Real-time Cutting Method for Soft Tissue Based on TLED Algorithm

WANG He-xiang, HAO Ai-min, LI duo
State Key Laboratory of Virtual Reality Technology and System
Beihang University, Beijing, China
wanghx@vrlab.buaa.edu.cn, ham_buaa@163.com, duo.li@cse.buaa.edu.cn

Liu Xue-mei
Department of Information and Engineering
North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou, China
liuxuemei@ncwu.edu.cn

***Abstract*—Surgery simulation system can provide a safe virtual training environment. Cutting of soft tissue plays a very important role in the system. During the operation, the soft tissue exhibits nonlinear property and topology change of the operated tissue usually causes the failure of the pre-computed quantity. The above reasons make the simulation of the real-time cutting a challenging task. This paper proposes a new cutting method, based on TLED nonlinear finite element algorithm which deals with real time simulation of deformation. The method combines virtual node algorithm and TLED algorithm, pre-computes related quantities on the element level and locally modifies topology of soft tissue after cutting, avoiding re-computation of pre-computed data. Experiments display its ability to simulate cutting of soft tissue with nonlinear property within real time.**

Keywords-* *surgery simulation; cutting; nonlinear; pre-compute

I. INTRODUCTION

Surgery simulator is a safe and effective equipment for surgical training. Surgeons can practice operation skills on a virtual patient via surgery simulator. In this way, surgeons need not to practice on real patients and the surgery circumstances can be reset for any times. Surgery simulator catches more and more researchers' attention and energy.

Cutting or incision is a very important surgical operation hence is also an important operation in surgery simulator. When human soft tissue is cutted, the topology of its geometry model changes, meanwhile it deforms under its inner stress and forces applied by surgical instruments. The most accurate mathematic model to describe soft tissue deformation is based on nonlinear continuum mechanics equations. Due to efficiency, most researchers use linear elastic model to simulate soft tissue, since linear model allows principle of superposition which enable pre-computation to promote efficiency. The basic assumption of linear model is that soft tissue undergoes small deformation while soft tissue usually undergoes large deformation in real surgical operation. So it is not appropriate to describe deformation of soft tissue using linear model. There is another reason makes simulation of cutting in real-time difficult: when topology changes, new nodes and elements may be added to the current mesh, causing element stiffness matrix changes accordingly. This induces reassembly of global stiffness matrix which is a costly procedure. The modification of the global stiffness matrix usually induces failure of the pre-computation which aims to reduce the runtime computation.

This paper's main contribution is to propose a real-time cutting method of soft tissue with nonlinear property. It pre-computes on the element level instead of global level, combines TLED (total lagrangian explicit dynamic, which will be addressed later) algorithm to simulate the property of soft tissue deformation and virtual node algorithm to handle topology change. The proposed method modifies topology locally and prepares the pre-computed quantity for newly added element by memory copy and solves the problem of pre-computed quantity failure. The proposed method preserves ability of TLED algorithm to simulate nonlinear soft tissue deformation while simulates cutting operation within real-time.

II. RELATED WORKS

The costly computation of FEM brings great challenge for surgical simulation, because the plausible visual feedback need 30Hz update rate. Many researchers apply simplified linear model to reduce computation, and proposed many techniques based on it. Bro-Nielsen et al. [1] adopted fast FEM model and condensation technique to achieve real-time performance. Berklye et al. [2] proposed banded matrix technology for real-time deformation. Cotin et al. [3] achieved real-time performance by taking advantage of superposition principle to pre-compute tensors. These methods do not work when cutting is simulated, for topology change can make pre-computed quantity failed. K. Miller et al. [14] proposed Total Lagrangian Explicit Dynamic (TLED) finite element algorithm simulated nonlinear soft tissue deformation in real-time. TLED algorithm need not assemble global stiffness matrix and uses explicit time integration to achieve real-time performance. The accuracy of the algorithm has been verified by Miller [4]. As far as we know, TLED algorithm has not been introduced to simulation of cutting operation.

