# A minimal invasive surgery simulator employing a novel hybrid cutting method

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*Abstract*—**In this paper, we propose full-fledged minimal invasive surgery simulator under laparoscopic environment. In addition, a novel hybrid cutting technique for volumetric tetrahedral meshed soft tissue models is presented. A progressive cutting method is applied to the model's surface elements, where the core of the model is cut non-progressively. Our work combines the advantages of both subdivision methods into one technique. It leads to an increase in the stability of the soft tissue deformation simulation and enhances interactivity, by reducing the cutting complexity. A laparoscopic resection of the kidney tumor surgery is used for case study.**

*Keywords*—**Virtual surgery, cutting, progressive, non-progressive**

## I. INTRODUCTION

Nowadays, with the development of the computer technologies, the surgery training can be performed on the computer with the haptic devices.

Our work covers the main steps to build a full-fledged virtual surgery training system enabling cutting operation. First, we shortly introduce the framework of the system, the step by step explanation of how to build the virtual surgery environment. Next, we shortly reviewed current cutting research and finally proposed an advanced hybrid cutting approach combining progressive and non-progressive cutting.

The paper is organized as follows: in the next section, the methods to build the architecture and the hybrid cutting method are described in detail. In the result section, a lot of tests have been done to demonstrate the performance of our algorithms. Then the discussion and conclusion follow.

## II. METHODOLOGY

### A. Framework of the minimal invasive surgery system under laparoscopic environment

The main architecture of our surgery simulation system is illustrated in Fig.1. It contains three major parts: a data processing unit (Fig.1.a) which converts DICOM data into volume mesh; a set of virtual surgery algorithms (Fig.1.b), a user interface façade part (Fig.1.c) and the devices (Fig.1.d and e).

The data processing unit performs two steps to convert the original DICOM (Digital Imaging and Communications in Medicine) data to volume mesh: smooth and volume meshing.

The component of virtual surgery algorithms is the core part of our system. "Observer" pattern is used in the design of the architecture. Methods of different functions are wrapped into a set of low-coupled modules. We have soft-tissue-modeling using constrained particle system [1], collision detection using hierarchical spatial hashing [2], collision response, cutting and clipping modules currently. They provide surface to interact with a 'whiteboard', which contains the global information of the system like the organ mesh or the device status. The surgery methods like cutting or collision detection work as the observer of the whiteboard. If the whiteboard's status changes, the whiteboard notifies its observer to take corresponding actions. For instance, if the organ mesh of whiteboard is changed by cutting module, the "whiteboard" will notify the soft-tissue-modeling module to rebuild the soft tissue model. This structure ensures the good encapsulation and the scalability of the system.

The user interface contains a monitor to render the 3D objects (Fig.1.d), and a "Virtual laparoscopic" interface device (Fig.1.e) which is provided by the 'IMMERSION' cooperation, enables the user to perform the common gestures like cutting, grasping and clipping,.

