An Integrated Simulator for Surgery of the Petrous Bone

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Abstract. This paper describes work being undertaken as part of the IERAPSI (Integrated Environment for the Rehearsal and Panning of Surgical Intervention) project. The project is focussing on surgery for the petrous bone, and brings together a consortium of European clinicians and technology providers working in this field. The paper presents the results of a comprehensive user task analysis that has been carried out in the first phase of the IERAPSI project, and details the current status of development of a pre operative planning environment and a physically-based surgical simulator.

1. Background

Today, planning of surgical procedures makes poor use of imaging data. In most cases surgeons simply study medical images from MRI, CT, etc. prior to surgery and construct a mental 3D model of anatomy in each individual case. Previous knowledge of normal anatomy is essential. Furthermore the ability to rehearse the surgical procedure using patient specific data is extremely rare. The IERAPSI (Integrated Environment for the Rehearsal And Planning of Surgical Intervention) project is addressing these shortcomings for surgery of the petrous bone - a common surgical site with complex anatomy. A range of surgical procedures with escalating levels of complexity is being covered: Mastoidectomy; Cochlea electrode implantation; Acoustic Neuroma resection. Solutions for both surgical planning and surgical simulation are being implemented.

IERAPSI brings together a consortium of European clinicians and technology providers to create this integrated simulator for surgery of the petrous bone. The project is being partly funded by the European Commission.

2. Methods & Tools

2.1 User Task Analysis

The project began with a detailed user task analysis of surgeons carrying out the procedures being targeted. The task analysis [1] followed the ISO 13407 standard [2], and focused on activities that ensure involvement of users, and a clear understanding of user and task requirements (including context of use and how users might work with any future system evolving from the project). This initial exercise has provided an input into early system design processes. We are also repeating the analysis periodically to ensure that the recommendations do not produce any unforeseen human performance artefacts or safety-critical consequences.

Figure 1: Translabyrinthine Acoustic Neuroma Resection in Progress. Note the use of additional "greens" to support the surgeon's left wrist and the need to clip the drill pneumatic supply pipe to avoid drag

With the support of the staff of the ENT unit, the Department of Otolaryngology, Head & Neck Surgery and the theatre personnel at Manchester's Royal Infirmary and the Institute of Laryngology and Otology, University College London, we were permitted to observe and, where possible, video record surgeon performance and close-in drilling activities (backed by additional important video contributions from the University of Pisa) – see Fig. 1, for example. Initially, five theatre sessions were analysed in detail, each lasting an average of six hours:

- Infantile Cochlea Implant.
- Middle Fossa Acoustic Neuroma.
- Translabyrinthine Acoustic Neuroma.
- Stapedectomy "Follow-Up" and Ossicle Prosthesis *(combined approach*).

With regard to planning, whilst IERAPSI concentrates on the development of software modules to support the processing of radiological data, the way in which surgeons actually use the data must be considered early and refined by consultation with users as the concepts emerge. Initial human interface proposals resulting from the task analysis describe an off-line (pre-operative) system based around a multi-user real-time 3D display and appropriate interactive controls. Amongst the key anatomical features to be highlighted are the facial nerve (and any other key neuronal features), the jugular bulb and sigmoid sinus, blood vessels of secondary importance, the semi-circular canals and close proximity of brain tissue.

The training environment is designed to simulate those aspects of the surgeon's task that are characterised by special procedures and operative skills. The task analysis highlighted key human interface features, including stereoscopic *vs.* conventional display, haptic feedback, fidelity and coding techniques for initial bone exposure, drilling/burring effects, use of other virtual instruments and materials, and error/performance recording. Careful consideration must be given to the display-control stereotypes expected by temporal bone surgeons and those delivered by the final training interface. Otherwise, a fixed display (or display frame) moveable image solution might foster negative transfer of training from the virtual to the real.

2.2 System Requirements and Functional Specification

Using the task analysis as input, a detailed system requirements and functional specification has been prepared for the main components of IERAPSI.

