Online Multiresolution Volumetric Mass Spring Model for Real Time Soft Tissue Deformation

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Abstract. Recent years have seen an increase in the acceptance and demand for Virtual Reality surgical simulators. Although significant advances have been made in the area, real-time accurate simulation of soft tissue deformation is still a major obstacle when developing simulators with haptic feedback. On this paper we present a new multi-resolution volumetric mass-spring model that offers high visual and haptic resolution in and around the region of interaction and other critical regions. Visual and haptic resolution decreases in proportion to the distance from such regions making it possible to distribute the computational workload optimally in order to achieve real-time haptic simulation.

1 Introduction

Surgical simulation is an extremely challenging area of research combining medical imagery, computer graphics and mathematical modelling. Recent advances make it possible to represent complex tissue structures and perform virtual fly-through operations, but a great deal of research in soft tissue modelling is still needed to develop the next generation of surgical simulators.

1.1 Physically-Based Deformable Models

Various approaches founded on the laws governing the dynamics of non-rigid bodies have been proposed for simulating deformable soft tissue.

The Finite Element Method (FEM) is a common and accurate way to compute complex deformations of soft tissue, but conventional FEM has high computational cost and large storage requirements. Hybrid models based on global parameterized deformations and local deformations based on FEM have been introduced [1,2,3] to tackle this problem. Large-scale multi-processor computers to obtain soft tissue deformation at interactive rates have also been employed [4], while in [5,6] pre-computed elementary deformations and speed-up algorithms were used. Most of these methods, however, are only applicable to linear deformations and valid for small displacements. Furthermore, they tend to rely on pre-computing the complete matrix system and are therefore unable to cope with topological changes occurred during cutting or tearing.

Mass Spring Systems (MSS) have been widely used in soft tissue simulation [7,8,9,10] because of their ability to generate dynamic behaviors that allow real time deformation and topological changes. The main limitation of MSS is

computing the masses and springs parameters in order to set up a homogeneous material. Since damped springs are positioned along the edges of a given mesh, the geometrical and topological structure of this mesh strongly influences the material behavior and may generate undesired anisotropy. This tends to disappear as the density of the mesh increases, but using an extremely dense mesh reduces efficiency. For these reasons, a trade off between accuracy and computational time is typically required in MSS.

1.2 Multiresolution in Physically-Based Simulation

Multiresolution is a very active field of research in computer graphics and image processing. It consists of using representations of a geometric object at different levels of accuracy and complexity. This concept can be extended to physically-based simulation by dynamically and locally adapting the density of the mesh in regions of interest depending on the desired accuracy.

Most of the work in deformable modelling has used fixed space discretization. However, there have been some attempts at using the idea of locally refining a model in and around regions of interest. Hutchinson *et. al* [11] simulated a piece of draped cloth with a MSS which can be refined in regions of high curvature using a multi-level hierarchical mesh to represent varying levels of granularity. More recently, a model based on a multiresolution triangulation stored with a preprocessed DAG was used to refine a volumetric mass-spring network near user-controlled cutting lines [12]. Debunne *et. al* [13] combined a linear finite-volume based mechanical model with a non-hierarchical refinement technique and Wu *et. al* [14] proposed a scheme for mesh adaptation based on an extension of the progressive mesh concept for simulation with non-linear FEM. The problem with these approaches is the use of a pre-processing phase. Such pre-processing fixes the range and accuracy of the stored resolutions and limits the flexibility of the method. Moreover, the pre-processed resolutions depend on the topology of the object and thus prohibit topological modifications.

1.3 Refinement for Unstructured Mesh Generation

Implementation of a flexible multiresolution soft tissue model requires the online refinement/simplification of an unstructured mesh. Starting with a coarse mesh, a refinement procedure based on traditional unstructured mesh generation algorithms can be applied until the desired nodal density has been achieved. One of the existing approaches to element refinement is to divide an element into several ones by inserting a single node inside or on the boundary depending on its location in the mesh [15,16]. The quality of resulting elements can be improved by deleting the local elements and connecting the nodes to the triangulation using the Delaunay criterion. Our refinement scheme is based on Shewchuck's Delaunay refinement algorithm for 3D quality mesh generation [16].

The remainder of this paper is organized as follows: Section 2 explains in detail the proposed online multiresolution approach. In section 3 we present and discuss the results of applying the new approach making a comparison with standard single resolution techniques. Lastly, in section 4 we formulate our conclusions and comment on our future work.

