Mastoidectomy Simulation with Combined Visual and Haptic Feedback

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Abstract. Mastoidectomy is one of the most common surgical procedures relating to the petrous bone. In this paper we describe our preliminary results in the realization of a virtual reality mastoidectomy simulator. Our system is designed to work on patient-specific volumetric object models directly derived from 3D CT and MRI images. The paper summarizes the detailed task analysis performed in order to define the system requirements, introduces the architecture of the prototype simulator, and discusses the initial feedback received from selected end users.

1. Introduction

Mastoidectomy is one of the most common surgical procedures relating to the petrous bone. It consists of removal of the air cavities just under the skin behind the ear itself, and it is performed for chronic infection of the mastoid air cells (mastoiditis). It is a surgical procedure undertaken by a wide range of surgeons in everyday practice. The site anatomy is widely variant. The main risks are related to the detection and avoidance of the facial nerve and of aberrant jugular veins (or branches) and to the resection of adequate amounts of the mastoid air cells. The ability to rehearse the procedure using patient-specific data is extremely rare. A VR simulator realistically mimicking a patient-specific operating environment addresses this shortcoming. A number of groups are working toward this goal [4][5][6][7].

In this paper we describe our preliminary results in the realization of a virtual reality mastoidectomy simulator designed to work on patient-specific volumetric object models directly derived from 3D CT and MRI images. The simulator runs on a multiprocessing PC platform and provides realistic visual and haptic feedback, including secondary effects such as the obscuring of the operational site due to the accumulation of bone dust and other burring debris.

The rest of the paper is organized as follows: first, we describe the detailed task analysis performed to define the system requirements; we then provide a brief description of the architecture of the prototype simulator, and we conclude with a discussion of the first results obtained and a view of our future work.

1. Human-Centered Design

A detailed task analysis, following ISO 13407 [3], has been carried out in order to identify the essential ergonomic components [9]. The analysis involved a review of existing documentation, training aids, and video recordings, interviews with experienced operators, as well as direct observation of the procedure being performed in theater.

In the typical mastoidectomy surgical setup, Fig. 1, the ENT surgeon looks at the region of interest through a stereoscopic microscope and holds in his hands a high speed burr and a sucker. These tools are used, respectively, to cut the bone and to remove water (used to cool the burr bit) and bone paste produced by the mixing of bone dust with water.

Figure 1: The typical mastoidectomy surgical setup: the ENT surgeon looks at the region interested by the procedure via a stereoscopic microscope and holds in his hands a high speed burr and a sucker, that he uses, respectively, to cut the bone and to remove bone paste produced by the mixing of bone dust with water.

Subjective analysis of video records, together with *in-situ* observations highlighted a correlation between drilling behaviours and type and depth of bone. In the case of initial cortex burring and recess preparation for, e.g., a cochlea implant receiver/stimulator, drill tip/burr motions of around 0.8 cm together with sweeps over 2-4 cm were evident, as were fine flexion and extension movements of the forefinger and thumb around the drill. Shorter (1-2 cm) motions with rapid lateral strokes characterized the post-cortex mastoidectomy. For deeper drilling, ~1 cm,- strokes down to 1 or 2 mm were evident with more of a "polishing"motion quality, guided using the contours from prior drill procedures. "Static"drill handling was also noted, eroding bone tissue whilst maintaining minimal surface pressure.

As for the visual effect of the drill on the surface of the bone, the task analysis hilighted that the graphical process must simulate drill site obscuration by bone dust paste, because its absence would reduce the importance placed by a trainee on the need for regular irrigation and suction. Realistic and meaningful bleeding is a perennial problem for VR researchers. We have concluded that, visually, the actual drill representation needs only be quite simple, and it is felt that representing the spinning of the cutter or diamond burr is unnecessary. What is considered necessary, from a functional standpoint, is an effective collision detection mechanism which not only copes with increased resolution as the virtual drill proceeds deeper into the temporal bone, but is also capable of generating error states when (for example) a large burr is inserted into a narrow drill site.

As for the nature of the technology required for displaying drill, drill site, bone, and so on, there is no conclusive evidence or support for the premise that the use of a stereoscopic system will aid performance in this case. Binocular viewing systems are deployed in the operating theatre and used by surgeons, and so binocular imaging should be available to the simulator. However, the wearing of any form of stereoscopic display, such as a head-mounted display or liquid crystal shutter glasses should be avoided. The surgeon or trainee does not want to use cumbersome eyewear that is not necessary for carrying on the real procedure. We make the hypothesis that, if the simulation achieves a reasonable level of fidelity, then the combination of high-resolution images and haptic feedback will, more than likely, suffice.

