for simulations of water, fire, clouds and other substances. Breen *et al* [3-4] first applied the concept of particle systems to fabrics, with order of the particle groups arranged according to those of fabrics, and using changes in the particles' geometric relationships to calculate the internal energy state of the fabric, and then deriving an energy equation for the particle's motion state. Rather than use the energy equation to spring-connect neighboring particles, Provot [22] directly used the mass of the spring force acting on the particles to build an equation for the particles' motion. Provot's suggested method is the simplest type of particle system – a spring-particle system.

Due to the material qualities of fabrics, a considerable number of studies have adopted ordered particle systems similar to those used by Breen *et al* or Provot [3-4],[6],[10],[22]. Although fabric is a non-homogenous material, it has the material properties of having two orthogonal axes (Warp and Weft) which, while similar to each other, have different axial tensile strengths [17]. The simplest and most direct way to simulate these material properties is to arrange the direction of the particles in a spring-connected rectangular array according to the order of longitude and latitude. Then the spring force between two points will be present by two principal axial forces, and the shear angle can be found by directly measuring angle variation at 90 degrees. For this reason, these studies used ordered particle systems (square or triangular grids).

Volino *et al* [25] proposed a model to simulate the characteristics of irregular mesh fabrics on the concept that three sides of a triangular grid can be seen as strain gauges. Through stress-strain relationships and stress transformation, one can arrive at the principal axis of the stress state. Baraff *et al* [2] offer a mapping method to build an arbitrary axis (triangular grid side) and its relationship to the deformation axis, and it can be said that the coordinates from the most basic coordinate conversion transform between an ordered grid and an irregular gird.

For Bend features, the energy or stress state from the angle of the adjacent grid can be calculated more accurately, but a linear spring approximation simulation method [27] is also used to compensate for the weakness of the fabric bend relative to the strength of the fabric.

In order to achieve intuitive virtual try-on clothing design system, a series of interactive commands needed to be built into the system. Meng *et. al* [21] built a system allowing user to drag, fix, move, and sew cloth patches. A realistic virtual try-on result is obtained by using physical-based simulation method.

A simulation using a particle system can be said to be a series of differential equations used to solve an initial value problem: obtain the current state of particles after a certain time interval and rectify the post-collision particle state, then execute the next differential equation. This process is repeated to reach the integral solution of ordinary differential equations to obtain the fabric's state of motion.

2 SYSTEM ARCHITURE

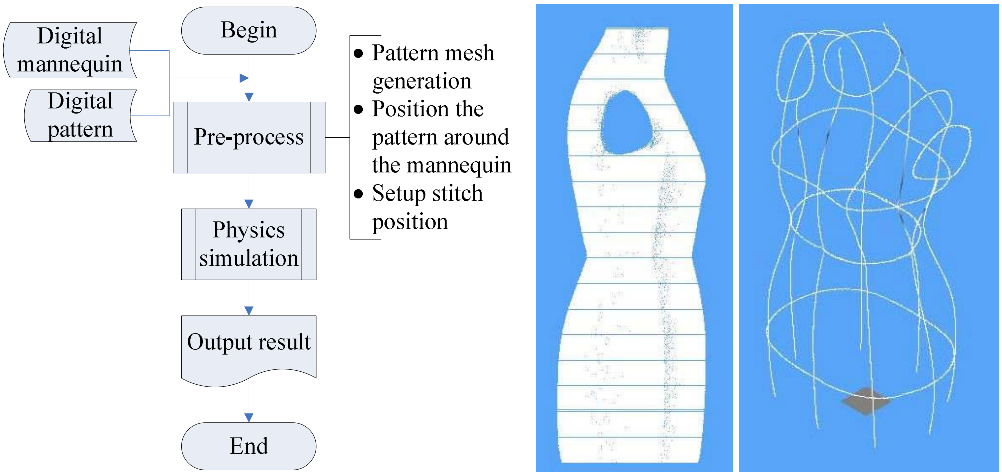
A good clothing simulation system must also take into consideration accuracy, calculation speed and ability to simulate the complexities of garment shapes [7]. These three factors are considered in Figure 1(a) which shows the process for simulating clothing recommended for this study: First, load the digital mannequin and digital clothing data and then conduct a pre-process for use in the simulation follow-up. Through a physical simulation, one can obtain the effect of the mannequin wearing the clothing, which can be shown on the screen.

