An Accuracy Approach to Robotic Microsurgery in the Ear

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Abstract:

Concerns of rising healthcare costs and the ever increasing desire to improve surgical outcome have motivated the development of a new robotic assisted surgical procedure for the implantation of artificial hearing devices (AHDs). This paper describes our efforts to enable minimally invasive, cost effective surgery for the implantation of AHDs. We approach this problem with a fundamental goal to reduce errors from every component of the surgical workflow from imaging and trajectory planning to patient tracking and robot development. These efforts were successful in reducing overall system error to a previously unattained level.

Keywords: Robot, Surgery, Ear, Instrument Guidance

1 Problem

Concerns of rising healthcare costs and the ever increasing desire to improve surgical outcome have motivated the development of minimally invasive surgical procedures for the implantation of artificial hearing devices (AHDs). Such minimally invasive procedures in the lateral skull base are complicated by the exact tolerances required to successfully avoid critical anatomical structures such as the facial nerve. Schipper et al projected that an accuracy below 0.5*mm* would be necessary to achieve reliable access to cochlear structures [1]. Toward this end, Labadie et al. investigated the feasibility of accessing the cochlea using a patient specific drill guide [2]. Although they were able to avoid the facial nerve and in most cases also the chorda tymani, the absolute accuracy of the system was not quantified. Furthermore, this method is inflexible and cannot accommodate changes in surgical planning. Majdani attempted a similar minimally invasive cochlear access using a robotic manipulator[3], but this system did not meet the 0.5*mm* accuracy requirement estimated by Schipper. Thus, this contribution discusses our approach to exceed the accuracy goal of 0.5*mm* set by Schipper et al. by improving accuracy throughout the entire system. The following error sources were identified and addressed: Imaging, Marker detection, Patient tracking, and Surgical manipulation. By reducing errors throughout the entire system, we hope to provide a versatile system which is capable of significantly reducing AHD implantation comorbidity and costs.

2 Methods

Standard image guided surgical approaches typically have cumulative errors on the order of a few millimeters at best. For high precision interventions, this uncertainty must be reduced to a few tenths of a millimeter. Table 1 compares the levels of error from various sources in standard image guided surgical interventions and compares them to errors in high precision surgical interventions. The positional error arising from each step in the clinical workflow was investigated, and high accuracy methods were sought in each case.

Imaging: The voxel size of high resolution CT scans is approximately 0.2 x 0.2 x 0.63 mm^3. This accounts for a significant portion of error within the workflow. Therefore, we evaluated a new imaging technology- digital volume tomography (DVT), which has a resolution up to 0.15 x 0.15 x 0.15 mm^3, as a possible alternative imaging modality. The suitability of this technology was assessed by scanning the temporal bone region of cadaver specimens with fiducial markers placed prior to imaging in both CT and DVT machines. Low and high resolution scans were obtained from each machine for a side by side comparison by an oto-neuroradiologist.

Marker Detection: Typical identification of fiducial marker locations is typically performed by hand-picking marker center points in image planes. This procedure results in voxel sized accuracy and is highly dependent on user experience and skill. In order to improve this process, a semi automated algorithm was developed to match 3D CAD data against image data. Once the two data sets were registered, the centroid of the CAD data is then transformed to the image coordinate system and used as the fiducial point [4].

Tracking and Registration: Typical image guides surgeries rely on a tracking device to register the patient to the image data and ultimately guide the surgeon to the proper tool pose. However, optical tracking systems have a limited accuracy. For this reason, we use the robotic manipulator to register fiducial marker positions rather than relying on optical tracking systems. However, optical tracking is retained in the system as a safety device, essentially confirming the position of the robot in relation to the patient. Thus, we identified a new micro-optical-measurement system (Cambar B1, Axios GmbH, Germany) with higher spatial resolution. The suitability of this measurement system for our application was assessed and compared to an NDI Optotrak (NDI, Waterloo, ON, Canada) system as a benchmark. This was done by moving trackers precisely in 3D space using a mechanical positioning device.

