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MULTI-SCALE SIMULATION FOR A ROBOTIC SURGICAL TRAINER

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Introduction

In microsurgery, surgeons need to stitch blood vessels together under a microscope. Extensive training is required to learn to control tremor at the microscopic level and to master different hand-eye coordination with angles rotated and distances magnified by the microscope. Much research effort has aimed at the development of real-time methods for simulating the physical behaviour of deformable tissue and the integration of these methods into simulators[1,2]. We are developing a robotic surgical trainer, which will allow surgeons to learn and familiarize themselves with work under the microscope. This paper describes a simulation workstation with three degrees of freedom (3DOF) haptic feedback and stereoscopic (3D) vision, coupled with a fast multi-scale computational algorithm to provide real-time simulation of the mechanical response of a virtual organ or tissue.

Haptic and Visual Workstation

Figure 1 shows our simulation workstation with the rigidly frame-mounted DELTA haptic interface[3]. This provides a 3D workspace usable in many ways, including a trainer for Chinese calligraphy[4]. A semi-transparent panel creates a virtual monitor image within the haptic workspace. A camera-based POLARIS system[5] actively or passively senses the position and orientation of a second (non-haptic) tool for the other hand.

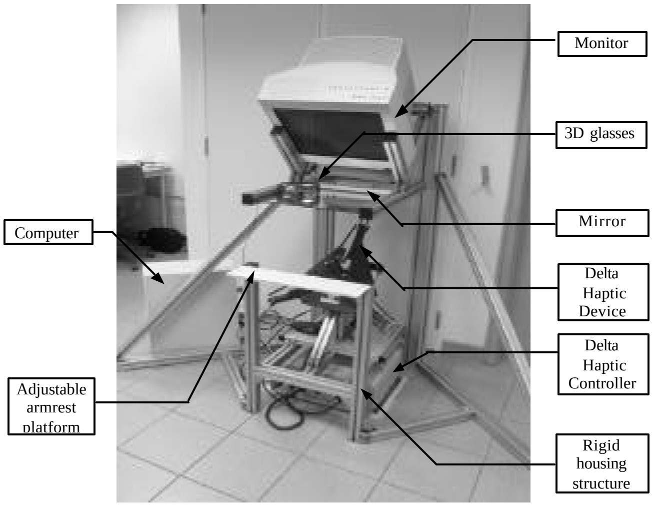


Figure 1: A simulation workstation with 3D view and haptic response provides intuitive manipulation and real-time interaction with virtual objects.

Multi-scale Simulation

Traditional finite element method (FEM) is widely used for simulation of mechanical deformation, but is too computationally intensive for use in real-time simulation. Several researchers have proposed methods to speed up computation for real-time surgical simulations. Astley and Hayward[6] use a coarse mesh of linear elements over the entire domain together with a finer mesh in the area of interaction with the tool. The complex implementation and the coupling of different layers of mesh result in slow update, unsuitable for haptic feedback. Wu *et al*. [7] use a dynamic progressive mesh with details created offline, which is stored in a mesh hierarchy and locally refined where necessary during online simulation. They have not demonstrated integration of this simulation with haptics.

For our surgical workstation, we have developed a multi-scale algorithm based on FEM to provide fast, efficient real-time simulation that is integrated with the visual and haptic feedback. The main idea of our method is to generate multiple levels of mesh, starting with a fine mesh and recursively combining adjacent elements to form a coarser mesh at the next level. We select elements from the different levels to cover the simulated domain based on the required refinement of results in different regions of the domain. This is especially suited for the present application of surgical simulation, as the surgical tool usually applies a concentrated force on the tissues/organs resulting in a localized deformation around the tool, needing detailed touch, while large deformations occur further away. The latter need not be modelled with great precision, but are critical to the surgeon's sense of the tissue (for instance, in what direction the tissue as a whole pulls against a suture). Hence, small elements are only needed in the region close to the tool tip, and progressively larger elements can be used as we move away from the tool. Such a multi-scale mesh greatly decreases the model's number of degrees of freedom compared to the fine mesh. It also significantly reduces computation time, as required for real-time simulation, while keeping a good order of accuracy in the results.

To date we have implemented the multi-scale method on two test problems: (i) a one-dimensional bar with axial displacement, and (ii) a two-dimensional out-of-plane or anti-plane strain problem. Their respective governing equations (1) and (2) below, where E and G are the Young's and shear modulus respectively, A is the bar's cross-sectional area, u and w are the axial and out-of-plane displacements, and x_f and y_f are the coordinates where a concentrated force F is applied (along the bar, orthogonal to the plane.

$$\frac{d}{dx}\left(EA\frac{du}{dx}\right)=F\delta\left(x-x_f\right) \tag{1}$$

$$\nabla\left(G\nabla w\right)=F\delta\left(x-x_f\right)\delta\left(y-y_f\right) \tag{2}$$

A finite element formulation transforms the governing equations to a matrix equation

$$\left[K\right]\left\{U\right\}=\left\{F\right\} \tag{3}$$

where {U} is the vector of nodal displacements to be solved, {F} is the vector representing the applied force, and [K] is the stiffness matrix of the system.