2.1 Pre-process

With a particle systems approach based on physical modeling methods, the digital mannequin and digital clothing pattern data should be expressed as grids.

In consideration of the convergence of commercial pattern making software, pre-process must be able to profile the clothing pattern to grid points before starting the particle system simulation. The characteristics of the grid generator depend on the requirements of each particle system. Basically, higher density grids can show more detailed transformation effects in the fabric, providing the uniform overall grid results needed to ensure overall congruence with the fabric.

The digital mannequin used for this study was built by scanning a physical mannequin through automatic feature extraction, after which the mannequin's features were used to create a basic framework for the digital grid mannequin. Since the digital mannequin was based on the features of a physical mannequin, the digital mannequin can be adapted to any body shape or size. Details on the creation of the mannequin and its zoom function are described below.



(a) (b) (c)

Fig. 1: Simulation procedure and standard mannequin, (a) simulation flow chart (b) input point cloud, (c) feature lines on the mannequin.

2.1.1 Mannequin Reconstruction

To establish a convincing virtual try-on system, we constructed a digital mannequin to serve as the model. To generate different body shapes, we scanned a number of standard mannequins using a 3D whole body scanner, shown in Figure 1(b). By applying techniques similar to those proposed in [19], the features of the mannequins were extracted automatically. To simplify surface reconstruction, the intersecting feature lines were used to segment the mannequin into 56 patches. Once the NURBS patches are constructed the designer can select customized body dimensions to scale the mannequin to fit a specific person. Finally, triangular grids are exported for the try-on system.

2.1.2 Feature Extraction

To speed up the process of virtual suturing and try-on, geometric features commonly used in the garment industry were selected on the mannequin, including the neck baseline, shoulder point, arm hole girth, shoulder line, bust point, bust girth, waist girth, hip girth, center line, princess line and side seam line. Figure 1(c) shows the feature lines on the mannequin.

2.1.3 Patch Modeling

Because of the complexity of the mannequin, general mesh generation techniques result in a slender-shaped grid. In the computer graphic and in the FEM analysis, the slender grid shape leads to undesirable rendering effects and reduced accuracy.

Figure 2 shows the horizontal and the vertical feature lines which divide the mannequin into many small rectangular regions under the bust girth. A regular NURBS surface patch can be built for each region. However, to preserve the topological structure between the neck baseline and the bust girth, this section is divided into 24 small four-sided regions using the feature lines (including neck baseline, shoulder line, princess line, armhole girth and the bust girth) and the auxiliary line (depicted in green in Figure 2). This method not only retains the mannequin's geometric characteristics, but also provides a triangulated mesh model without slender triangles. Figure 2 shows the patch number and surface direction with respect to the mannequin.