2 Methodology

Recently, we presented a volumetric MSS that offers topological and geometric flexibility for the efficient modelling of complex anatomical structures and simulation of interactions such as cutting or suturing [17]. Building on our model, we now introduce a flexible and truly dynamic multiresolution volumetric mass-spring representation offering high visual and haptic resolution in and around the region of interaction and other critical regions.

2.1 Behavior Consistency

One of the main problems in multiresolution models is ensuring that the deformable model stays self-consistent despite changes of resolution. Since there has never been any underlying physical model to refer to in order to find what parameter changes will guarantee the most consistent behavior at different resolutions, it has been commonly assumed that it is difficult to change the density of the mesh during the simulation while maintaining the same global mechanical properties. To address this problem, we studied the oscillations of a deformable tissue block under gravity at several resolutions using different parameter definitions as described below. Some frames of the simulations are presented in Figure 1. Figures 2 and 3 show the results of the simulation at three different resolutions and at combined resolutions.

Fig. 1. Deformable tissue block (a) under gravity forces using different parameter definitions. (b) single resolution. (c) combined resolutions using $k = \frac{1}{l}$ and constant damping. (d) combined resolutions using (2) and (3).

Point mass. In our volumetric MSS, masses are allocated at the vertices of the tetrahedral mesh and damped springs along the edges. To accurately distribute the total mass of the mesh, we compute the mass m_i of each vertex i according to the volume V_j of its adjacent tetrahedron j . If D is the material density, then:

$$m_i = \frac{D \sum_j V_j}{4} \quad (1)$$

Spring stiffness. The easiest way is to use a constant value for the stiffness (k). More commonly, k is computed as $k = \frac{1}{l}$, where l is the length of the spring at rest. In [18], Van Gelder suggested a formula to compute spring stiffness for a 3D mesh that is the closest to an elastic continuous representation. Let E be the material elastic modulus, then:

Fig. 2. Comparison of the vertical position of an oscillating cube at several and combined resolutions using different k : (a) constant. (b) $k = \frac{1}{l}$. (c) Using (2).

$$k = \frac{E \sum_j V_j}{l^2} \quad (2)$$

Figure 2 shows the behavior of the tissue block using (1) to obtain the mass of each element and the above stiffness definitions. It clearly illustrates that using a constant k and $k = \frac{1}{l}$ fails to ensure the same amplitude and frequency of oscillations at different resolutions, while using (2) results in a consistent physical behavior at different and combined resolutions.

Spring damping. The question of how to assign different damping (c) values to the various springs in a MSS has been largely ignored in the literature. Traditionally, c is treated as a constant throughout the system. If we assume that our multi degree-of-freedom (DOF) system can be transformed into a set of uncoupled single DOF systems, the damping ratio d_i of each spring taken separately can be expressed as $d_i = \frac{c}{2\sqrt{k_i M_i}}$, where k is the spring stiffness and M the effective end mass $m_i + m_j$. To limit the oscillations of the system without overdamping it, we let $d_i = 1$, such that $c = 2\sqrt{k_i M_i}$.

We performed the same simulation as before using (1) and (2) to calculate m and k , first letting c be a constant and then defining it as $c = 2\sqrt{k_i M_i}$. Figure 3(b) shows that the proposed formula guarantees the best frequency consistency for different resolutions, but fails to ensure the same amplitude of oscillation that tends to increase with the resolution. To compensate for this effect, we adjust c to be inversely proportional to l , the length of the spring at rest:

$$c = \frac{2\sqrt{k_i M_i}}{l} \quad (3)$$

As shown in figure 3(c), this new formula ensures the best behavior consistency for different and combined resolutions.

We have thus demonstrated that it is possible to ensure a coherent physical behavior of a volumetric mass spring system at different and combined resolutions by dynamically updating the parameters using equations (1), (2) and (3).

2.2 Online Tetrahedral Refinement

In order to refine a given mesh at a desired location, we extend the concept of tetrahedral Delaunay refinement. A coarse mesh is created offline by forming an

Fig. 3. Comparison of the vertical position of an oscillating cube at several and combined resolutions using different c : (a) constant. (b) $c = 2\sqrt{kM}$. (d) $c = \frac{2\sqrt{kM}}{l}$.

initial boundary constrained Delaunay tetrahedralization of the input vertices and triangles. The input vertices are used as a reference and can not be deleted. During online simulation, the given mesh can be locally refined/simplified by inserting/deleting vertices. In this section, we present the details of our method.

Addition of mass points. During the simulation, additional mass points can be inserted in a tetrahedron of the previous triangulation in its resting configuration. Using the barycenter point coordinates within the tetrahedron, we interpolate its previous and actual position and velocity in the deformed mesh.