Results

Figure 2 plots axial displacement against length for the 1D rod problem. A concentrated force is applied at $x = 20$ to a non-uniform rod. The multi-scale mesh displacements are exactly the same as for the fine scale mesh.

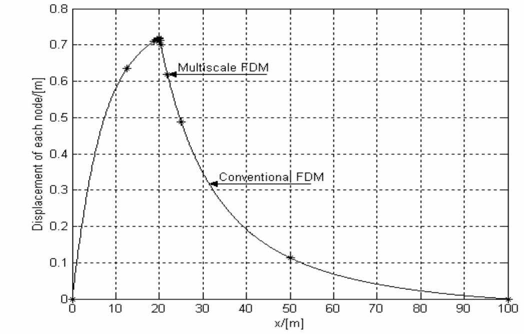
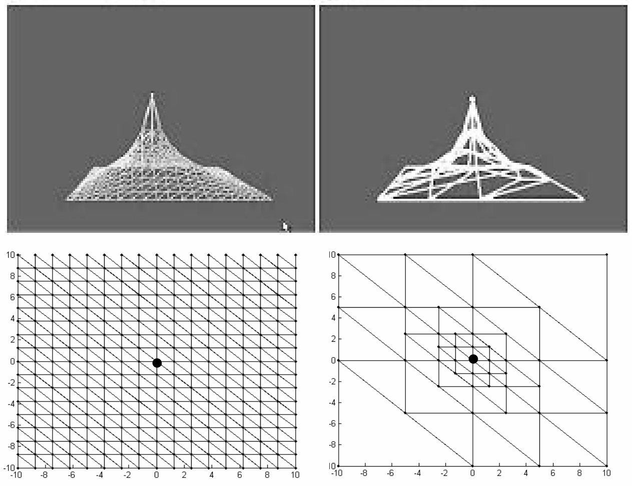


Figure 2: Axial displacement results for the rod problem. The multi-scale results (plotted as points) are identical to the fine-scale FEM results (plotted as line).

Figure 3 shows out-of-plane displacement results for the 2D problem. The fine and multi-scale meshes used are both shown for the case where the middle node of the square domain is given a unit displacement.



(a) FEM level-4 mesh (b) Multi-scale level-4 mesh

Figure 3: Two-dimensional out-of-plane displacement results. The top figures are the side plane view and the lower ones show give the view from above. Haptic force is returned at the point marked '•' where the applied displacement is imposed.

The 2D case gives comparable displacement fields using the multi-scale and fine-scale meshes. The force at the moved node, computed for haptic feedback, differs between the two meshes by about 4%.

Figure 4 compares computation time using the multi-scale and fine meshes. The results plotted against the number of elements used show the scaling of computation time with the number of degrees of freedom in the model.

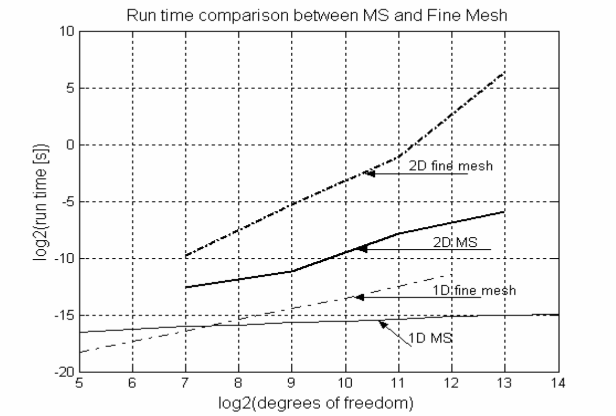


Figure 4: Computation time for multi-scale (MS) and fine mesh, with the number of degrees of freedom used.

For the 1D case the matrix [K] is essentially banded, so the fine mesh requires computation time of order *O(N)* where the system has *N* degrees of freedom. For the multi-scale method, the computation time scales by *O(log N)*, as the number of elements reduces to (*log N*). The multi-scale mesh gives tremendous savings in the computational time, though at some overhead cost in revising the mesh as the point of touch moves. A similar trend holds for the 2D case, where computation time for fine and multi-scale meshes scales by $O\left(N^2\right)$ and $O\left((\log N)^2\right)$ respectively.

Conclusion

The mechanical simulator proposed in this paper can provide visual and haptic feedback realistic enough for surgical training. The main advantage of the multi-scale method is the high time saving time vis-à-vis FEM. It can be extended for non-linear deformation of 3D bodies. Our ultimate goal in applying this method is to model deformable human organs. It shows great potential to realize a real-time haptic simulation system.

References

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