

- a friction stir welded magnesium alloy. *Mater Design*. 2011,32,p.p.1-11.
17. Wang Z, Yang Y, Li B, Zhang Y, Zhang Z. Effect of hot-deformation on microstructure and mechanical properties of AZ80 magnesium alloy. *Materials Science and Engineering A*. 2013,582,p.p.36-40.
 18. Pareek M, Polar A, Rumiche F, Indacochea JE. Metallurgical evaluation of AZ31B-H24 magnesium alloy friction stir welds. *J Mater Eng Perform*. 2007,16,p.p.655-662.
 19. Darras B M, Khraisheh M K, Abu-Farha FK, Omar MA. Friction stir processing of commercial AZ31 magnesium alloy. *Journal of Materials Processing Technology*. 2007,191,p.p.77-81.
 20. G. Padmanaban, V. Balasubramanian. An experimental investigation on friction stir welding of AZ31B magnesium alloy. *Int J Adv Manuf Tech*. 2010,49,p.p.111-121.



3D Virtual Fabric Dynamic Simulation Based on Improved Spring-Mass Model

Yan Fanlei*, Yang Lianhe

*Key Laboratory of Advanced Electrical Engineering and Energy Technology,
Tianjin Polytechnic University, Tianjin 300387, China
School of Electrical Engineering and Automation, Tianjin Polytechnic University,
Tianjin 300387, China
School of Computer Science and Software Engineering, Tianjin Polytechnic University,
Tianjin 300387, China*

Abstract

The dynamic simulation technology of virtual fabrics has a wide range of applications in e-commerce, garment CAD, digital games and other fields. By focusing on the dynamic simulation of 3D virtual fabrics, and taking full account of the internal and external forces received by fabrics, this paper has simplified the classic spring-mass model, omitted the bending spring, and merged the structural spring and shear spring into linked spring; full considerations are given to the properties of fabric materials during the calculation of stress, and some critical mechanics parameters are also estimated; furthermore, the “hyper elasticity” problem is solved through self-adaptive control of particle positions according to inverse order and in the light of particle stress size; numerical integration is conducted through the selection and use of Velocity-Verlet method; the experimental results show that the simulation has achieved good velocity and realist effects.

Keywords: VIRTUAL FABRICS, DYNAMIC SIMULATION, SPRING-MASS MODEL

1. Introduction

As a current hot spot research field, the realistic simulation of fabric shapes is widely applied in 3D garment CAD system, computer animation, virtual display, and many other fields. It mainly studies how the deformation of fabrics occurs in the 3D space, i.e. dynamic simulation of fabrics. With the continuous development of computer simulation theory and the substantial increase in hardware performance, the demands from various sectors for realistic and real-time properties of fabric simulation are increasingly high. It is imperative to explore more realistic fabric simulation models on the basis of application requirements.

In the existing research results, based on the method adopted during the simulation process, the fabric dynamic simulation technologies can mainly be divided into three categories: geometric method, physical method, and hybrid method. Among them, and hybrid method. Among them, the simulation result of physical method is better, and proves to be more suitable for fabric simulation. In the physics-based method, the classic spring-mass model is widely used. In this paper, detailed studies and improvements shall be implemented on the spring-mass model, in order to achieve the dynamic simulation of 3D virtual fabrics.

2. Spring-Mass Model and Stress Analysis

2.1. Classic Spring-mass Model

In 1995, Provot [1] presented a classic spring-mass model for fabric simulation. For ease of implementation, it is assumed in the spring-mass model that the density and thickness of fabrics to be studied are homogeneous, and the physical & mechanical properties of both warp wise and across warp of fibers are identical. From the vision meaning, the thickness of fabrics, if compared with their lengths and widths, can be neglected. For this reason, the mathematical model of fabrics can be conceived as an ideal space curved surface with zero thickness. The spring-mass model divides, as per warp wise and across warp, fabrics into several independent units. Assuming that the mass of each unit is the same, and concentrated to the mass of particle, it is possible to treat the shell fabrics with uniform density as the set of particles with regular arrangement and the same mass. The spring-mass model evenly distributes the whole piece of fabric mass on each and every particle, applies several species of springs to connect among particles, and set different elastic coefficients and damping coefficients for different types of spring, for the interaction between fibers in different directions within the simulated fabrics [2].

Typically, there are three kinds of acting forces within fabrics, i.e. tension & compression force, shearing force, and bending force. All these forces can be respectively simulated by means of structural spring, shear spring, and bending spring [1][3]. These three types of springs are as indicated in Figure 1.

