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ROBO-SIM: A Simulator for Minimally Invasive Neurosurgery using an Active Manipulator

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Abstract. This application report describes the software system ROBO-SIM, which is a planning and simulation tool for minimally invasive neurosurgery. Using actual patient's datasets, ROBO-SIM includes all planning steps necessary. These are; defining the trepanation point for entry into the skull and the target point within the depth of the brain, checking the surgical track, performing virtual trepanations (virtual craniotomy), and defining sanctioned volumes for use with an intra-operative active manipulator. With the additional simulation part, neurosurgeons are able to simulate whole surgical interventions directly on the patient's anatomy using the same instruments as for the real operation. First tests with ROBO-SIM are performed on actual patient's datasets with ventricular tumours.

1 Introduction

With the advent of computer-assisted methods in surgery, image-guided planning has become an increasingly accepted procedure in neurosurgery under the term of 'neuro-navigation'. Complex preoperative planning and simulation are mandatory and represent an important part of the total duration of operations. Therefore, the development of surgical simulators, comparable to flight simulators, has been initiated in a number of institutions (see, for example, [1-6]). Simulations, such as the real-time visualization of movements during manipulations, the transfer of tactile sensations to the surgeon, or the visualization of the effect of robotic activities, provide a formidable challenge for high-end graphical computing and other disciplines. To reduce the required amount of graphical power and nevertheless enable planning and simulation of neuro-surgical procedures on actual patient's datasets, the use of a combination of volume- and surface-rendered data for visualization and simulation seems most practical. 3D-MRI datasets of the brains of actual patients are used to pre-plan surgical approaches and to simulate views of the outer surface of the head as well as of inner surfaces, such as the ventricular system or cystic brain lesions, by aid of virtual endoscopy. Surgical manipulations are simulated for training using segmented surface models of the ventricular system.

The integrated planning and simulation station called ROBO-SIM is designed for manipulator-assisted virtual procedures through a trepanation in the skull of 1-2cm diameter and a miniaturized approach of a few millimetres diameter to target areas in the depth of the brain and its ventricular system. ROBO-SIM is part of the overall system ROBOSCOPE (project of the EU-Telematics program), including the robot arm NEUROBOT (see Fig. 1). For real surgical interventions, NEUROBOT is used by the surgeon as an active manipulator with built in robotic capabilities such as active constraints, which prevent the manipulator from leaving pre-planned volumes, precise pattern control and the ability to automatically track features as they move and deform. For ROBO-SIM the robot is used at an input device. Thus, the surgeon who plans and performs a virtual surgical procedure works with the real instruments to be used for actual surgery, while looking at a virtual scenario of the operating field created from a 3D-MRI-dataset of an actual patient.

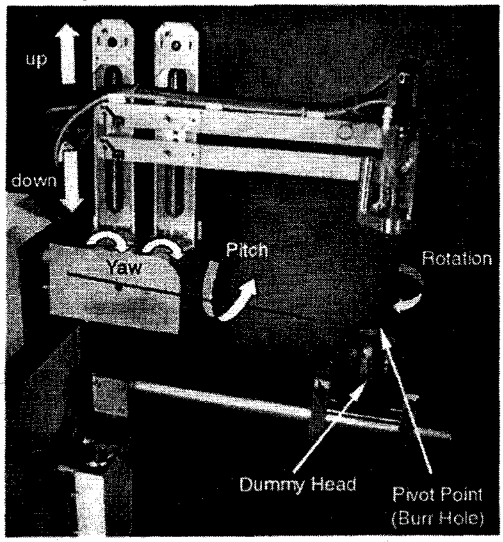

Fig. 1 NEUROBOT, the active manipulator developed within the ROBOSCOPE system. Using a standard neuro-endoscope, which is attached to the end effector, NEUROBOT can be freely moved in four degrees of freedom about a pivot point at the burr-hole. A dummy head is clamped to the robot, which is registered to the MRI data to simulate the positioning of the patient. (Courtesy of Fokker Control Systems, B.V.)

2 ROBO-SIM

The computer platform for the development and use of the system is a SGI Onyx2 Infinite Reality with two MIPS1000 CPUs. The rendering engine is based on OpenGL Volumizer [7]. To speed up the rendering process, especially for virtual endoscopy, an extension of OpenGL Volumizer, called Flight-Volumizer, was developed [8]. Flight-Volumizer uses a field of view rendering facility, which allows only the data that would be visible through the field of view of an endoscope to be rendered. In addition, arbitrary clipping (e.g. for virtual trepanations) and simulated deformations of volumetric data-sets are possible at interactive frame rates [8].

