# Multi-Level Safety Concept for Robot Assisted ENT Surgery für die 11. CURAC Jahrestagung 2012

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***Abstract:***

*During image guided interventions the surgeon depends on feedback provided by the surgical support system, in some cases exclusively. Because image guided surgery consists of a number stages during which errors may be introduced, the final system accuracy and robustness can be compromised without knowledge of the user. These errors become particularly important in cases in which extremely high accuracy is required, such as during microsurgery on the lateral skull base. We believe that a navigation system, in addition to providing high accuracy image guidance, could also benefit from additional redundant systems which provide further information about the location of the surgical tool in relation to vital structures. Presented here is a system for robotic cochlear implant surgery which utilizes redundancy and various levels of automation for safety in registration, tracking and tool positioning.*

*Schlüsselworte: Roboter, Chiurgie, Ohr, Sicherheit*

## 1 Problem

During image guided interventions the surgeon depends on feedback provided by the surgical support system, in some cases exclusively. Because image guided surgery consists of a number stages during which errors may be introduced, the final system accuracy and robustness can be compromised without the knowledge of the user. These errors become particularly important in cases in which extremely high accuracy is required, such as during microsurgery on the lateral skull base. One such operation is the direct cochlear access (DCA); an alternative to the traditional mastoidectomy for accessing the inner ear. During this procedure, a trajectory is drilled directly from the surface of the mastoid, through the facial recess to a target on the cochlea. Due to the proximity of many vital structures in the region, the accuracy required to perform this procedure is prohibitively high for normal navigated surgery techniques [1 – 4]. As such, a high accuracy robotic system has been developed at the University of Bern to assist with this task. While the system provides a promising level of accuracy (0.56 ± 0.41 mm [5]), we believe it could also benefit from additional redundant systems which ensure accurate tool placement or provide further information about the location of the surgical tool in relation to vital structures. Presented here is a system for robotic cochlear implant surgery which utilizes redundancy and various levels of automation for safety in registration, tracking and tool positioning.

## 2 Methods

**Registration:** Patient to pre-operative image registration is one of the major error sources in traditional image guided surgery [6]. In an effort to reduce the error associated with this process, the robotic system utilizes a semi-automatic,



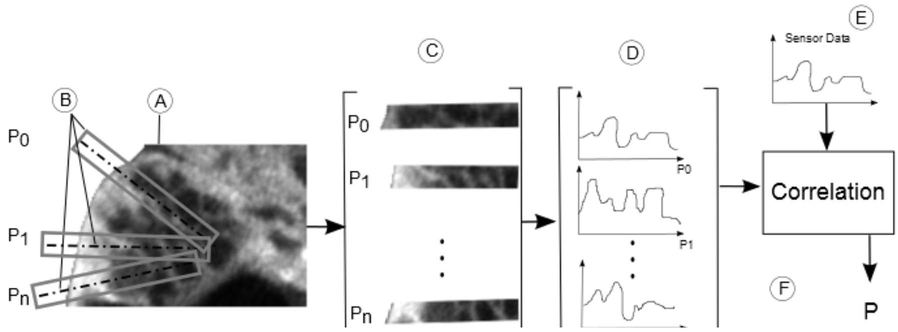
force based, screw localization technique for registration. First, the user places the robot end effector above each of the pre-operatively implanted fiducial registration screws using simple force-admittance control. At this point the system takes over control of the registration process wherein a 1N bias force is applied along the axis of the registration tool, causing the tool to contact the conical inner surface of the registration screw. Lateral forces are simultaneously minimized causing the tool to settle in the center of the screw. The position of each screw is then digitized in two separate coordinate systems: based on the robot encoder values and an optical-tracking system (CamBar B1, Axios3D, Germany). Screw localization in the image is also completed semi-automatically within a custom-built planning software (OtoPlan) using a method similar to that described in [7].

The accuracy of the proposed scheme was validated on a technical phantom: screws were implanted and ground truth positions measured using a coordinate measurement machine (CMM, Tesa 3D Micro-MS 454, Switzerland). Fiducial localization error (FLE) was determined by repeatedly registering a single screw from different angles and positions and measuring the final position of the tool within the screw with the CMM. Target registration error (TRE) was calculated by registering the technical phantom and measuring designated target screws. The TRE was then defined as the distance between the (transformed) measured targets and the ground truth CMM target positions.

**Detection of Navigation Errors:** Additional error sources such as tool calibration, tracking or process errors (tool bending, backlash) will also contribute to the ability of the system to accurately reach the defined target position. As such, the system integrates additional sensor sources for the detection of an incorrect drilling path or potential harm to anatomy, even in the presence of these errors. These methods include integrated facial nerve monitoring and force-density based pose estimation, as described below.

**Integrated Facial Nerve Monitoring:** The facial nerve is the major structure at risk during cochlear implantation surgery. It is responsible for the innervation of the ipsilateral facial muscles, and damage may result in paralysis. Facial nerve monitoring systems are common within the ENT operating theater, and many surgeons are familiar with their use. A Medtronic StimBur drill (StimBur, Medtronic, USA) is directly integrated into the robotic hardware and navigation software.

