Interactive Soft Tissue for Surgical Simulation

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Abstract

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Medical simulation has the potential to revolutionise the training of medical practitioners. Advantages include reduced risk to patients, increased access to rare scenarios and virtually unlimited repeatability. However, in order to fulfil its potential, medical simulators require techniques to provide realistic user interaction with the simulated patient. Specifically, compelling real-time simulations that allow the trainee to interact with and modify tissues, as if they were practising on real patients.

A key challenge when simulating interactive tissue is reducing the computational processing required to simulate the mechanical behaviour. One successful method of increasing the visual fidelity of deformable models while limiting the complexity of the mechanical simulation is to bind a coarse mechanical simulation to a more detailed shell mesh. But even with reduced complexity, the processing required for real-time interactive mechanical simulation often limits the fidelity of the medical simulation overall. With recent advances in the programmability and processing power of massively parallel processors such as graphics processing units (GPUs), suitably designed algorithms can achieve significant improvements in performance.

This thesis describes an ablatable soft-tissue simulation framework, a new approach to interactive mechanical simulation for virtual reality (VR) surgical training simulators that makes efficient use of parallel hardware to deliver a realistic and versatile interactive real-time soft tissue simulation for use in medical simulators.

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Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed:

Date:

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Glossary

Ablation	The volumetric removal of tissue.
API	Application Programming Interface. (Software library.)
BEM	Boundary Element Method of mechanical simulation.
CT	Computed Tomography medical imaging.
CRMS	The Cubic Rotational Mechanical Simulation described in Ch. 5.
CUDA	Nvidia's Compute Unified Device Architecture API for GPUs.
DirectX	Microsoft's real time 3D graphics API.
ENT	The field of medicine concerned with the Ear, Nose and Throat.
ESS	Endoscopic Sinus Surgery.
FEM	Finite Element Method of mechanical simulation.
FLOPs	A measure of processing performance. Floating Point Operations per second.
FPGA	Fully Programmable Gate Array. A type of programmable computing hardware.
Fragment Shader	Pixel Shaders and Vertex Shaders are two types of Fragment Shaders. A small program that is part of a graphics pipeline.
GPGPU	General Purpose Graphics Processing Unit.
GPU	Graphics Processing Unit. A piece of computing hardware used to perform processing to generate interactive 3D graphics.
Haptics	The field related to precision force feedback (tactile feedback).
IMT	Interactive Marching Cubes (describe in 0).
ISim	An Endotracheal Intubation Simulation (described in 0).

Iso-surface When a volume contains a 3D grid of density values, an iso-surface is an interpolated surface that connects locations of the same density.

MIS Minimally Invasive Surgery (e.g. key-hole surgery).

MRI Magnetic Resonance medical Imaging.

NURBS Non Uniform Rotational Bezier Splines.

Pixel Shader A program that defines the lighting algorithm used to compute the colour of a given pixel in a rendered 3D scene.

Polytopes Types of polygonal elements (e.g. triangles, squares (quads), etc).

Quaternion A mathematical method commonly used to represent rotations.

Rasterize The process of converting polytopes into pixels.

Shader A shading algorithm.

SIMD Single Instruction, Multiple Data

SPMD Single Program, Multiple Data

SOFA Simulation Open Framework Architecture.

TSF The Tissue Simulation Framework that is the subject of this thesis.

Vertex Shader A GPU program that maps vertex (point) locations to screen-space (pixel) locations.

Voxel A volumetric pixel. A quantum of a regular cubic grid.

Chapter 1. Introduction

Unlike interactive computer entertainment, the key interactions within virtual reality (VR) surgical simulations do not simply move a vehicle, aircraft or point of view. Surgical simulations must allow the user to perform subtle interactions with simulated tissues in a realistic manner. Even though many of the requisite technologies have matured to a level that supports the degree of realism required, new techniques are required to enable interactive mechanical simulation of tissues and organs with realistic tactile feedback. Consequently, new medical simulations are expensive to develop and leave little time to focus on overarching requirements like content, scenarios, and learning outcomes.

In traditional teaching, opportunities to practice skills are often limited by access to willing patients or cadavers. Furthermore, practise of any non-expert on patients exposes these patients to increased risk. Hence, there is great potential for medical simulators to improve medical training and reduce the training system's reliance on early skills development on patients. Immersion is an important part of the simulation-based learning experience. Contextual learning facilitates recall of the skills practised and hence improves learning outcomes. However, realism needs more than visual or auditory effects; tactile feedback is critical in a large number of medical interventions.

Delivering a realistic and compelling manual interaction requires a user interface that replicates the key interactions that normally occur with a real patient. Relatively recent advances in computer interfaces have produced devices that accurately capture the motion of a stylus in three dimensions. A number of these devices also deliver precise force feedback. These haptic devices provide the hardware required to develop a new range of medical simulations with the ability to accurately simulate the key manual interaction. However, just as a computer display requires algorithms and rendering techniques to deliver visual realism, haptic devices also require the development of specialised algorithms to deliver the same levels of realism to our sense of touch.