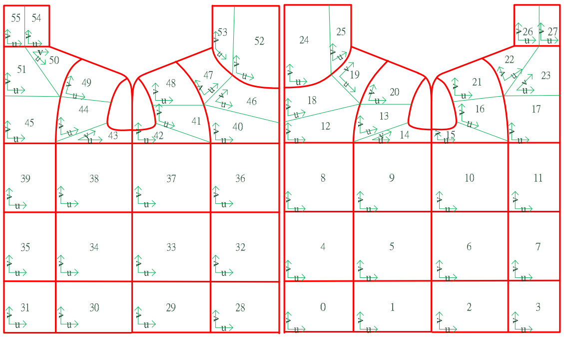
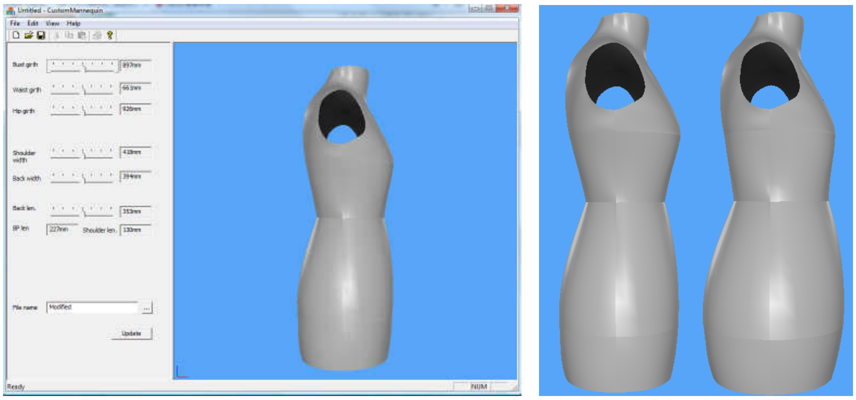


Fig. 2: Illustration of patch segmentation.

2.1.4 *Customized Mannequin*

Traditionally, mannequins are built to several specific sizes. However, to meet demand of changing body sizes and markets for custom clothing, this study proposes a method to modify the digital mannequin to fit a specified dimension. The customized mannequin is controlled by seven parameters: bust girth, waist girth, hip girth, shoulder width, back width, shoulder length and back length. All dimensions are entered via the slider on the left pane in Figure 3(a).



(a) (b)

Fig. 3: Customized mannequin user interface (a) Slider controlled dimensions, (b) two instances of customized mannequin.

After the designer enters the dimensions of the mannequin, the system will find the closet match in the digital mannequin database. Because the mannequins were stored as a series of NURBS surface patches, the scaling process is relatively simple. First, the relative ratios between the standard mannequin and the required dimensions are calculated. Next, the control points of the NURBS are moved based on both the position on the mannequin and the scaling ratios. Since the boundary control points are moved the same distances, the continuous condition of the mannequin does not change during the scaling process. Finally, a triangulated mesh was exported to be used in the virtual try-on system. Figure 3(b) shows two examples of the customized mannequins.

Through the appropriate mesh generator as well as the above-mentioned structured mannequin approach, a new triangular mesh for the styled clothing data sets can be generated [12]. In a physical simulation-based particle system, the grid points are taken as particles, while the grid is expressed directly or indirectly through the interaction of the particles. The entire simulation process calculates the physical state of each particle based on the interaction of the particles, thus showing an overall system status with algorithms described below.

2.2 Physical Simulation Algorithm

Variables x_i, v_i, F_i, respectively indicate the position, velocity and force of a particular particle, creating a three-dimensional column vector. The particle's position, velocity and force are written as position vector $x=[x_1,x_2,\ldots,x_i]^T$, velocity vector $v=[v_1,v_2,\ldots,v_i]^T$ and force vector $F=[F_1,F_2,\ldots,F_i]^T$. Assuming that all particle mass is m, then Newton's second law of motion can be written as $m\ddot{\mathbf{x}}(t)=\mathbf{F}(t)$, and the results are two first-order ordinary differential equations:

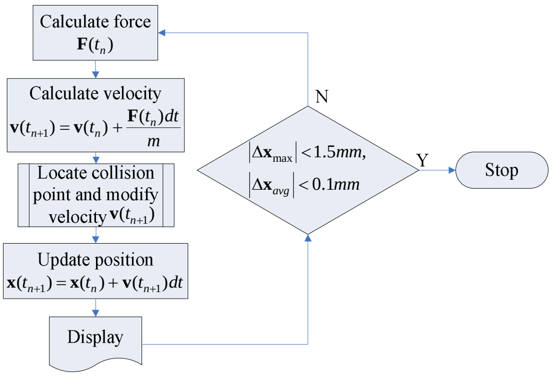
$$\begin{cases}\dot{\mathbf{v}}(t)=\mathbf{F}(t)/m \\ \dot{\mathbf{x}}(t)=\mathbf{v}\end{cases} \tag{1}$$

