Fast Simulation of Cloth-Rigid Body Based on PBD

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Abstract. Because the excellent performance of the position-based dynamics (PBD) method, the PBD gains popularity among cloth simulation and computer animation. Based on unified adaptive PBD, we apply collision constraints to cloth and rigid body models to speed up the process of collision detection between cloth and complex models, we conduct a bounding box high-level collision culling detection algorithm. Moreover, friction is calculated by the speed of the cloth to make the cloth simulation more realistic. Compared with continuous collision detection (CCD), our method improves the simulation speed several times. The experimental results demonstrate that we has the wide range of applicability and the the simulation effect is stable.

1. Introduction

Physically based simulations of cloth and model have been widely used for computer graphics applications, such as computer game animation and film industry. In various natural phenomena, cloth-rigid body coupling is a complex physical and dynamic behavior. Recent work has made great strides in visually feasible cloth animation\textsuperscript{1}. However, the efficiency and stability of cloth-rigid body collision simulation still need to be improved, especially for thin and light physical structures like cloth\textsuperscript{2}.

By formulating and solving a range of positional constraints, PBD-based solvers\textsuperscript{4} leave out the velocity layer and straightway work on the particle positions. So far, PBD has been successfully applied to simulation phenomena such as rigid objects\textsuperscript{3}, elastic objects\textsuperscript{2}, and incompressible fluids\textsuperscript{6}.

To achieve a stable and efficient simulation of the cloth-rigid body phenomenon, we use PBD-based collision constraints to simulate the interactive process. In addition, adding bounding box tests to eliminate non-existent collisions to speed up the simulation process. We also considered the effect of the friction of the cloth. As the results shown in Figure 1, our method provides an effective way to model realistic and stable cloth rigid body phenomena in a unified PBD framework.
2. Related work

Compared with general force-based animation methods, which are unstable at large time steps. PBD methods directly manipulate particle positions by solving nonlinear equations or inequality constraint systems, such as:

\[ C_i(x) = 0 \quad \text{or} \quad C_i(x) \geq 0, i, j \in [1, \ldots, m] \]  

Where \( x = [x_1, x_2, \ldots, x_n] \) T is the vector of particle positions, \( n \) and \( m \) are the number and constraints of the particles system. The intensity of each constraint is defined by the stiffness parameter \( \kappa \in [0, ..., 1] \).

The constraint of PBD is solved by the method of constraint projection. Given the particle’s position, a position correction quantity \( \Delta x \) that satisfies a constraint \( C_i(x + \Delta x) = 0 \) is found. The constraint equation is approximated by Taylor expansion:

\[ C_i(x + \Delta x) = C_i(x) + \nabla C_i(x) \cdot \Delta x = 0 \]  

The direction \( \Delta x \) must be the same as the direction of the gradient:

\[ \Delta x = -\lambda_i \nabla C_i(x) \]  

Substitute Equation 3 into Equation 2, solve \( \lambda_i \), and then substitute it into Equation 3 to get the final formula for \( \Delta x \) as follows:

\[ \Delta x = -\frac{C_i(x)}{\|\nabla C_i(x)\|^2} \nabla C_i(x) \]  

Where all particles of \( \Delta x \) are the same. If the particles have separate masses, the PBD method weights each particle \( j \) by an inverse mass \( w_j = 1/m_j \) weighted correction amount \( \Delta x \).

The position is updated by solving each constraint independently one by one, and after multiple iterations, the velocity is calculated as \( v = \Delta x / \Delta t \). To consider the stiffness of the
constraint, the PBD multiplies the correction vector by $1 - (1 - \kappa)^{1/n}$ in each iteration, as shown below:

$$x^* = (1 - (1 - \kappa)^{1/n}) \Delta x$$

(5)

Where $\kappa$ is the defined stiffness parameter and $n$ is the number of iterations.

3. Method

3.1. Bounding Box High-level Collision

We propose a collision between bounding boxes. First, a cloth bounding box $cloth_{AABB}$ is constructed for the position of the current frame and the position of the next frame of the cloth triangle, as shown in Figure 2:

![Figure 2. Cloth_AABB bounding box of cloth triangles](image)

Determine whether the cloth bounding box collides with the surrounding model bounding box, thereby removing the cloth and model that will not collide. If the cloth bounding box $cloth_{AABB}$ collides with the model bounding box $scene_{AABB}$, establish a collision constraint between the cloth and the model triangle. The two-dimensional scheme of the collision of bounding boxes is shown in Figure 3:

![Figure 3. Two-dimensional plan of bounding box in model grid (a) not intersect. (b) Intersect](image)

3.2. Solving Collision Constraints

The bounding boxes that did not intersect have been removed in 4.1. For intersecting collision boxes, we establish collision constraints between cloth particles and model triangles as shown in Figure 4:
Figure 4. Collision constraints of cloth particles and model triangles.