ROBO-SIM consists of two main components: the planning tool and the simulation tool. Using the planning tool all the steps necessary to pre-plan a minimally invasive neuro-surgical intervention are included. These steps are; 1. 'Define Entry and Target points' for planning of an approach and positioning the trepanation, 2. 'Check Surgical Track' for checking and changing the trajectory from entry to target point, and 3. 'Virtual Craniotomy' for simulating the trepanation.

Define Entry and Target Point

Usually, the pre-operative planning begins with the definition of the point of entry into the skull for the trepanation (entry point) and the target point. Several pre-defined planning screens are included in ROBO-SIM consisting of a number of components. These components are: Two editors for planning the entry and target points, including axial, coronal and sagittal images of the patient; A virtual endoscopic view; A planning view; A main (global) view and several views with slices along the axis of the virtual endoscope. All screens are interactive and new screens can be defined by the neurosurgeon using the main components. Fig. 2 shows an example of such a planning screen. Moving the crosses for the entry or target points results in changing other slices and the virtual endoscopic view. The main or global view shows the position of the endoscope with respect to the patient's skull.

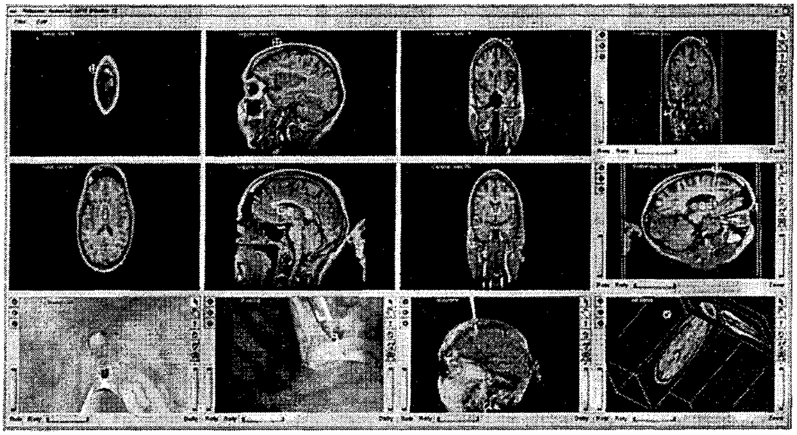

Fig. 2: An example screen of ROBO-SIM: The upper row of images allows the definition of the entry point and the middle row defines the target point. All images are primarily interactive; interaction may, however, be blocked. The image on the lower left shows the surface-rendered virtual endoscopic view of the lateral ventricle with a small foramen of Monro squeezed by a tumour of the third ventricle (colloid cyst). Lower middle image: view with a remote virtual endoscopic camera along the ventricular lumen shows the position of the virtual trans-endoscopic instrument. Lower right image: volume-rendered view of the patient's head with a virtual endoscope in position for a left frontal approach. The images on the right show virtual slices along the endoscope.

Check Surgical Track

The next step is to check if the surgical track – i.e. the line from entry to target point - avoids areas of the brain that should not be damaged by the endoscope. The standard screen to check the surgical track consists of a main view and a virtual endoscopic view. The axial, sagittal and coronal images are also displayed, with the overlaid surgical tracks and marked red dots where the surgical track intersects the slices (see Fig. 3). These images are used to check the damage that is done to the patient by introducing the endoscope. The surgical track can be moved by dragging the spheres at the track's start and end points with the mouse.

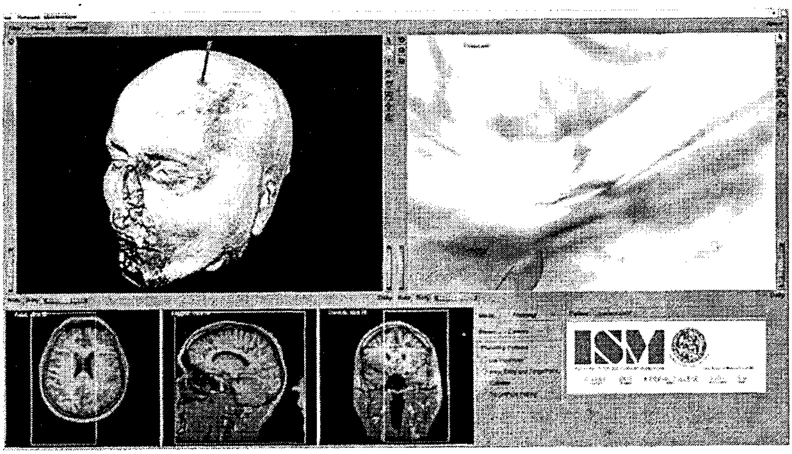

Fig. 3: The upper left image shows a volume-rendered view of the patient's head. The red sphere indicates the entry point. The upper-right image shows the target point as an endpoint of the surgical track. The lower row shows axial, sagittal and coronal images of the patient's dataset overlaid with the surgical track and the intersection point of the track and the image.