Delaunay refinement. The resting configuration of the mesh is then updated using the Bowyer/Watson [19,20] algorithm to maintain the Delaunay property. Once all the new points have been inserted, the tetrahedrons which might have appeared in the concavities are removed.

Vertex removal. If a vertex is removed, all tetrahedrons incident at the vertex are also removed leaving a "hole" in the mesh. The re-triangulation of the hole is done by building the Delaunay triangulation of adjacent vertices [21].

Parameters update. Each time a tetrahedron is created or removed, all relevant parameters (m , k , c), are updated using equations (1), (2) and (3).

Data structures. The efficiency of the on-line tetrahedral refinement depends heavily on the data structures. We use dynamic memory reallocation and two mesh data structures for mesh manipulation: the tetrahedron-based data structure [22] and the triangle-edge data structure for face classification and mesh manipulation [23]. The data structures have been extended by adding various flags to quickly trace mesh changes after an update and specific attributes related to the mesh deformation.

2.3 Refinement Locations

An essential step in the implementation of our model is to determine where to refine the mesh. Our refinement locations are defined based on the region of interaction and on the topology of the mesh.

Region of interaction. The interactions between the surgical instruments and the soft tissue structures are handled by our collision detection algorithm. We approximate the geometric models of the instruments with a set of oriented

bounding boxes (OBBs) and have further optimized the collision detection by also using axis-aligned bounding box (AABB) trees for both the surgical instruments and soft tissue models. AABB trees can be updated very quickly as the shape of the model changes [24] allowing us to compute in real-time the exact points of intersection between the surgical instrument and the soft tissue model. New points into the soft tissue mesh are then inserted at the points of intersection and the mesh is refined using the Online Tetrahedral Refinement method described above. Our collision detection also allows us to quickly compute the distance between the new points inserted into the original mesh and the OBBs of the surgical instrument. If the distance is larger than a specified threshold, the point is removed from the mesh using the Vertex Removal algorithm.

Mesh Topology. We use a quality refinement procedure to incrementally insert new points in the areas of high strain in the mesh. Such areas are normally represented by low quality tetrahedra in the initial coarse mesh input. One possible measure for analyzing the quality of a tetrahedron is the circumradius-to-shortest edge ratio of a tetrahedron. Any tetrahedron whose circumradius-to-shortest edge ratio is larger than B is split by inserting a vertex at its circumcenter. By using different values for the threshold B , it is possible to make the degree of refinement dependent on local strain.

3 Results and Discussion

To demonstrate the accuracy and efficiency of our refinement method, we simulated the deformation of an organ under the interaction of a surgical instrument using single (low/high) resolution and multiresolution models. The multiresolution model incorporated refinement at the regions of interactions as described in section 2. Every simulation lasted 20 seconds, including the time the instrument is approaching and leaving the organ. Figure 4 shows three frames taken during each simulation as the instrument is deforming the organ. They clearly illustrate the lack of deformation accuracy for the low-resolution model, whereas the high resolution and the multiresolution models show similar behavior. The underlying physical model as described in 2.1 allows the refined mesh to stay perfectly consistent despite the combination of several resolutions. Unlike continuous models which introduce diverging instabilities when different resolutions are combined [13], our refinement model behaves smoothly, without any visual artifacts.

In order to quantify the performance of our model, we plotted for each simulation the elapsed time of every iteration broken down into different steps. The results are shown on figure 4. The relaxation time of the multiresolution model being proportional to the density of the mesh is kept as small as that of the low-resolution model. Figure 4 (c) also shows that the time required for the refinement is small enough to keep the simulation at a rate much faster than the high-resolution model. In fact, the iteration rate of the multiresolution model varies between 2 and 20 times that of the high-resolution model.

Fig. 4. Performance comparison between different models. (a) Single low resolution. (b) Single high resolution. (c) Multiresolution

4 Conclusions and Future Work

We have developed a soft tissue model that allows localized online refinement, offering high visual and haptic resolutions in the regions of interest. Our results show that the refinement is made completely transparent to the user, as the model stays self-consistent despite the changes of resolution. Our method for 3D mesh refinement is truly dynamic offering full flexibility even in the case of topological changes. In fact, we believe that our multiresolution model will facilitate the implementation of topology modifying interactions such as cutting since we are able to refine the model along the path of a surgical instrument.

As part of our future work, we will implement an original method for accurate soft tissue cutting. We also plan to develop a multifrequency relaxation for our model. The integration time step of classical MSS is closely dependent on the spring parameters. Since our parameters are directly proportional to the resolution, we shall optimize the relaxation time in relation to the density of the mesh. This will enable us to distribute the computational workload and help us towards achieving real-time haptic simulation.

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