Building soft-tissue constraints through a mass spring system for liver surgical simulations

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Building soft-tissue constraints through a mass spring system for liver surgical simulations

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1. Purpose

Constraint between soft tissues (derived from MRI/CT image datasets) is a special type of intra-collision, with a spectrum of values for all the intra-surface frictions, e.g. an infinitely large value for those joined together. Different tissues have respective densities and stiffness, exhibiting various viscous and elastic characteristics. In liver surgical operations, when multiple tissue deformation occurs and interventional imaging through CT/MRI is not highly recommended due to its potential hazard to surgeons, there is no simple way to trace the surgically significant relative locations of tumours and major hepatic vessels. We make this difficulty our challenge. Because of its real-time response, our system was firstly developed as a surgical training simulator.

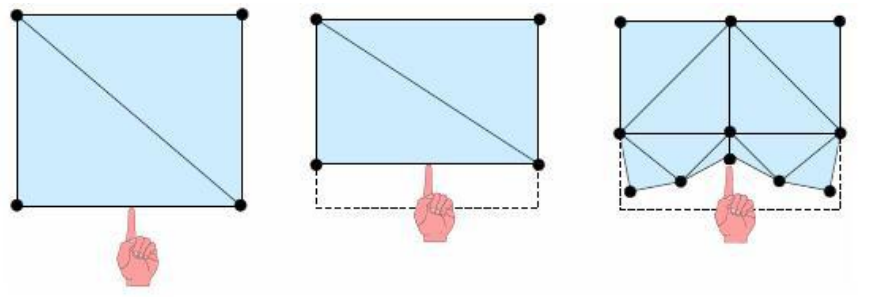
An enhanced physical model generation method was presented to best keep the boundary relationships between connecting soft tissues in surgeon training

simulations. This secured the deformations on the tissue boundaries, which within a distance of both sides of the boundary areas, were calculated in real-time with an improved accuracy. The underlying approach is the single organ Mass Spring System (MSS) (by Paloc C., Belo F., et al 2003) which, for the first time, introduced an on-the-fly mesh refinement to the physical modelling circle. This method allows a real-time eformation response on a normal PC with only one CPU (Pentium 4, 2 GHz) and 512MB of RAM.

Refining and simplifying a three-dimensional mesh are topics which have been widely studied in various research areas to achieve efficiency and high performance. In physical modeling, previous classic work which relied on a multiresolution presentation was built on single objects, and mostly off-line in a preprocessing step. In contrast, our new proposed model is a continuous process based on Paloc's model whose most significant feature was able to on-line refine a local adaptive three-dimensional Delaunay mesh during the real-time interaction. Paloc's method was designed for presenting a single object, and assumed the initialized original mesh structure was randomly coarse, which demonstrated the compatibility and efficacy of its on-the-fly mesh refinement. However, when considering multi-soft object combinations, one of the most important tasks is to keep the boundary relationships among tissues, which is beyond the capability of this coarse original mesh model. To extend Paloc's strategy to multi-soft tissue models, our new method combined the shape-preserving advantages from traditional pre-processing multi-resolution mesh adaptation to build the starting physical model for maintaining tissue boundary relationships during deformations corresponding to manipulations. To also preserve the real-time response, some simplification is still crucial whereby acceptable performance is guaranteed.

Before moving on to work out a quality solution for this specific project, the requirements on mesh quality have to be clarified first.

1) tailored for mesh topological transformation; sensitive but tolerant to element size and shape changes;



A: before interaction; B: early stage of applying force; C: mesh adaptation

Figure_1A-C: Adaptation location based on region of interaction. (drawn by Paloc)

