Virtual Model of the Human Brain for Neurosurgical Simulation

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Abstract. The aim of this work is to develop a realistic virtual model of the human brain that could be used in a neurosurgical simulation for both educational and preoperative planning purposes. The goal of such a system would be to enhance the practice of surgery students, avoiding the use of animals, cadavers and plastic phantoms. A surgeon, before carrying out the real procedure, will, with this system, be able to rehearse by using a surgical simulator based on detailed virtual reality models of the human brain, reconstructed with real patient's medical images. In order to obtain a realistic and useful simulation we focused our research on the physical modelling of the brain as a deformable body and on the interactions with surgical instruments. The developed prototype is based on the mass-spring-damper model and, in order to obtain deformations similar to the real ones, a three tiered structure has been built. In this way, we have obtained local and realistic deformations using an ad-hoc point distribution in the volume where the contact between the brain surface and a surgical instrument takes place.

Keywords. virtual reality, neurosurgical simulation, physical modelling, mass-spring-damper model

1. Introduction

Minimally invasive surgical methods require different training from those used in traditional techniques; frequent training should be carried out in a safe environment which mimics the anatomy and physiology of the body as closely as possible to ensure adequate transfer of skills.

It is possible to develop many different virtual reality models of the organs, in normal or diseased states, and dynamic interaction with these can show their responses to externally applied forces provided by medical instruments.

The most critical issues in designing simulators for surgical training are accuracy – the simulator should generate visual and haptic sensations which are very close to reality – and efficiency – deformations must be rendered in real-time. Accuracy and efficiency are two opposite requirements; in fact, increased accuracy implies a higher computational time and vice versa. Thus it is necessary to find a trade-off in terms of the application.

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The aim of this work is to present the development of a realistic virtual model of the human brain that could be used in a neurosurgical simulation for both educational and preoperative planning purposes.

The goal of such a system would be to enhance the practice of surgery students, avoiding the use of animals, cadavers and plastic phantoms. A surgeon, before carrying out the real procedure on the patient, will be able to rehearse by using a surgical simulator based on detailed and realistic virtual reality model of the human brain.

This work has been carried out at MeGI of the Institute for Process Control and Robotics of the Karlsruhe University (TH), Germany.

2. Physical Modelling of Soft Tissues

Obtaining a correct deformation and adding realism to a soft-tissues simulation, it is necessary to design a physical modelling with the task of determining the dynamic behaviour of virtual organs. Information about the tissue displacements is used to graphically model the organ deformations and to calculate their response to external stimuli.

To obtain a correct representation of deformability it is necessary to compare the computed physical modelling with the deformed soft tissues. For this reason we need a qualitative knowledge of the biomechanical behaviour of tissue. Many algorithms have been developed for deformable objects modelling. The most common 3D models fall into two broad categories: mass-spring meshes and finite elements.

The mass-spring model consists of a set of nodes linked by springs; a mass is assigned to each node in addition to a damping coefficient [1].

Springs exert forces on neighbouring points when a mass is displaced from its rest positions and the spring behaviour is governed by a deformation law.

The amount of the stiffness of the springs can be derived, for instance, from the intensity of voxels in a CT-scan image and in this way it is proportional to tissue density and, therefore, to the Hounsfield units.

The mass-spring method does not require a continuous parameterization, it can be used to model cutting or suturing of the tissue simply by removing or adding connections between vertices. The behaviour of a mass-spring mesh depends heavily on its topological and geometric configuration. In addition, configurations with large forces (e.g., nearly rigid objects) lead to stiff differential equations with poor numerical stability, requiring small time-steps for integration.

Nevertheless a mass-spring model is an easily understandable concept which is simple to implement and requires low computational load, which depends on the number of nodes used to model the object.

On the other hand, mass-spring models have disadvantages; finding an appropriate set of parameters that is realistic can require considerable trial and errors.

Mass-spring method is used in a wide range of computer graphics and virtual reality applications, e.g., in the animation of facial expressions, the cloth motion and the modelling of inner organs in surgery simulations [2–4].

Cover et al. were the first to present a real-time model for gall bladder surgery simulation [5].

Kühnapfel et al. used a mass-spring model to simulate a realistic interaction between surgical tools and organs in the KISMET system, a virtual reality training system for minimally invasive surgery [6].

Gibson proposes a "ChainMail" model, where volume elements are linked to their nearest neighbours. Each node must satisfy a given maximum and minimum distance constraint to its adjacent nodes [7].

Brown et al. present an algorithm for animating deformable objects in real-time and the target of the application domain is microsurgery. They have designed an integrated system for simulating and suturing small blood vessels [8].

Kawamura et al. propose the development of surgical simulation, based on a physical model, for intra-operative navigation by a surgeon; the proposed simulation system consists of an organ deformation calculator and virtual slave manipulators [9].

Several improvements to spring models have been proposed, specifically with regard to their dynamic behaviour [10, 11].

3. Physical Modelling of the Brain

The virtual environment has been described using X3D, an open software standard for defining and communicating real-time, interactive 3D content for visual effects and behavioural modelling [12].

The physical model used in our application in order to simulate the brain's behaviour takes into account the mass-spring-damper method. The aim of our work is to obtain deformations similar to the real ones when there is contact with the surgical instruments, in order to guarantee local deformations and a return to the previous shape when there is no longer contact. The surface described by the X3D specifications corresponds to a mass-spring-damper mesh.

Experimentally the structure obtained using a single layer of springs results not appropriate enough for simulation of the behaviour of the real brain. In order to obtain deformations of the organ which are correctly situated and react in a way which is as similar as possible to the real brain, a three-tiered structure of springs has been built; each tier has been modelled using the mass-spring method. Together with the external layer of springs, two other layers (identical in shape and inner to the external surface but reduced in size) have been modelled. All the nodes of each inner tier are connected to the corresponding points of the tier immediately above by means of springs and dampers.