**Fig. 1**: Tool pose estimation based on the correlation of observed axial drilling force and bone density. Imaging data is obtained and a region of interest defined (a). A number of candidate trajectories (b) are selected within this region of interest. Imaging data along these candidate paths is extracted (c), the density along each path calculated (d) and then correlated with the observed force (e) to provide the estimated position of the tool (f).




**Force-Density Pose Estimation:** We have recently developed a novel method for the localization of a surgical drill based on the forces developed during the drilling process. The algorithm correlates these forces with the particular bone density along a particular trajectory describing a possible drill path. Because the mastoid contains many air cells, any particular path through the bone exhibits a unique density profile. Thus, the specific force pattern obtained during the drilling process can be correlated with each candidate density profile obtained preoperatively, and that density profile with the highest correlation represents the highest probability of representing the actual location of the drill. A diagram showing the main process steps is shown in Fig. 1.

Validation of the algorithm was completed by drilling a total of 10 trajectories in 3 human cranial cadaver specimens. A rigid titanium wire was inserted into each of the trajectories and post-operative imaging completed; the actual final drilled trajectory as determined from this post-op imaging was then compared to the planned and estimated trajectories.



**Control:** As a final safety measure, the surgeon remains in control of the robotic system at all times. A 3-state dead man switch, consisting of wait, proceed and emergency halt conditions, ensure that the robot will not carry out the planned trajectory unless the surgeon is completely satisfied with the state of the procedure and allows the reversion to a standard mastoidectomy at any time.

e) a) b)

c)

d)

**Fig. 2** The robotic system consists of a 5 DoF robotic manipulator (a), high accuracy micro-tracking system (b) and associated custom designed active infra-red LED trackers (c). A force-torque sensor is integrated at the wrist (d) allowing intuitive haptic control, high accuracy semi-automatic patient registration and measurement of process information for force-density based tool pose estimation. A Medtronic StimBur with facial nerve monitoring is integrated directly into the system (e).

# 3 Results

**Registration:** The semi-automatic registration technique was found to be highly accurate, with excellent repeatability. The technique is independent of user variability and can be quickly and reliably accomplished. The RMS FLE of the scheme was determined to be 0.05 mm, while a mean TRE of 0.101 mm was found.

**Integrated Facial Nerve Monitoring:** Facial nerve monitoring was successfully integrated into the existing robotic system; the integration of facial nerve monitoring together with standard image guidance, into the ENT micro-surgical system shown in Fig. 2.

**Force-Density Pose Estimation:** The force-density estimation algorithm demonstrated a mean tool localization accuracy of 0.29 mm when utilizing data from the surface of the mastoid to the middle ear canal, 0.38 mm at the level of the facial nerve and 0.49 mm when utilizing only data from the initial 50% of the drilled path. The results are shown in Table 1, errors are calculated from the esimated tool pose to the actual position of the tool, as determined from post-operative imaging.

**Table 1:** Accuracy of force based pose estimation, with increasing data availability. Errors are calculated from the esimated tool pose to the actual position of the tool, as determined from post-operative imaging. Accuracy was evaluated with 50% of the trajectory completed, at the level of the facial nerve and at the target position.

| | 50 % | Facial Nerve | 100 % | Angle |
|---|---|---|---|---|
| Error [mm] | 0.48±0.24 | 0.38±0.16 | 0.29±0.21 | 0.67±0.15 |



# 4 Discussion

In this work we have presented a multi-level safety concept for robot assisted ENT surgery and demonstrated the implementation of this concept within our micro-surgical robotic system. High accuracy semi-automatic registration, integrated facial nerve monitoring, force-density based pose estimation and high level surgeon control were all integrated successfully into the hardware and software of the existing robotic system. The system is able to provide a level of safety higher than that of traditional image guidance through the incorporation of information from a variety of sensor sources and types. The registration scheme decreases the likelihood of errors during the referencing phase of the procedure by removing inter-user variability in fiducial screw localization, as well as being highly accurate and repeatable.

Integrated facial nerve monitoring provides the surgeon with feedback similar to that currently utilized within the ENT operating theater directly in the robot user interface and allows the surgeon to make decisions about the progress of the procedure based on individual experience. A live sheep study is currently underway to determine more precise relationships between facial nerve stimulation and probe position. Force based pose estimation provides a means of localizing the tool within the mastoid even in the presence of registration, calibration, navigation or other errors and can be completed quickly and accurately. Of particular interest is the accuracy of 0.39 mm at the level of the facial nerve, which can be utilized to determine if the facial nerve or other nearby anatomy is at risk.

Finally, as the robotic system does not move without surgeon input, the surgeon remains in control of the system at all times and can make the decision, based on the variety of feedback provided, whether to continue with the robotic procedure or revert to a traditional mastoidectomy.

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