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Clinical evaluation of an image-guided surgical microscope with an integrated tracking system

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Abstract We have developed an image-guided surgery system based on a surgical microscope and incorporating a novel design concept, which consists in mounting a small and precise 3D tracking camera directly onto the housing of the surgical microscope The camera tracks the movements of the surgical tools and of the patient. This setup offers improved ergonomics and gain in accuracy. The integration of the tracking system in the microscope includes the calibration of the microscope optics and the registration of the tracking camera to the microscope. We propose several methods to register the patient by using a marker attached to a dental splint, and we describe the different overlay visualizations the system can provide. A complete accuracy study has been carried out in order to validate the concept by measuring the error of the overlay in different environments, starting with phantom skulls, cadaver specimens and finally the clinical interventions performed to date.

Keywords Augmented reality · Computer assisted surgery · Surgical microscopy · Tracking·Registration

1. Introduction

An augmented reality system should enable surgeons to view hidden critical structures such as pathologies (e.g. tumours) and dangerous structures (e.g. arteries or nerves) as if they were beneath the surface of the surgical scene. Different techniques are applied to this end, like navigation systems where surgical data and guidance are shown. In addition, overlay systems have been developed in order to display surgical images directly to the patient. Semi-transparent screens can be used to display the images between the patient and the surgeon [1–3]. However, such a system adds some constraints to the user, being the overlay accuracy very dependent on the angle of view. Stereoscopic binoculars are also used in augmented reality systems [4–6]. They can provide surgical guidance including 3D perception, but they require the surgeon to wear a cumbersome head-mounted device.

Surgical microscopy is used in many complex procedures in the area of ENT and neurosurgery. To avoid the need to look away from the surgical scene, guidance information can be displayed directly in the surgical microscope view. In order to display a correct overlay image, changes in patient position have to be determined. Several approaches have been developed, mainly using external tracking systems [7–9]. In this case, the motion of both patient and microscope need to be tracked. In addition, to circumvent the need for optical tracking, systems based on image processing have also been developed [10], but their accuracy is not sufficient for clinical use.

We have developed an image-guided microscope with a new design concept, which consists in mounting a small and precise 3D tracking camera directly in the surgical microscope. The camera tracks the movements of the surgical tools and of the patient. This setup, which is described in more detail in the following section, offers improved ergonomics and gain in accuracy. A complete accuracy study and our first experiences in the operation room are described next.

2 Materials and methods

2.1 System description

The image-guided microscope consists of a Leica 500M surgical microscope with a Leica DI C500 image injection module, which allows the injection of colour overlay images in one of the eyepieces. We have mounted on it a small optical tracking camera, the Atracsys easyTrack 200, which offers a tracking accuracy of 0.2 mm, with a working volume of $20 \times 20 \times 20$ cm^3 (Fig. 1). To track the movements of the patient, a maxillary splint with a mounted infrared marker-shield is used, and also marker shields are mounted on the surgical tools to track their motion.

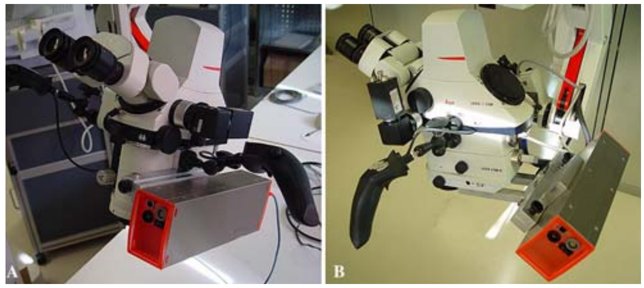

Fig. 1 Two designs for the tracking integration in the surgical microscope. The position of the tracking camera can be changed depending on the working distance needed for the operation and the position of the patient

2.2 Microscope calibration

Calibration of the optics of the microscope is done using the Camera Calibration Toolbox for Matlab created by Jean-Yves Bouguet [11]. The extrinsic parameters consist of the 3D translation and rotation vectors that bring the object frame of reference into the frame of reference of the microscope optics. The intrinsic parameters include focal length, principal point, and radial and tangential distortions. This model is based on a full-perspective projection. We have used a planar grid as a 2D calibration standard, giving us subpixel accuracy (0.2 pixels)

2.3 Patient registration

In order to align the preoperative images to the patient space the patient has to be registered to the tracked marker. This alignment is an essential part of any image-guided surgery system. Two methods have been implemented in the system: pair-point matching and surface matching. Pair-point matching has been used when testing the system with plastic skulls in the laboratory and in the tests with cadaver heads reported in Sect. 4. The registration is calculated by digitizing several points from a CT using a tracked pointer, and then applying a least-squares fitting algorithm [12]. In addition, during the clinical tests a surface matching technique has been used after a pair-point matching registration in order to refine it by taking more points from the patient.