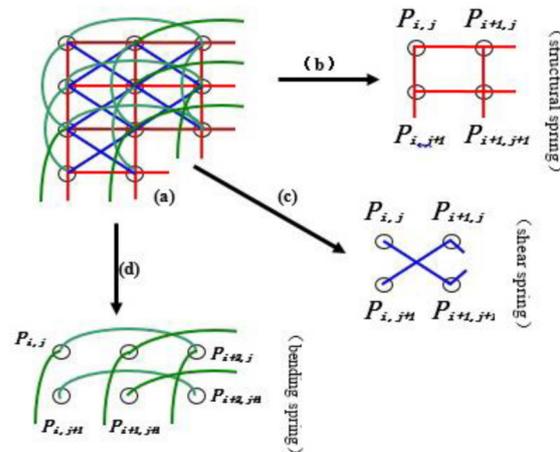


Figure 1. Spring-mass model and three kinds of spring types

(1) Structural spring

Structural spring is applied to simulate the acting forces along warp wise and across warp directions within the fabrics. Its elasticity coefficient is quite large so as to prevent the excessive tension and compression deformations of fabrics in warp wise and across warp directions. As shown in Figure 1(b), the spring between particle $P_{i,j}$ and $P_{i+1,j}$, $P_{i,j}$ and $P_{i,j+1}$ serves as the structural spring.

(2) Shear spring

Shear spring is applied to simulate the acting force in oblique direction within the fabrics. Its elasticity coefficient is also comparatively large so as to prevent the excessive oblique deformation and simulate the extensibility of fabrics. As shown in Figure 1(c), the spring between particle $P_{i,j}$ and $P_{i,j+1}$, $P_{i+1,j}$ and $P_{i+1,j+1}$ serves as the shear spring.

(3) Bending spring

Bending spring is relatively special, as it connects the spaced particles in warp wise and across warp directions, and applies to simulate the anti-bending performance of fabrics at the time of bending or folding. Its elasticity coefficient is also relatively small. As shown in Figure 1(d), the spring between particle $P_{i,j}$ and $P_{i+2,j}$, $P_{i,j}$ and $P_{i,j+2}$ serves as the bending spring.

The reason why these three types of springs is distinguished lies in the fact that the deformation of fabric model can be divided into two different forms, i.e. facing inward and facing outward. The deformations of fabric plane along warp wise and across warp

directions are restrained by structural spring, the deformations of fabric plane along oblique direction are restrained by shear spring, while the outward bending deformation of the plane is restrained by bending spring.

In the fabric dynamic simulation, under the interaction of various forces, springs are in a state of constant stretching and contraction. Dynamic simulation of fabrics is actually the changes in particle motion state under the action of force, i.e. the kinetic process of spring-mass model system.

2.2. Model Modification

It is assumed in classic spring-mass model that fabrics are woven by criss-crossed warp and weft, for which the modeling is simple. However, the author believes that this model has some shortcomings that need to be corrected depending on the circumstances.

Under normal circumstances, the use of bending spring may not be considered, as long as no excessive bending of fabrics is involved. In consideration of the fact that the bending force is not too large, this can also achieve the ideal simulation results. A large number of experimental results also show that the acting force of bending spring should be much smaller than that of the other two springs in most cases. Otherwise, unstable numerical solution may be easily caused in simulation process, making the positions of fabric patches become chaotic.

As for such common simple rectangular fabrics as curtain or banner, it is feasible to use program for direct generation and efficient simulation; however, as for garments and other complex fabrics, it is difficult to use program for generation. At present, most garment models are generated through the application of 3DS MAX, MAYA and other third-party model tool software. The triangle patches can represent any complex model, and can thus be universally supported by 3DS, OBJ and other 3D model file formats. The tool software, when converting its model into the program-readable 3DS and other universal model files, can be partitioned into triangular mesh patches. In order to facilitate the process of simulating these garment models by using spring-mass model, it is required to modify the typical quadrilateral spring-mass model. As it is difficult for triangular mesh to distinguish the warp and from the weft, this paper shall merge the structural spring and shear spring of classical models into structural spring, i.e. the side of triangle. The modified spring-mass model can widely apply the garment model data loaded from 3DS files and generated by 3DS MAX, MAYA and other third-party tool software.

In summary, this paper neglected the bending spring, and merged the structural spring and shear spring into linked spring. The modified spring-mass model is as shown in Figure 2:

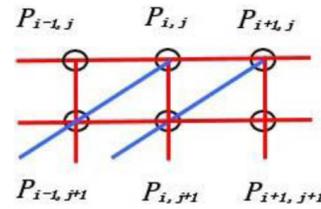


Figure 2. Modified model and linked spring

2.3. Stress Analysis

Following the establishment of physical model of fabrics, it is required to conduct stress analysis in the next step. According to the existing mechanics knowledge, the forces received by particles can be divided into internal force and external force [4, 5]. The internal force mainly comprises acting force of spring between particles within the fabric, while the external forces comprise gravity, wind force, air resistance, collision response force, and user-defined forces and so on. To calculate the force received by particles, it is required to assume that the particles are connected by linear springs, springs are used to simulate the elasticity of fabrics, and the resistance to tension of springs is correlated to the materials and physical properties of those fabrics to be simulated.