This is a first-order simultaneous ordinary differential equation initial value problem, which can be processed through numerical methods [15]. We combined the Explicit Euler method and the Implicit Euler method to solve (1) this problem as:

$$\begin{cases}\mathbf{v}(t_{n+1})=\mathbf{v}(t_n)+dt\cdot\mathbf{F}(t_n)/m \\ \mathbf{x}(t_{n+1})=\mathbf{x}(t_n)+dt\cdot\mathbf{v}(t_{n+1})\end{cases} \tag{2}$$

where t_n and t_{n+1} denote the current time and the subsequent time point, and $dt=t_{n+1}-t_n$ as the size of the steps. Since this is non-linear stress situation, we therefore invoke the Explicit method to solve $\mathbf{v}(t_{n+1})$. Once $\mathbf{v}(t_{n+1})$ has been obtained, $\mathbf{x}(t_{n+1})$ can easily be solved through the Implicit method. It's worth noting that the combined use of the Explicit and Implicit methods, doesn't require solving the equations simultaneously in Eq. (2) and the same calculations can be accomplished by the Explicit Euler method alone. We found that if Eq. (1) is calculated exclusively by the Explicit Euler method, its time span must be much smaller than those of Eq. (2) to achieve convergence, showing that combined use contributes to the system convergence.

Figure 4(a) shows physical simulation process within the overall simulation process in Figure 1. First the particle force is calculated, including the external and internal forces applied on the fabric. Our study considered external forces such as gravity and the stitching edge, and internal forces such as stretch, shear and bend. Once force $\mathbf{F}(t_n)$ is obtained, using Eq. (2) to find particle velocity $\mathbf{v}(t_{n+1})$. Following collision detection and response processing, velocity is revised to a new $\mathbf{v}(t_{n+1})$ to avoid collisions. Finally using Eq. (2) to obtain a new particle position $\mathbf{x}(t_{n+1})$, thus completing the state update of time step dt. This calculation process can be repeated as the fabric deforms over time until the terminal conditions are met for the finished simulation. This study used the particles' maximum displacement $|\Delta\mathbf{x}_{max}|<1.5mm$ and average displacement $|\Delta\mathbf{x}_{avg}|<0.1mm$ as the terminal conditions.



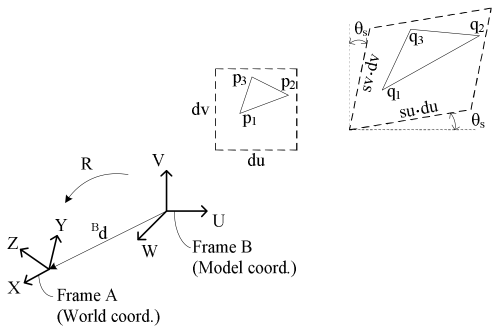


Fig. 4: (a) Physical animation, (b) strength and shear models.

2.3 Tensile, Shear, Flexure Strength

Finding the internal force $\mathbf{F}(t_n)$ in Eq.(2), requires determining the relationship between geometry and force. Previous studies of particle system simulations used the grid as a unit with which to calculate and accumulate force on the grid point, a concept similar to the finite element method. Most studies used a square grid, with the material properties of the sides being that they are on the main axis. The relationship between geometry and force can be directly simulated as a linear spring, and this type of system is called a spring particle system. This study simulated an irregularly-shaped triangular mesh, and will use geometry as the starting point to obtain a geometric force relationship.

