

HIERARCHICAL MULTI-RESOLUTION MODEL

For Fast Energy Minimization of Virtual Cloth

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Abstract: In this paper we present a method for fast energy minimization of virtual garments. Our method is based upon the idea of multi-resolution particle system. When garments are approximately positioned around a virtual character, their spring energy may be high, which will cause instability or at least long execution time of the simulation. An energy minimization algorithm is needed; if a fixed resolution is used, it will require many iterations to reduce its energy. Even though the complexity of each iteration is $O(n)$, with a high resolution mass-spring system, this minimization process can take a whole day. The hierarchical method presented in this paper is used to reduce significantly the execution time of the minimization process. The garments are firstly discretized in several resolutions. Once the lowest resolution particles system is minimized (in a short time), a higher resolution model is derived, then minimized. The procedure is iterated up to the highest resolution. But at this stage, the energy to minimize is already much lower so that minimization takes a reasonable time.

1 INTRODUCTION

With advances in computer graphics over the last few decades, virtual garment simulation became popular in many applications, from movie industry to fashion and textile. Many papers in the area of virtual clothing have been published, from simplified cloth models (Jerry, 1986), (C.Feynman, 1986), to more accurate ones (Baraff and Witkin, 1998) (Lafleur et al., 1991) (Choi and Ko, 2002) (Philippe Decaudin, 2006), some surveys and comparisons of recent researches are available in (Hing N.Ng, 1996), (House and Breen, 2000). A virtual garment is normally represented by its two-dimensional patterns. These patterns can be used to produce real garments in the textile industry (CAD systems), or produced by a fashion designer. More information is needed to be added to the 2D patterns in order to produce garments. The automatic pre-positioning of a garment around a digital body is a difficult and challenging problem as we have to sew the different pieces correctly. Some approaches for dressmaking have been proposed. Some have been introduced in the literature (Lafleur et al., 1991),

(Clemens Gross, 2003). In this approach, 2D patterns are positioned by hand around the body and then, sewing is performed automatically. We developed an automatic virtual dressing system (T. Le Thanh, 2005) which can be used easily by a normal user who wants to try garments virtually. This technique proposes a 2D manipulation method which will be coupled to a 3D mapping technique allowing to reach the final positioning. Even though this method gives a fully automatic pre-positioning, the springs used in the particle system are usually very deformed, which implies a very high energy that the system has to dissipate; this requires a very small time step in the simulator leading to a long simulation time, so that an energy minimization algorithm for the particle system is needed. In this paper we introduce an efficient method for the energy minimization using hierarchical decomposition. The garment is firstly discretized in various resolutions (from lowest to highest). Then the lowest resolution particles system is minimized using a local minimization algorithm, since the complexity of this algorithm is $O(n)$, it requires a short time to perform the minimization. Next, a higher resolution of the gar-

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ment is reconstructed from the previous minimization result and the spring deformation are further reduced. This procedure is iterated until the highest resolution garment is minimized.

1.1 Related Work

Hierarchy decomposition methods have been proposed to accelerate simulation for deformable objects using finite element methods (Demetri Terzopoulos and Fleischer, 1987), subdivision frameworks (Steve Capell, 2002b), skeleton driven deformations (Steve Capell, 2002a), physically based subdivisions (Chouraqui and Elber, 1996), multi-resolution collision handlings (Nitin Jain, 2005), etc. Multi-level optimization algorithms have also been proposed in (Dave Hutchinson, 1996) to accelerate the performance of a nonlinear optimizer. Li and Volkov in (Li and Volkov, 2005) also introduce an adaptive method to refine and simplify the cloth meshes locally.