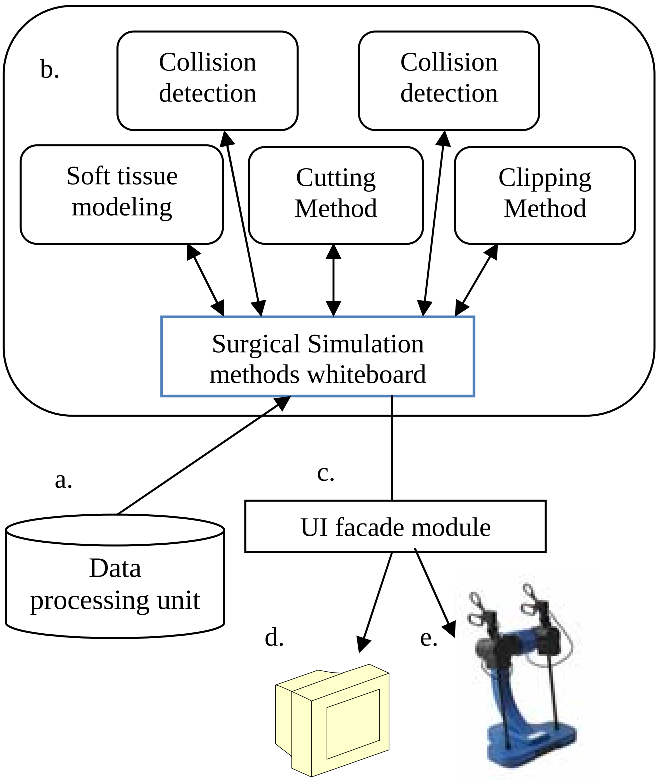

Fig.1The architecture of the system

### B. Hybrid cutting combing Progressive cutting and non-progressive methods

Generally, cutting procedures fall into two categories: the progressive cutting [3] and non-progressive cutting [4].Non-progressive cutting methods subdivide the elements after the tool has left the element. The cutting procedure is not visualized for the duration from the tool's first entry into the element until the tool's exit. A noticeable lag between the actual tool's position and the cut occurs, especially for low refined meshes.

Progressive cutting methods avoid the lag-behind effect. It subdivides elements while the tool is still in intersection with them. The progressive approach addressed the lag-behind problem by the removing and replacing the temporary subdivisions [5] or by using a state machine [6].

Though the progressive cutting prevents a lag-behind effect and yields a visually more satisfactory result, it is more complex in matters of time and storage for managing the temporary subdivision. Additionally, it poses more instability problems to the soft tissue simulation, since for short time periods very small and degenerated tetrahedra can be generated which are devastating to soft-tissue modeling.

We present a novel hybrid cutting method that combines both advantages of the visual appealing progressive cutting and the benefits of the non-progressive method, which is superior in performance and stability. The crucial concept of the method is, firstly, to cut an outer margin of tetrahedra along the outer hull of the organ progressively (Figure.2), and secondly, to apply non-progressive cutting to the inner core of the soft tissue model. This generates the impression of a smooth cut, where the user has the main visual access to the model and at the same time a more efficient algorithm for the model core can be used. The outer margin of the model's hull is given by tetrahedra that share a point with the surface.

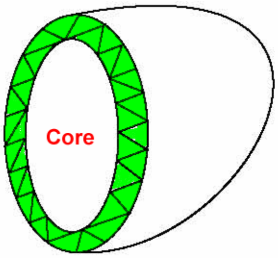

Fig.2 the surface tetrahedra of the outer hull in the model are cut progressively (green). For the core part of the model non-progressive subdivision is applied.

Progressive cutting of the outer hull is realized via an optimized state machine algorithm. We deploy minimal elements subdivision pattern [7] within the state machine framework, in order to keep the mesh complexity low.

The inner core of the model is non-progressively subdivided, consistently with the same subdivision patterns as the outer mesh part. Those patterns correspond to the final states of a state machine. Degenerated tetrahedra also emerge when cutting is performed close to a mass point. For stability increase, snapping [8] was implemented for non-progressive cutting part of the algorithm.

## II. RESULTS

### A. *Experiments setup*

Our tests were conducted on a standard PC running Ubuntu Linux as operating system. It is equipped with 1.25GB RAM, AMD Athlon 64bit and a 3000+ with a Nvidia Geforce4 440 Go graphics card with 64 MB video memory. Meshing and cutting methods were implemented in C++. For the visualization of the model and the cutting tool, we employed the open source graphics library VTK . The assembly of the system components, user interface and graphics pipeline was done with Python.

### B. *System overview*

Fig.3 shows the visual view of our system. Two views are switchable; one is the global view while the other is the laparoscopic view. The user moves the endoscope by mouse to locate the area of interest inside the human abdomen cavity.