In order to simulate cutting, Cotin et al. [5] proposed a method which combines tensor-mass model and FEM model to realize deformation and cutting. In their method, any element touched by the knife will be removed. Zhong

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et al. [6] and Popescu et al. [7] also adopt element removal method to cope with cutting, then they all update the pre-computed inverse of global stiffness matrix effectively using Shermen-Morrison-Woodbury formulation, achieving real-time performance. Nienhuys et al. [8] confines cutting on the border of the elements then simulation cutting using conjugate gradient method based on the sparse property of the stiffness matrix. The above mention method all suffer from jagged surface. Other researchers subdivide the cutted element into many sub-elements to achieve good visual feedback [9, 10]; Wu Wen et al. [13] adopt hybrid condensed FEM model with GPU acceleration. They partitioned the soft tissue into operational region and non-operational region, only simulated cutting on the operation region. As operational region is just a small portion of the whole soft tissue, real-time simulation is achieved. However subdivision method suffers from ill-conditioned elements that impose severe time step restrictions. The virtual node algorithm [11] is a compromise method which separates visual and physical representation. It replaces a cutted element by 2 half void elements whose geometry is same as the origin one. It preserves the quality of the elements while achieving smooth surface. However this algorithm has not been used for real-time simulation of soft tissue with nonlinear property. The existing cutting simulations usually base on linear model, yet they are not accurate to simulate cutting in surgical operation since soft tissue usually displays nonlinear property during the surgery.

III. REAL-TIME CUTTING METHOD FOR SOFT-TISSUE BASED ON TLED ALGORITHM

The main idea of this paper is to combine advantages of TLED algorithm and virtual node algorithm to create pre-computed quantity of newly added element efficiently. As TLED algorithm pre-computes on element level, local topology change will not affect pre-computed quantities on the rest part of soft tissue. Therefore the proposed method solves the problem of pre-computed quantity failure caused by cutting, making real-time cutting simulation possible.

The two adopted algorithm will be briefly introduced in the following sections. For more detail, please refer to related papers.

A. TLED algorithm

For dynamic system, the equilibrium equation of FEM is

$$M\ddot{U} + D\dot{U} + K(U)U = R \tag{1}$$

Where U is vector of nodal displacement, M is a mass matrix, D is a damping matrix and K is a stiffness matrix non-linearly dependent on the deformation, and R is a vector of nodal forces. For efficiency, lumped mass matrix is introduced which is a diagonalized matrix. Further, assume damping matrix is proportion to mass matrix: $D = \alpha M$, where α is a constant. So D is also diagonalized. Miller suggests using explicit time integration to solve unknown U. The stiffness term in equation (1) can be calculated by the follow equation

$$K(U)U = F(U) = \sum_e \tilde{F}^{(e)} \tag{2}$$

Where $\tilde{F}^{(e)}$ is nodal forces created by stress in element e. Nodal forces at time t can be evaluated by following equation

$$^{t}F = \int_{^0V} {}^{t}_{0}B_L^T \, {}^{t}_{0}\hat{S} d^0V \tag{3}$$

where ${}^{t}_{0}\hat{S}$ is second Piola-Kirchhoff stress in vector form, ${}^{t}_{0}B_L^T$ strain-displacement matrix, ^0V is element volume at the initial time. All symbols are same as [18]. Equation (3) means there is no need to assemble global stiffness matrix *K(U)*, since nodal force distribution resulted by stress can be calculated on the element level. Because mass matrix and damping matrix are diagonalized, equation (1) can be solved on element level. In nonlinear analysis, geometry shape varies during the simulation. This means strain-displacement matrix *B* also varies. *B* can be calculated by the following equation

$${}^{t}_{0}B_{\mathbf{L}}^{(i)} = {}_{0}B_{\mathbf{L}0}^{(i)} \, {}^{t}_{0}X^{\mathbf{T}} \tag{4}$$

$${}_{0}B_{\mathbf{L}0}^{(i)} = \begin{bmatrix} \frac{\partial N_i}{\partial^0 x} & 0 & 0 \\ 0 & \frac{\partial N_i}{\partial^0 y} & 0 \\ 0 & 0 & \frac{\partial N_i}{\partial^0 z} \\ \frac{\partial N_i}{\partial^0 y} & \frac{\partial N_i}{\partial^0 x} & 0 \\ 0 & \frac{\partial N_i}{\partial^0 z} & \frac{\partial N_i}{\partial^0 y} \\ \frac{\partial N_i}{\partial^0 z} & 0 & \frac{\partial N_i}{\partial^0 x} \end{bmatrix} \tag{5}$$

where ${}^{t}_{0}B_{\mathbf{L}}^{(i)}$ is the *i*th sub-matrix of ${}^{t}_{0}B_L^T$, ${}^{t}_{0}X^{\mathbf{T}}$ is deformation gradient from time 0 to time t, i means nodal number in element, ${}_{0}B_{\mathbf{L}0}^{(i)}$ is defined by derivatives of shape functions with respect to spatial coordinates. N_i is *i*th shape function of element, ^0x, ^0y and ^0z are coordinate basis at initial time.