By adding these other inner surfaces within the first one it is possible to obtain more accurate deformations so as to be able to simulate the behaviour of the brain correctly; we obtain local and realistic deformations using an ad-hoc point distribution in the volume where the contact between the brain surface and a surgical instrument takes place.

The external layer is provided with geometrical and haptic rendering, the second one, without rendering, has the same shape as the first one but is scaled down by a factor equal to 1.2; the third layer, with the same shape but scaled down by a factor equal to 2.0, is made up of fixed and rigid nodes.

In addition, it is possible to modify at run-time the parameters of mass-spring model (spring, mass and damper coefficients) using a specific menu.

Although the model ends up being slightly heavy in terms of computational time when using this type of physical modelling, the level of realism increases when compared to a model with a single layer and the dynamic behaviour is closer to the behaviour of the real brain.

Figure 1 shows the brain model obtained using the detailed method.

Some tests have been performed to estimate the computational time of the algorithm executed on inputs of growing complexity.

A PC has been used with processor Intel Core2 CPU 6600 2.40 GHZ, 1GM RAM, video card NVIDIA GeForce 8800 GTS, Windows XP Pro operating system; the haptic device used is the SensAble PHANTOM Desktop with the OpenHaptics library.

The preliminary tests have been carried out using as model a sphere made up of 1926 nodes and 8964 springs; the obtained frame rate was between 59.9 fps and 60.6 fps. The following tests have been carried out on the brain model made up of 27 531 nodes and 128 604 springs; the obtained frame rate was between 6.9 fps and 7.4 fps.

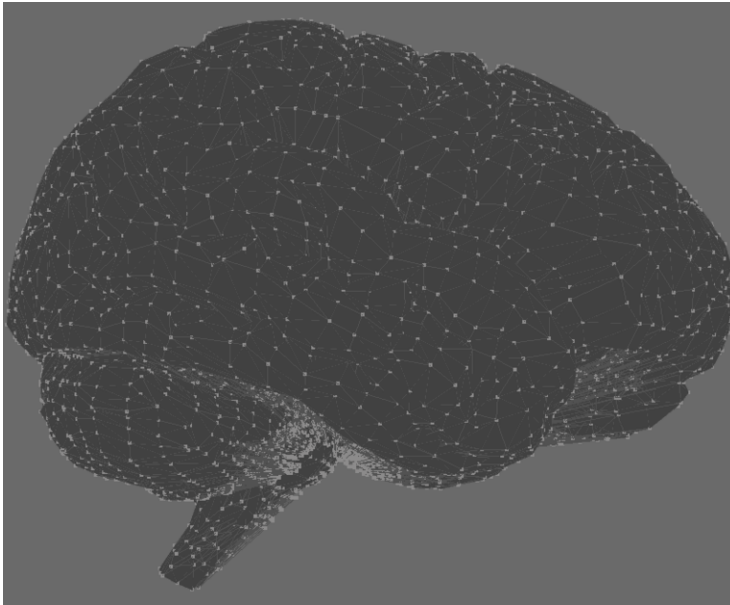Figure 2 shows a test phase using the haptic interface.

Figure 1. The brain model

4. Conclusions and Future Work

The aim of this project was to simulate the physical behaviour of a brain model when it comes into contact with surgical instruments. In developing the application we took into account the need to obtain a realistic and reliable model using, if possible, open-source software.

The developed prototype is based on the mass-spring-damper model and, in order to obtain deformations similar to the real ones, a three-tiered structure has been built. Compared to a model with a single layer, in the developed model the level of realism has increased and the dynamic behaviour is closer to the real one.

By increasing the number of points, the graphical realism of the simulation increases, but it is necessary to find a trade-off with the requirements of real-time interactions. In order to obtain at the same time a very high realism of the surface deformation and real-time interactions, it is necessary to increase the number of nodes and springs and, as a consequence, the numerical time integration of spring

displacements needs to be accelerated. To fulfill this requirement, the exporting of the developed model onto a multi-processor architecture or the exploitation of the features of recent graphics accelerators to simulate spring elongation and compression on the GPU is being considered.
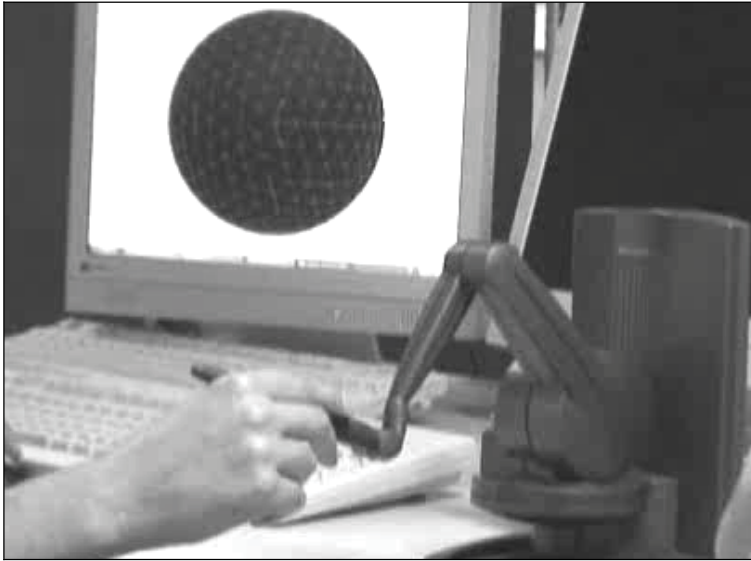

Figure 2. A test phase using the haptic interface

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