Adaptive Local Refinement and Simplification of Cloth Meshes

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ABSTRACT
An adaptive method for local refinement and simplification in application for cloth simulation is presented in this paper. The adaptive refinement concentrates computational efforts in the regions of cloth where more detailed consideration is necessary in order to increase the performance of cloth simulation. Our method locally refines mesh in the regions where fine details tend to appear and simplifies it back later when coarse mesh is sufficient. Refinement and simplification operators keep good mesh qualities in terms of triangle aspect ratios. This multisolution scheme is applied for cloth simulation using curvature-based criterion as a trigger for refinement and simplification. Resulting simulations demonstrate improved performance of the cloth simulation.

KEY WORDS
Modelling of Natural Phenomena, Dynamic Behavior of Moving Components, Cloth Simulation, Adaptive Refinement

1. Introduction
For cloth modeling and animation, garment is usually discretized into a number of vertices whose movement is governed by physical laws. Some physical simulations imply uniform discretization of cloth surface into rectangular grid while others allow discretization into arbitrary triangular meshes. The latter are usually preferred for real applications since they pose lesser restrictions on the surface topology. Level of details provided by cloth mesh is naturally bounded by the triangle size. Smaller triangle size results in more realistic simulation results but requires higher computational cost. There is always a tradeoff between the realism of simulation and the computational cost.

The computational efficiency can be improved by adapting element size to the local detail level. Plain areas of cloth surface can be approximated by larger triangles and only regions with more wrinkles require small elements for good approximation. Adaptive meshes have been extensively studied in numerical mathematics for solution of various PDE and recently proved to be effective in the simulation of 3D deformable bodies [2, 3, 13] and a few applications in cloth simulation are also available. Generally simplification process is missing in the previous attempts and hence they are not sufficient to be used for dynamic simulation. Many of them have heavy restriction on mesh topology.

Thingvold and Cohen [11] proposed an adaptive refinement scheme for mass-spring network based on B-splines. B-splines impose heavy restrictions on mesh topology - the control points should form rectangular grid in the parametric coordinates. Due to this feature of B-splines, the entire bands of surface must be refined along with the target region. The criterion used for refinement was not stated clearly and no simplification methods were provided.

Hutchinson et al. [8] proposed an adaptive mesh refinement scheme for rectangular mass-spring network. The angle between two strings joining a mass is used as the trigger for local refinement. When the angle exceeds certain threshold grid cells in the neighborhood are split into four smaller cells. No method for simplification was provided either.

Zhang and Yuen [14] used a global refinement scheme for the draping simulation. They started simulation with a coarse mesh and when the mesh reached its balanced position, e.g. when vertex velocities fall below certain threshold, every mesh triangle was subdivided into four smaller triangles. After a period of simulation with the refined mesh it was refined again and so on until the maximum level of refinement was reached. They stated a 2.5:1 computational cost saving in comparison with simulation using the maximally refined mesh.

There are another group of methods which are also based on inserting of new vertices to the cloth mesh but of different nature. Newly inserted points do not participate in the physical simulation together with original points but are calculated geometrically and therefore do not contribute to the realism of simulation [7, 5, 4].

Simulation of other deformable surfaces is closely related to the cloth simulation. Park et al. [10] used deformable surfaces for the boundary extraction problem from voxel data. Their method includes both global and local refinement and simplification. Refinement operations guaranteed to keep the mesh regularly refined. Criterion for the refinement and simplification is the size of triangle. The triangles are being stretched and compressed during the animation and the refinement process is designed to keep the triangle size within a certain range. Although this refinement criterion may be natural for the boundary extraction problem it does not suit well for cloth animation. If another criterion used the refinement scheme will not guaranty conservation of mesh qualities in terms of triangle aspect ratios.
Gain and Dodgson [6] used an adaptive local refinement and simplification method for the animation of Free-Form Deformations. Their refinement and simplification scheme guarantees to return the mesh to its initial topology state. Unfortunately the proposed refinement mechanism may greatly reduce the mesh quality in terms of the triangle aspect ratios. Each refinement operation increases the valence of two mesh vertices by 1 and creates a new mesh vertex of valence 4. Mesh degeneration effect of successive refinements may accumulate. Their examples demonstrated an excess of vertices with valences 4 and 8. They use two criterions for refinement and simplification. One is based on edge compression and other on the divergence of the endpoint normals.

In our method both local refinement and local simplification of mesh are used. Special attention is paid to the conservation of mesh qualities. Criterion for refinement and simplification is based on the estimation of the local curvature. The method was successfully applied to several cloth animation examples including complex draping scenes and dynamic problems.