Referring to Figure 4(b), we consider the deformation of a very thin fabric material as plane strain. Assuming uniform deformation throughout the grid, the grid deformation includes three components S_u, S_v, θ_S, displaying respectively U and V the directions of scaling and angle of shear in object coordinate B. The deformation of a grid can be written as

$$^{B}\mathbf{q}_i = \mathbf{M_{SH}}\mathbf{M_{SC}}\,{}^{B}\mathbf{p}_i, \qquad i = 1,2,3 \tag{3}$$

in which $\mathbf{p}_i$ is the pre-deformation coordinate, $\mathbf{q}_i$ is the post-deformation coordinate, $\mathbf{M_{SH}}$ is the shear matrix, and $\mathbf{M_{SC}}$ is the stretch matrix where the two matrices are

$$\mathbf{M_{SH}} = \begin{bmatrix} \cos\theta_s & \sin\theta_s & 0 \\ \sin\theta_s & \cos\theta_s & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad \mathbf{M_{SC}} = \begin{bmatrix} S_u & 0 & 0 \\ 0 & S_v & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

Eq. (3) expresses the grid deformation relationship in the object coordinate B. In practical applications, it needs to be transferred into world coordinate system A. By setting the rotation matrix as R, and the translation as ${}^{B}\mathbf{d}$, the position of grid with respect to coordinate system A can be written as:

$$^{A}\mathbf{q}_i = \mathbf{R}\,{}^{B}\mathbf{q}_i + {}^{B}\mathbf{d} = \mathbf{R}\left(\mathbf{M_{SH}}\mathbf{M_{SC}}\,{}^{B}\mathbf{p}_i\right) + {}^{B}\mathbf{d}. \tag{5}$$

When accumulating the internal force $\mathbf{F}_i$, ${}^{B}\mathbf{p}_i$ and ${}^{A}\mathbf{q}_i$ are known, and Eq. (5) has nine unknown values including S_u, S_v, θ_S the three independent variables of rotation matrix $\mathbf{R}$ and the three components of $\mathbf{d}$. Nine formulae are needed in order to determine these nine unknowns. Each vertex of a has three components, so taking three points of the original position the designated grid ${}^{B}\mathbf{p}_1$, ${}^{B}\mathbf{p}_2$ and ${}^{B}\mathbf{p}_3$ and new locations ${}^{A}\mathbf{q}_1$, ${}^{A}\mathbf{q}_2$ and ${}^{A}\mathbf{q}_3$, and expanding Eq. (5) provides the nine formulae allowing for the solution of the nine unknown values.

However, this formula contains nine trigonometric functions in nine-element nonlinear simultaneous equations, which are not easily solved. In fact the key unknowns are S_u, S_v and θ_S, and the six unknowns in the rotational matrix $\mathbf{R}$ and the movement vector $\mathbf{d}$ do not need to be solved. Through eliminating unknowns, we can first eliminate the six unneeded unknowns, reducing it to a three-element non-linear simultaneous equation and then solving for S_u, S_v and θ_S. Finally, the obtained geometric relationship can be written as:

$$S_u = \frac{\sqrt{k_{11}\Delta v_2^{\,2} + k_{22}\Delta v_1^{\,2} - 2k_{12}\Delta v_1\Delta v_2}}{\Delta u_1\Delta v_2 - \Delta u_2\Delta v_1}, S_v = \frac{\sqrt{k_{11}\Delta u_2^{\,2} + k_{22}\Delta u_1^{\,2} - 2k_{12}\Delta u_1\Delta u_2}}{\Delta u_1\Delta v_2 - \Delta u_2\Delta v_1}, \tag{6}$$

