Dissection of Hybrid Soft Tissue Models Using Position-based Dynamics

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Abstract

This paper describes an interactive dissection approach for hybrid soft tissue models governed by position-based dynamics. Our framework makes use of a hybrid geometric model comprising both surface and volumetric meshes. The fine surface triangular mesh is used to represent the exterior structure of soft tissue models. Meanwhile, the interior structure of soft tissues is constructed by coarser tetrahedral meshes, which are also employed as physical models participating in dynamic simulation. The less details of interior structure can effectively reduce the computational cost of deformation and geometric subdivision during dissection. For physical deformation, we design and implement a position-based dynamics approach that supports topology modification and enforces the volume-preserving constraint. Experimental results have shown that, this hybrid dissection method affords real-time and robust cutting simulation without sacrificing realistic visual performance.

CR Categories: I.3.3 [Computer Graphics]: Three-Dimensional Graphics and Realism—Display Algorithms I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Simulation;

Keywords: Position-based Dynamics; Hybrid Geometric Models; Deformation; Interactive Cutting; Tetrahedra

1 Introduction

In recent years, there have been remarkable progresses in the application of virtual reality based (VR-based) surgery simulation and training. Several successful VR surgical simulators have been developed [Simbionix] [Pan et al. 2011] [Mao et al. 2013] with great success. An essential component of surgical simulators is the technique that supports realistic dissection of soft, deformable tissues in real time. The major challenge of dissection simulation is the efficient and realistic integration of cutting into deformable models. It necessitates the accurate modification of both geometric and topological representation for soft tissues in real time. In principle, soft tissues can be represented by surface or volumetric models. Tetrahedral meshes, as one primary type of volumetric geometry, are frequently applied to the cutting simulation since the interior structure of objects must be present during virtual surgery for the purpose of physical fidelity. However, the computational cost for topology modification in volumetric models tends to be extremely high due to its geometric and topological complexity [Wu et al. 2014]. In contrast, surface mesh models are relatively easy to handle in deformation and dissection simulation [Pan et al. 2009]. Nonetheless, it can not exhibit the interior structure of soft tissues to visually display the cutting result since the surface model is a simple skin that wraps around the model without volumetric substance.

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In this paper, we introduce a hybrid geometric model comprising both surface and volumetric meshes for interactive dissection simulation. For physical deformation, we improve the position-based dynamics (PBD) [Muller et al. 2007], and devise a new method to support the topology modification and enforce volume-preserving constraints. Figure 1 intuitively illustrates the pipeline of framework for our method.

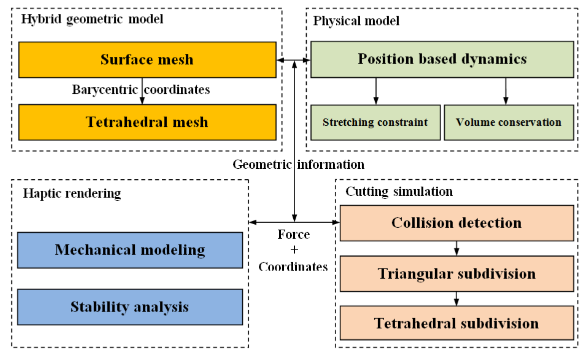

Figure 1: *The framework of our dissection simulation method.*

2 Hybrid Geometric Models

We use both the surface and volumetric models to describe soft tissue. A fine triangular mesh is applied to represent the exterior structure of soft tissue model. With an accurate geometric structure and texture information at the detailed level, this surface model can afford a realistic graphics performance. Meanwhile, we represent the interior structure of soft tissue model with larger and coarser tetrahedra. This tetrahedral mesh is also used as physical model in deformation. The less details of interior structure can reduce the computational cost in cutting and deformation. The volumetric model is slightly larger than the surface model to make sure that the tetrahedral mesh contains the triangular mesh completely. To generate the connection between tetrahedral model and surface model, the coordinate mapping method in [Muller and Gross 2004] is used to compute the geometry of surface mesh derived from tetrahedra.

3 Deformation Computing using Position-based Dynamics

For physical deformation, we use the position-based dynamics (PBD) [Muller et al. 2007] method. And two types of constraints, which are directly applied to the positions of tetrahedral vertices, are considered. One is the stretching constraint. Another is the volume-preserving constraint. In [Muller et al. 2007], authors provided the following equation to calculate the positional increment $\Delta \mathbf{p}_i$.