The movement rule of particles, determined by Newton's Second Law of Motion, i.e. $F = ma$, mainly describes the relations between acceleration of object, the force acting on the object, and mass of object. Normally, when a plurality of forces acts on an object at a time, the vector sum of each force should be the final resulting force. Each of the particles on the fabrics can add together all the forces acting on particles, and thus determine the acceleration:

$$ma = F_{total} \tag{1}$$

$$m \frac{\partial^2 S}{\partial t^2} = F_{ext}(S,t) + F_{int}(S,t) \tag{2}$$

Wherein, m represents the mass of particle; a represents the acceleration of particle, serving as the second derivative of position vector with respect to time; $S(S \in R^3)$ represents the position vector of particle at the time of t ; $F_{ext}(S,t)$ represents the external force received by particle at the time of t ; $F_{int}(S,t)$ represents the internal force received by particle at the time of t , and they change with the location and time of particle; and F_{total} represents the resulting force received by particle, and represented by the sum of $F_{int}(S,t)$ and $F_{ext}(S,t)$. The followings aim to analyze the in-

ternal and external forces, according to the modified spring-mass model previously-discussed.

(1) Internal forces

The internal force of fabrics represents the force that enables fabrics to maintain a certain shape, and reflects the intrinsic mechanical properties and physical properties of fabrics. Furthermore, each of particles in the grid is connected via structural spring and its adjacent particles. Therefore, the internal force received by each of particle can be expressed as:

$$F_{int}(S, t) = F_{structural} \quad (3)$$

Wherein, $F_{structural}$, representing the structural force of structural spring, can be summarized as the elastic deformation force of spring.

Hooke's Law can be applied to calculate the elastic deformation force of spring. Assuming that there exists the particle P_0 , and the set of its adjacent particle as R , the elastic deformation force F_{elast} received by P_0 shall be:

$$F_{elast} = \sum_{i \in R} C_e (\|\overrightarrow{P_0 P_i}\| - \|\overrightarrow{P_0 P_i}\|_0) \cdot N_{P_0 P_i} \quad (4)$$

Wherein, C_e , representing the coefficient of stiffness of spring, can be determined according to the curve of material performance parameter; $\|\overrightarrow{P_0 P_i}\|$ represents the distance between particle P_0 and P_i at the time of t ; $\|\overrightarrow{P_0 P_i}\|_0$ represents the distance between particle P_0 and P_i at the zero time; and $N_{P_0 P_i}$ represents the unit vector[5] that points from P_0 to P_i .

The coefficient of stiffness of spring shall generally be determined as per the parametric curves of fabric material properties, and also properly adjusted in accordance with specific needs, in order to further enhance the realist simulation. Typically, the tensile properties of fabrics are non-linear curve, as shown in Figure 3, it is represents the elasticity curve of frequently-used natural fiber fabrics, and the gradient of curve is the coefficient of stiffness of fabrics. In the previous studies, the settings of spring stiffness coefficient basically rely on experience, and there are no positive connections with the mechanics parameters of fabrics in the real world. In view of this, this paper estimates the spring stiffness coefficient in section II.D. As the material properties of fabrics are considered in the internal force, the calculation results can thus present good realistic effects.

(2) External force

In the fabric simulation, to simulate particle motions and collisions with obstacles in the surrounding environment, it is also required to take account of gravity, collision response force, damping force, air

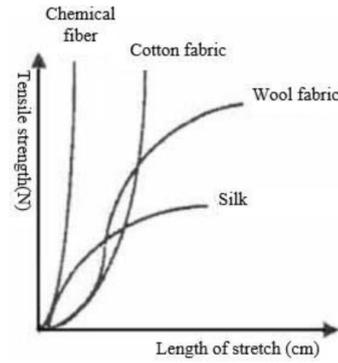


Figure 3. Tensile curves of natural-fiber fabrics

resistance and other external forces that really exist in natural world, together with the user-defined forces.

$$F_{ext}(S, t) = G + F_{collision} + F_{damping} + F_{aero} + F_{user} \quad (5)$$

Various external forces received by particles are introduced as follows:

i) Gravity

Since regular grid is applied in the model to describe the fabric model, assuming that the springs have no mass, and the masses of fabrics are all distributed to each of particle. Therefore, it can be considered that each particle has the same mass, and this mass equals to the quantity after the total mass of fabric is divided by the particle. For this reason, the gravity G received by each of particle shall be:

$$G = \frac{M}{n} g \quad (6)$$

Wherein, M represents the total mass of fabric, n represents the number of particles contained in fabrics, g represents the acceleration of gravity which is a constant with its general value taken as 9.8 m/s^2 .

ii) Collision response force

Collisions may occur with the external objects and the fabric itself. In this case, the interpenetration phenomenon may occur, if the particle motions are not restrained. To this end, it is required to handle through the application of collision response method. To be specific, when the collision between particle and triangular patch of fabrics is detected, it is required to add in a collision punitive force $F_{collision}$ and pull back the particle to the side of correct triangle. Here is the equation for particle P and collision occurrence point P_0 :

$$F_{collision} = \begin{cases} C_p * \exp(\|\overrightarrow{PP_0}\|^{-1}) \cdot N_{P_0} & \text{(With collision)} \\ 0 & \text{(Without collision)} \end{cases} \quad (7)$$

Wherein, C_p represents anti-collision coefficient which is proportional to the anti-collision force generated at the time of collision; N_{P_0} represents the unit

normal vector at P_0 point; $\|\overline{PP_0}\|$ represents the distance component along the direction of N_{P_0} between particle P and collision point P_0 .