As well as the visual and 6-DOF input/3-DOF haptic feedback for drill simulation (including high frequency vibration), the training system might also be enhanced by the inclusion of audio effects. Some surgeons suggest that they are able to detect subtle changes in sound depending on the nature of the bone they are working with (eg. cortex *vs.* petrous). However, this quality is considered to be "overkill" in a training system such as that being considered here.

2. Prototype System Architecture

We have built a prototype system, simulating the effects identified by the task analysis. The system is running on a dual PC platform (Fig. 2). It exploits both message passing and shared-memory parallelism to meet the performance constraints imposed by the human

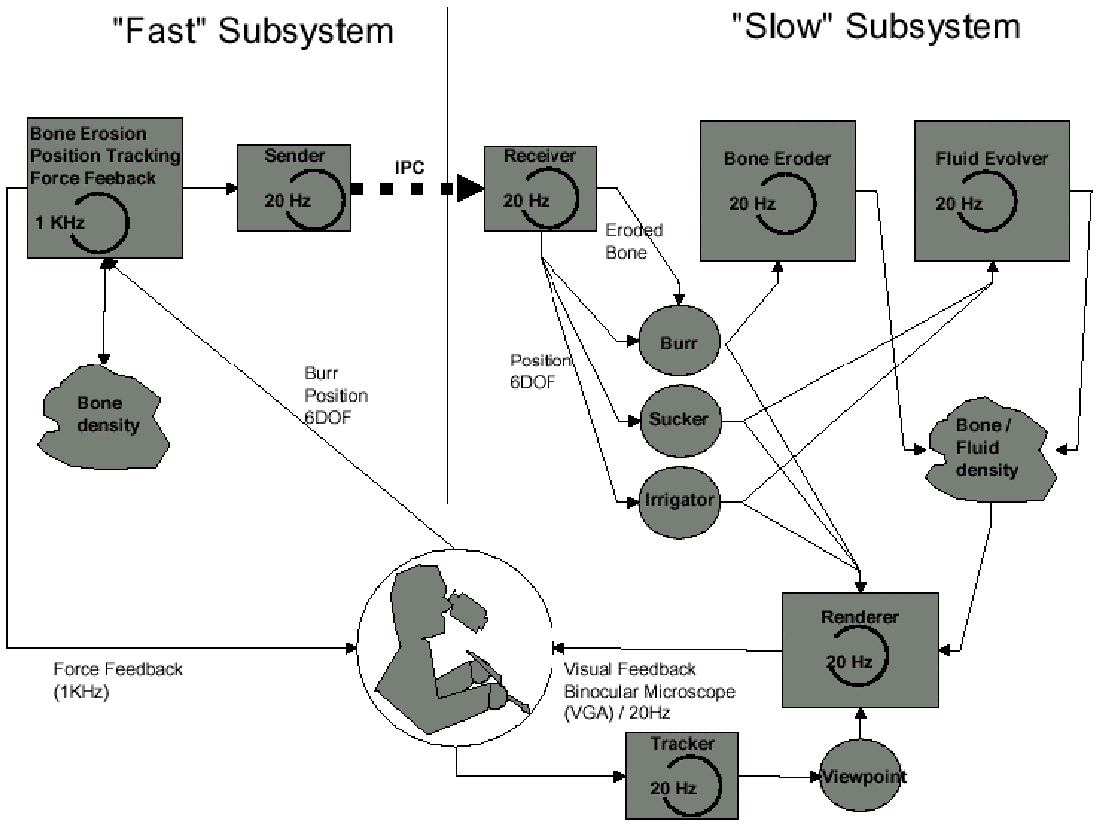

Figure 2: Decoupled simulation architecture. The system uses a volumetric approach, with the initial configuration of the model directly derived from patient CT data. The data is initially replicated on the two machines. The first machine is dedicated to the high-frequency tasks: haptic device handling and bone removal simulation. The second machine concurrently runs at 10-20 Hz the low-frequency tasks: bone removal, fluid evolution and visual eedback. The two machines are synchronized using one-way message passing with a dead reckoning protocol.

perceptual system. The system uses a volumetric approach, with the initial configuration of the model directly derived from patient CT data. The final version will use volumetric tissue probability maps derived from CT, MRI and MRA data using a multi-dimensional classification technique [8]. The data is initially replicated on the two machines. The first machine is dedicated to the high-frequency tasks: haptic device handling, one for the dominant hand controlling the burr and the irrigator, and the other controlling the sucker, as well as bone removal simulation. These tasks require at least 1 kHz update frequency because of the need of simulating hard contacts. The second PC concurrently runs at 10-20 Hz the low-frequency tasks: bone dust evolution and visual feedback. The two machines are synchronized using one-way message passing with a dead reckoning protocol.