The functionality of IERAPSI is being provided by three independent subsystems: pre-operation planning, surgical simulation, and educational and usage demonstrator. These components will be integrated as a single data handling pipe-line through data exchange based on common file formats, introducing and supporting a novel and innovative training strategy based on patient-specific pre operative and simulation environments. Relevant technological state-of-the-art, including hardware/software issues have been considered. IERAPSI is making extensive use of 3D visualization, physics based simulation, and virtual reality technologies, including autostereoscopic visual and bi-manual haptic feedback.

An implementation specification has been produced, which describes the software architecture, the link between the system components, as well as the required hardware configurations. The reference hardware for the pre-operative system will be a single-processor PC Linux/NT platform with the Dresden autosteroscopic display [3] for visual feedback. The surgical simulation system will be designed for being run on a multiprocessing PC Linux platform, using two PHANToMs for haptic feedback and a microscope-like display for visual feedback.

2.3 Pre-Operative Planning

A pre-operative planning module is currently under development containing a suite of image segmentation and visualization tools, and allowing rapid and accurate identification of individual structures based on their imaging characteristics. Techniques to allow the segmentation of the facial nerve are being investigated as part of this task. Different stages addressed involve: an automatic co-registration system to align the specified data sets based on mutual information, data non-uniformity correction [4], multi-spectral classification for data segmentation and optimal boundary representation for visualisation purposes.

The most principled approach to MRI, CT and MRA image segmentation is based on techniques that utilise statistical models. Devised multi-spectral classification system will make probability maps available for bone, blood vessels and soft tissues, which then can be used to segment regions or locate the boundaries between tissues. Availability of multiple images provides more information for separation of ambiguous regions present due to overlapping tissues and requires multivariate distribution model for each pure tissue and partial volume distribution.

The methodology of probabilistic data segmentation involves constructing a likelihood model for each tissue component present in data. A common approach involves modelling only pure tissue distributions, but in order to account for the fact that in a single voxel a mixture of tissues can be present, a partial distribution must also be modelled [5]. Pure tissues have been modelled using Gaussian distributions, P_t, while partial volume distributions for paired tissue combinations take the form of a triangular distribution convolved with a Gaussian, P_{ts}, which is intended to model the response function of the measurement system.

A multi-variate distribution for each pure tissue t is defined as:

$$P_t(g) = \alpha_t e^{-(g-G_t)^T C_t (g-G_t)}$$

where G_t is the mean tissue vector and C_t its covariance and α chosen to give unit normalisation.

Partial volume distributions are modelled along the line between two pure tissue means G_tG_s.

$$P_{ts}(g) = \beta_{ts} P_{ts}(h) e^{-(g-h.g/|h|)^T C_h (g-h.g/|h|)}$$

with $h = (g - G_s)C_h(G_t - G_s)/|(G_t - G_s)C_h(G_t - G_s)|$, $C_h = C_t h + C_s(1-h)$.