iii) Damping force

To reduce the excessive oscillations due to stress caused during particle motion, it is required to introduce damping force. Appropriate damping force is of critical importance to maintain the stability of system during the dynamic fabric simulation. For example, to avoid the irregular vibrations appearing between two particles, one spring tension must be accompanied by a stable damping force. The faster the particle motion is, the greater the damping force will be. In this way, the unreal stretched and deformed fabrics caused by excessive oscillations can be avoided. In general, the easiest damping model is listed as follows:

$$F_{damping} = -C_d \frac{\partial X}{\partial t} \quad (8)$$

Wherein, $F_{damping}$ represents the damping force; C_d represents the damping coefficient, a non-negative scalar quantity.

iv) Air resistance

To achieve real fabric simulation, the air resistance F_{aero} serves as an important factor. In the experiments of this paper, due to the smaller number of particles, fabric patches, and corresponding air resistance, this force will not be considered temporarily. It is hereby set as $F_{aero}=0$.

v) User-defined forces

F_{user} represents user-defined forces. In the simulation, in order to achieve the effect of user interaction, it is allowed to apply user-defined forces for particles. For example, mouse tension, wind force, etc. It is hereby set as $F_{user}=0$.

Estimation of some key mechanics parameters

In section II, C of this paper, the stress condition of fabrics is analyzed, some of the parameters reflect the interaction between fabrics and the external environment, and whether or not these parameters are correct plays a key role in the success or failure of entire system. For this reason, it is imperative that some estimation about the approximate range of its values should be arranged.

(1) Estimations of stiffness coefficient along warp wise and across warp directions

Firstly, it is required to know the Young's Modulus E of fabrics. In the literature [6], the Young's Modulus of PET (i.e. Dacron) is $1200\text{kg}\cdot\text{mm}^{-1}$, equaling to $1.2\cdot 10^{10}\text{Pa}$ if converted into international unit. In the literature [7], there are some Young's Modulus and densities for common fibers, as shown in Table 1 to 3. It can thus be seen that the Young's Modulus of fabrics is at the order of magnitude of 10^{10}Pa .

Therefore, after the Young's modulus of this fabric is determined through access to information or experiments, the coefficient of stiffness along both horizontal and vertical directions shall be:

(2) Estimations of fabric density

In the literature [6], the density of PET (i.e. Dacron) is $1.38\text{g}\cdot\text{cm}^{-3}$, equaling to $1.38\cdot 10^3\text{kg}\cdot\text{m}^{-3}$, if converted into international unit. In the literature [8], the densities of some common fibers are also listed, ranging basically from $1.1\cdot 10^3$ to $1.5\cdot 10^3$. As gaps exist between the actually-used fibers, the apparent density should be used. The apparent density is usually slightly smaller than the density of material, and it basically ranges at the order of magnitude of $10^3\text{kg}\cdot\text{m}^{-3}$.

3. Analysis and Solution of the "Hyper elasticity" Problem

3.1. "Hyper elasticity" Problem

Due to its simplicity and efficiency, the spring-mass model has found wide applications in the dynamic fabric simulation. However, the particles in this model are connected via springs and it is assumed that the expansion and contraction quantity of spring presents linear relation with the stretching size. These factors may cause overstretching at some local areas where stresses are concentrated, and thus leads to serious distortions, particularly at the position where fabrics are hung, hence the so-called "hyper elasticity" problem, as shown in Figure 4.



Figure 4. Apparent overstretching phenomenon at the hanging position

Table 1. Comparisons of experimental time required by several numerical integration methods

Integration methods	Number of particles	Fixed step length (s)	Total time (s)
Explicit Euler method	30×60	0.001	85.46
Implicit Euler method	30×60	0.01	17.32
Four-order Runge-Kutta method	30×60	0.01	19.67
Velocity-Verlet method	30×60	0.01	11.58

In fact, the “hyper elasticity” phenomenon is not likely to occur in fabrics, and the scalable deformation quantity is extremely small in real fabrics. According to empirical statistics, the fabric elongation of common fabrics in the real world is generally not more than 10% of its original length. The reason for the generation of overstretching lies in the fact that ideal linear relationship between expansion and contraction quantity and elasticity will generally no longer be met, and it is a kind of non-linear relationship instead, provided that the expansion and contraction quantity of real fabric exceeds a certain range.

3.2. Solutions

To change this kind of unreal hyper elasticity phenomenon in fabric simulation model, the conventional solutions shall comprise:

(1) Improve the elasticity coefficient of spring

To avoid the occurrence of "hyper elasticity" phenomenon in a fabric simulation model, the simplest way is to directly increase the hardness of spring, i.e., increase the coefficient of elasticity. Under the same external force, the spring with excessive small spring coefficient is extremely easy to be stretched, while the spring deformation rate with high hardness and coefficient of elasticity is relatively low. This method looks very simple and easy to understand, yet, there are obvious disadvantages in it. To be specific, since the spring coefficient is inversely proportional to the time step of numerical integration, if too high spring coefficient is taken, the spring with large coefficient will inevitably lead to a smaller time step, cause the increased frequency of integration within the unit time, and thus cause the significant increase in time overhead.