Robotic Manipulator: A newly designed robotic manipulator was created specifically for the task of ORL microsurgery. The characteristics of the robot are summarized in table 3. Most notably, much effort was expended in making the robot as light as possible so that it could be easily mounted directly to the operating table, making OR integration as simple as possible. This feature also has the added benefit of reducing relative motion between the patient and the robot. Additionally, the robot incorporates a force-torque sensor mounted between the end effector and the surgical instrument. The sensor also functions as a safety device by limiting tool tip forces encountered during surgery. Finally, the sensor provides a method for the surgeon to interact directly with the manipulator and essentially guide the robot by hand.

Table 1: Errors in computer assisted ORL surgery

Approach	Imaging	Tracking (RMS)	Regist. (TRE)	Calib.	Overall*
	[mm]	[mm]	[mm]	[mm]	[mm]
Standard	0.50	0.25	1 – 2	0.1	2 – 3
High Precision	0.15	-	0.1 – 0.2	0.01	0.2 – 0.3

Accuracy Assessment: The accuracy of the entire system was assessed by performing the entire clinical workflow on a technical phantom. The phantom consisted of a polyurethane foam block fitted with fiducial markers (figure 2). This was scanned using a CT scanner, and the resulting data was processed for multiple drilling operations. Trajectories originating on the top surface of the phantom and ending at internal fiducial markers were planned and sent to the robot system. Once this process was completed, the phantom was registered using the robotic manipulator. This registration process was performed by ‘driving’ the robot tool tip to the fiducial markers located on the phantom, and recording each position in the robot coordinate frame. Following registration, the robot was commanded to automatically perform a drilling operation. The registration and drilling process was repeated 7 times. Finally, the phantom was reimaged and the resulting drill trajectories were segmented and compared to the planned trajectories.

3 Results

Imaging: Lack of ground truth makes evaluation of the absolute accuracy of imaging and image registration procedures difficult. However, quantitatively, DVT images provide much higher spatial resolution, though, qualitatively, they suffer from lower contrast and increased noise. In spite of these problems, an oto-neuroradiological expert found the images to be qualitatively sufficient and the benefit of increased resolution overrides the loss of contrast.