In our volumetric description of the scene, voxels labeled as bone must bone must react to the manipulators through the haptic feedback devices, but they do not evolve unless they are removed by burring. In the data replicated in the machine dedicated to low frequency tasks, further values are introduced in the volume labelling voxels occupied by dust, blood and water. These values are used directly by the volume rendering thread.

The "fast"subsystem performs the burring simulation, i.e. the force feedback calculation and the bone removal from the dataset, sending the force value to the haptic devices, and sending information on manipulator positions and bone removed to the "slow"subsystem.

This task is extremely difficult to perform at over 1 Khz. We have thus organized our simulation so that each time step is divided into two sub-steps. The first sub-step estimates the bone material deformation and the resulting elastic forces, given the relative position of the burr with respect to the bone. The second sub-step estimates the local rate of cutting of the bone by using a postulated energy balance between the mechanical work performed by the burr motor and the energy needed to cut the bone, which is assumed to be proportional to the bone mass removed.

The "flow" subsystem performs the visual simulation of bone dust and fluid dynamics as well as the visual rendering of the scene. We are modeling the dust/fluid dynamics using what essentially amounts to a hybrid particles/sand pile model.

The visual rendering subsystem must operate within the timing constraints imposed by the human perceptual system (i.e. a latency of less than 300 ms, and a frequency above 10-15 Hz). We reach this goal by using a parallel processing approach, which exploits the capabilities of current graphics PC architectures. In our system, the renderer is totally decoupled from the simulator and the tracking system, and runs at its own frequency. The rendering system is based on a volumetric approach. We use texture mapping and alpha blending for a back to front reconstruction of the scene. Shading effects are implemented by exploiting the register combiner OpenGL extension on most modern commodity graphic boards. Surgical instruments are rendered as polygons, and combined with the volumetric rendering of the rest of the scene using Z-buffering.

3. Implementation and Results

Our current configuration is the following:

- a single-processor PIII/600 MHz with 256 MB PC100 RAM for the high-frequency tasks; two threads run in parallel: one for the haptic loop (1 KHz), and one for sending volume and instruments position updates to the other machine;
- a dual-processor PIII/800 MHz with 512 MB PC800 RAM and a NVIDIA GeForce 2 GTS and running a 2.4 linux kernel, for the low frequency tasks. Three threads are continuously running on this machine: one to receive volume and position updates, one to simulate bone removal and fluid evolution, and one for visual rendering;
- a Phantom Desktop haptic device for the dominant hand; the device is connected to the single processor PC. It provides 6DOF tracking and 3DOF force feedback for the burr/irrigator;
- a Phantom 1.0 haptic device for the non-dominant hand; the device is connected to the single processor PC. It provides 6DOF tracking and 3DOF force feedback for the sucker;

- a N-vision VB30 binocular display for presenting images to the user. The VB-30 contains a small high resolution LCD display and is connected to the S-VGA output of the dual processor PC.