(2) Change the spring start & end position

It was Provot [9] who first proposed the solution of changing spring start & end position to deal with hyper elasticity problem. He solved the overstretching by limiting the maximum expansion and contraction quantity of the spring. When the expansion and contraction quantity is less than 10%, it is required to calculate the elasticity size in accordance with the linear spring model. On the other hand, when the expansion and contraction quantity is greater than 10%, it is required to adjust the particle position, and limit the expansion and contraction quantity to be within 10%. If the spring is free at both ends, it is required to adjust two particles towards the intermediate position, and ensure that the expansion and contraction quantity is less than 10%; if one end is free while the other is fixed, it is required to adjust the free particle towards the fixed particle; if both ends are fixed, there is no need for adjustment. In this case, the original

shape should be maintained. This method can adjust some hyper elasticity problems of spring. However, the changes of spring start & end position may also cause adjacent springs to produce “hyper elasticity” problems. Thus, this strategy is suitable for those fabrics with local deformations. As for those fabrics with total deformations, a definite conclusion is still missing at present.

In fact, within the areas where “hyper elasticity” problems occur, the spring tensions received by particles are also relatively high. If the “hyper elasticity” particles within these areas can be determined at first, it will be possible to effectively avoid repeated adjustment and dithering phenomenon, significantly reduce the number of iterations. Knowing that the force serves as the fundamental reason for the changes in the state of object motion and stress represents the changes in the trend of particle motion. By basing upon the Provot [9] method and using the method proposed by Li Hanwen [10] as reference, this paper recommends the specific algorithms and procedures as follows:

Step1: Calculate the force received by such particles as P_1, P_2, \dots, P_n ;

Step2: Sequence the particles as per the size of stress, and the sequencing result is $P_{k1}, P_{k2}, \dots, P_{kn}$;

Step3: Apply Provot method, and sequentially update $P_{k1}, P_{k2}, \dots, P_{kn}$.

The schematic algorithm is as shown in Figure 5:

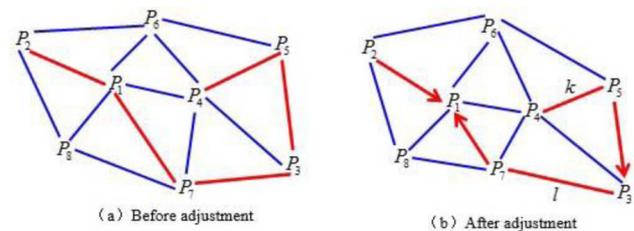


Figure 5. Schematic algorithms for “hyper elasticity” problem

In the light of this algorithm, the particles with lower stress approach to those particles with higher stress, and the regulated particle positions will not repeat the adjustment in this iteration. By taking Figure 5(a) as an example, the springs on red sides indicate that the "hyper elasticity" phenomenon has occurred. Assuming that stress received by P_i is greater than or equals to P_j 's stress size ($1 \leq i < j \leq 7$). After sequencing as per the stress size of particles, it is possible to determine the position of particle P_i , and detect whether or not “hyper elasticity” problem occurs in its adjacent particles. Due to the “hyper elasticity” between P_i, P_2 and P_7 , it is thus possible to successively adjust the positions of P_2 and P_7 along the direc-

tion of P_1 , until the “hyper elasticity” is eliminated. Temporarily fix P_1 's all adjacent particles, and detect the next particle. As a particle adjacent to P_1 , the position of P_2 has been temporarily fixed. For this reason, it is necessary to directly determine the position of P_3 , and detect whether or not “hyper elasticity” has occurred in such adjacent particles as P_4, P_5 , and P_7 . As the positions of P_4 and P_7 have been temporarily fixed during the detection of P_1 , we can only adjust P_5 and enable it to approach P_3 , so as to eliminate “hyper elasticity”, and temporarily fix P_5 . In turn, we can continue to identify other particles. Since P_4, P_5, P_6 , and P_7 have been temporarily fixed as adjacent particles of associated particles, this round of adjustment concludes. Through this round of adjustment, the final result of adjustment is as shown in Figure 5(b). The “hyper elasticity” on side k and l will generate the adjustment of dynamic simulation at the time of next frame. This kind of method takes priority to determine the particle positions where collisions and overstretching have ever occurred. As a result, repeated adjustments can be avoided, and the number of iterations required also remains less.

4. Numerical Solution of Kinetic Equation

4.1. Principles and Methods for Numerical Solution

The core idea of the fabric dynamic simulation based on modified spring-mass model can be summarized as follows, conduct the stress analysis of the system, list the differential equation according to Newton's laws of motion, take the initial conditions of system as initial value of equation, and select the appropriate numerical integration methods to determine the numerical solution of system, i.e. characterize the state of particle motion in the next moment, through the numerical integration of resultant force received by every particle. As for the kinematics solution of this flexible surface, the designing of highly-efficient numerical algorithms for solving the kinetic equation plays a vital role in maintaining the performance and stability of virtual fabric dynamic simulation system.