$$\theta_s = \frac{1}{2}\sin^{-1}\left(\frac{k_{12}\left(\Delta u_1\Delta v_2 + \Delta u_2\Delta v_1\right) - k_{11}\Delta u_2\Delta v_2 - k_{22}\Delta u_1\Delta v_1}{S_u\cdot S_v\left(\Delta u_1\Delta v_2 - \Delta u_2\Delta v_1\right)^2}\right), where \begin{cases} k_{ij} = \Delta x_i\Delta x_j + \Delta y_i\Delta y_j + \Delta z_i\Delta z_j \\ \left[\Delta u_1 \quad \Delta v_1 \quad 0\right]^T = {}^{B}\mathbf{p}_2 - {}^{B}\mathbf{p}_1, \\ \left[\Delta u_2 \quad \Delta v_2 \quad 0\right]^T = {}^{B}\mathbf{p}_3 - {}^{B}\mathbf{p}_1, \\ \left[\Delta x_1 \quad \Delta y_1 \quad \Delta z_1\right]^T = {}^{A}\mathbf{q}_2 - {}^{A}\mathbf{q}_1, \\ \left[\Delta x_2 \quad \Delta y_2 \quad \Delta z_2\right]^T = {}^{A}\mathbf{q}_3 - {}^{A}\mathbf{q}_1. \end{cases}$$

Eq. (6) depicts the relationship between plane strain and geometry. Planar strain energy is derived from plane strain and bending strain energy is derived from the included angle θ_b between two adjacent grids. The force components of each point can be derived from the partial differentiation of strain energy. With E_u, E_v, E_s and E_b respectively representing the Young's modules in u-direction, v-

direction, shear and bending, a representing the pre-deformation area of the grid, then the strain energy of (6) is

$$U_u = \frac{E_u a}{2}(S_u - 1)^2, \qquad U_v = \frac{E_v a}{2}(S_v - 1)^2, \qquad (7)$$
$$U_s = \frac{E_s a}{2}(2\theta_s)^2, \qquad U_b = \frac{E_b}{2}\theta_b^{\ 2}.$$

By summing the all strain energy components together, the force exerted on the vertex can be derived from a single differential equation

$$\mathbf{F}_i = -\left(\frac{\partial U}{\partial x_i}, \frac{\partial U}{\partial y_i}, \frac{\partial U}{\partial z_i}\right)^T, \quad U = U_u + U_v + U_s + U_b. \qquad (8)$$

2.4 Stitching Simulation

In our study, fabric is represented by meshes. The most basic method of stitching fabric patches is to directly assign each patch a grid pair, but this method is too labor intensive. A stitching interface is not only more intuitive, but can also save much setup time.

First the fabric patches must be placed correctly on the mannequin. This not only reduces the need to put clothes on the mannequin in the simulation stage, but is also more conducive to the intuitive operation of the virtual stitching setup.

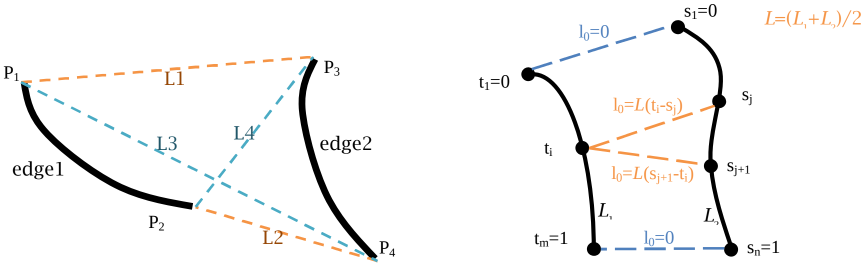


Fig. 5: (a) Two possible seam arrangements, (b) connection diagram of edge-to-edge seam.

In Figure 5(a), there are two possibilities when stitching the two selected edges: P_1 to P_3 and P_2 to P_4, or P_1 to P_4 and P_2 to P_3 Therefore, the direction of the stitching must be determined. In operation, the user will expect to stitch the closer endpoints with practical decision making as follows: if (L1+L2)<(L3+L4) then stitch P_1 and P_3, and stitch P_2 and P_4. Otherwise, stitch P_1 and P_4, and stitch P_2 and P_3. This ensures the coordination of the direction of the edge stitching.

