A Virtual Surgical Training System that Simulates Cutting of Soft Tissue Using a Modified Pre-computed Elastic Model

Kyaw Kyar Toe[1]; Weimin Huang[1]; Tao Yang[1,3]; Yuping Duan[1]; Jiayin Zhou[1]; Yi Su[2]; Soo-Kng Teo[2]; Selvaraj Senthil Kumar [2]; Calvin Chi-Wan Lim[2]; Chee Kong Chui[3] and Stephen Chang[4]

Abstract— **This work presents a surgical training system that incorporates cutting operation of soft tissue simulated based on a modified pre-computed linear elastic model in the Simulation Open Framework Architecture (SOFA) environment. A pre-computed linear elastic model used for the simulation of soft tissue deformation involves computing the compliance matrix *a priori* based on the topological information of the mesh. While this process may require a few minutes to several hours, based on the number of vertices in the mesh, it needs only to be computed once and allows real-time computation of the subsequent soft tissue deformation. However, as the compliance matrix is based on the initial topology of the mesh, it does not allow any topological changes during simulation, such as cutting or tearing of the mesh. This work proposes a way to modify the pre-computed data by correcting the topological connectivity in the compliance matrix, without re-computing the compliance matrix which is computationally expensive.**

Keywords—Virtual surgical training, laparoscopic surgery, physically-based simulation, mesh cutting, pre-computed elastic model.

I. INTRODUCTION

Laparoscopic surgery is a minimally invasive surgery or keyhole surgery commonly used for abdominal surgeries where operations are performed using instruments inserted through small holes. This intervention is popular as it does not require large incision to be made on the abdomen. Though laparoscopic surgery is relatively safe, special training is needed as there are challenges such as limited operational cavity space, lack of depth perception, and lack of proficiency in long tool manipulation. These limitations necessitate that the surgeon develops the appropriate skills to perform laparoscopic surgery proficiently [1]. Traditionally, the *master-apprentice* model is used to train novice surgeons, whereby the senior surgeon forms a small group of trainees to teach the basic laparoscopic skills and shares his/her expertise on the operation. Due to technological advances, medical training paradigm has changed these days. Virtual reality technologies are used to set up surgical simulators specially designed for training purpose. To this end, we have built the Image-guided Robot Assisted Surgical (IRAS) Training System to address the training needs of laparoscopic surgery. The IRAS system consists of hardware and software components. An important feature of the software components is the computational system that simulates the cutting operation of deformable soft tissue.

As presented by Delingette and Ayache [2], the simulated deformation of human organ using a pre-computed linear elastic model can achieve high biomedical realism while maintaining high computational efficiency. Such a model required that the compliance matrix be pre-computed before the simulation, based on the topological information of the finite element mesh. This allowed subsequent computation to take place efficiently. Topological changes in the mesh cannot be performed on the fly with this method. To perform mesh cutting, a hybrid model was proposed [3]. The hybrid model was constructed with a part simulated by the Tensor-Mass method which was used for the cutting operation, and the other part simulated using the pre-computed method which will be intact during the cutting. These two parts are connected. The interface vertices need to be handled specially to maintain continuity between the two parts. Essentially, this method limits the area (vertices) for cutting, since only the Tensor-Mass simulation part can be cut and it should be limited to a minimal size to increase the performance.

Wang *et al.* [4] proposed a method to combine the TLED (Total Lagrangian Explicit Dynamic) algorithm and virtual node algorithm to perform the cutting. Due to the virtual node algorithm, it added new nodes and tetrahedrons to the mesh. To incorporate the newly added nodes, the pre-computed matrix was updated by copying information from elements of the original matrix and adding new information to new matrix. This method is applicable to partial cutting of meshes. For full cutting of the organ, i.e., cutting the organ into two disconnected parts, a problem will occur since the two parts of the organs are still logically connected in the compliance matrix and deformation in one part will affect the other.