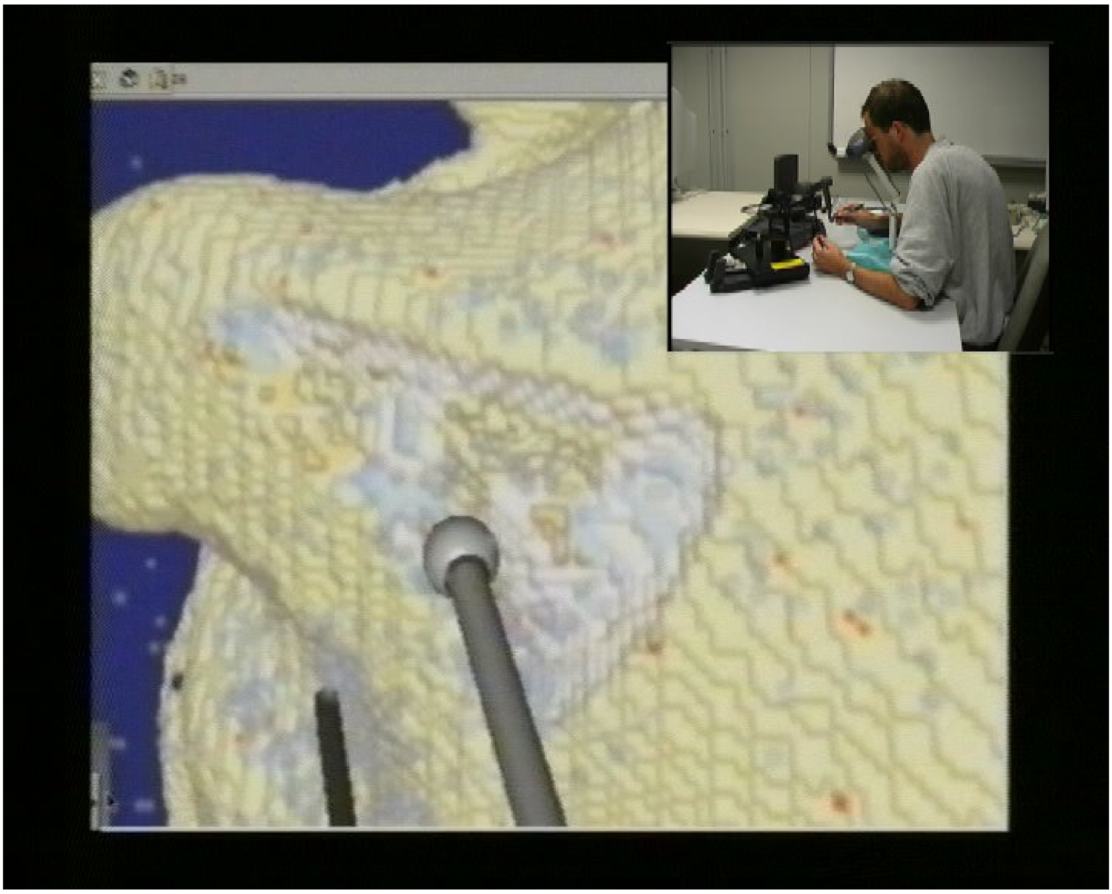

Figure 3: Snapshot from a video demonstration of a simulated mastoidectomy. The central image show the image viewed by the training surgeon with bone, water, blood and manipulators. In the top right corner it is possible to see the corresponding external view with the training surgeon feeling the haptic feedback through the Phantoms while observing the scene in the binocular display

We have gathered initial feedback about the prototype system from the Otolaryngology surgeons that are collaborating with this project.

The performance of the prototype is sufficient to meet the timing constraints for display and force-feedback effects, even though the computational and visualization platform is made only of affordable and widely accessible components. We are currently using a volume of 256x256x128 8-bit cubical voxels (0.3 mm side) to represent the region where the operation takes place. The force-feedback loop is running at 1 KHz using a 5x5x5 grid round the tip of the instruments for force computations. The computation needed for force evaluation and bone erosion takes typically 20 usec, and less than 200 usec in the worst case configuration. Shaded volume rendering of dynamic volumes currently takes 70 ms per frame (i.e. over 14 frames per second) using 256 depth slices on an 800x600 window with 16 bit color and 2X zoom rendering.

The overall realism of the simulation is considered sufficient for training purposes. As required by the task analysis, the haptic sub system is able to provide a reasonable force feedback effect, bone removal and noise simulation. The visual system is able to provide bone dust and water bleeding effects, blood simulation, and manipulators displayed at the required frame rate.

Subjective input is currently being used to tune the parameters that control force feedback. The speed of the water flow simulation has been identified as a principal area for improvement.

Fig. 3 shows a snapshot of the current system in use. The surgeon is looking at the scene with the binocular display and manipulates the burr and sucker through the two PHANToM devices. Fig. 4 shows selected frames of the initial phase of a virtual mastoidectomy, where debris formation and suction effects are clearly visible.

4. Conclusions and Future Work

We have described our preliminary results in the realization of a virtual reality mastoidectomy simulator designed to work on patient-specific volumetric object models directly derived from 3D CT and MRI images.

We carried out an in-depth task analysis, that highlighted key human interface features, including visual and haptic feedback requirements, as well as burring primary and secondary effects. Our simulator prototype demonstrates the possibility of building, exploiting parallelism on a PC platform, and a VR simulator mimicking a realistic patient-specific operating environment, including key secondary effects such as debris formation and the related visual masking effects.