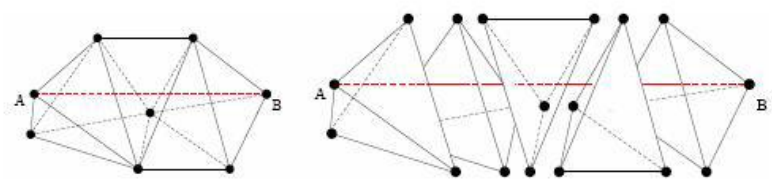
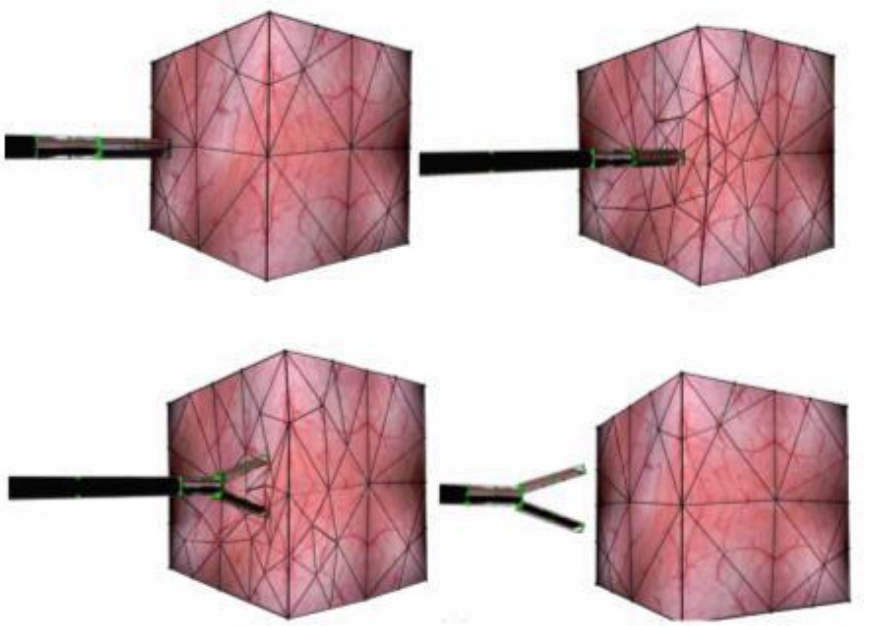


Figure_2: Mesh traversal from the vertices A to B (drawn by Paloc)

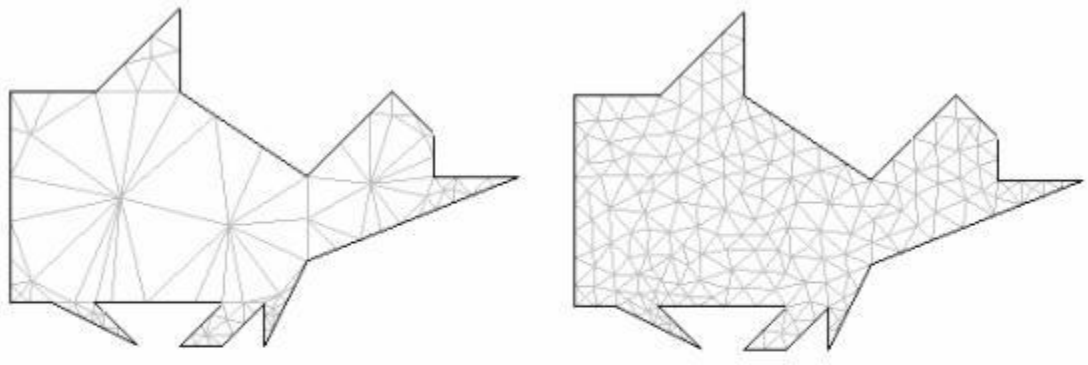
2) being sufficiently optimized to maintain tissue boundaries during simulation, at the same time, keep model fast enough to compute real-time response - on-the-fly local mesh adaptation;



A(upper left): before interactions; B(upper right)&C(lower left): local mesh adaptation happened in collision area; D(lower right): instrument left.

Figure_3A-D: on the fly mesh local adaptation in proximity of surgical instruments (Paloc 2002)

3) being smooth almost everywhere in any direction and therefore more amenable to numerical optimization; (Mesh-optimization based smoothing means making appropriate tradeoffs between the size and shape of an element to obtain higher numerical optimization in the discrete simulation. Figure_4 illustrates two types of non-smoothed mesh: A was non-smoothed in element sizes which might produce fake boundary effects on the sides of large primitives; B was non-smoothed in element shapes, or directions, which could be easily overcome by relocating all central points to element centers.)



A: non-smoothed mesh in primitive sizes; B: non-smoothed mesh in element shapes

Figure_4: non-smoothed mesh examples

2. Material and Methods

Generally speaking, physical modeling and its reaction to manipulations relies on the availability of meshes whose elements have the right shapes and sizes. The accuracy and speed of applications can be compromised by just a few bad elements. Intuition from asymptotic mathematics and engineering experience told us that equilateral elements were usually good, while skinny or skewed elements were usually bad. Classic methods in the literature all aim to avoid small angles; however, there was insufficient mathematical guidance for choosing the better of two elements of intermediate quality before the work of Shewchuk (2000) appeared.

