Mixed Reality System for Neurosurgery based on Operating Microscope

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Abstract:
The aim of this project is to provide a Mixed (Augmented and Virtual) Reality platform, both educational, pre- and intra-operative purposes. The architecture is based on a prototype of a stereoscopic Augmented Reality (AR) microscope for ergonomic intra-operative presentation of complex preoperative three-dimensional structure (obtained by real patient’s images) for neurosurgical interventions realized in our institute. We are expanding this work using a haptic interface with force feedback to obtain the first example of neurosurgical training system using a real operating microscope.

Keywords: Augmented Reality, Virtual Reality, Mixed Reality, Training System, Neurosurgery, Haptic Interface, Collision Detection, Physical Modeling, Tracking, Navigation.

1. Motivation
In neurosurgery, microscopes are regularly used, for almost all the interventions.

Minimally invasive surgical methods require different training from traditional techniques especially in neurosurgical field and the outcome of the operations is closely related to the surgical skills of the surgeon.

These skills are being developed over years of surgical training on animals, cadavers and patients. In many countries it is becoming increasingly difficult to train on animals and cadavers due to ethical reasons, and the surgeons’ daily work schedule allows for much fewer hours per week in the operating theater. For surgeons to remain at a high level of technical skills and for young surgical trainees to reach such a high accuracy level, new and alternative ways of performing surgical training are required.

Our research is motivated by the following consideration based on the state of the art:

- There are only few examples of Virtual Reality (VR) neurosurgical simulators which use force feedback (see [1]) and for all of them the architecture use only displays or HMD and not a real surgical microscope.

Actually, in the operating theatre, all the best commercial systems provide the surgeon with only a real two-dimensional, overlay of the region of interest (ex. tumor) inside the oculars of the operating microscope related on the preoperative processed patient’s image data. The three-dimensional environment reconstruction from 2D is another difficult and critical mental work for the surgeon.

In our institute has been realized a prototype of a stereoscopic Augmented Reality (AR) microscope for ergonomic intra-operative presentation of complex preoperative three-dimensional for neurosurgical procedures [2].

The aim of this project is to extend this work reusing a part of this existing AR intraoperative platform (the image injection part), providing a neurological training system directed towards both educational and preoperative purposes based on a virtual environment set up on reconstructed human organs from real patients’ images. According to the scientific convention (see [3]) we are working about a Mixed Reality system for neurosurgical pre- and intra-operative aid to the surgeons (Fig.1).
2. Methods

2.1. Physical Modeling

The realism of the simulation has to be provided by an accurate human tissue modeling, by the use of a force feedback device and, for the visual feedback, rendering the virtual scene directly on the oculars of the operative microscope.

We are using a haptic feedback device (Phantom Desktop from Sensable Tech.) in order to provide to the surgeon an immersive experience while the interaction between the surgical tools and the brain and skull of the virtual patient’s.

The collisions between organs and surgical tools produce forces (which have to be replicated by the haptic interface) and organ deformations, which have to be graphically rendered. The force computation and the organ deformation is strictly related to the physical model describing the mechanical properties of the virtual bodies.

There are different methods actually used for the physical modeling in medical simulation field: Finite Element Method (FEM) [4], Long Element Method (LEM) [5], Mass spring Damper [6]. FEM and LEM are continuous models, mathematical robust with high level of realism and a high computational load. Mass Spring is a discrete method characterized by low computable load, simplicity. Even the lower accuracy respect to the continuous methods we decided to adopt this one for the first prototype because, at this point, we want to put more effort on the integration between the AR system and haptic interface without overload the computation and respecting the real-time constraints and anyway this model has been widely used to simulate elastic soft tissue in other medical applications.

In the Mass Spring Damper model, the deformable objects (organs) are modeled using a mesh of virtual masses. Each point of the mesh is linked to adjacent points by means of springs. Each spring is characterized by an elastic constant, which describes the deformable properties (Hook’s law):

\[
\vec{F}_i (\Delta \vec{L}_i) = - k_i \frac{\Delta \vec{L}_i}{L_i}
\]

This formula measures the strength \( \vec{F} \) that is exerted by an ideal spring being elongated or compressed. \( \Delta \vec{L}_i \) represents the relative elongation or compression factor with respect to the initial rest length and \( k_i \) is the elastic constant that rules the spring rigidity (Fig.2).

2.2. Collision Detection

The heart of any system that simulates the physical interaction between objects is the collision detection. It is the ability to detect when two objects have come into contact. As key factor of a physical simulation, it is very important to build a fast, accurate and robust collision detection algorithm.
The method used is based on model partition [7], the strategy of subdividing a set of objects into geometrically coherent subsets and computing a bounding volume for each subset of objects. The bounding volume should fit the object as tightly as possible in order to have a low probability of intersecting the volume but not the object. A bounding volume should be represented using a relatively small amount of storage and the overlap tests between bounding volume should be computationally cheaper than intersection tests for the enclosed objects.

The geometric coherence of the objects is captured by means of a hierarchy of a tree structure in which primitive are stored in the leaves. The intersection test is performed by recursively testing pairs of nodes between the organs and the medical instrument (Fig. 3).

If a contact is detected, the new position and the velocity are calculated for each point of contact; these values take into account the constraints imposed by the chosen physical modeling.

In addition, data coming from the collision detection algorithm are used by the collision response algorithm to compute the force that is sent to the user by means of the used haptic interface.

![Figure 2: Interaction between rigid body and brain tissue](image1.png)  
![Figure 3: Bounding boxes structure Collision Detection](image2.png)

### 2.3. Patient’s Data Navigation

In the operating theater, usually the surgeon’s eyes are on the microscope oculars but sometime they need to see the screen in order to understand the right position compared to the preoperative images (CT, MRI).

This important navigational tool is usually provided by commercial and expensive systems (ex. BrainLab or Stryker).

For this reason, in order to have a complete training and an AR intra-operative platform we are connecting our system with 3DSlicer [8]. This software has been used routinely for biopsies and open craniotomies and for our needs can be used to complete the system offering the navigation in the intra-operative data or as radiologist training, to segment the region of interests or particular organs from the preoperative images.

The 3D environment can be exported directly in the microscope oculars.

### 3. Conclusion

The architecture (Fig. 4) and the main features and the collision detection and physical modeling of the first prototype of the simulator were defined in tightly collaboration with the surgeons (Neurosurgical Department Clinic University of Heidelberg).

We are testing different parameters for the tissue behaviors modeling and integrating the system with 3D Slicer to complete the navigational system and to take advantage from several processing and analyzing procedure tools.

This will be the first example of mixed reality system based on a real operating microscope. It can be a neurosurgical training system using VR or an AR intra-operative stereoscopic microscope. The
architecture evolution and the main new features were defined in tightly collaboration with the surgeons (Neurosurgical Department Clinic University of Heidelberg). This is a part of CompuSurge project funded by “Marie Curie” research network.

Figure 4: Neurosurgical Training System Architecture

References