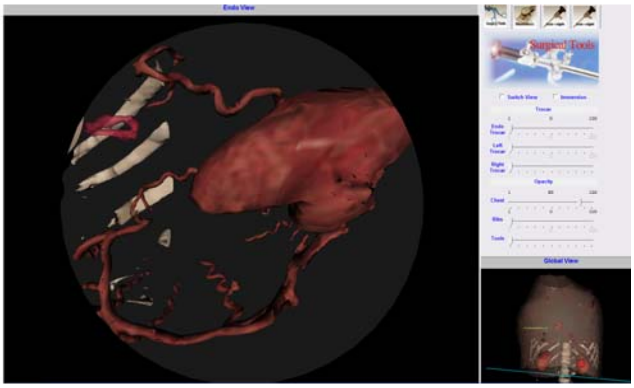

Fig.3. The visual view of our system

The virtual laparoscopic device enables the users to perform the basic surgery gestures such as object grasping, transferring, clipping and cutting. Surgery tools are modeled as real tools and keep synchronous with the device. Thus the user can perform cutting operation on the virtual organs in the system.

The coronary and the rib in this environment are displayed for realism enhancement, the target organ, the kidney in this work, is modeled into the mathematical model for future manipulation like cutting. In the future, other gestures, like suture, can be easily integrated into our system by adding an independent module which providing interface to the 'whiteboard' module.

### C. *Visual performance of Hybrid cutting approach*

In this and the following 2 subsections, we will evaluate our hybrid cutting method from four aspects: the visual performance, the impact on the mesh complexity, the impact on the mesh quality, and the algorithm efficiency.

A comparison of the visual result of the very same cut with non-progressive minimal element subdivision and with our hybrid approach can be found in Figure 4 on the following page. Note the lack-behind effect that occurs with non-progressive cutting. The incision is not modeled up to the current tool's position and this creates uncontinuities while the cut is performed.

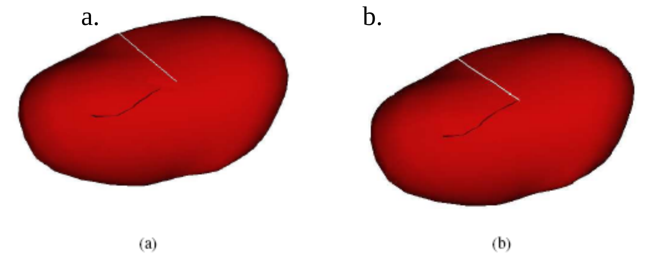

Figure 4: The same cut into a kidney with (a) non-progressive cutting and (b) hybrid cutting. The incision with non-progressive cutting is lacking behind the cutting tool's position.

Fig.5 shows the visual result in dissecting a part of kidney tumor in our surgery simulator system. The dissected part falls because of the gravity on the soft-tissue model.