2.4 Integration of the tracking system

After calibrating the microscope, we next calculate the transformation between the calibration space and the tracking space. To this end, the standard grid used for the calibration is registered. By using a tracked pointer, twenty points from the surface of the planar grid were digitized according to the same coordinate system of the optics calibration, then using a pair-point registration we can calculate the transformation needed with an accuracy of 0.2 mm.

3 Visualization

Although 3D visualization is the goal of most of the existing augmented reality systems, it is hard to achieve a good depth perception, and it is always very operator-dependent. Instead of trying to solve this problem, our efforts have been concentrated in developing a monocular overlay system independent from the user perception that will provide useful surgical information to the surgeon. To this end, several modalities of overlay have been developed, including a CT viewer where the surgeon can choose a plane from the CT and display it as an overlay in the patient, a 3D viewer to render 3D models of segmented structures and an interactive mode where the surgeon can use tracked tools to be guided and to measure distances and trajectories.

- CT Viewer: the goal of our CT viewer is to avoid the need to look away from the surgical scene, as is required in existing CAS systems. Thus, once the patient has been registered the system tracks his position and displays correctly scaled CT cut-views through the image injection module to the microscope view.
- 3D Viewer: before the operation a preoperative planning has to be done in order to create the 3D models needed from the CT or MRI datasets. Such models can be, depending on the operation, segmented tumours or targets, risk regions like nerves or arteries, or even access pathways to guide the surgeon.
- Tracked tools: since the tools can be tracked by using markers, 3D models of them can be projected in the overlay so the surgeon can see their position and obtain better depth perception. Additionally, when using the tracked tools, the system can project the actual trajectory of the tool, together with distance measurements and intersections.

4 Accuracy study

4.1 Phantom study

A phantom skull was equipped with several fiducial markers and a marker shield was fixed by using a dental splint. The error of the pair-point registration in this case was 0.3 mm rms. A CT cut-view was then projected to the overlay. The accuracy was calculated by looking at the difference in pixels of the contours, obtaining a mean of 3–4 pixels, with an estimated accuracy of 0.5–0.6 mm.

4.2 Cadaver study

In addition to the first accuracy study, a cadaver test was necessary in order to verify more aspects of the system, like the registration procedure and the visualization.

The accuracy was calculated by measuring the overlay in several parts of the skull: supraorbital notch, infraorbital foramen, frontozygomatic suture, anterior nasal spine, nasal bone and external acoustic meatus. The measured overlay accuracy was 0.8 mm, with only 0.7 mm when we were close to the DRB position and 1.5 mm at the farthest position. This accuracy depends strongly on the registration accuracy (about 0.5 mm in these cases).

5 Clinical evaluation

To date, the system has been employed on three patients. The first patient underwent removal of polyps in the right maxillary sinus and the second patient was affected of a mucocele in the right frontal sinus. The procedure was similar in both cases. The DRB was fixed to the patient with a dental splint, and then the surgeon performed the registration obtaining 0.6 and 0.8 mm respectively. In both operations the surgeon was able to visualize CT cut-views and projections of 3D models of the targets previously segmented from the CT datasets. The feedback from the surgeon was positive regarding the visualization of structures and targets.

The third patient was affected of a malignant tumour, an adenocarcinoma of the nose. In addition to the CT views and the 3D model of the target (Fig. 2), we planned to display the risk regions that were close to the region of interest, like the eye or the closest part of the brain. The registration of the patient was performed in this case with 0.7 mm accuracy. The measurements taken with the tools were useful in order to see how close the surgeon was to the risk regions, and to point the tools in the good trajectory to intercept the targets. The measured accuracy was ~1 mm, with which the surgeon visually agreed.

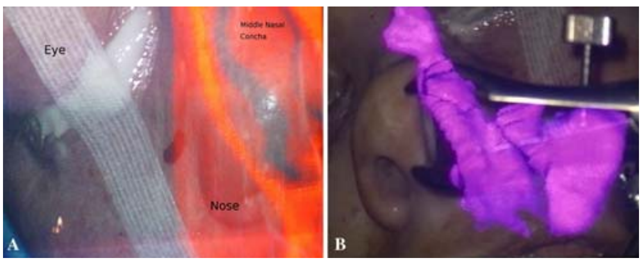

Fig. 2 **a** CT cut-view displayed directly in the microscope's view. Several anatomic structures can be identified. **b** 3D model of the tumour, which has been previously segmented from a CT dataset

6 Conclusion

A new augmented reality system for surgical microscopy has been developed in order to provide guidance to the surgeon during the operation. The system integrates basic navigation techniques like a CT viewer with different angles and tracked pointers, together with a more complex viewer including 3D rendering and virtual 3D tools. The integration of the tracking camera in the microscope improves the accuracy of the system, with an error below the millimetre. Moreover, the miniaturization and integration of such a tracking camera increases the ergonomics, a very important aspect when a computer assisted system has to be used in the operation room.

Our first clinical cases were successful, and the surgeon validated the accuracy of the system. This is part of a larger clinical study that is in progress.

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Image-based bronchoscope tracking using motion predication and multiple searches

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