Energy minimization for mass/spring systems is used to avoid an expensive computation. As physically-based methods require a large computation time to compute equation 1 at each time step (See (Baraff and Witkin, 1998)):

$$(M - h \frac{\partial f}{\partial v} - h^2 \frac{\partial^2 f}{\partial x^2}) \Delta v = h(f_0 + h \frac{\partial f}{\partial x} v_0) \quad (1)$$

the simulation of a complex nonlinear and hysteretic garment can require a whole day to a week (in an early work of Breen). To avoid the use of the simulator to minimize the energy of the mass/spring system, we propose a fast geometrical minimization algorithm. Adopting the idea of multi-resolution, we introduce an efficient method to decompose the garment in several resolutions; each resolution can be reconstructed easily from another one. Once the energy of the lowest resolution has been minimized, we then reconstruct the next one from this one and its minimization is applied. This process loops until the highest resolution has been minimized.

The remainder of this paper is organized as follows: Section 2 describes input data used in our algorithm. Section 3 details the principle of energy minimization for mass/spring systems. We present our multi-resolution technique for virtual garment simulation in Section 4, by explaining the decomposition of garments keeping their boundaries untouched. Section 5 briefly presents the method used for collision detection in our system. We finally give some results validating our approach in Section 6, before concluding in Section 7.

2 INPUT DATA



Figure 1: Input garment shape (left, middle) and output result using simulator (right).

The shape of the virtual garment is reconstructed from a set of 2D patterns; these patterns come from a CAD system or are created by a designer. In general, a mass/spring system is used to model the mechanical behavior of cloth. Any virtual cloth modeled by a mass/spring system can be applied to our method. The input to the technique presented in this paper is simply the output of the technique presented in (T. Le Thanh, 2005). Such an input is visualized on the left and middle part of figure 1. The garment is already positioned around the body but its energy is very high (the garment is highly deformed compared to the final result - See the right of figure 1). Therefore a long computation time is required to obtain an acceptable result (stable position of the garment).

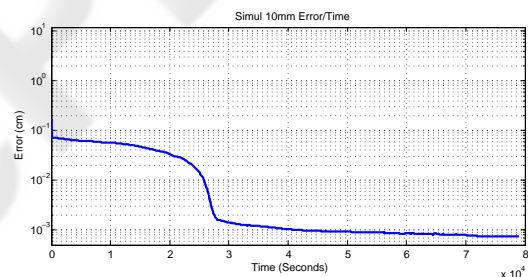


Figure 2: Simulation time (average spring error in cm) convergence after 80,000 seconds, spatial resolution 10mm.

The discrete resolution of the cloth used in our work varies from 50mm to 5mm. These resolutions are nowadays used in most physically-based simulation systems. The higher the resolution, the better the garment is modeled, but the computing times grows exponentially.

3 ENERGY MINIMIZATION

Garment models are modeled as triangular or rectangular grids, with points of finite mass at the intersections of the grids and the mass points are joined by

springs having no mass but modeling various mechanical behaviors of cloth (tension, shear, bending). The energy of the garment is estimated by the average elongation of all the springs of the system. We will calculate the energy of the whole garment from a set of equations and determine the shape of the garment by moving the points to achieve a minimum energy state. The reconstruction from 2D patterns to 3D shape can be denoted as a function:

$$F : R^2 \rightarrow R^3 \text{ or } (u, v) \rightarrow (x, y, z)$$

where each particle P_i of the garment has its 2D coordinates (u_i, v_i) and 3D coordinates (x_i, y_i, z_i) . We denote by r_{ij} the spring connecting P_i and P_j . The equilibrium length of r_{ij} is its length in 2D coordinates denoted by L_{ij} , its current length is its length in 3D coordinates denoted by l_{ij} . The energy equation of the garment shape can be represented as follows :

$$E_{total} = E_{ten} + E_{sh} + E_{bend} + E_{grav} \quad (2)$$

Where E_{ten} is the energy due to tension, E_{sh} to shear, E_{bend} , the bending energy, and the gravitational energy is E_{grav} . In fact, springs strongly resist the deformations. We aim to develop an equation so that the elasticity energy is high when the spring is stretched or compressed. There is a lot of research in cloth modeling, (David E.Breen, 1994) propose a Kawabata model, some models of cloth ((Baraff and Witkin, 1998), (Lafleur et al., 1991)) use a linear model for fast simulation. Kawabata model gives a more realistic cloth simulation but it has a drawback: its computation time. For energy minimization purposes, we used successfully the function:

$$Er_{ij} = C_s k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 \quad (3)$$

where Er_{ij} is the energy of the spring r_{ij} . C_s is an elasticity constant. The function E_{elast} , the part of E_{total} corresponding to tension and shear is calculated by summing over all springs:

$$E_{elast} = \sum_{r_{ij} \in M_e} Er_{ij} = C_s \sum_{r_{ij} \in M_e} k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 \quad (4)$$

where M_e is the set of tension and shear springs, k_{ij} is the stiffness constant of the spring r_{ij} . Observing that the tension energy of cloth is always much higher than the bending energy, we can approximate the bending along an edge AB by a virtual spring connecting two points of two triangles sharing the edge AB. (See Figure 3).

This presentation of the bending force makes E_{bend} simple to compute. E_{bend} is simplified as:

$$E_{bend} = \sum_{r_{ij} \in M_b} Er_{ij} = C_b \sum_{r_{ij} \in M_b} k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 \quad (5)$$

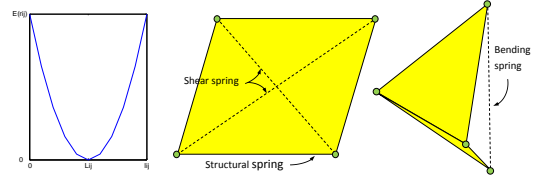


Figure 3: Springs structure and energy function.

where M_b is the set of bending springs. The particle's energy due to gravity is simply defined as:

$$E_{grav} = C_g \sum_{i=0}^N m_i g h_i = C_g \sum_{i=0}^N m_i g (z_i - Z_0) \quad (6)$$

where N is the number of particles, m_i is the weight of particle P_i . C_g, Z_0 are a density constant and the reference altitude of the system respectively. The energy of the cloth shape can be represented as:

$$\begin{aligned} E_{total} = & C_s \sum_{r_{ij} \in M_e} k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 \\ & + C_b \sum_{r_{ij} \in M_b} k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 \\ & + C_g \sum_{i=0}^N m_i g (z_i - Z_0) \end{aligned} \quad (7)$$

In fact, we store these springs in only one array $M = M_e \cup M_b$, each spring has its own stiffness constant, E_{total} is calculated as:

$$E_{total} = \frac{1}{2} \sum_{r_{ij} \in M} k_{ij} \left(\frac{l_{ij}}{L_{ij}} - 1 \right)^2 + C_g \sum_{i=0}^N m_i g (z_i - Z_0) \quad (8)$$

Note that E_{total} is defined as a continuous function, if we let $a_{ij} = \frac{l_{ij}}{L_{ij}}$ and call E as E_{total} , the partial differential equation of the total energy can be easily calculated:

$$\frac{\partial E}{\partial x_i} = \sum_{r_{ij} \in V_i} k_{ij} (x_i - x_j) \left(\frac{a_{ij} - 1}{a_{ij} L_{ij}^2} \right) \quad (9)$$

$$\frac{\partial E}{\partial y_i} = \sum_{r_{ij} \in V_i} k_{ij} (y_i - y_j) \left(\frac{a_{ij} - 1}{a_{ij} L_{ij}^2} \right) \quad (10)$$

$$\frac{\partial E}{\partial z_i} = \sum_{r_{ij} \in V_i} k_{ij} (z_i - z_j) \left(\frac{a_{ij} - 1}{a_{ij} L_{ij}^2} \right) + C_g m_i g \quad (11)$$

where V_i is the set of springs connected to particle P_i . We used the conjugate gradient method to determine the minimum of E_{total} (William H. Press, 1992). The result is given in figure 5.