$$\Delta \mathbf{p}_i = \frac{w_i C(\mathbf{p}_1, ..., \mathbf{p}_n)}{\sum_j w_j |\nabla_{\mathbf{p}_j} C(\mathbf{p}_1, ..., \mathbf{p}_n)|^2} \nabla_{\mathbf{p}_i} C(\mathbf{p}_1, ..., \mathbf{p}_n), \quad (1)$$

where $C(\mathbf{p}_1, ..., \mathbf{p}_n)$ is the constraint of an object for all of its points: $\mathbf{p}_1, ..., \mathbf{p}_n$, and $\nabla_{\mathbf{p}_i} C(\mathbf{p}_1, ..., \mathbf{p}_n)$ is the constraint's gradient at point $\mathbf{p}_i$. [Muller et al. 2007] only provides the formulation of stretching constraint. We give the following equation to express the constraint of volume conservation:

$$C_{volume}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3, \mathbf{p}_4) = \frac{1}{6}[(\mathbf{p}_1 - \mathbf{p}_2) \times (\mathbf{p}_1 - \mathbf{p}_3)] \cdot (\mathbf{p}_1 - \mathbf{p}_4) - V_0, \tag{2}$$

where V_0 is the original volume of tetrahedron before deformation. From Eq.(1) we can get

$$\triangle \mathbf{p}_i = \frac{w_i C_{volume}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3, \mathbf{p}_4)}{\sum_{j=1}^{4} w_j \left| \nabla_{\mathbf{p}_j} C \right|^2} \nabla_{\mathbf{p}_i} C. \tag{3}$$

4 Interactive Dissection of Hybrid Soft Tissue Models

Once the dissection starts on the surface mesh model, the cutting in tetrahedral model and surface mesh model will be processed simultaneously. We treat the motion of scalpel as a finite length cutting edge passing through a soft object. In our algorithm, the position of line segment in both current and previous time step are stored to form the sweep surface, which is built by connecting the corresponding endpoints of the two line segments. To determine the sweep surface and intersections created by the cutting edge, the following two tests are required. One is to detect the intersection between the scalpel tip path and the tetrahedral faces. The other is to detect the intersection of the sweep surface and the tetrahedral (triangular) edges. We use the global search method to handle these two detection tests because of the parallel characteristic of the global search. If an intersection occurs, the intersection information of the current tetrahedron (triangle) will be updated and the tetrahedron (triangle) will be subdivided. We use the approach in [Steinemann et al. 2006] [Pan et al. 2011] for the tetrahedral and triangular subdivision. To update the PBD physical model, the processed stretch and volume-preserving constraints shall be removed. And new constraints for the subdivided tetrahedra must be added as well. Finally, once the scalpel has left the mesh surface, the cutting in tetrahedra ends at the same time.

5 Experimental Results and Discussion

We have implemented our interactive dissection simulation technique using C++, OpenGL, CUDA, and OpenHaptics. All the experiments run on a desktop with NVIDIA GeForce GTX 580, Intel(R) Xeon(R) CPU (2.53GHz, 8 cores), and 12G RAM. Our experiment is cutting a liver model. The first row in Figure 2 illustrates the simulation results of a small incision on the surface of liver tissue. Due to the influence of gravity and neighboring strain in biological soft tissue, we can observe the incision grows bigger afterwards. And at the initial frame before cutting, there is an obvious deformation due to pressure on liver surface. It is realistic and acts in agreement with the common understanding. The second row in Figure 2 illustrates the procedure which is cutting off a piece of tissue from the liver. The number of tetrahedra is 4079. The time for simulation is 4.64ms with 3 5 iterations. We can observe that our method easily handles the large topology and volumetric structure change.

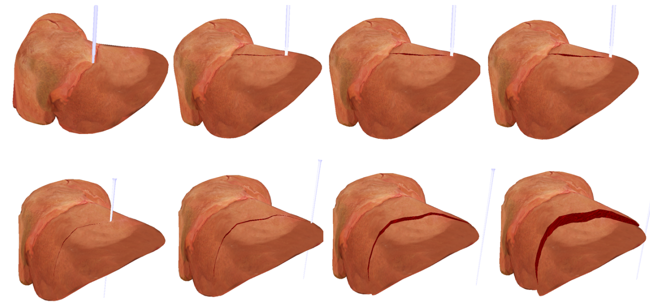

Figure 2: *The cutting simulation of liver tissue.*

6 Conclusion and Future Work

We have designed an interactive dissection simulation approach based on the position-based dynamics for hybrid soft tissue models. Our method employs a hybrid geometric model comprising both surface and volumetric meshes. The fine surface triangular meshes with accurate geometric structure and texture are necessary for soft tissues' exterior representation, while the interior structure of soft tissues are built up using coarser and larger tetrahedral meshes. It significantly reduces the computational cost of deformation and model refinement in cutting. Our physical deformation is governed by the improved position-based dynamics that accommodates the topology modification and enforces the volume-preserving constraint. Based on our experimental results, we have shown this new dissection method offers realtime and robust simulation without sacrificing the realistic visual performance. In future, we plan to further exploit the parallel acceleration and apply CUDA to both deformation and geometric refinement during cutting simulation.

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