Interpolation quality measures, based on $\|f-g\|_\infty$	
Size and shape (mostly size)	$\frac{1}{c_t r_{\text{mc}}^2}$
Scale-invariant (rarely useful)	$\frac{A}{r_{\text{mc}}^2}$
Conditioning quality measures	
Scale-invariant	$\frac{A}{3\ell_{\text{rms}}^2 + \sqrt{(3\ell_{\text{rms}}^2)^2 - 48A^2}}$
Scale-invariant (smooth)	$\frac{A}{\ell_{\text{rms}}^2}$

Table_1: Quality measures related to interpolation error or stiffness matrix conditioning for a single triangle. (Shewchuk 2000)

Although previously it was believed that small angles must be prohibited, in practice they are no harm to interpolation. Babuška and Aziz (1976) demonstrated that the accuracy of physical model solutions on triangular meshes degrades seriously if angles are allowed to approach 180°, but the same is not true when angles are allowed to approach 0°, so long as the largest angles are not too large (for instance, do not exceed 140^o, depending on the required level of simulation accuracy). In other words, small angles are not deleterious to the interpolation accuracy or the discrete error. However, small angles are still bad for matrix conditioning, as in physical models the conditioning of the stiffness matrices also depends on the sizes and shapes of the elements. Hence, other than small angles, the overall mesh quality can be better summarized via mathematical connections between mesh geometry, interpolation errors, and stiffness matrix conditioning. These relationships can be expressed by error bounds and element quality measures, which indicate the fitness of a triangle or tetrahedron for manipulations.

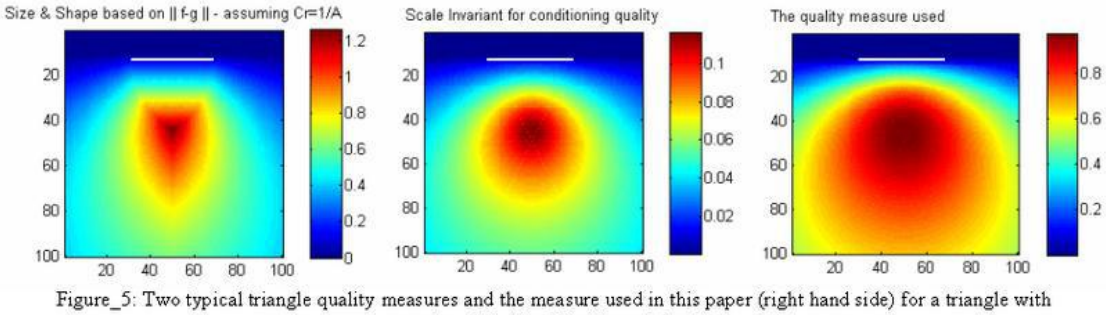


Figure_5: Two typical triangle quality measures and the measure used in this paper (right hand side) for a triangle with vertices (30, 15), (70, 15), and (x, y).

The quality of a mesh depends on the application that uses it. Based on Shewchuk's suggestion, for our purposes, error bounds and quality measures protecting the stiffness matrix conditioning are more important than minimizing interpolation errors. We obtained the tailored quality measure by choosing suitable values for the constant parameters and weighted the quality factors. Then this criterion was used to evaluate the primitive quality in the multiple soft tissue mesh initialization produced by different mesh optimization strategies.

In Constraint Delaunay Triangulation (CDT), in order to preserve the tissue boundaries, the input segments are included in the triangulation and the empty circle property is modified to apply only to points that can be seen from at least one edge of the triangle where the segments are treated as opaque, so that the boundary edges are preserved and not split into smaller edges by avoiding the insertion of additional points.

