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Virtual reality simulation of surgery with haptic feedback based on the boundary element method

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Abstract

A virtual reality real-time simulation of surgical operations has been developed using the boundary element (BE) method. Other numerical techniques and related approaches to real-time modelling of deformable objects are briefly reviewed. The challenges raised by a key application – the simulation of neurosurgery – are identified. A brief review of the BE method is presented followed by a description of its implementation for three basic actions of prodding, pinching and cutting deformable objects. An initial implementation of these techniques is described in which haptic and visual feedbacks are generated when these operations are carried out on simple deformable objects.

Keywords: Boundary element method; Virtual reality; Surgery simulation; Haptic feedback; Cutting; Real-time

1. Introduction

Advanced haptic interfaces require techniques for simulating the deformation of complex objects as a result of users' interactions through haptic devices. A variety of such techniques have been developed, most notably the use of the finite element (FE) method to model the structure of a deformable object. However, the boundary element (BE) method is now well established as an accurate computational mechanics technique with its unique feature of surface-only modelling for elastic problems. The BE method has many attractive features that are suitable for implementation in virtual reality simulations which require a real-time response to the forces applied to a deformable object.

This paper explores the potential of the BE method to support haptic interfaces and real-time simulation of deformations. The simulation of neurosurgery is chosen as a challenging driving application for this work as this requires trainees to carry out a variety of actions – prodding, pinching and cutting – on models of the highly deformable soft tissues of the brain. It is also potentially a very beneficial application of haptic technologies. In this paper, the BE method is briefly reviewed in relation to previous approaches, the requirements of neurosurgical simulations are discussed and the use of the BE formulation to provide haptic feedback is presented. The paper is an extended version of the authors' conference paper presented at the seventh international conference on computational structures technology, Lisbon, 7–9 September 2004 [1].

The paper is organised as follows. A brief review of the techniques used for simulating deformable objects is presented in Section 2, followed by a discussion in Section 3 of the main challenges and difficulties encountered in simulating surgical procedures in real-time. Section 4 presents an overview of the BE formulation for displacement and traction integral equations, while Section 5 summarises

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the pre-solution BE technique used to simulate prodding and cutting. An overview of the implementation of the haptic simulation system is given in Section 6, followed by a general discussion and conclusions.

2. Techniques for simulating deformable objects

Various approaches have been proposed for modelling deformable objects, many of them driven by the desire to develop surgical simulators. James and Pai [2] and Gibson and Murtich [3] review much of the published work, including several papers by Terzopoulos [4] and his co-workers who presented important early work on deformable models. Techniques for modelling deformable objects in computer simulations have included simple non-physical models using splines and patches, and physical models using mass-spring techniques.

Of greater interest here are the methods based upon computational continuum mechanics techniques, notably the FE method [5]. There is an established literature on applying the FE method to surgical simulation. Bro-Nielsen [6] describes a number of approaches to the speeding-up of the FE process for use within surgical simulations. These include the condensation of a solid FE model to consider only the surface degrees of freedom and the use of the inverse of the stiffness matrix for repeated multiplications with the force vector. However, the cutting simulation was not considered in the work because the condensation and inverse stiffness matrix would become invalidated immediately after cutting. Zhuang and Canny [7] discuss their simulation system based upon a geometrically non-linear FE model to allow a human operator to perform real-time interaction with soft 3D objects that undergo large global deformations, achieving the high update frequency (over 1000 Hz) required for force feedback simulation by interpolating between simulated states. Woodcock et al. [8] describe the use of adaptive mesh refinement/coarsening to achieve interactive rates with complex deformable and fracturable FE models in a virtual surgical environment. Song and Reddy [9] study the feasibility of simulating cutting in a virtual surgical environment. In general, the FE models have been thought to be too slow to achieve visual and haptic feedback in real-time.

The focus of this paper is on an alternative computational mechanics technique, the BE method (see e.g., [10–12]). The BE method differs significantly from the FE method in that only the surface is discretised in order to apply boundary conditions to the continuum equations governing the behaviour of the body bounded by the discretised surface. In elastic problems, the interior of the body is not discretised, thus reducing the size of the system equations to be solved, and also avoiding the need to generate interior node and element data which do not contribute to satisfying the requirements of a VR model. These factors raise the intriguing possibility that the BE method might offer a more computationally scalable approach to modelling real-time deformable objects than the FE method.

Very little has been published on the use of BE analysis for real-time simulation applications. Examples of such work are James and Pai [2], Monserrat et al. [13] which both identify surgical simulation as a primary or possible application. They also describe BE simulations of irregular objects subjected to arbitrary "poking" loads. However, none of this published work has as yet considered the issues of the cutting of a solid, large deformations, contact between flexible bodies and the enclosure of the object in a tough membrane, all of which are important considerations in surgical simulations. These issues would therefore appear to be the critical ones that need to be addressed before BE-based surgical simulation can become a reality. Some aspects of the present BE surgery simulator have been published earlier [14,15].

3. The challenges of neurosurgical simulation

The long-term aim for this work is to develop a simulation system for the neurosurgery process, incorporating a deformable model of the tissue being operated upon, together with visual and haptic feedback for maximum realism. This is intended both to aid the training of surgeons and the planning of operations. These skills are currently developed over years of surgery training and practice. The training process involves gathering theoretical knowledge, assisting an experienced surgeon, being assisted by an experienced surgeon and ultimately coming to the "solo" experience. National standards (e.g., those of the UK's Royal College of Surgeons) require trainee surgeons to be exposed to and to perform an appropriate number and variety of operations before being "signed off" as competent. In certain specialties, however, the number of cases is relatively small and there may be limited opportunities to achieve this. Surgical simulation is therefore an attractive alternative and can take several different forms:

(i) Operation planning tools such as [16], where there is no attempt to simulate the physical movements and forces occurring during the operation.
(ii) Simulation of operations on rigid structures such as bones, prostheses and bone grafts such as [17] which simulates a wide range of procedures on these structures.
(iii) Simulation of surgery on deformable objects representing human organs and soft tissues, either for the simulation of the surgical process itself [18–20] or to understand the effects of surgery upon deformable tissues [21]. Again, a wide range of surgical procedures need to be simulated, including prodding, displacing, lifting and cutting.

Viewed from the modeller's (rather than the surgeon's) perspective, a simulation of the surgery process on an organ, such as the brain, based upon the BE method must