Next section presents an overview of our method. Refinement and simplification operators are described in the section 3. The adjustment of physical properties along the refinement and the simplification process is described in Section 4. In Section 5 criterion used for refinement and simplification is derived. Implementation and results are presented in Section 6 and the paper is concluded in Section 7.

2. Outline of the Technique

Along with putting more details to some regions it is desirable to keep the quality of the mesh in terms of the triangle aspect ratios. The simplification process should also maintain quality of the mesh. Although the case when simplification process returns mesh to the original state is usually considered sufficient.

Ill-shaped triangles inevitably appear along individual refinement and simplification operations. To prevent them from reducing their quality even more but convert them to the regular triangles instead the stack of auxiliary structures LOD is introduced. LODs keep track of irregular triangles. Using this monitoring it is possible to prevent further degeneration of the irregular triangles and convert them to the regular triangles whenever possible. LOD i retains the topology of mesh obtained on the i-th level of refinement while LOD 0 is a copy of the original mesh (Fig. 1). Using this information mesh can be easily simplified back to the i-th level from the level above.

Figure 1. Refined mesh and LODs involved.

LOD consists of regular triangles which are available for refinement. Refinement operations on the LOD i produce smaller triangles. Regular of them are added to LOD i+1 and irregular are staying on the LOD i to be converted to the regular triangles later.

Each LOD triangle can be in one of two states: refined or not refined. Refinement criterion provides information on whether every LOD triangle should be refined or not. Having known the desirable state the current state of refinement is synchronized with the desirable one using certain refinement scheme as one discussed below. Refinement of LOD i may add new elements to LOD i+1. It is possible that some of these new elements also should be refined. Therefore refinement process should start with LOD 0 and finish with the top LOD which does not need any refinement. Simplification is an inversion of refinement and should be done in the reverse order.

3. Refinement and Simplification Operators

There are a few refinement schemes are known. We choose $\sqrt{3}$-subdivision [9] since it is simple, slow in terms of the rate of increase of the total number of triangles, refined mesh is usually of good qualities, have good localisation properties. Name $\sqrt{3}$-subdivision is due to the fact that one pass of this subdivision reduces edge lengths by the factor $\sqrt{3}$. Refinement of entire mesh using this subdivision result in the increase of mesh elements by the factor of three.

Figure 2. The first stage of the $\sqrt{3}$-subdivision: vertex insertion.

Refinement is done using operations of vertex insertion and edge swap. New vertex is inserted at the center of the face producing three irregular triangles (Fig. 2). If neighboring LOD triangles are present and refined then the edge swap is performed (Fig. 3). Two new triangles arising in the edge swap are considered to be regular and are added to LOD above. The edge swap operation transforms irregular triangles to the regular triangles.

Simplification procedure is done in exactly opposite order - first all edges are rotated back and then center point is removed. It may remove several LOD triangles from the LOD above.

Figure 3. The second stage of the $\sqrt{3}$-subdivision: edge rotation.
Boundary edges require special attention since they can never be rotated. Kobbelt [9] does not refine boundary edges when even LODs are being refined but splits them into three smaller edges when odd LODs are being refined. We have found this method visually implausible since even refinements do not increase resolution on the boundaries of the surface. √3-subdivision is supposed to reduce edge length by the factor of √3 ∼ 1.7. But for the border edge the reduction is possible only by an integer factor. We subdivide boundary edge by factor of two since it is better approximation of 1.7 then factor of one used by Kobbelt. On the odd LODs we revert to 1-to-3 edge split (Fig. 4). It results in slightly excessive refinement on the mesh boundaries in contrast to slightly insufficient refinement in Kobbelt’s method.

![LOD 0](split) ![LOD 1](swap) ![LOD 2](swap)

Figure 4. √3-refinement with boundary edge split.

4. Adjustment of the Physical Properties

Constants, describing the properties of material, such as Young modulus $E$, Poisson coefficient $\nu$ and density $\mu$ do not depend on element size and are not changed by refinement. The physical properties which should be recalculate for the refined and simplified regions are the size of new triangles in the undeformed state and the masses of vertices.

If calculation of the undeformed state dimensions for new triangles is trivial the mass redistribution appears somewhat more complex. At first we calculated mass of each triangle and distributed it equally among triangle vertices. The method results in nonuniform distribution of masses across cloth surface. Unfortunately implementation have shown that in this case cloth deforms even in free fall. This effect may arise due to limited level of accuracy provided by Conjugate Gradients algorithm is usually visually plausible it produces undesirable artifacts in this case.