B. Virtual node algorithm

The key idea of virtual node algorithm is: if an element is cutted, it is replaced by two half-void elements with the same geometry as the cutted one. Each created element contains part of material of cutted element. Virtual node algorithm realizes topology change not by subdivision of element or cutting on element border, but by duplicating element, shown in Figure. 1.

Soft tissue boundary after cutting is the boundary bounds material, so it has to be updated after cutting. The geometry of the half-void element is used for finite element analysis. The advantage of the algorithm is that no ill-conditioned element was created and incision is smooth. Virtual node algorithm is more promising than element removal method or cutting on element border, because it provides good visual feedback for surgery simulator.

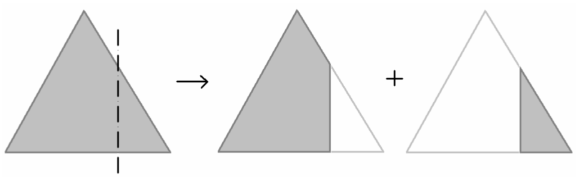

Figure. 1 Virtual node algorithm

C. Real-time cutting method for soft-tissue based on TLED algorithm

When handle topology change, virtual node algorithm provides good visual feedback without affecting element quality, so it will not affect accuracy and convergence of the numerical solution. This is a very important aspect to combine virtual node algorithm and TLED algorithm because TLED algorithm uses explicit time integration which is conditionally stable and ill-conditioned element significantly reduces critical time step. Severely restricted critical time step may make simulation with TLED algorithm meaningless.

The created elements are merely copy of the cutted element; the pre-computed quantities for the new elements can be copied from the cutted element as well. The failure of pre-computed quantity is eliminated. As no global stiffness matrix is assembled, cost of cutting is mainly cost of topology modification. So combining TLED algorithm and virtual node algorithm reduces the cost of cutting, making simulation of cutting in real-time easier. Figure.2 shows the combination of TLED algorithm and virtual node algorithm.

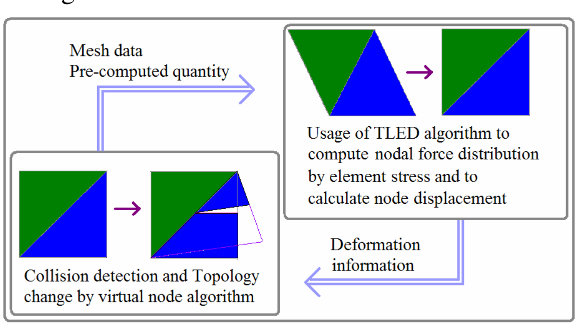

Figure. 2 Combination of TLED algorithm and virtual node algorithm.

The process of the proposed method describes as follow:

Pre-computation stage

1) For each element, calculate derivatives of shape functions with respect to spatial coordinates and ${}_0B_{\mathbf{L}0}^{(i)}$ *using equation (5), calculate initial volume of each element, calculate mass and damping of each node.*

2) Generate information of mesh topology for virtual node algorithm.

Time stepping

1) Loop over elements: calculate deformation gradient ${}_0^tX^{\mathbf{T}}$*, strain-displacement matrix* ${}_0^tB_{\mathbf{L}}^{(i)}$ *and second Piola-Kirchhoff stress* ${}_0^t\hat{S}$*, calculate element nodal forces* $\widetilde{F}^{(e)}$*.*

2) Loop over nodes: obtain net nodal reaction forces at time t and explicitly calculate displacements using central difference formula.

3) Collision detection and topology change: obtain location of knife and check whether soft tissue is cutted or not. If cutted, use virtual node algorithm to change mesh topology. Copy the pre-computed quantities from the cutted element to newly added elements.

IV. Result

The propose method is realized on a 3.0 GHz PC based on a liver model. We use the simplest nonlinear model-neo-Hookean material model with Young's modulus 5000Pa and Poisson's ratio 0.35, to demonstrate the effectiveness of our cutting method.

Scene 1: the left side of cuboid shaped soft tissue is fixed, the rest part deforms under gravity, shown in Figure.3. While it deforms, a knife in shape of line segment cuts the soft tissue. For simplicity, the knife is assumed to be extremely sharp, so it cuts the soft tissue without applying forces to the tissue. The incision grows open as the soft tissue deforms.