The results obtained thus far were judged of good quality by the Otolaryngology surgeons collaborating to the project. The prototype is currently running directly using patient specific data as input, opening, therefore, the road towards the use of the simulator for pre-operation planning and rehearsal. This would make it possible to plan surgery directly on a model of the individual patient, rather than by referring to a model surgical procedure on a standard anatomy.

While subjective input from selected end users is encouraging, it has been realized that it would be of extreme interest to have available direct forces measurements obtained by drilling actual samples, since there are, to our knowledge, no available data on the subject in the literature. In the near future we plan to start an activity aimed at defining an experimental setup and measurement procedures.

Our current work is also concentrating on improving the quality and speed of fluid flow simulation.

Acknowledgments

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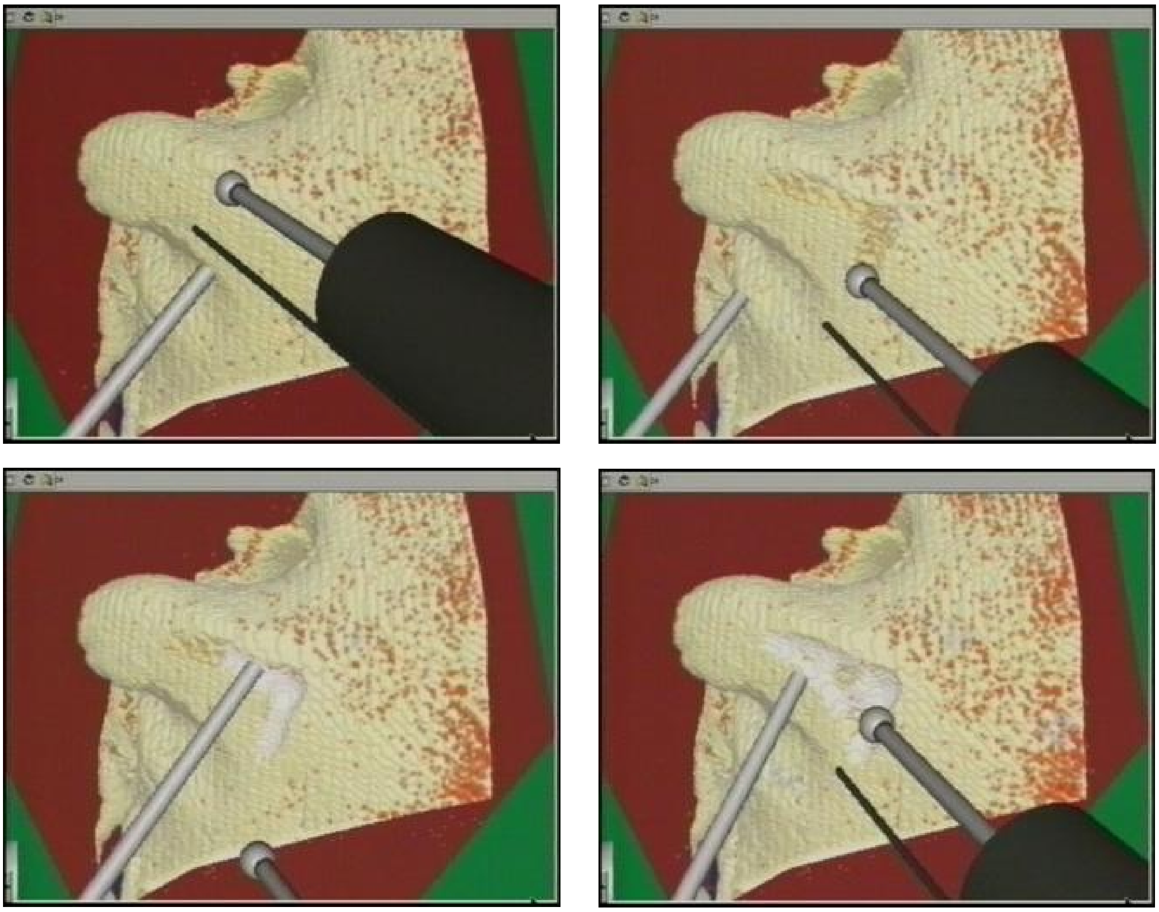

Figure 4: From top left to bottom right, selected frames of the initial phase of a virtual mastoidectomy. Debris formation and suction effects are clearly visible.