The constraints for cloth and model are as follows:

\[ C(c_p, p1, p2, p3) = ||(c_p - p1) \cdot n|| - h \]  

(6)

Where \( c_p \) is the cloth particle, \( (p1, p2, p3) \) is the model triangle. \( n \) Represents the normal vector of the model triangle. \( h \) is the threshold distance of the constraint function.

Then determine the direction of movement of the cloth particles:

\[ d_{vn} = v \cdot n \]  

(7)

\( d_{vn} < 0 \) Indicates that the cloth particles trigger collision constraints and the cloth moves in the opposite direction of the model normal. Update the position of cloth particles when the constraint functions \( C(c_p, p1, p2, p3) < 0 \) and \( d_{vn} < 0 \)

Correct the position of the cloth particle according to the PBD method:

\[ \Delta c_p = -w_{c_p} \frac{||(c_p - p1) \cdot n|| - h}{3 * w_s + w_{c_p}} \Delta dcs \]  

(8)

Where \( w_{c_p} \) is the inverse of the mass of the cloth particles, \( w_s \) represents the reciprocal of the mass of the model triangle vertex particles. \( \Delta dcs \) is the repulsive force of cloth and model and its approximate value is \( k \frac{\partial C}{\partial c_p} \).

Finally, the position of the cloth particle is updated to as:

\[ c_{p}^* = c_{p} + \Delta c_p \]  

(9)

The above equation does not involve the stiffness coefficient \( \kappa \) bound by the constraint.

3.3. Adding Friction

To make the interaction between the cloth and the model more realistic, add friction. The cloth can move on the model under its own gravity. The friction force is calculated according to the movement speed of the cloth particles. Calculated as follows:

\[ \Delta v_{tan} = \mu_s \max(0, 1 - \frac{||\Delta c_p||}{|c_p - c_p^*|}) \cdot v_{tan} \]  

(10)
Among them, $\Delta \tan v$ is the correction amount of the tangential velocity, and $\mu_c$ is the friction coefficient between the cloth and the model, which is related to the material of the cloth. $c_p'$ is the position of the predicted frame of cloth particles, and $v^{\text{tan}}$ is calculated as:

$$v^{\text{tan}} = v - v \cdot n$$

(11)

Where $v$ is the speed of movement of the cloth particles. Velocity of cloth particles after update is divided into tangential component $\text{vel}_T$ and normal component $\text{vel}_N$. As shown in figure 5:

**Figure 5.** The speed of the cloth particle is corrected

4. Results
All testing cases have been implemented on a PC with an NVIDIA GeForce GTX745 GPU, an Intel Core(TM) i7-4790(3.6GHz) CPU using C++, and OpenGL 4.0.

4.1. Cloth covers the model
We used two cloths with a resolution of 200*200 and 500*500 for collision tests with lion and rabbit models respectively. The higher the resolution of the cloth, the more precise the details will be displayed (regardless of friction).

**Figure 6.** The effect of different precision cloth interact with complex model: (a) Cloth with the resolution of 200*200, (b) Cloth with the resolution of 500*500
4.2. Adding Friction
When friction is applied to the cloth and the model has no obvious edges, the cloth can slide off the model. Figure 7 is an animation diagram of a collision between a rabbit model and the cloth with a resolution of 250 * 250.

![Figure 7. The cloth slips off the model](image)

4.3. Simulation data
Algorithms for high-level collision rejection based on hierarchical bounding boxes speed up the simulation. We use different resolution cloth to interact with the model, and compares with continuous collision detection (CCD) in simulation speed. The simulation average speed is improved. The results are shown in table 1.

| Resolution(triangles) | Model | Our method (s/frame) | Tang’s method (s/frame) |
|-----------------------|-------|-----------------------|------------------------|
| 20k                   | Lion  | 0.79                  | 3.10                   |
| 20k                   | Dragon| 0.46                  | 3.40                   |
| 500k                  | Lion  | 3.76                  | 52.72                  |
| 500k                  | Dragon| 2.97                  | 38.90                  |

4.4. Conclusion and Future Work
To quickly and realistically simulate the interaction between cloth and rigid model. We create a cloth bounding box based on the cloth's current frame and the next frame. Speed up simulation by high-level collision culling with model bounding boxes. In addition, we calculated the friction of the cloth by its movement speed. The cloth can slide off the model. In future work, we would like to extend the cloth to handle more complicated cloth phenomena, which will take into account the shape influences and material properties of the cloth.
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