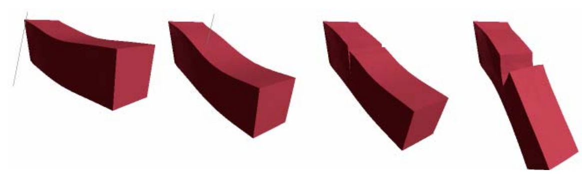

Figure. 3 Cutting and deformation of a cuboid.

Scene 2: To demonstrate the effectiveness of the creation of pre-computed quantity of newly added element, a comparison is made between the proposed method and method which re-computes the need quantity for the newly added element. Comparison is made between the different processing time to modify mesh topology and to update pre-computed quantity by two methods. Method 1 is our cutting method, which copies pre-computed data for newly added elements from the old element. Method 2 represents method which re-computes the pre-computed quantity for newly added elements while other aspects are the same as our cutting method. Hundreds of elements are cut all at once and processing time is recorded, Shown in Figure 4.

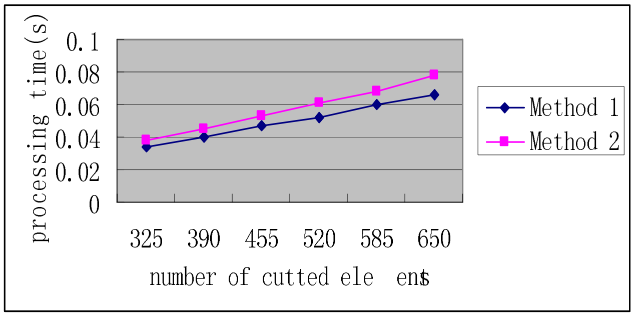

Figure. 4 Performance comparison between proposed method and method re-computes pre-computed quantity for newly added element.

Figure 4 shows Method 1 reduced much processing time compared with Method 2, which is helpful for real-time simulation.

Scene 3: The mesh which represents liver contains 6097 tetrahedra. Some of left most nodes of the mesh are fixed. A line segment which represents the knife in surgery cuts the soft tissue. In the beginning of cutting simulation, the liver deforms under gravity, and then it reaches equilibrium because of gravity and inner stress. When the knife moves, the liver is cutted gradually. The old balance is destroyed and the right part of the liver begins to sag, resulting the incision open. This process is illustrated by Figure. 5.

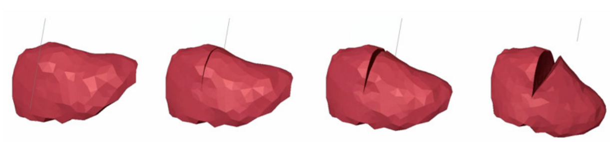

Figure. 5 Cutting simulation of liver.

As the more and more part of the mesh cutted, the number of elements in the mesh increases, making the cost of computation of deformation increases. However, cutting is still simulation in real-time, since the frame rate of our simulator always stays above 40Hz.

Comparison between proposed method and some other method in literature is also made. Zhong [6] can simulate cutting on mesh with 1097 nodes and 4780 element in real-time, but incision appearance is not good and the soft tissue is linear, shown in Figure. 6(a). Wu Wen [13] can get a smooth incision, but its model is linear and the size of the operational part which can perform cutting is small, with 152 nodes and 416 elements, shown in Figure. 6(b). Figure. 6(c) is the outcome of our method.

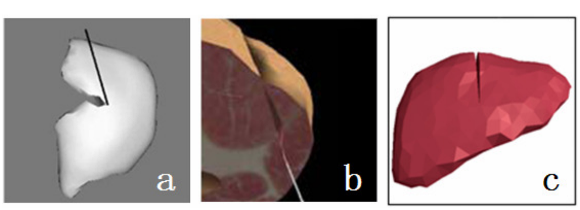

Figure. 6 Visual feedback comparison between proposed method and other methods

V. Conclusion

This paper proposed a new real-time cutting method for soft tissue. It pre-computes on element level, locally modifies mesh topology. Our method can eliminate re-computations of the pre-computed quantities. Cutting simulation of soft tissue with 6097 tetrahedron elements in real-time is achieved. Nonlinear property exhibits where cutting proceeding. A comparison shows our method can achieve a good visual feedback.

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