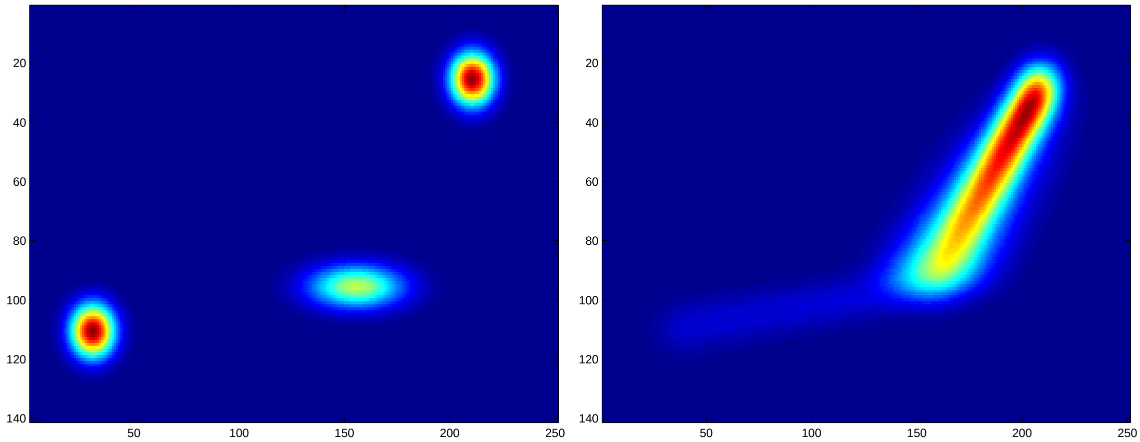

Figure 2: 2D probability density model for 3 pure tissues and their mixture for two medical images

The parameters for the density model must be determined using an optimisation algorithm to minimise the difference between the model and the data. Parameters can be iteratively estimated by taking weighted averages over the selected volume V using a maximum likelihood process generally referred to as Expectation Maximisation [6]. This approach is expected to deal successfully with multiple tissue segmentation from multiple images for boundary representation and data visualisation. Extension of this technique to deal with pathological (unmodelled) tissues can be incorporated by allowing an additional category for infrequently occurring outlier data [7].

2.4 Surgical Simulation

Physical modelling is a computationally expensive approach to virtual reality, but is essential in this specific field of application since it provides the only practical way to accommodate arbitrary positioning in the area affected by the operation of the surgical tools, e.g. drilling, and the use of realistic anatomical models derived from patients CT data. The computational costs due to physical modelling are partially mitigated by the fact that the surgical procedures mentioned above are constrained by a restrictive field of view and limited haptic interaction between the surgeon and the patient, and thus the overall computational cost is compatible with available computer technology.

Research and development for the real-time physically based simulator is at this stage focusing on physically motivated solutions for drilling into the petrous bone. The task analysis has indicated that the most common actions to be simulated are performed by three different manipulators: a burr reducing trabecular bone in fine dust, an irrigator introducing water that is mixed with the bone dust, and a sucker removing bone dust and water. In order to provide a useful training platform, the simulator should not model only the primary effect (bone removal), but should also be capable of replicating the secondary effects caused by the different physical processes (in particular, bone paste creation and obscuring effects). Wiet and colleagues [8] have done some preliminary work toward the simulation of temporal bone dissection, but their approach is purely geometric and limited to the modelling of the bone removal process.

In our simulator, different specific solvers cooperate in determining the time evolution of the model in response to external actions and in computing the feedback to be returned to the user. Our approach, as well as preliminary simulation results, is described in the following sections.

2.4.1 Bone drilling

Bone is hard and has a stress-strain relationship similar to many engineering materials. Hence, as discussed by Fung [9], stress analysis in bone can be made in a way similar to the usual engineering structural analysis. The simulation of the drilling of the petrous bone involves first the detection of collisions of the drill burr with the bone surface, then, depending on the type and location of the contact, a prediction on the amount of bone to be removed and of the forces that should be returned to the hand of the user via the haptic feed-back device. Given the particular nature of the process simulated, the natural way to model the petrous bone anatomy is by using a volumetric approach, with the initial configuration of the model directly derived from patient CT data.

Currently, we model the scene with a set of voxels, and we define each voxel of the scene as “empty”, “bone” or “bone dust or water”. The bone removal process is modelled with a set of rules that define what happens when the burr intersects the bone. This is simply obtained by cleaning voxels where the distance from the burr centre is less than the burr radius, and filling the first empty voxel with dust following some basic rules: if under the burr the space is empty, the material falls, if it is full, the material is put at the borders of the hole created. The force to be returned to the hand of the user via the haptic feedback device is computed using an inverse dynamics approach.