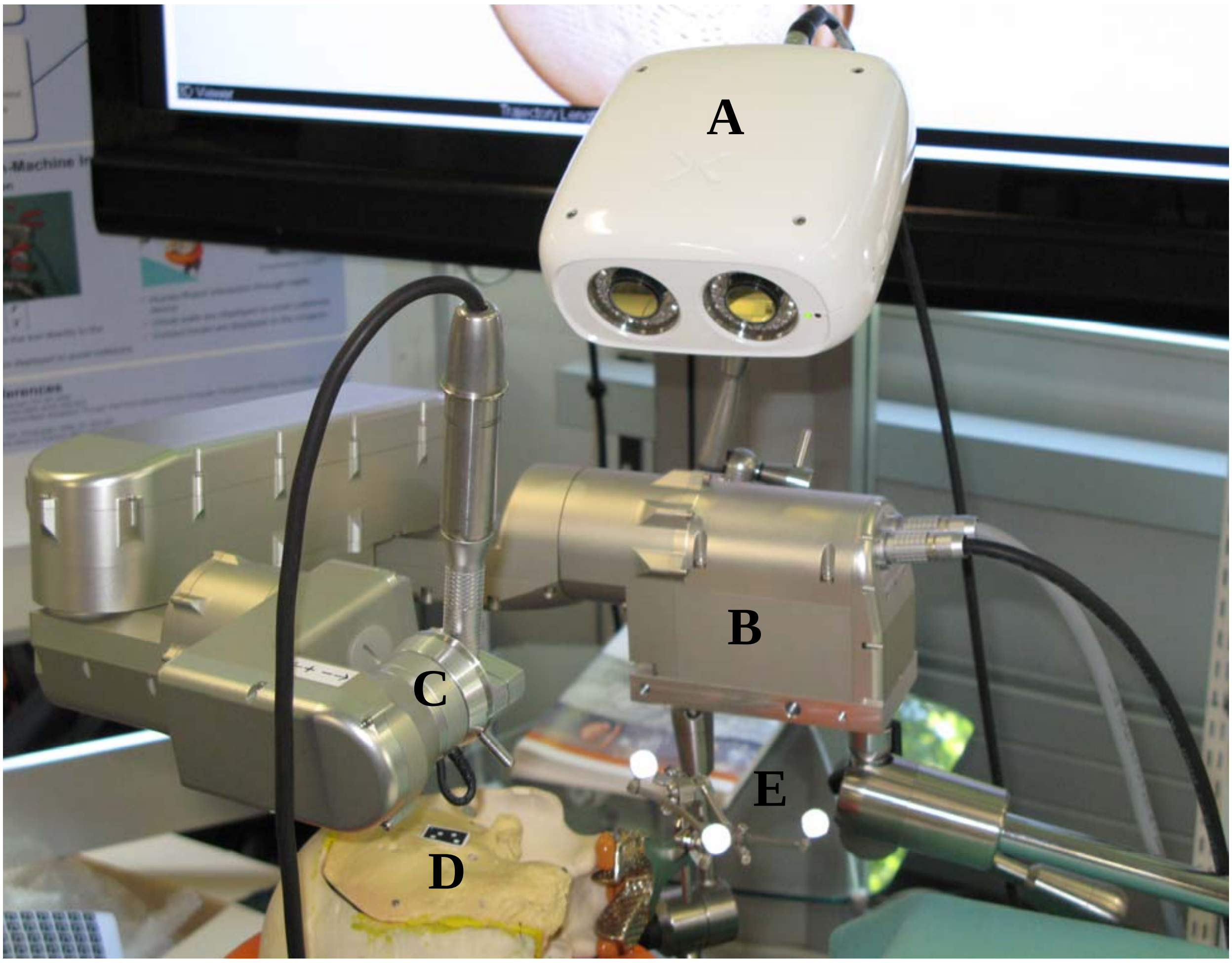

Figure 1: The robot system includes: Axios micro-measurement camera (A), robotic manipulator (B), end effector with force-torque sensor (C), and patient tracking devices (D-micro, E-conventional).

Table 2: Standard deviations (mm) of manual versus semiautomatic fiducial marker detection.

Marker	1	2	3	4
CT Manual	0.329	0.590	0.567	0.563
CT Semiautomatic	0.143	0.335	0.219	0.357
DVT Manual	0.216	0.118	0.082	0.241
DVT Semiautomatic	0.067	0.031	0.049	0.011

Marker Detection: Use of the semi-automatic registration technique was clearly advantageous compared to manual marker detection. Results of the semi-automatic marker detection procedure are summarized in Figure 1: **The robot system includes: Axios micro-measurement camera (A), robotic manipulator (B), end effector with force-torque sensor (C), and patient tracking devices (D-micro, E-conventional).**

Table 2, where it is readily apparent that the semi-automatic procedure reduced the standard error from a maximum of 0.59*mm* for manually selected markers in CT data to a minimum of 0.011 for the semi-automatic detection in DVT data. This result highlights the synergistic effect of higher resolution datasets and the semiautomatic detection technique.

Table 3: Features of the robotic manipulator

Kinematics	Weight	Payload	Repeatability	Stiffness	F/T Sensor
5 DoF	5Kg	1 Kg	0.01mm	$0.01mmN^{-1}$	6 DoF

The newly developed robotic manipulator was successfully used to drill holes in a phantom representing the temporal bone. Its light weight makes it easy to handle and mount to the OR table, and because all the motor drives are integrated into the robot, it only requires two cables to communicate with and control (summarized in Table 3). The small work-space of the camera (Figure 1A) allows it to be mounted directly to the robot base (B), while the small tracking markers are attached to the patient in a pattern (D). The rigid body depicted by the markers is much smaller than traditional tracking markers (E).

Drilling Experiment: Figure 2 shows a segmentation of the technical phantom in the post operative CT scan. Pre and post operative trajectories were compared to analyze the accuracy of surgical assist system. The drilled segment of the model had a thickness of 8 mm. These holes were segmented in the model and represented with a blue shade as seen in figure 2. A line was fit to the center of each segmented portion, and compared to the planned trajectory (white lines). Using this method, it was possible to calculate the angle and Euclidian distance between the planned and achieved tra-jectories at the entry point of the block as reported in table 4. The max/min distances were measured at 0.39/0.05 mm respectively, whereas max/min angles were0.52/2.17°.