In this paper, we provide a new way to perform full cutting without expensive re-computation of the compliance matrix. To achieve better visual appeal, the portion where cutting is to take place is adaptively meshed with denser elements so that removal of elements will not be visually apparent. The paper is organized as follows: Section II presents an overview of the surgical system that we had developed. Session III is a brief on the physical engine used

[1] K.K. Toe, W. Huang, T. Yang, Y. Duan and J. Zhou are with the Neural and Biomedical Department, Institute for Infocomm Research, A*STAR, Singapore, 138632 (email: {kktoe, wmhuang, tyang, duany, jzhou}@i2r.a-star.edu.sg)

[2] Y. Su, S.K. Teo, S. Senthil Kumar and C.C.W. Lim are with the Institute of High Performance Computing, A*STAR, Singapore, 138632 (email: {suyi, teosk, selvarajsk, limcw}@ihpc.a-star.edu.sg)

[3] T. Yang and C.K. Chui are with the Department of Mechanical Engineering, National University of Singapore, Singapore, 119077, (email: mpecck@nus.edu.sg)

[4] S. Chang is with the National University Hospital, Singapore, 119074, (email: cfscky@nus.edu.sg)

for simulating different objects and the associated pre-computing model. Session IV is the proposed method to enable full cutting operation using a modified pre-computing model. Session V is the result and Session VI concludes this paper.

II. SURGICAL SIMULATION SYSTEM AND SCENARIO

The Image-guided Robot Assisted Surgical (IRAS) Training System (see Figure 1) is a surgical simulation system used for training in laparoscopic cholecystectomy, i.e., surgical removal of the gallbladder. It consists of a robot surgical manipulator which is the main hardware user interface. For the simulation platform, we use Simulation Open Framework Architecture (SOFA) as the core physics engine. And this had been integrated with our in-house OpenGL-based graphics rendering module. The virtual scenario for cholecystectomy in the IRAS System consists of a group of interconnected organs: the liver and biliary connected by connective tissues; and the cystic duct connects the biliary and common bile duct.

Figure 1. IRAS for patient specific surgical training.

The IRAS System is designed to be patient-specific. The virtual organs used in the system are generated from computed tomography (CT) data of real patients. The dataset generated is then configured for the system. The advantage of using patient-specific information is that training can be conducted for certain operation involving special cases, or the surgeon can use the system for surgical planning of a particular patient.

The graphics rendering module is developed based on OpenGL. It incorporates texture mapping, bump shading, and lighting and shadow effects to increase the realism of the rendered scene [5]. In addition, visual effect for real-time bleeding is activated to mimic bleeding and perfusion due to injury of the organ by inappropriate manipulation of the surgical tool based on the degree of impact, collision angle, contact pressure, etc. Smokes effect and audio feedbacks to the user are also incorporated in the system for the tissue burning process. It is activated by stepping on the foot paddle when the hook is in contact with the tissues [6]. To mimic real clinical requirements, the IRAS System is equipped with different virtual surgical instruments used for different purposes. These include the bowel graspers, the clip applicators, the curved forceps, the scissors and the hook. A user has the freedom to select the tool, but the user needs to choose the right and suitable instrument for the operation, which is part of the training objective.

The robotic surgical manipulator is the main human-machine interface of the IRAS System. It is used for controlling the virtual surgical instruments to perform the virtual surgery. It is designed to mimic real instruments used in actual laparoscopic surgery. In the IRAS System, the full detailed procedure of the gallbladder removal can be simulated. The procedure consists of the following six sub-tasks, as illustrated in Figure 2:

1. Lifting up and securing of the liver
2. Exposing the cystic duct by removing fat tissues between cystic duct and liver
3. Checking the clearance of tissues between the cystic duct and liver
4. Applying the clips so that no bile liquid is leaked from cystic duct
5. Cutting the cystic duct
6. Dissecting the gallbladder by removing the fat tissue between gallbladder and liver

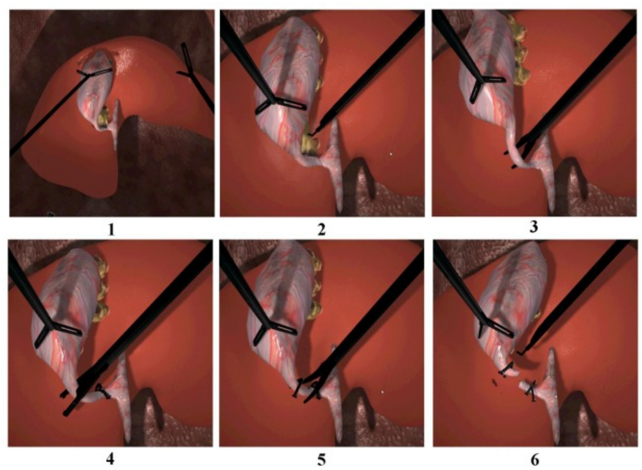


Figure 2. Sub-tasks to perform removal of gallbladder.

The user has to perform the operation in a correct sequential manner as it is designed as a linear procedure. After the cutting operation, the system is paused for a while to modify the old compliance file. The system then reload the scene with new modified compliance file to adapt the current system state. After reloading the scene, the two parts of the organ are fully seperated making the simulation realistic in subsequent processes.