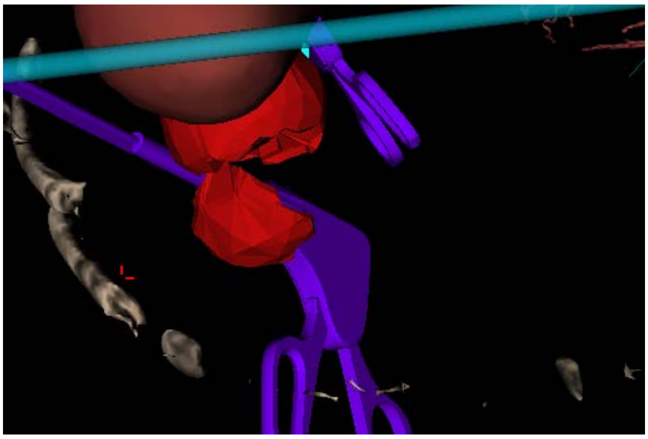

Fig. 5. Dissecting a part of tumor

### *D. Impact on mesh quality and mesh complexity of Hybrid cutting approach*

Fig. 6 illustrates the mesh quality decrease over the duration of a sample cut into a kidney mesh. The quality is measured by the average mean of the maximal edge aspect ratio over all elements. The maximal aspect ratio is obtained by the quotient of the shortest and longest edge of a tetrahedron. The diagram shows that for progressive cutting the overall mesh quality is lower during the cut than for non-progressive cutting. Additionally the progressive cutting graph possesses abrupt fall-offs into local minima. These originate from extremely shaped temporary sub-tetrahedra. With hybrid cutting, less of these temporary degeneracies occur, since the non-progressive subdivided tetrahedra leave the aspect ratios more balanced. This improves the mesh quality and simulation stability during cutting.

To measure the impact on the mesh complexity, the diagram in Figure 7 compares the element increase of the ordinary symmetric subdivision [9], with our hybrid cutting approach that uses minimal subdivision patterns [8] in the inner core and the symmetric subdivision in the hull. The reason to choose symmetric subdivision patterns for progressive cutting is that the symmetric subdivision enables the progressive cutting to have the minimal number of operations. Observing the chart in Fig.7, the standard symmetric subdivision almost triples the initial number of tetrahedra during the cut while the hybrid cutting generates 1.5 times as much elements as the initial number of elements. Hybrid cutting keeps the mesh complexity much lower than the ordinary symmetric subdivision approach and consequently promotes performance and speed of the soft tissue simulation.

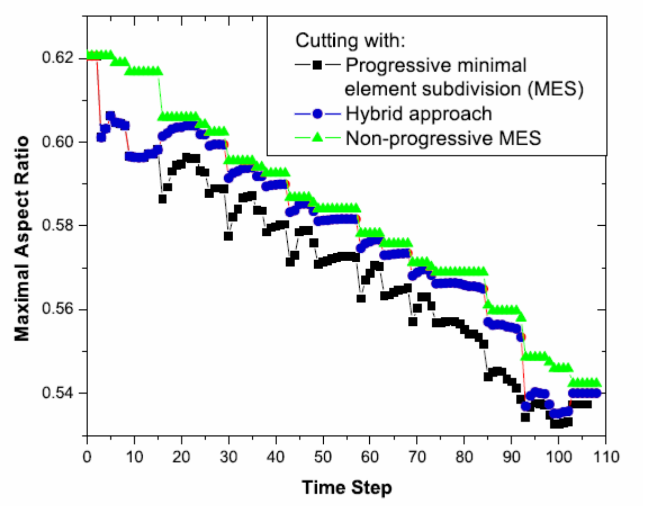

Fig.6. Shows the decrease of the mesh quality during cutting with progressive, non-progressive and hybrid cutting

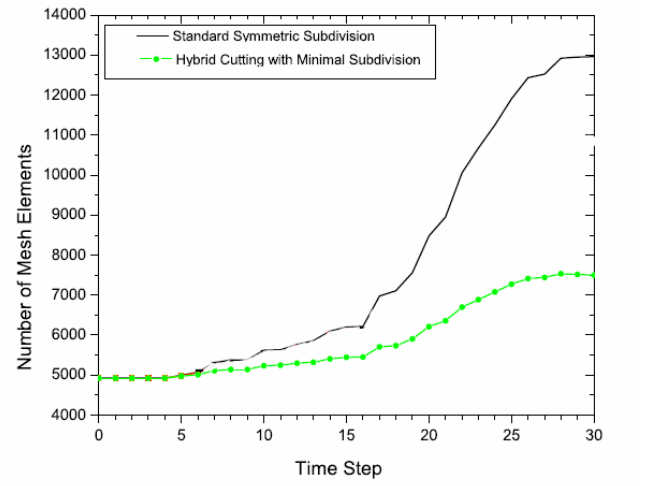

Figure 7: The overall element increase in the kidney model over the period of the cut with symmetric and minimal element subdivision implementations. Hybrid cutting generates much less mesh elements than the ordinary symmetric subdivision approach. Although the short cut improved algorithm clearly leads to an improvement.