2.4.2 Bone dust and paste

The behaviour of bone dust and of the dust paste created by the mixing of blood, water, and dust, is modelled using a technique derived by sand-pile simulation [10, 11]. The problem in our application is that the material cannot be modelled as a single height field, so the evolution algorithm is more complex. At each simulation step, we consider each voxel in a region around the burr and check if it contains dust. In this case, we look at the surrounding columns of dust and measure the local height difference. A redistribution algorithm is then applied to move the system to a more stable state. The algorithm is defined by a set of evolution rules that are derived from the equations that describe the physical behaviour of dust. As in [11], we use the Mohr-Coulomb theory to determine shear stress and shear strength and then calculate the critical slope angle and the forces, which push material along a failure plane.

2.4.3 Irrigation and suction

The irrigator is modelled as a source generating a flow of water particles. These particles have a velocity and are affected by gravity. When they are close to a dust or bone voxel they interact with the material. In our first implementation, we consider only an extremely simplified model, where particles that collide with a "dust" voxel are merged with it, creating a new dust voxel with a "wet" attribute. The sand pile falling threshold of wet voxels is set to zero, thus the created "mud" will behave like a liquid.

The sucker, removing bone dust and water, is the simplest element in the simulation. A process that empties all the "mud" voxels in contact with the sucker tip models it. Force feedback for the irrigator and sucker is computed using a simple collision model that considers only the bone voxels.

3. Results

The modules produced for the pre-operative planning tool are providing high image quality 3D visualization, and segmentation precision to increase available information for operation planning. Algorithms based on probabilistic labelling and deformable templates are performing well. The new techniques being developed for multiple tissue segmentation from multiple images for boundary representation and data visualisation augurs particularly well.

Research and development for the physically based simulator is at this stage focussing on real-time physically motivated solutions for drilling into the petrous bone. We are currently in the phase of testing our system off-line, without connection to the I/O devices, by modelling the effect of pre-determined instrument actions on test datasets. Figure 3 shows a sequence of frames in a bone drilling simulation. The combined effects of the different simulation components are clearly visible.

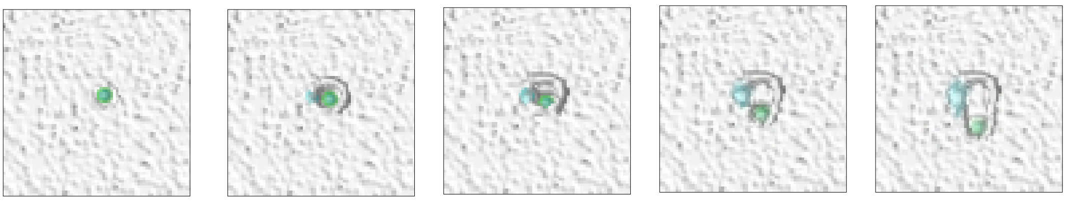

Figure 3: Sequence of frames in a bone drilling simulation. The drill is excavating a flat bone structure. The bone dust accumulates around the hole following a sand pile dynamics. The irrigator drops of water are visible.

It is planned to use two 6 DOF/3 DOF PHANToM haptic devices for the user interface, although a lower specification device could be used for the non-dominant hand.

Anatomical models are provided from the pre-operative tool and a process to augment the segmented voxel data with information on the organ's physical properties is being developed.

4. Conclusions

Other groups are developing simulators for surgical procedures of the petrous, or temporal, bone [8, 12-15]. This project, however, introduces several novel factors: a detailed user task analysis (based on ISO 13407); the use of patient specific data with tight integration between the medical image analysis and simulator components; the use of new autostereoscopic technology.

The use of patient specific data with tight integration between the medical image analysis and simulator components is proving to be an effective approach. At the end of the project we expect a high-fidelity solution for surgical planning and training in the field of otology, providing:

- A high quality user interface designed through ergonomic task analysis.

- A state-of-the-art system for pre-operative planning using advanced image analysis and visualization techniques.
- A leading system for physics-based surgical simulation.
- Innovative use of 3D display technology for a clinical application.

In addition, the project partners will have established a framework on which further surgical applications can be developed.

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