Real-Time Surgical Simulation for Deformable Soft-Tissue Objects With a Tumour using Boundary Element Techniques

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Abstract. A virtual-reality real-time simulation of surgical operations that incorporates the inclusion of a hard tumour is presented. The software is based on Boundary Element (BE) technique. A review of the BE formulation for real-time analysis of two-domain deformable objects, using the pre-solution technique, is presented. The two-domain BE software is incorporated into a surgical simulation system called VIRS to simulate the initiation of a cut on the surface of the soft tissue and extending the cut deeper until the tumour is reached.

1. Introduction
The training of neurosurgeons typically involves the stages of observing an experienced surgeon, undertaking operations under close supervision, and finally undertaking unsupervised operations to gain experience. There are currently concerns about the decreasing opportunities for the training of neurosurgeons, for reasons which include: (i) the introduction of working time directives, which limit the amount of time trainee surgeons can spend in the theatre, (ii) concerns about inexperienced surgeons performing their earliest operations on live patients, and (iii) concerns about litigation.

All these are acting as drivers towards the use of virtual reality simulation to replace or supplement the initial on-the-job training of neurosurgeons. In order to address this need, the present authors and their collaborators have developed a prototype virtual reality surgical simulator system (called VIRS), in which several basic skills in neurosurgery can be simulated. Initial developments of the VIRS system have been reported elsewhere [1-5], and include the following real-time facilities:

• Pushing (prodding) and pulling (pinching)
• Initiation of a cut or separation of tissue, including multiple-cuts
• Contact with a rigid retractor to separate the cut surfaces
• Cutting deeper into the deformable organ
• Post-cutting manipulation of the deformable organ
• Gravitational deformation of the cut tissue
• 3D stereo vision

The present paper reports further developments to the prototype VIRS system to simulate the presence of hard tumours. This will initially entail probing into the brain model in order to detect (feel) the presence of a hard tumour (after possibly analysing MRI scans of the patient to visualise the
tumour itself). The ‘cutting’ process involves separating the various structures of the brain with a probe-like device to ascertain the tumour’s exact position. Once confirmed, the surgeon may cut the surrounding brain tissue to reveal the enclosed tumour, before its subsequent removal. To perform this, the VR system would also need to incorporate the facility for a two-handed operation, i.e. the use of two haptic devices that can interact independently with the brain structure.

2. Background

In order to undertake a virtual reality simulation of surgery, a real-time deformable and cuttable model of the tissue is required. An excellent review of the various deformable model techniques applied to surgery simulation is presented by Meier et al [6], concentrating on material published up to 2001; techniques used include various heuristic methods (spring-mass, deformable splines, linked volumes and mass-tensor), as well as continuum-mechanical models such as the Finite Element (FE) and Boundary Element (BE) methods. A review of deformable models was also undertaken by Montagnat et al [7]. The survey in this paper is not intended to duplicate the reviews in those papers; however, a brief review of applications and developments dating from the most recent few years is included here for completeness.

Nonlinear FE calculations are very well-established in engineering applications and have also been applied, for example, to the simulation of laparoscopic surgery on the liver [8] via the explicit FE method. Other recent surgical simulation applications of the FE method include laparoscopic uterine surgery [9] and suturing [10-12], though there appears to be no publications on the use of FE for neurosurgical simulation.

In their review, Meier et al [6] identified BE analysis as being potentially one of the most promising routes to real-time deformable models for surgical simulation. However, with the exception of the VIRS project reported here, relatively little work has been done to continue the progress made in the late 1990s by James and Pai [13,14] and Monserrat et al [15], and subsequent developments in this area appear to have been restricted to the same authors [16,17].

The “pre-solution” techniques described in the present team’s earlier publications [1,2] utilise the superposition principle to create look-up tables of pre-computed displacements and forces, and can be used to achieve real-time interaction with either FE or BE models of a deformable physically-based virtual object. However, the creation of new incisions or cuts is a difficult task because of the need to re-calculate the displacements and forces. Zhong et al [18] describe an adaptive FE approach which is based on pre-solutions but uses an iterative updating approach for each cutting step. Wu and Heng [19] describe an interactive FE approach where the FE mesh is partitioned into “operational” and “non-operational” regions, the operational region being capable of being subjected to cutting.