### *D. Algorithm efficiency of hybrid cutting approach*

In the following we have a look on the efficiency in term of operation types that are used for the management of temporary subdivisions. The column diagram in Figure 8 on the following page shows the comparison of the overall number of used delete operations and update operations for three different algorithms over the interval of the cut. The number of operations used is plotted on the y-axis. The x-axis shows two types of operations used for the realization of temporary subdivision replacements. We compare the standard progressive cutting approach, our implementation of non-progressive cutting to our hybrid cutting approach.

Observing the chart, we can see that It is possible to avoid 4 out of 5 operations in total with our hybrid cutting approach compared to the ordinary progressive cutting. Though the operation number of the hybrid cutting is much higher to the number of non-progressive cutting, which is too low to be visible in the diagram, the result is still a preferable moderation considering the visual performance.

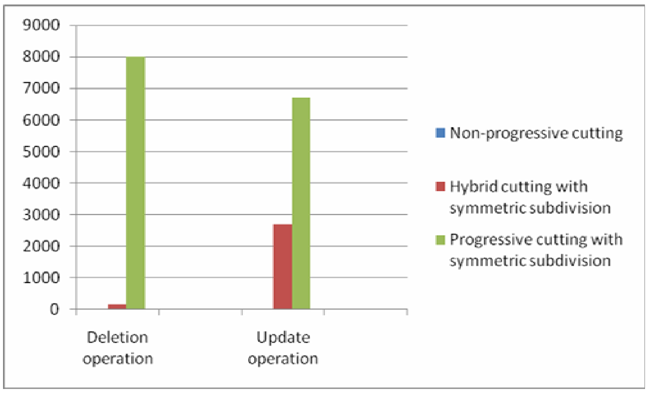

Figure 8: The comparison of the number of two types of operations used for the realization of temporary subdivision replacements with different methods for the sample cut is shown.

## IV. DISCUSSION

We evaluated our cutting methods on how the different cutting algorithms influence the mesh complexity, the mesh quality, the effectiveness, and how the methods perform visually. The experiment concerning the mesh complexity generally shows that cutting with subdivision methods leads to a rapid increase of elements in the model. Hybrid cutting in comparison to the ordinary symmetric subdivision approach reduces the model's complexity severely.

From the experiments of the mesh quality, regarding the max aspect ratio (maxAR) follows that all cutting methods with minimal element subdivision, including our hybrid technique, retain a better mesh quality than both symmetric approaches.

In matters of simulation stability, we did investigations on the impact of progressive cutting on the mass spring model in respect to the temporary mesh quality during a cut. The non-progressive subdivision, the progressive subdivision and the hybrid approach were compared according to their average values of the maxAR of all tetrahedral over the duration of a cut. When solely progressive cutting is applied abrupt fall-offs of the averaged maxAR value into local minima occur, due to extreme shaped temporary subdivisions. Non-progressive cutting has a steady stepwise fall-off. The measurement points out that the hybrid method reduces extremely shaped elements due to temporary subdivisions. Consequently, hybrid cutting, that has a similar result as progressive cutting in terms of the constant follow-up of the modeled incision to the tool's position, can avoid the simulation instabilities inflicted by degeneracies due to temporary subdivisions for the core part of the mesh. This way the overall stability of the mesh is increased

## V. CONCLUSION

In this paper, we present a full-fledged surgery simulator with good scalability and high encapsulation. The hybrid cutting approach proposed in this contribution improves performance and soft tissue simulation stability. The model is partially cut with the benefits of the non-progressive cutting without the drawback of major visual disturbances. It is best applicable for voluminous organs with a homogeneous mesh representation. This meets the requirement for stable soft tissue simulations. The efficiency of the hybrid cutting depends on the percentage of core elements in respect to the overall element count, which is influenced by mesh quality and refinement.

## ACKNOWLEDGMENT

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