Spring-mass model serves as the kinetics-based simulation model, and the movement rule of particles is determined by Newton's second law $F = ma$. Within every time step, it is required to conduct the stress analysis of particle position once again, and then allow particles to move under the new acceleration.

The second-order differential equation of particles in the time domain is listed as follows:

$$m \frac{\partial^2 S}{\partial t^2} = F_{ext}(S, t) + F_{int}(S, t) \quad (11)$$

Wherein, $S(t)$ represents the position vector of particle, $S \in R^3$ serves as the target for solution; m represents the mass of particle; F_{ext} represents the sum of external force received by particle, F_{int} represents the internal force received by particle, they will vary with the change of particle position and time. The solution of this differential equation can get the movement path of fabric.

In this case, if the velocity vector $v = \frac{dS}{dt}$ is introduced, equation (11) can be converted into a first-order differential equation:

$$m \frac{\partial v}{\partial t} = F_{ext}(S, t) + F_{int}(S, t) \quad (12)$$

Wherein, the initial state of fabric is known, a represents the initial position of fabric that is:

$$x_0 = a, \frac{dx}{dt} = 0, \frac{d^2x}{dt^2} = 0 \quad (13)$$

Therefore, the dynamic simulation of fabric can be summarized as the numerical solution of ordinary differential equation, and the method of numerical integration is usually applied in solution.

The principle for numerical solution lies in the process of seeking for approximation of function value y_n from a series of discrete nodes x_n within the known evaluation interval. The whole solution process progressively steps forward according to the priority order of node x_n , and utilizes the already-obtained nodal value to deduce the subsequent node values. Among them, the space between adjacent discrete nodes is called as the step length, indicated as Δt .

During the simulation process, the selection of numerical integration method serves as the key issue relating to the sense of reality and real-time performance in the results of fabric dynamic simulation. The velocity and stability of convergence rate of different numerical integrations have direct impact on the simulation performance. The common numerical integration methods comprise explicit Euler integration method, implicit Euler integration method, trapezoidal method, four-order Runge-Kutta integration method, Verlet explicit integration method, etc. Among them, the explicit Euler integration method, although it is simple in solution, yet, it belongs to the first-order accuracy. For this reason, to meet certain accuracy, it is required to adopt the step length with less time, which leads to an increase in the frequency of integration within unit time, and thus affects the operating efficiency of this system. The implicit Euler integration method is characterized by the application of step length with larger time and stable perfor-

mance. However, the solving process involves complex sparse linear equation set, and its computational complexity and computing workload are much higher than the explicit integration method at the same order. The calculation accuracy of trapezoidal method, if compared with the implicit Euler method, is slightly higher. However, this method uses conventional explicit Euler method, and outputs the initial forecast value of the first iteration. As a consequence, the initial value errors in the first iteration are comparatively large, while more iteration is needed. The four-order Runge-Kutta integration method belongs to the five-order accuracy. However, due to its complicated calculations, it is more suitable for engineering calculation. Verlet explicit integration method belongs to the second-order accuracy. For this reason, the evaluation can be greater in the time step, and one-time calculation is enough. It is much higher than that of explicit Euler method in terms of computational efficiency and accuracy. In this paper, Velocity-Verlet integration method is selected and put into use.

4.2. Velocity-Verlet Integration Method

Generally speaking, in the explicit integration method, the step lengths of dynamic simulation of 3D virtual fabrics are less than 1 second. As for the solution of function $y = y(x)$, under the condition that the step length is the same and smaller than 1, the errors caused by Verlet method will be far less than the explicit Euler method, and better stability can be obtained.

In this paper, it is planned to select and use Verlet integration method. However, it also reflects obvious shortcomings in practical applications, that is, during the processing of velocity, two positional parameters of particles before and after a moment is required to seek the solution of kinematic velocity at current time. For this reason, Verlet integration method needs to be improved before it is used as the numerical integration method in this paper.

In 1982, Swope W C et al. made further improvements in Verlet integration algorithm, and proposed Velocity-Verlet algorithm [11]. It has the following form:

$$\begin{cases} x(t + \Delta t) = x(t) + v(t) + \frac{f(t)}{2m} \Delta t^2 \\ v(t + \Delta t) = v(t) + \frac{f(t + \Delta t) + f(t)}{2m} \Delta t \end{cases} \quad (14)$$

Wherein, m represents the mass of particle, $x(t)$ represents the particle position at t moment, $v(t)$ represents the velocity at t moment.

As shown in equation (14), if compared with Verlet algorithm, this method has such merits as acqui-

sition of position, velocity and acceleration at the same time, and possession of explicit velocity entry. If this method is applied under the premise that the truncation error of displacement remains unchanged, the velocity truncation error decreases as $O(\Delta t^4)$, the computed results of displacement and velocity can be obtained at the same time, and its stored variables remain the same as Verlet algorithm.

In addition to exerting the merits of Verlet method in error, another advantage is that the calculation of the velocity can be omitted, which further reduce the amount of calculation and the accumulated error.

5. Algorithm Steps and Procedures

In summary, the algorithm steps for the fabric dynamic simulation process are listed as follows:

Step1: Establish the initial triangular grid model, and conduct texture mapping.