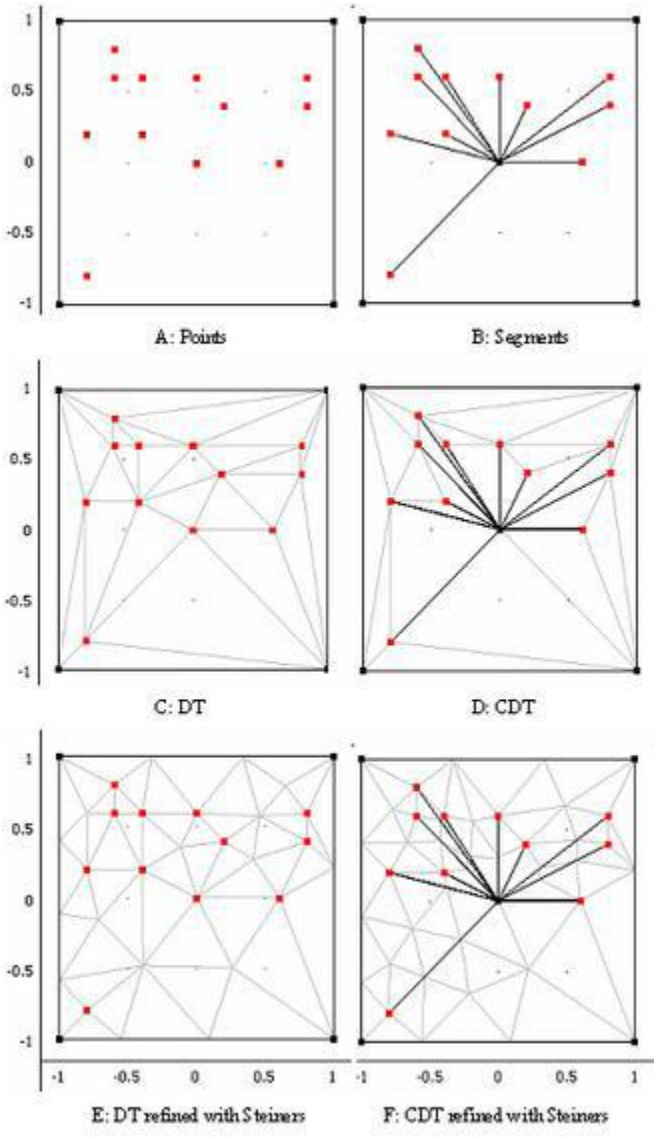
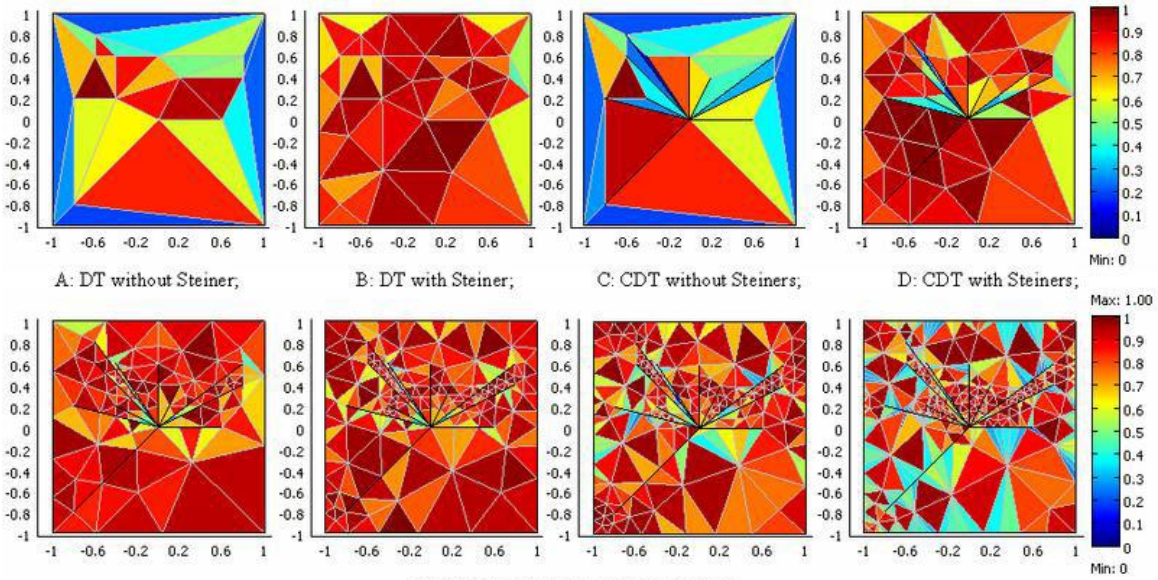


Figure_6 A-F: CDT vs. DT and their Delaunay refinement with Steiners

According to the quality criterion, either too few Steiners or too many will both cause trouble.



E-H: CDT with more and more Steiners.
Figure_7A-H: DT & CDT quality measurement

Curvature preservation appears to be very useful in helping improve element quality.