4 MULTI-RESOLUTION FOR THE ENERGY MINIMIZATION

As presented in figure 5, the computation time for a small resolution garment is much faster than for a high one, but the error reached remains much higher. The problem we want to solve is to decrease substantially the computing time to reach the same minimum as that one of the highest resolution.

Multi-resolution methods are presented in many papers as (Li and Volkov, 2005), (Dave Hutchinson, 1996), but they are restricted to the case of simple triangular meshes to model cloth. The triangular mesh can be easily decomposed in several child triangles to obtain a new unified mesh. However, these methods cannot be applied in the case of our model (T. Le Thanh, 2005; Provot, 1995), where the connectivity of springs is more complex.



Figure 4: Multi-resolution of a shirt garments.

We developed a new decomposition method that can work independently of the cloth structure. The main idea is to predefine the 2D garments in several resolutions beforehand. We then determine the correspondences of each particle in a given resolution with other particles in other resolutions. Given a 3D cloth particle at a certain resolution, we can calculate its location in another resolution without difficulty.

Each garment is discretized in N resolutions. Its shape S at level n with $n = 1..N$ is denoted by S_n . The shape is defined by a set of particles $\{P_n\}$, springs $\{R_n\}$ and triangles mesh $\{T_n\} : S_n(P_n, R_n, T_n)$. For each particle $p \in P_n$, we find a triangle $t_i \in T_{n-1}$ so that the *distance* from p to t_i is minimum:

$$distance(p, t_i) = \begin{cases} 0 & \text{if } t_i \text{ contains } p \\ |po_i| & \text{if } t_i \text{ does not contain } p \end{cases}$$

where o_i is the gravity center of t_i . The correspondence between p and t_i is computed by employing a positional constraint method. We call p_0 , p_1 and p_2 the particles of triangle t_i , the barycentric coordinates of p on t_i are (w_0, w_1, w_2) . The particle is reconstructed so that its barycentric coordinates on the triangle t_i does not change. When the cloth shape S_{n-1} is minimized, the new position of particle p is calculated as follows :

$$p = w_0p_0 + w_1p_1 + w_2p_2 \quad (12)$$

In order to reconstruct S_n from S_{n-1} , we have to know the correspondences of all particles of S_n on the triangles of S_{n-1} . The most time consuming task is to compute the distance from each particle of S_n to the triangles of S_{n-1} . A naive approach is to compute the distance from each particle to all triangles. Since the task has complexity $O(K^2)$ with K is the number of particles, the computation time is small at low resolution. However, with a higher one (for example about 30,000 particles), the computing time can take a whole day. It is unacceptable even if the computation will be performed only one time before the minimization process starts.

We propose an efficient method to compute the correspondences. This method uses bounding boxes ((Bergen, 1998)) for the set of triangles for each level. Each node of the bounding box contains a linked list of triangles. For each particle, we find the node corresponding to its bounding box. Distances from the particle to all triangles contained by the node are computed in order to find the minimum one.

Since the bounding box method has the complexity $O(n)$, we can compute the correspondences for very high resolution with a reasonable time.

5 COLLISION DETECTION

The geometrically based minimization has to handle self collisions and collisions between the human body and the cloth. Several methods have been proposed in the last few years (Lafleur et al., 1991), (Zhang and Yuen, 2000), (Robert Bridson and Anderson, 2002). We have decided to solve the problem approximately by not testing particles against triangles and edges against each other; we consider only particles. Clearly, we now have to hold the particles a little bit away from the human body or away from each other to avoid artifacts of not detected intersecting triangles. But this approach saves a lot of computation.

We have used a hierarchy of bounding boxes for the garment. The hierarchy is built once at the beginning and the bounding boxes are updated after each step. For collision detection between the garment and the human body we hold the particles away from the body surface at a predefined distance δ . Now we are able to determine the closest distance between the particles and the triangles. From the surface normal at the closest distance we can determine if the particle is inside the body or just close to it. In any case the collision response moves the particle so that it is away from the body by δ .

tance β . The self-collision process will allow us to obtain much better results.

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