III. SIMULATION BASED ON SOFA

The SOFA is an open source framework targeted for medical simulation [7]. It is a fast prototyping tool and good platform for bio-material testing for medical research.

For fast and efficient prototyping, SOFA's modeler application can be easily used for testing material properties such as stiffness of the organ, tissue deformation, interaction of surgical tool with organ, and kinetic tool movement using spring-joints. A scene graph structure is used to represent the virtual scene in an editable XML format. SOFA can be integrated into a C/C++ program as an open source library.

In building the SOFA scene for IRAS, the liver is created as static model. And the biliary is created as dynamic model (since the topology and geometry of the biliary needs to be changed when the cystic duct is being cut). The soft tissue simulation is done by using the finite element method (FEM) based on tetrahedral elements. Linear Complementary Problem (LCP) formulation is used to solve the constraints. Simple and fast method of tetrahedrons removal is used to mimic tissue division. Virtual object interactions in the system, such as grasping and holding the organs, are physically simulated using friction forces between the surfaces of tool and organs. Surgical tools are simulated as articulated kinematic rigid objects. The handles from surgical manipulator directly control the virtual tool movement.

A. Pre-computed Model

The standard FEM computation time is too long for real time deformation of the mesh. To achieve real time performance, a pre-computed model is used by pre-generating the compliance matrix before the simulation starts and using it during the simulation. The time taken to generate that compliance matrix is time consuming. It is based on the number of vertices of the mesh and the stiffness of the soft tissue [2]. A large model consisting of 2442 vertices and 9651 tetrahedrons is used for testing. The Poisson ratio of the model is set to 0.45 and the Young's modulus is set to 1000kPa. The computation takes nearly 13 hours 30 minutes on Intel Core i7 2600 CPU @ 3.40 GHz. The file size of the compliance matrix is 409 MB. Obviously, it is undesirable to re-compute the model again after the cutting operation. However, any cutting operation would change the topology of the mesh, and the compliance matrix file has to be re-generated.

IV. COMPLIANCE MATRIX MODIFICATION METHOD

To cater to topological changes in the mesh due to cutting operations, we propose a method to modify the compliance matrix without having to perform a complete re-generation. Prior to the simulation, the pre-computed compliance matrix binary file is generated as a one-time operation. This file is used throughout the simulation. During the cutting of the cystic duct, the region to be split by the cut is determined by the intersection between cutting plane of the scissors and the cystic duct. The tetrahedrons in this cut region are removed resulting in two disconnected meshes. In this process, the topology of the tetrahedron mesh of cystic duct is changed. Since cutting is represented by removal of elements, to achieve better visual quality, the cystic duct was adaptively meshed with denser tetrahedrons as compared to other parts of the organ.

If the pre-computed model is not updated correspondingly after the cutting operation, all the vertices will still be logically connected by means of displacement correction, even though the gallbladder and common bile duct appear as two separate pieces visually. This implies that if neighboring organs or surgical tool should touch the gallbladder, the internal forces caused by the interaction on the gallbladder will be disseminated to the common bile duct. It causes the common bile duct being affected as well, even though they should be independent of each other.

A. Compliance matrix

In the work by Cotin *et al.* [8], the compliance values of fixed nodes in the mesh are set to zero. It means that these nodes are fixed at particular locations. These fixed vertices will not be affected by the displacement of other vertices in the mesh. When the gallbladder and common bile duct are separated, the forces on the vertices from one organ should not affect the vertices on the other. To achieve this, we need to modify the compliance values for such pairs of vertices.

B. Algorithm

The data structure of the compliance matrix is illustrated in Figure 3. The size of compliance matrix is $3N_s \times 3N_s$, where G_{ss} is the n×n matrix such that each component is the 3×3 sub-matrix.

G_{ss}^{11}	G_{ss}^{12}	⋯	G_{ss}^{1n}
G_{ss}^{21}	G_{ss}^{22}	⋯	G_{ss}^{2n}
⋮	⋮		⋮
G_{ss}^{n1}	G_{ss}^{n2}	⋯	G_{ss}^{nn}

Figure 3. The illustration of compliance matrix where [G_{ss}^{ij}] is the 3×3 submatrix of G_{ss} associated to the i-j vertice pair. N stands for the number of vertices in the mesh s.

The first phase of the process is the removal of vertices. In the cutting process, some of the vertices may be deleted from the vertex list. These deleted vertex IDs are marked in a separate array. The compliance values related to these deleted vertices need to be deleted from the compliance matrix as well. The algorithm used for this purpose is described as Algorithm 1where N stands for the number of vertices.