Several papers, notably those of Mahvash and Hayward [20] and of Hansen et al [21], concentrate on the interactions between the surgical instruments and the simulated tissue.

Other physically-based methods used include a meshless approach [22] which appears to be restricted to simulations which do not include cutting. Zhong et al [23] describe a new methodology based on autowaves and the propagation of energy through a deformable structure. Its application to virtual reality surgery is illustrated via a deformable kidney model. Mass-spring methods continue to be used, and one ingenious variation on this tunes the parameters defining such a model to match the behaviour of a FE model of the structure [24,25]; however, real-time cutting was not incorporated into this system. Other methods such as spline-based techniques continue to be used, for example for simulation of the intestines [26].

3. Review of the Boundary Element Formulation

BE analysis relies upon the existence of surface integral equations to model the continuum behaviour. An integral equation can be derived to describe the effect of a point force at a an internal “load” point on the displacements ($u$) and tractions ($t$) at a “surface” point within the domain of the problem with volume $V$ and surface $S$. Details of the derivation of the integral equation can be found in BE Textbooks, e.g. Brebbia et al [27] and Becker [28]).
In linear elastic BE analysis, only the surface is discretized into elements, and the displacements and tractions over each element are described by an interpolation shape function. For simplicity, constant triangular surface elements are used in this work where the displacement is assumed to be linear over each element and the elements can be represented by a node placed at the centroid of the triangle. Other more sophisticated surface elements, such as quadratic or higher-order elements, can also be used. The simplicity of the triangular surface elements means that fine meshes are needed to model awkward geometries.

By taking each node on the boundary in turn as the “load” point and performing numerical integrations over all the surface elements, a set of linear algebraic equations is obtained as follows:

\[
\begin{bmatrix}
A
\end{bmatrix}
\begin{bmatrix}
\{u\}
\end{bmatrix}
= \begin{bmatrix}
B
\end{bmatrix}
\begin{bmatrix}
\{t\}
\end{bmatrix}
+ \{R_G\}
\]

(3)

where \([A]\) and \([B]\) are fully populated matrices that contain the numerical integrations and \(\{R_G\}\) contains the gravitational load. Further manipulation is required in order to group the unknown tractions and displacements on one side of the equation and the known quantities on the other side, in order to yield a set of simultaneous linear equations involving a system matrix \([A^*]\), as follows:

\[
\begin{bmatrix}
A^*
\end{bmatrix}
\begin{bmatrix}
\{x\}
\end{bmatrix}
= \begin{bmatrix}
R_{bc}\end{bmatrix}
+ \{R_G\}
\]

(4)

where \([A^*]\) is the solution matrix, \(\{x\}\) contains all unknown variables (either displacements or tractions), and \(\{R_{bc}\}\) contains all prescribed values of displacements and tractions. After solving the algebraic equations, all tractions and displacements on the surface are known.

In practice, the task of solving such an equation system is too lengthy to perform in real time, at least in terms of solving for each load case. In order to address this problem the following approach is taken: (i) A matrix of “pre-solutions” is created by applying, respectively in the x, y and z directions, a hypothetical unit displacement on all surface nodes in turn and solving the system of equations without gravitational loads, (ii) Using the principle of superposition, which is only applicable to a linear system, the relevant data from the pre-solution matrices are superimposed to arrive at the deformations resulting from any set of applied displacements along with the applied forces which are required to apply these displacements.

In brain surgery, the cutting process is performed using a special pair of forceps operating on the principle of diathermy (high-frequency electric current passing between the tips). The aim is to pinch the brain tissue to be removed but not to close the forceps completely. The material, which has been softened by the forceps, is sucked away with a suction tube. The difficulty of performing cutting in real time has already been alluded to within the literature survey, and arises from the fact that cutting (the separation of elements) alters the geometry of a body and invalidates all the pre-solutions which have been computed based on the old geometry. In references [4] and [5], the present team describe some of the approaches taken here to cutting, which are summarised only briefly in this paper. The problem can be tackled from several viewpoints:

- Because of the nature of the cutting process, it is assumed that a gap is introduced between the newly-created cut surfaces, rather than assuming that the two surfaces form a “crack” (with no gap between the separated surfaces). This avoids problems in BE analysis associated with having two coincident surfaces (and particularly the problem of singularities caused by coincident nodes).
- Adding new elements to the BE model will leave a large block of the system matrices unchanged, with the existing system matrices simply being expanded by three much smaller sub-matrices. This makes it possible to re-use the original solutions by making use of the inverse of the original \([A^*]\) matrix within the calculation of the inverse of the new (expanded) \([A^*]\) matrix. Although this was pursued for the situation where the cut took the form of a narrow crack and is reported in reference [4], it is not directly applicable to the case where cutting results in a finite-width gap because some of the original surface elements are either modified or removed. The original system matrices will therefore now contain several invalid rows and columns, making the re-use of the existing solution inappropriate. Re-calculation of the solutions using an iterative approach is therefore necessary.
- In order to allow the simulation to continue without disruption after cutting, an approximate update is performed in real-time during each cutting step by interpolating displacements from either side of
the cut so that the newly-created surfaces within the cut can have plausible deformations. However, this does not take account of the structural weakening of the organ after material has been removed; this will particularly affect the deformations of the area near the cut.

- Whilst the simulation continues uninterruptedly using the approximate (interpolated) solution, the pre-solutions may be re-calculated to take account of the changed structure of the organ. For this purpose, a multi-threaded BE program was written to allow the re-calculation to take place as a background task. With current technology, the updating process remains rather slow (minutes rather than seconds), and we anticipate that the structuring of the code to support this multi-threaded approach will allow for the parallelisation of certain aspects of the system, which will be investigated in due course.

4. Modelling a Hard Tumour

To model a tumour grown inside the brain tissues, two domains are defined; one for the tumour and one for the soft brain tissue, as illustrated for a simplified case in Figure 1. A tumour is usually harder than the surrounding soft tissues and this can be modelled by assigning a greater Young’s modulus to the tumour than the soft tissues. To obtain the system equations, the numerical integrations are performed separately over domain (a) and domain (b) respectively. For easier understanding, these two domains are represented separately in Figure 2. Domain (b) represents the tumour which has only one surface (T) whereas the soft tissue, domain (a), has two surfaces, an internal surface (T) and an outside surface (S).

Since the cutting process takes place only in domain (b) without affecting the surface (T) of the tumour, the numbering system for the nodes allows the tumour nodes to appear first, followed by the node numbers of the surrounding soft tissues. This is very convenient for the subsequent matrix manipulation that will be necessary after a ‘surgical cut’ has been initiated and propagated in the surrounding soft tissue. All new terms from the numerical integrations relating to the newly generated nodes and elements arising from the ‘surgical cutting’ will be grouped together in the matrix system, so that the matrix expansion due to re-meshing occurs only within the set of sub-matrix coefficients containing relevant to the surface ‘S’.

Before the system equations can be solved, boundary conditions must be applied to prohibit rigid-body movement of the whole organ. The traditional boundary conditions are known (prescribed) values of tractions or displacements specified at nodes on the outer boundary, and their treatment forms standard matrix manipulations (see e.g. Becker [28]). In addition, the contact conditions between the hard tumour and the soft tissue must be satisfied. These are different to the surface boundary conditions and form the relationships between the tumour and soft tissues which are always bonded to each other. Nodes at the contact points must satisfy the equilibrium conditions (equal and opposite tractions) and compatibility (continuity of displacements with no gaps forming between the contact surfaces). Since the number of unknowns in the above equation remains equal to the number of the simultaneous equations, all the unknown displacements and tractions on boundaries of both domains can be computed.
Figure 3 shows a symmetrical half of a simplified three dimensional geometry where the hard tumour is located inside the soft tissue. For clarity, the tumour is moved out and shown separately. The tumour is designed as a half sphere and is discretized into 72 triangular surface elements in which 48 elements are on the spherical surface and 24 are on the bottom circular surface. The soft tissue domain is discretized into 616 surface elements.

5. Pre-Solutions for the Soft Tissue and Hard Tumour

For a linear system, the superposition principle can be applied. The deformations due to the gravitational load \( \{R_G\} \) can be calculated separately then added together when required. This is a constant vector for a defined model and can be solved only once and saved in an array.