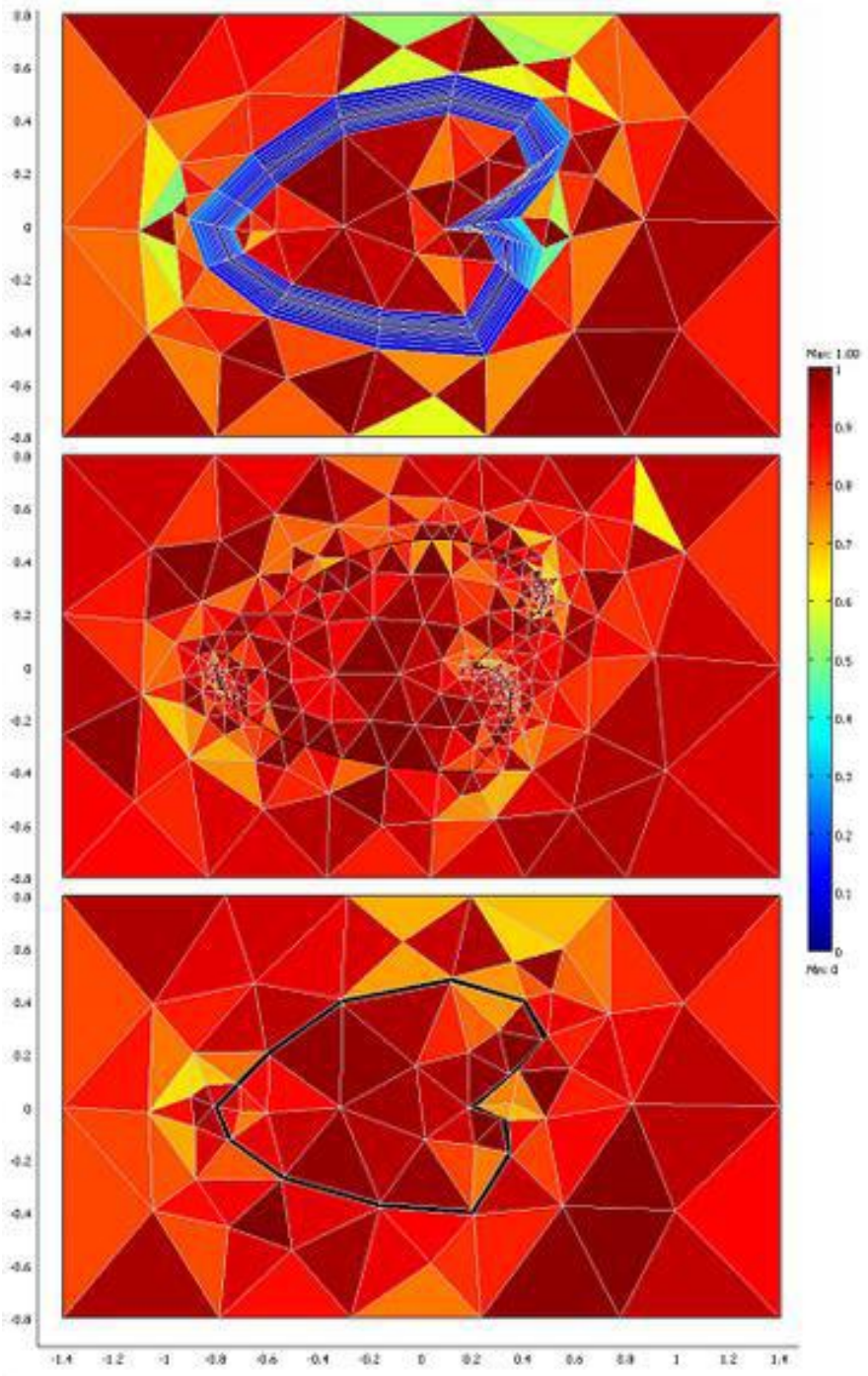


Figure_8. Curvature preserving is more helpful than sliver edge protection

However, too much curvature preservation will, on the contrary, make CDT 3-D solutions suffer large errors (the quality measure can be extended to three dimensions for tetrahedrons, following Shewchuk's recommendation).