However, in the particle system, all forces and restraints are exerted on the particle, not an edge or surface. Here we use a spring to simulate the stitching, and the spring force can directly accumulate on each particle. Figure 5(b) shows two line segments with the start and finish represented by 0 and 1 respectively. The parameter and length of the shorter segment are shown as t and L_1; the parameter and length of the longer segment are shown as s and L_2. For any t_i search for s_j, there are two possibilities:

a. if $s_j = t_i$, then connect t_i and s_j, with spring length of 0.
b. if $s_j < t_i < s_{j+1}$, then connect t_i with s_j and s_{j+1}, with spring length differentiated as $L(t_i - s_j)$ and $L(s_{j+1} - t_i)$, $L=(L_1+L_2)/2$.

We extended the abovementioned method to simultaneous multiple edge-to-edge stitching. The trick is to treat two groups of edges as a single continuous line segment to be stitched in the manner described above. For example, when stitching the two line segments of a sleeve piece to the back and front panels of the garment body (that is, two edges to one edge), one must first merge the two line segments of the sleeve front and back panels into a single line segment to then complete the edge to edge stitching of the sleeve.

2.5 Collision Detection and Response

This study refers to the approach taken by Bridson *et al* [5] to triangular mesh collision detection and response. Here we briefly describe the concept.

Figure 6 shows possible geometric relationship on the grid at a fixed point in time, for which the collision problem can be differentiated as two types, Proximity and Intersection. In the image, the solid line shows the grid plane; the dotted line shows the thickness of the space occupied by the grid, thus representing the actual thickness of the fabric. As the grid has no volume, when two grid approaches each other (the intersection of the dotted lines), their simulated fabrics have already collided, which is a Proximity problem. When the grid is moving at high speed, it's possible that after one time step integration that the grid will manifest a mutually intersecting situation (solid line intersection), which is an Intersection problem. Collision detection requires that the detection of the initial state of each integration step and the movement trajectory of the process by separately handled as Proximity and Intersection problems.

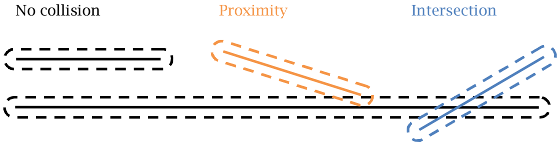


Fig. 6: Types of facet collision.

For collision detection, Bridson *et al* [5] used parametric methods to solve 22 triangular grids for closes proximity in two kinds of test: “point opposite collision” and “edge to edge collision”. After obtaining the closest proximity, then using point location and the relevant geometric parameters of related grid points to impose different values, thus correcting the particle's velocity to satisfy the appropriate physical reaction for the collision. This study uses this method to model positive force and friction.

3. RESULTS AND DISCUSSIONS

This study used C++ and OpenGL to develop a simple clothing simulation software suite [5]. We conducted a total of 14 garment simulations, including four sleeved tops, five sleeveless tops, two dresses and three skirts (shown in Figure 7).

As we used a structured digital mannequin, regardless of the mannequin number, its grid is fixed at 448, with the simulation process running on an Intel Core2Duo 2.4GHz CPU 3.5GB RAM personal computer as the test platform, completing in an average of 100 seconds, with the longest simulation for a long sleeve top running to 272 seconds. The fastest simulation took 28 seconds for a sleeveless top.

Fig. 7: Various clothes simulated on mannequin.

4. CONCLUSION

This study proposes a particle system method for a garment simulation structure, divided into three stages: pre-processing, physical simulation and results. Pre-processing includes inputting the digital mannequin and the digitized clothing, mapping the clothing pieces to a grid, setting the clothing pieces' initial placement and stitching. We also propose an intuitive user interface for edge-to-edge stitching. The physical simulation uses a particle system method, which simulated fabric through the obvious differences in tensile strength in warp and weft. Most of the relevant research deals only with square grids, and only a few studies have offered triangular simulation methods. In this study, the basic geometric relationship between coordinates of the geometric phase is derived from strain, strain energy and stress, and this is the core of the particle system simulation. This simulation method can be used for model triangular grids, and shows that the process has physical meaning and can be used to process large deformation problems. Combined with collision detection and response methods, this approach can improve the simulation of complex objects and multi-piece fabrics.

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