Many medical procedures involve manipulating and modifying intricate structures with diverse mechanical characteristics using subtle visual and haptic cues for guidance. For example, even the relatively simple surgical procedure performed to remove a patient’s tonsils involves identifying the boundary of the tonsil and following a thin layer of separating tissue. This separating layer is identified using subtle cues involving not only the appearance, but also subtle variations in the mechanical characteristics at and around this boundary layer that influence the ‘feel’ encountered by the surgeon. Many other surgical procedures are even more intricate.

Developing the simulation software to achieve the required subtleties and levels of realism requires a range of technologies to work efficiently in unison. Software libraries developed for other types of simulation and computer entertainment provide a range of useful features. Rendering and visualisation alone can consume a large fraction of a simulation project’s development time. Scene graph and rendering libraries can save considerable time during development via features such as managed asset loading and efficient management of the graphics pipeline for high-quality rendering. Similarly, software libraries to support common tasks such as real-time collision detection and physics-based effects are also available. Prudent use of these libraries can save time by reducing the need to re-implement common features. However, despite the apparent benefits of using these libraries, simulating tissue realistically requires systems to be efficiently integrated at a low level. Hence, very few features of existing high-level software libraries can feasibly be combined to deliver the high quality key interactions required in medical simulations.

A compelling tissue simulation must exhibit realistic mechanical behaviour in response to user interaction. Modelling mechanical behaviour at interactive rates is the subject of continuing research. One strategy for reducing run-time computations is to move as much processing offline as possible. This approach has produced some excellent results, although it does not produce a model that can be ablated or cut interactively as needed in surgical simulations. Similarly, existing techniques that use a coarse mechanical simulation bound to a detailed visual representation result in a model that cannot be modified (cut or ablated) interactively. Hence, a new approach is required to cater to medical simulation's unique requirements.

This thesis describes a new method for simulating interactively ablatable soft-tissue with haptic feedback at higher resolution than existing methods. The method exploits the parallel computing capabilities of modern graphics processing units to achieve diverse material mechanical characteristics at higher resolution and haptically interactive rates. In order to place the new tissue simulation in context this thesis also reviews the state-of-the art of medical simulation and the relevant existing technologies.

1.1 Thesis Aims

The tissue simulation framework presented in this thesis improves the effectiveness of virtual reality medical simulations by addressing the following aims:

Aim 1: To review the current state of medical simulation and relevant developer tools.

Aim 2: To plausibly simulate the mechanical characteristics of a diverse range of tissues.

Aim 3: To enable users to manipulate (deform, cut and ablate) the simulated tissue realistically.

Aim 4: To provide accurate force feedback in response to interactions with the tissue.

Aim 5: To maximise detail and visual realism.

1.2 Thesis Outline

This section provides an overview of the remainder of this dissertation.

Chapter 2 begins with a discussion of the role of medical simulations in medical teaching. The relative advantages of simulation-based teaching over existing teaching methods are summarised. A closer focus on how simulations can further improve the learning experience of students is provided beginning with an overview of learning modalities and a discussion of how simulations can better cater to students with different learning styles. The current state of the art of VR medical simulations is then presented. Thereby, Chapter 2 develops a deep understanding of the current state of medical simulation in partial fulfillment of Aim 1.

Chapter 3 critically reviews and summarises the software libraries and existing developer tools that are available for VR medical simulation development. Performance of real-time interactive systems is limited by the computing hardware on which it executes. Significant recent advances in parallel computing hardware have resulted in devices with substantially increased processing capabilities. Two such devices are summarised together with their significance to medical simulations.

Chapter 3 completes the discussion of existing simulations and development tools thereby addressing Aim 1. Subsequent chapters contain more specific reviews of the literature related to the development of the tissue simulation framework that is the subject of this thesis.

Chapter 4 presents the design rationale and an overview of the tissue simulation framework (Aims 2-5).

Chapter 5 addresses Aim 2 (and also relates to Aims 3 and 4). Prior work in the area of real-time mechanical simulation of soft bodies is presented. An overview of mesh topologies is given to provide context for the design decisions made. A new method of modelling deformable soft-tissues in real time is presented in which the algorithms developed allow the system to work efficiently with the other components of the tissue simulation. Specific optimisations to facilitate efficient execution on GPGPU hardware are detailed together with a number of enhancements which enable the simulation to model a diverse range of tissues with minimal impact to processing load.

Chapter 6 addresses Aims 3 and 5. It reviews current methods for polygonal surface mesh generation from volumetric data and presents a new method for creating polygonal surfaces from volumetric data that can be interactively modified.

Chapter 7 addresses Aims 2, 3 and 5. It describes how the mechanical simulation (Chapter 5) and interactive marching tetrahedra (Chapter 6) components were combined to create the tissue simulation framework.

Chapter 8 addresses Aim 4. It briefly presents the range of haptic devices currently available and reviews the available haptic rendering software libraries. It then describes three alternatives for haptic rendering of the tissue simulation. Best usage scenarios for each approach are discussed. A simple new approach for testing and presenting haptic rendering algorithms is described and used to evaluate the haptic rendering methods.

Chapter 9 describes three new medical simulators developed by the author. The simulators make use of the tissue simulation framework (described in chapters 4 to 8) and demonstrate its effectiveness when used to provide the key interaction.

Chapter 10 summarises the contributions of this thesis and identifies promising directions for future work.