The contact of a surgery tool with the surface of an organ can be considered as a non-zero displacement applied on a specific surface node of the deformable model. For real-time implementation, a look-up table or a set of pre-solutions can be created prior to the simulation by imposing a hypothetical unit displacement, respectively in the x, y and z directions, on all surface nodes in turn, solving the system of equations and storing the solutions in look-up tables. During the surgical simulation, these solutions are retrieved, scaled and added together to represent the real deformation of the model. This procedure can be easily performed in real-time.

Creating the pre-solution look-up tables involves applying a hypothetical unit displacement in turn at each node/element in order to find the displacement and traction solutions. The traction vector \( \{t\} \) contains zeros except the node/element on which the unit displacement applying. The computed traction resulting from the ‘unit displacement load’ can be calculated directly and forms the pre-solution vector to be found.

6. Implementation

6.1 Simulation of a two-handed operation

To enable better manipulation of the organ surface while a cut is introduced, it is necessary incorporate a second haptic device, which simulates a two-handed operation. This can be accommodated using the superposition principle, provided that the behaviour of the deformable organ remains linear elastic. No further pre-solutions need to be computed, and the displacements and feedback forces caused by the actions of the two haptic devices can be obtained in real-time and saved in separate arrays to record separate results for each haptic device.

The superposition principle is used to arrive at the final resultant deformation of the organ displayed on the screen, and the feedback forces passed to the relevant haptic device. If one of the haptic devices is released from contacting the object, its relevant displacements and forces are immediately set to zero so that the deformation displayed is only caused by the other haptic device remaining in contact with the object. If both haptic devices are released, there is no deformation and the deformable object returns to its initial model. Figure 4 shows an example of the application of two haptic devices.
6.2 Simulation of self-contact

After initiating a cut, self contact may occur as the two separated surfaces may come into contact due to gravity or further manipulation of the cut. It should be emphasised that self contact is much more complex than the contact of the organ with a retractor which assumes that the retractor is a rigid non-deformable body. The main difficulty associated with the contact of two deformable bodies is that they cannot be linearly scaled. Contact problems are non-linear and the solution requires incremental and iterative approaches.

Iterations have to be performed in order to arrive at the correct contact area. In each iteration, the system matrices must be modified and re-computed to simulate the latest contact conditions between the contact elements. This means that the system equations must be solved again and the contact area updated. Although the solution time can be reduced to under 0.5 second through the use of fast iterative solvers, the iterations needed to arrive at the correct contact area require several seconds to complete. Furthermore, to improve the accuracy of the computed displacements and forces, it may become necessary to re-mesh the surface around the contact areas which would increase the overall processing time.

The BE technique has been shown to be very accurate in modelling complex three-dimensional contact problems between two deformable bodies, see, e.g. [29]. However, it has not been possible to achieve the contact computations in real-time. The real-time simulation of self-contact or contact between deformable bodies remains a challenge for further research.

6.3 Cutting to Reach a Tumour

Figure 5 shows a simplified three-dimensional example in a wire-frame form. In order to simulate a ‘hard’ tumour, Young’s modulus of the tumour is specified as five times greater than the Young’s modulus of the soft tissue. During a surgical simulation, the outer surface of the soft tissue is ‘virtually’ deformed by one or two indenters, which will result in a small deformation of the hard tumour. With experience, the user can identify the location of the tumour by gently prodding the outer surface of the soft tissue. In practice, the position of the tumour would be determined by a pre-surgery MRI scan.

A cut can be introduced on the surface of the soft tissue by one of the two indenters, and then propagated deeper in the soft tissue until the tumour surface is reached. During the cutting process, new surfaces are automatically created either side of the cutting path. This operation can be performed in real-time using a multi-threading programming approach as discussed in reference [4]. The process of extending the cut such that the tumour surface is separated from the contact surface in real-time is planned for future development of this surgical simulation system.
7. Conclusions

This paper presents the development and the implementation of a two-domain surgical simulation model which incorporates a hard tumour included inside soft-tissue. Both domains are deformable, but the tumour is given a higher modulus of elasticity to distinguish it from the soft tissue. BE formulations are derived for the system matrices based on using algorithms to create pre-solution look-up tables. The two-domain BE model has been incorporated within the authors’ surgical software system (VIRS) which allows continuous real-time cutting until the tumour surface is located.

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