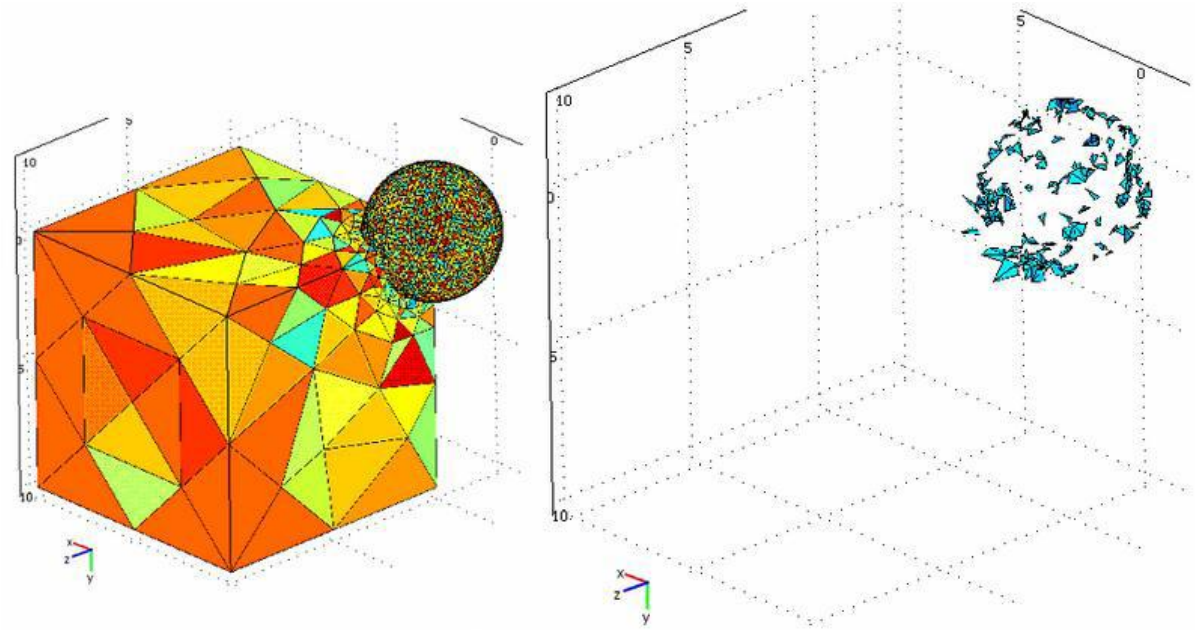


Figure_9: 3-D quality measure on multiple soft tissue model

Thus, we reach the solution: medium curvature preservation plus perfect mesh smoothness. Detailed parameter values can be flexible, depending on the application. To obtain the final result demenstrated in figure_10, the curvature factor was set to "1".)

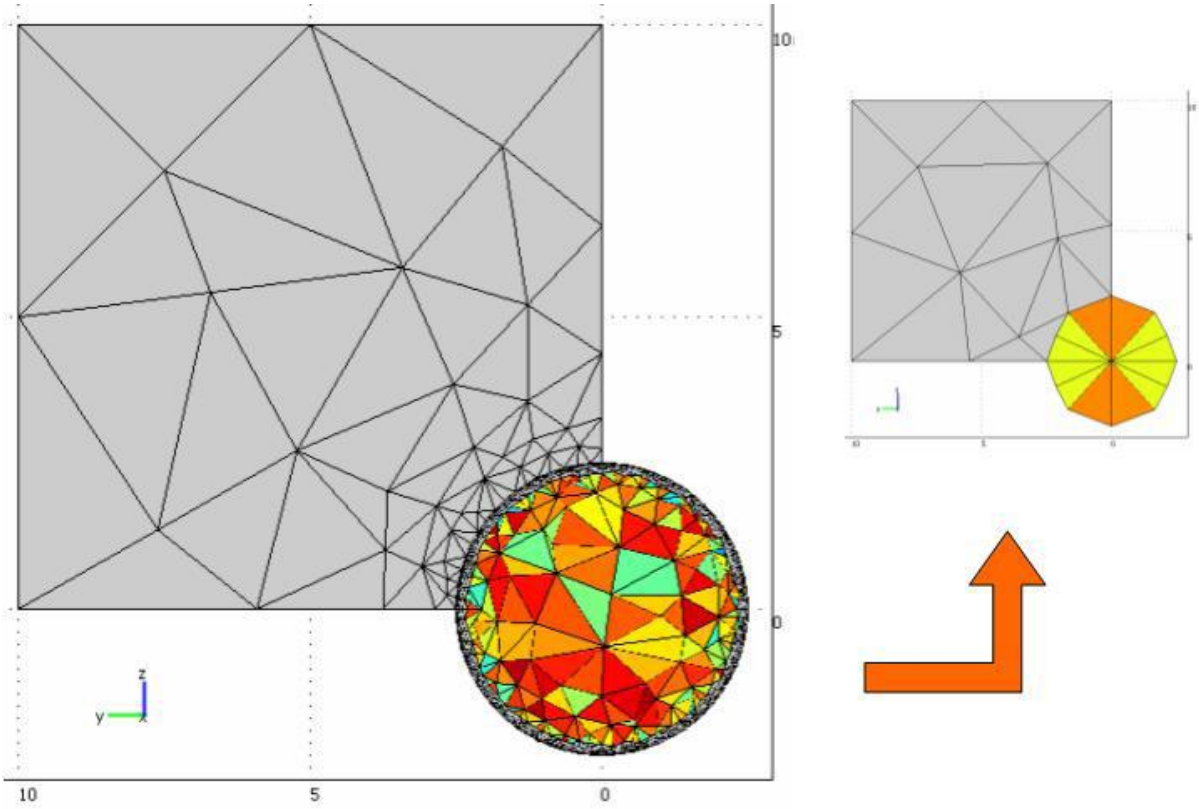


Figure_10: Medium curvature preservation plus perfect mesh smoothness made real-time surgical simulation

3. Results

The constraint built between tumour, hepatic vessels and surrounding tissues is illustrated in the following figures 1-3. The averaged stiffness value / bulk modulus of benign liver tissue was set to be 18000 Pa, corresponding to an averaged Young's modulus value of 11000 Pa.