To handle the problem we assign masses uniformly for each refinement level. Every vertex of original mesh have mass $m_0 = \mu S/N$, where $S$ is the total area of cloth and $N$ is the number of vertices. √3-refinement being applied globally increases number of vertices by factor of three for every level of resolution. To keep mass of the mesh constant mass of each particle should decrease by the same factor, that is $m_i = m_0 / 3^i$ for vertices of $i$-th LOD. If vertex belongs to several LODs then the highest LOD is used for the calculation of the vertex mass.

5. Refinement Criterion

Refinement criterion provides estimation of the local approximation error for the each LOD element. Approximation error higher then certain threshold signals about the need for refinement. If it is below the threshold the refinement of the element is not needed any more and the element should be simplified. Approximation error is measured in the units of distance and threshold values are usually taken as a certain fraction of the LOD triangle size.

Criterion is calculated for each two neighboring LOD elements on the base of their size $l$ and bending angle $\alpha$. We suppose that actual shape of cloth in the bending situation is cylinder and calculate maximum distance between cylindrical surface and LOD surface. This distance is considered as an error of the current approximation. Let $l$ be the distance between bending edge and another vertex of one of two considered LOD elements. let $\alpha$ be angle between normals of these LOD elements (Fig. 5). Assuming that these LOD elements are of the same size, the radius of circumscribed cylinder is

$$R = \frac{l}{2 \sin \frac{\alpha}{2}}.$$

Maximum distance $\delta$ between circumscribed cylinder and LOD elements concerned is obtained along the ray originating on the axis of cylinder and perpendicular to the LOD element. Distance $h$ from the axis of the cylinder to the LOD element is $R \cdot \cos \frac{\alpha}{2}$. Therefore

$$\delta = R - h = \frac{1 - \cos \frac{\alpha}{2}}{2 \sin \frac{\alpha}{2}} l.$$
When alpha is small then $\delta \sim l/\alpha$. In this approximation the criterion resembles criterion used by Hutchinson et al. [8] but with different scaling by the resolution level. Element size $l$ decreases by factor $\sqrt{3}$ with each finer resolution level. $\delta$ is constant and the change of $l$ scales the threshold value for $\alpha$ by the same factor.

6. Implementation and results

In our system the physical model proposed by Baraff and Witkin is used, along with implicit Euler integration, cloth-rigid collision detection involving hierarchical bounding box tree for rigid objects [1] and the collision response method proposed be Volino et al. [12].

We tested our adaptive simulation system with three types of scene. First is the dynamic draping problem illustrating how cloth mesh is being refined with time. A piece of cloth is dropped on a ball and slides down (Fig. 7). The initial mesh consists of 109 vertices, during simulation it was refined up to the 784 vertices but later simplified to less then 400. In this simulation the refinement process takes about 10% of the total simulation time. Simulation of one time step takes $\sim$ 450 milliseconds on average. The simulation of globally refined mesh with the maximum level of details needs 2557 vertices and each time step takes $\sim$ 2 seconds on average.

Second simulation demonstrates ability of cloth to simplify back to its original state (Fig. 8). In the first moments of simulation the falling ribbon is refined at the corners of the block (left picture). Then refinement state gradually changes while the ribbon slides down (center) and finally the ribbon simplifies back to its original state when it leaves the block (right). Number of vertices changes in range from 64 to 164. Refinement process takes 13% of the computational cost. Average time for single time step is 49 ms. Simulation of the globally refined mesh with 460 vertices takes $\sim$ 180 ms per time step.

The third test is the dressing of garment on mannequin as shown in Fig. 6. The initial cloth mesh is seameds without refinement and the final draping shape is obtained with adaptive refinement and simplification. Although the first refinement pass takes 95% of the time step but on average the refinement and simplification again takes about 10% of the total computation cost. The initial number of vertices is 385 and after first pass it increases to $\sim$ 2000. The maximum number of vertices observed is 3715 and on average - 2821. An average time step takes 2.7 seconds. Globally refined cloth with the maximum level of details requires 9871 vertices and it takes $\sim$ 6.5 seconds per time step.

7. Conclusion

In this paper a method for adaptive refinement of cloth based on $\sqrt{3}$-subdivision scheme and curvature-based refinement criterion was presented. Physical properties of cloth are easily corrected when using a continuous physical model. Practical application has shown that the refinement and simplification overhead is only 10% of the total computational cost on average. Application examples show the generation of fine detailed wrinkles while plain areas are still approximated with coarse mesh. Practical experiments have shown a significant improvement on computational efficiency of our refinement and simplification scheme, in comparison with cloth simulation without refinement process.

References


Figure 6. Draping on the mannequin.
Figure 7. Sphere draping.

Figure 8. Falling ribbon.