Algorithm 1 Deleting the removed vertices from matrix

```
Input: Compliance Matrix Gss, The list of deleted vertices
Output: Compliance Matrix without deleted vertices
1: for all i such that N >= i >= 1
2:     if i has been removed
3:         for all j such that N >= j >= 1
4:             delete G_ss^ij and G_ss^ji
5:         end for
6:     end if
7: end for
```

The second phase of the operation is setting 0 to the logically disconnected vertices. Before performing this algorithm, the vertices on the two parts of organs, i.e., the biliary and common bile duct, are marked as part 1 and part 2, respectively. If the vertices pairs are from different organ parts, it needs to be set to 0.

```
Algorithm 2 Setting 0 to the disconnected vertices pairs

Input: Compliance Matrix G_ss without deleted vertices,
       Part 1 and Part 2 vertices list
Output: Modified Compliance Matrix
for all i such that 1 <= i <= N
    if i is from Part 2
        for all j such that 1 <= j <= N
            if j is from Part 1
                Set G_ss^ij to 0
            else
                Leave G_ss^ij unchanged
            end if
        end for
    else if i is from Part 1
        for all j such that 1 <= j <= N
            if j is from Part 2
                Set G_ss^ij to 0
            else
                Leave G_ss^ij unchanged
            end if
        end for
    end if
end for
```

V. RESULT

After cutting the cystic duct, we modify the pre-computed compliance matrix by using Algorithms 1 and 2. The time taken for modifying the binary is much less than the time for re-computing it. After the modification, the scene is then reloaded using the modified pre-computed model. The result is shown in Fig 2(6). It was observed that the common bile duct is in equilibrium state. The grasper is holding the gallbladder, pushing it up. The deformation of the gallbladder does not affect the common bile duct.

We compared the deformation of the organ simulated by two different methods. The same force is applied to the identical vertex and the deformation states of the organ is recorded and analyzed. The comparison is illustrated in Figure 4. The maximum distance between the vertices is 0.1246 mm. The mean difference of the vertex position is 0.0198 mm and the standard deviation between two set of vertices is 0.0192. These statistics show that the modifying method can achieve the similar deformation results.

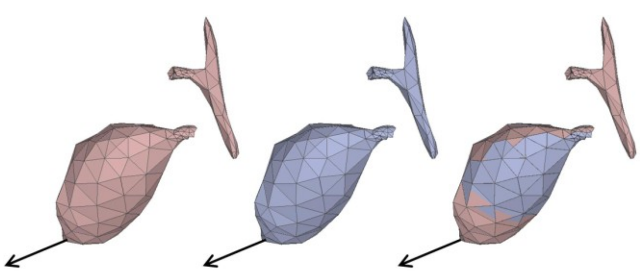
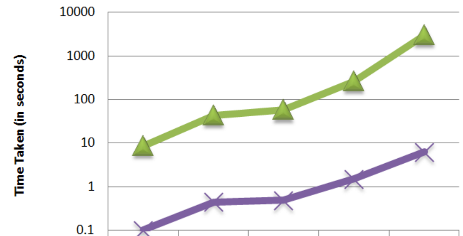


Figure 4. The deformation simulating by the re-generated compliance matrix is taken as benchmark (pink). The deformation by the modified method (blue) was observed that two deformations are almost identical.

We have measured the time taken to re-generate the compliance matrix and the time taken to modify and update the compliance matrix, as illustrated in Figure 5. The comparison is done on five mesh models with different numbers of tetrahedrons. By adding our proposed solution to the pre-computed model, cutting operations are now feasible without sacrificing realism and compute efficiency.



Number of tet	140	399	407	961	1918
Pre-computed	8.6	42.9	57.6	263.2	2992.3
Proposed	0.1	0.44	0.49	1.5	6.23

Figure 5. The comparison of time taken to re-generate the compliance matrix (Pre-computed) and to modify the compliance matrix (Proposed) for five different meshes comprising of 140, 399, 407, 961 and 1918 vertices. In all meshes, the parameters used are Poisson ratio = 0.45, and Young's modulus = 1000k.

VI. CONCLUSION

Even though the method has the weakness of a slight pause during the simulation to allow modification of the compliance matrix and to reload the scene, it is still acceptable and can afford the full advantage of using a pre-computed model, where cutting was previously infeasible. This method is only applicable to single cut operation which splits the organ into two pieces. Future work comprises simulation of gradual cutting and multi-cut procedures.

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