Step2: Traverse all particles in fabric model, and calculate the resultant forces received by every particle.

Step3: Traverse all particles in fabric model, and use Velocity-Verlet integration method to calculate the new position and new velocity of particles.

Step4: Detect the occurrence of "hyper elasticity", and in case of occurrence, it is required to carry out the self-adaptive control of particle stress size according to the inverse order.

Step5: Detect the occurrence of collision, and in case of occurrence, it is required to conduct collision response and handling.

Step6: If the simulation is not completed, it is required to clear the stress at every particle, and jump to Step 2 for cycle simulation.

The flow chart of this algorithm is as shown in Figure 6.

6. Experimental Results and Analysis

In this experiment, Visual C++ 2005 serves as the development platform, Windows XP as operating system, AMD Athlon(tm) II X2 240 2.8GHZ, 2GB of RAM, and NVIDIA GeForce 310 graphics card as hardware environment, OpenGL as underlying graphics library. In addition, the modified spring-mass model, proposed in this paper, serves as the physical model. The specific experiments and relevant results analysis are listed as follows.

Experiment I: Simulation of suspended fabric

A piece of suspended bed sheet serves as the simulated object with parameters set as 35×35 of grid, 0.5 of particle mass, 10.0 of grid spacing, and 20.0 of stiffness coefficient. The stress conditions comprise gravity and structural spring force. The restriction at two fixed points of the top is applied, as shown in Figure 7.