Instrument manipulations of probing, grasping, and simple cutting were successfully simulated on constraint liver tissue deformable models. Experimental results proved that, during the process of a surgical operation, this system would be capable of simulation with reasonable accuracy to track the key vessel movements. Videos were taken and will be presented in oral presentation.

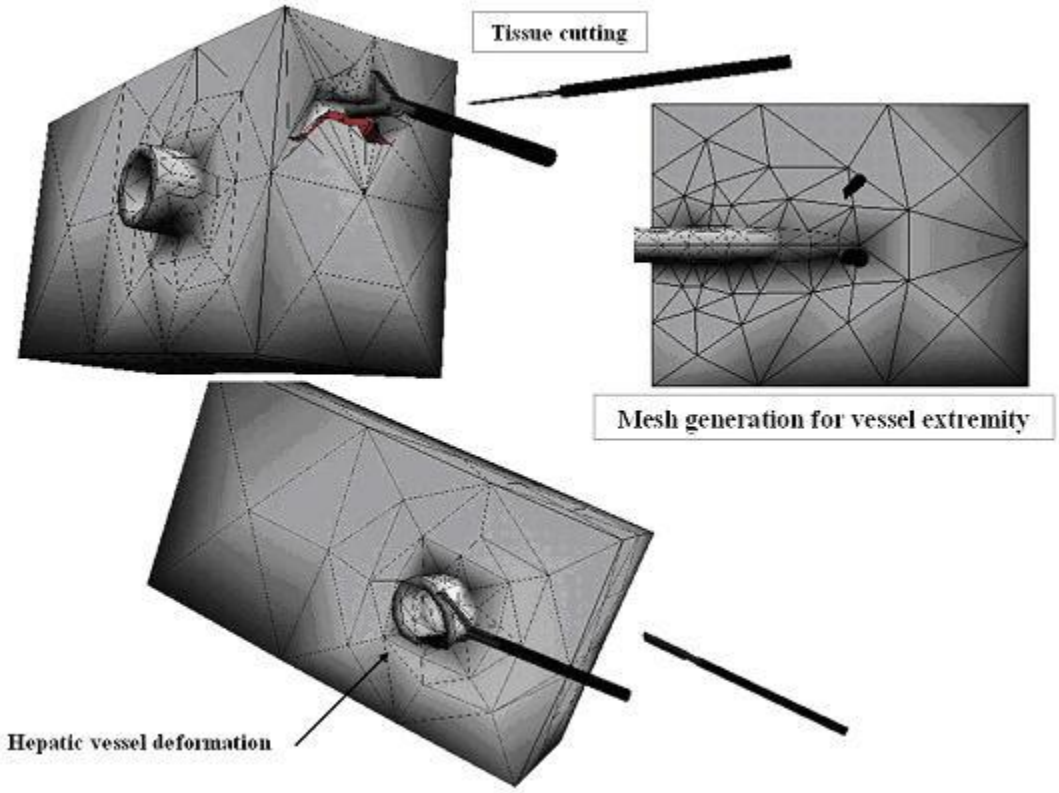


Figure 1: Tissue cutting and blood vessel deformation

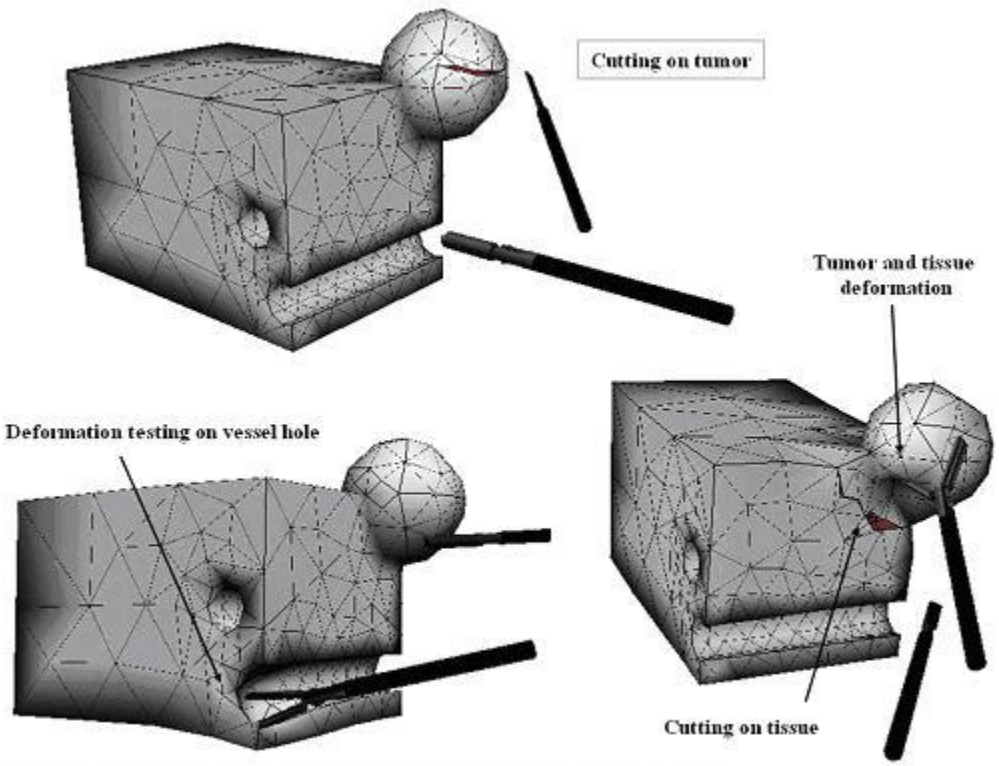


Figure 2: Cutting and deformation effects on a combination of tumour, blood vessel holes, and the surrounding tissue

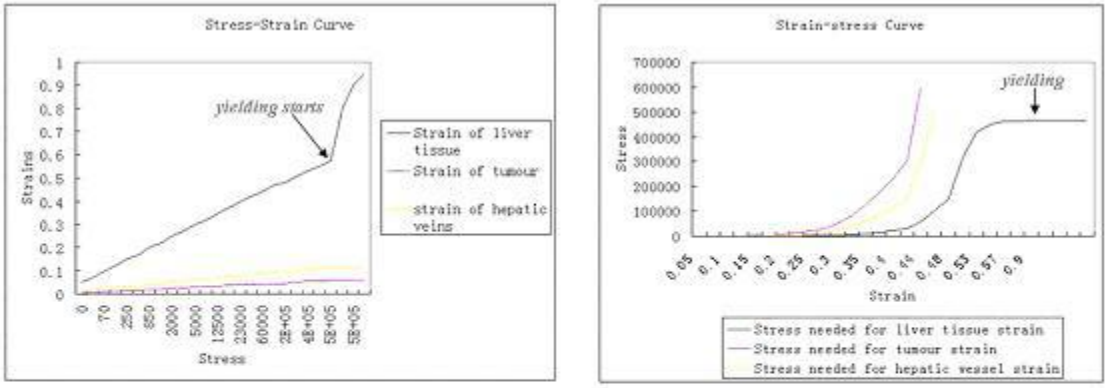


Figure 3: Strain-stress Curves

For benign liver tissue, let average Young's modulus E=11000pa, so that its stiffness k_tissue=18000pa
For hepatic vessel, we assume k_vessel=5*k_tissue
For hepatic tumour, we assume k_tumour=10*k_tissue

4. Conclusion

In sum, to achieve real-time interactivity in CT or MRI guided surgery simulation, the deformation regime of this system was based on a single-organ mass-spring system (MSS), which introduced an on-the-fly local mesh refinement to raise the deformation accuracy and the mesh control quality. This method has now been extended to a multiple soft-tissue constraint system, by supplementing it with an adaptive constraint mesh generation. A mesh quality measure was tailored based on a

comparison of classic measures. Adjustable feature and parameter settings were thus provided, to make tissues of interest distinct from adjacent structures, meanwhile, keeping the mesh suitable for on-line topological transformation and deformation.

This project was implemented in conjunction with the Division of Surgery, Hammersmith Hospital, London; the preliminary reality effect was judged satisfactory by the consultant hepatic surgeon.

5. References

Top three references:
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[2] Shewchuk R. J. (2000), U C Berkeley. Lecture Notes.
[3] Babuška I. and Aziz A. K. 1976. SIAM, Journal on Numerical Analysis 13(2):214–226.

6. Personal Information

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