Virtual Craniotomy

After checking the surgical track, a virtual trepanation can be performed. The size, depth and position of the trepanation can be planned. The virtual craniotomy screen has a similar layout to the screen above, but instead of showing the spheres for changing the surgical track the virtual trepanation is shown.

Simulation

After finishing the planning steps, the simulation can be performed using the same active manipulator, which is used during real surgery. A volume rendered view of the ventricle can be used for real-time virtual endoscopy with an update of 7-15 frames per second. Also, direct manipulations of the volumetric dataset are possible with interactive frame rates [8]. However, the image quality during these manipulations is very low because of the low resolution of the MR-dataset, leaving a virtual endoscopic field of view that mostly has only 13 pixels width. Better image quality can be achieved by using segmented models of the ventricle, which are simulated by deformable meshes. For the physically based simulation of these surface meshes, neuro-fuzzy systems [9] are used, which can emulate the real deformation, even without a properly defined mesh structure [10, 11]. In addition, tools for coagulation and fragmentation of tissue are integrated into ROBO-SIM (see Fig. 4). Deformations are applied locally to the mesh around the contact point. Static collision detection between the ventricle and the endoscope is performed using OBB-trees [12]. To update the static collision model after a fragmentation, two OBB-trees of the ventricle's surface model are used. While a collision of one model is checked, the other model is updated in the background.

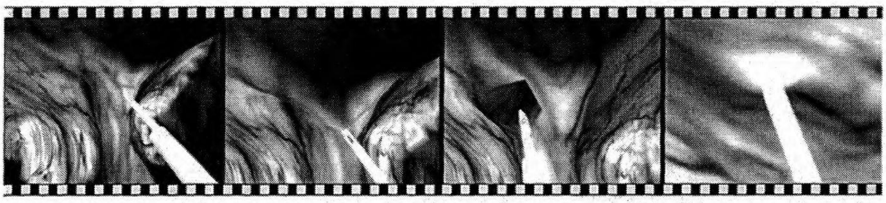

Fig. 4: Virtual local tissue manipulation inside the ventricle. From left to right: Original ventricle, virtual deformation using biopsy forceps, virtual fragmentation simulated by moving some of the nodes normal to the surface gradient and fixing them, virtual coagulation.

For the evaluation procedure of ROBO-SIM, actual patient data-sets are used by experienced neurosurgeons. Using the real instruments mounted onto the robot arm, as well as the visual impression from the simultaneously moving virtual instruments and the virtual endoscopic anatomical landscape and its changes during manipulations, the surgeons are simulating real procedures such as the removal of a tumour. The neurosurgeons will fill in a questionnaire on subjective parameters concerning practicality, user friendliness and the quality of the simulation.

3 Conclusions

Most of the simulators currently under development are working with simplified models of the human anatomy instead of using the anatomy of a real patient. ROBO-SIM is able to use directly the digital imaging datasets of the actual patient's neuro-anatomy. A simulation of minimally invasive neuro-surgical procedures is considerably more complex than in most other areas, because the creation of the illusion of reality is required at a microsurgical level. 3D-MRI datasets of the brains from actual patients are used to simulate views of the outer surface of the head as well as of inner surfaces, such as the ventricular system or cystic brain lesions, by aid of virtual endoscopy. Although direct manipulation of the MRI data sets is possible on high-end graphic systems [8], it has been proven that this approach is not useful simulating minimally invasive neuro-surgical procedures. The MRI data sets show too few details and too low resolution for realistic impressions of deformations and fragmentations. Instead, the simulation works with surface models that represent a very precise model of the actual patient's ventricle.

At present ROBO-SIM is only capable of simulating tumour removal. Currently we are working on creating and simulating thin membranes, which could make the approach more difficult during real surgery. Also, more elaborated texture mapping and the use of higher resolution images are under development to further improve the impression of reality.

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