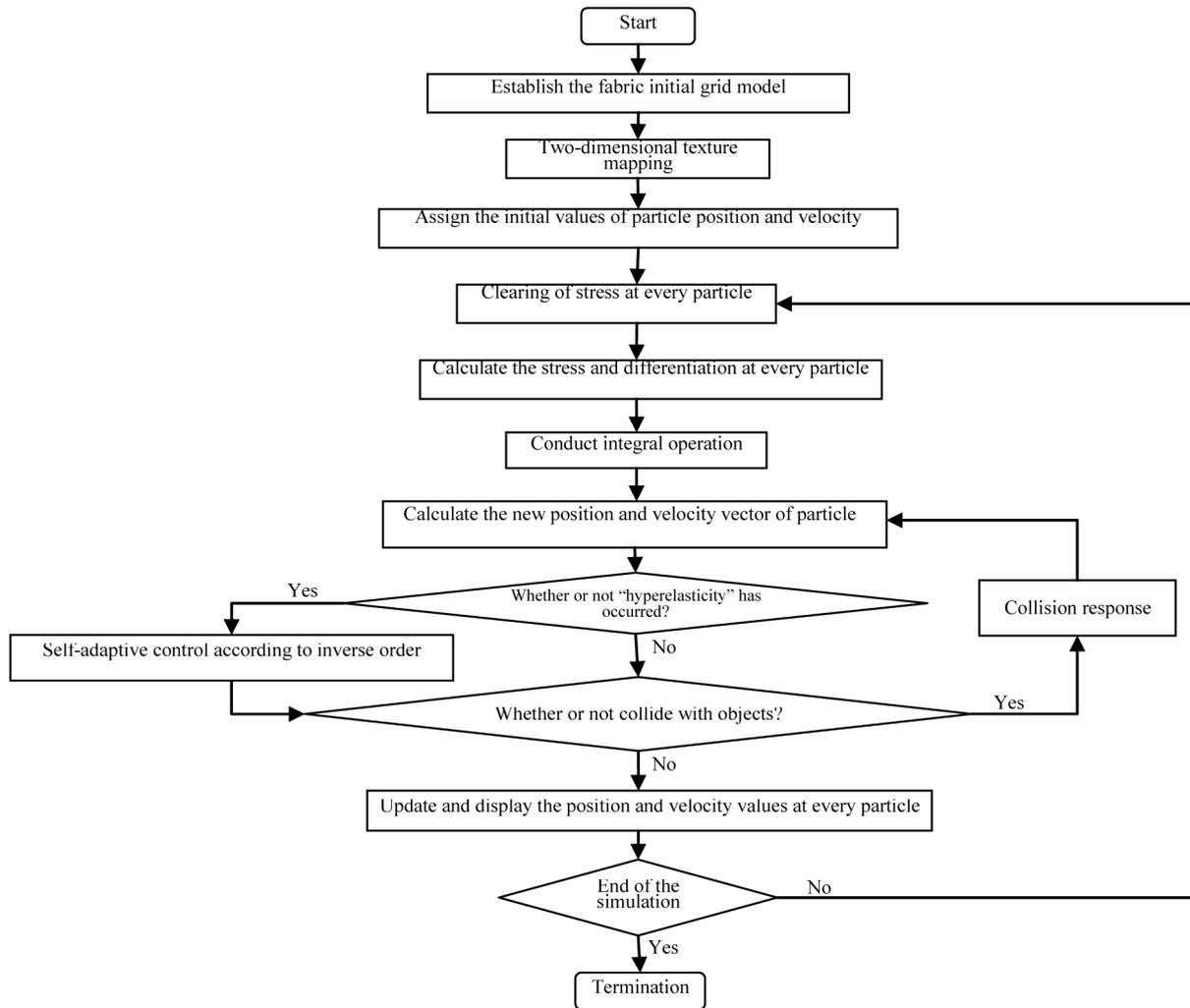


Figure 6. Flow chart of fabric dynamic simulation

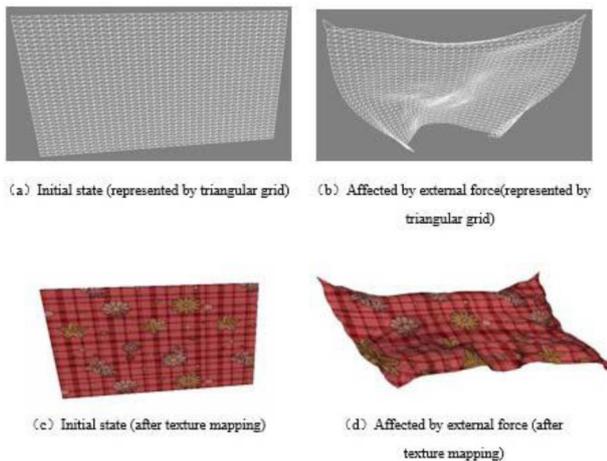


Figure 7. Effect picture of simulation of suspended fabric

Judging from the simulation results, the simulation velocity is greater than 50 frames /sec, which can meet both the real-time requirement and the visually-realistic requirement. In addition, there are no “hyper elasticity” deformations at the suspension point.

Experiment II: Simulating the fabric that drops vertically and covers desktop, through the application of Velocity-Verlet algorithm

In this experiment, rectangular fabric cloth is applied, with its grid set as 30×60, particle mass 0.5, grid spacing 10.0, coefficient of stiffness 20.0, and time step as 0.01s. The fabric carries out the motion of a free falling body, and finalizes the desktop coverage process. The stress conditions comprise gravity, structural spring force, and collision response force. Velocity-Verlet algorithm is applied in numerical solution, and the time required for the completion of entire process and realization of a steady state is 11.58s, as shown in Figure 8.

By setting appropriate integration steps and system parameters, it is possible for several numerical integration methods to reach as the simulation results as shown in Figure 8, under the premise that the system stability can be met. However, due to varied efficiencies, Table 1 shows the time required by several integration methods for the completion of simula-



Figure 8. Effect picture of simulation through the application of Velocity-Verlet integration algorithm

tion within the fixed step length. The simulation results obtained from the application of explicit Euler method with minimum time step is closest to the real situation. However, due to its minimum efficiency, it is often used as the basis of judging the error productions of other methods.

Summary

In this paper, in combination with the requirements for fabric dynamic simulation applications, and on the basis of giving full considerations to the internal and external forces received by fabrics, it is possible to simplify the classic spring - mass model, omit bending spring, and merge the structure spring and shear spring into structure spring. In the stress calculation, full considerations are given to the material properties of fabrics, and estimations of some key mechanics parameters are also made. Furthermore, the “hyper elasticity” problem is solved through self-adaptive control of particle positions according to inverse order and in the light of particle stress size Numerical integration is conducted through the selection and application of Velocity-Verlet method. In this paper, actual test of the proposed theory is conducted, through the application of VC ++ platform and OpenGL. The experimental results show that the proposed method is characterized by real visual effect, quick computing speed, and good stability. In

short, the method can simulate the simulation results of fabric motion in a relatively realistic manner.

References

1. X. Provot, Deformation constraints in a mass-spring model to describe rigid cloth behavior. Proc. of Graphics Interface. Quebec: Canadian Information Processing Society, 1995, 1:147-155.
2. Zhang Lei. Research on collision detection of flexible cloth in virtual environment. Master Thesis, Jiangnan University, 2008.
3. D. Baraiff and A. Witkin. Large steps in cloth simulation. ACM Computer Graphics (Processings of SIGGRAPH'98), 1998, 1(4):43-54.
4. Chang Yuanzhang. Cloth simulation based on mass-spring model. Master Thesis, Tianjin University.2008.
5. Liu Hui, Chen Chun, Shi Baile. Simulation of 3D garment based on improved spring-mass model. Journal of Software, 2003, 14(3):619-627.
6. Liu Yue. Development and application of biodegradable fiber lactron. Fiber raw materials, 2000, 6.
7. Cheng Nenglin, Chen Xianzhi, Liu Qinqing. Handbook of Non Metallic Materials, Changsha: Hunan science and Technology Press, 1989:276-310.
8. L.E. Sutherland. The ultimate display. In Proceedings of the IFIP Congress 65, 1965, Volume 2.
9. D. Zhang, M. F. Y. Matthew. Cloth simulation using multilevel meshes. Computer Graphics, 2001, 25:383-389.
10. Li Hanwen, Research and Implementation of Key Technologies in 3D Virtual Clothing Animation. PhD thesis, Lanzhou University, 2012.
11. Xia Dongyu, Zhang Wenfei, Sun Xishan. The comparison among different algorithms in molecular dynamics simulations for liquid argon model. Journal of Wuhan University of Technology, 2010, 32(24):66-69.