Table 4: Results of accuracy experiment

Trajectory number	Angle between planned and drilled trajectory [°]	Distance between entry points [mm]
1	0.53	0.15
2	1.59	0.39
3	2.17	0.31
4	1.05	0.05
5	1.03	0.21
6	1.25	0.21
7	0.52	0.31
Min	**0.52**	**0.05**
Max	**2.17**	**0.39**
Average	**1.16**	**0.23**
Std dev	**0.59**	**0.11**
Median	**1.05**	**0.21**

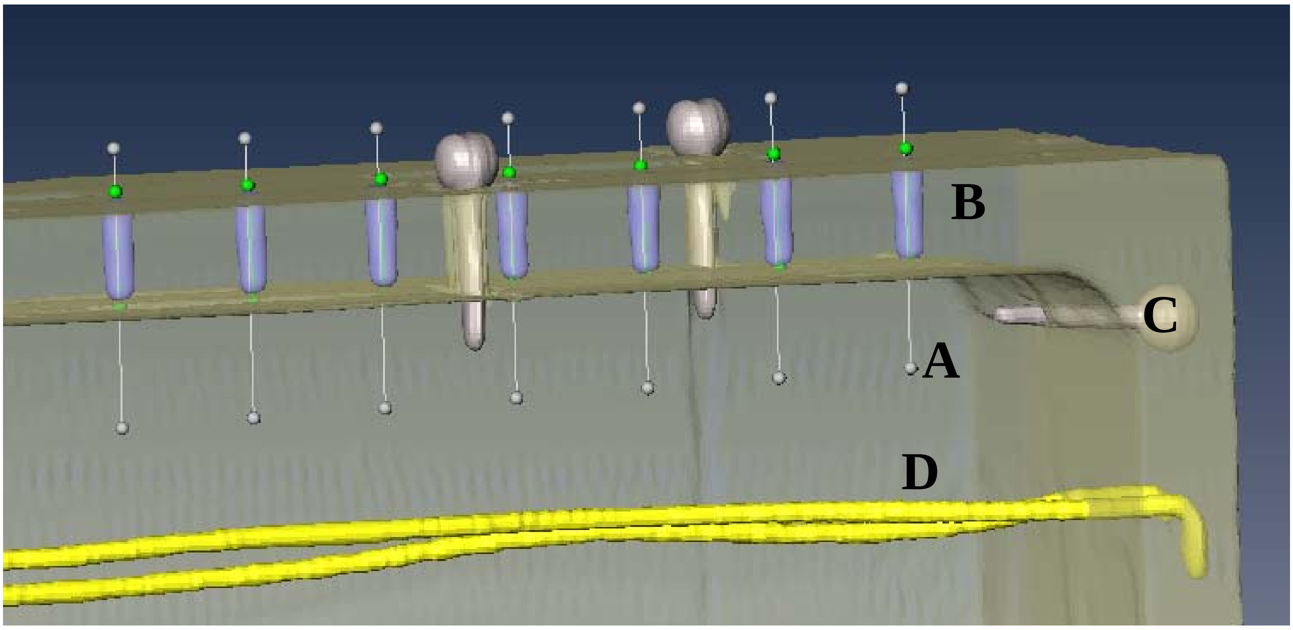

Figure 2: Segmentation of planned (A) and executed (B) trajectories in the technical phantom. Fiducial markers (C) and wires representing nerves (D) are also depicted.

4 Discussion

In this work, we have represented a computer controlled surgical manipulator specifically designed to aid surgeons in implanting AHDs. In contrast to rigid drill guides, this approach benefits from the ability of the surgeon to change the drill trajectory at any time, even drilling multiple trajectories if the surgeon were to implant multiple electrode arrays. Furthermore, the future development of a milling mode will allow the creation of complex forms in addition to a simple drill path.

One major drawback of the current robotic system is the mounting fixture. Currently, three 7 DoF arms are used to fix the robot to the OR table which allows the robot to be mounted rigidly (>10 as rigid as the robot) in a more or less arbitrary position. However, this fixation system is too difficult to mount in a surgical setting. Thus, a simple light weight mounting structure is being designed.

By systematically addressing each stage in the surgical procedure (imaging, trajectory planning/registration, tracking, robotics), we have successfully met the 0.5*mm* goal to safely access the cochlea (avoiding nerves) through a single drill pass. Additionally, the demonstrated accuracy exceeds previous attempts by Majdani et al [3]. This achievement is most likely attributable to using the robot as a registration tool. This technique essentially eliminates the errors due to an optical tracking system, which are 0.25 mm at a minimum. Furthermore, because registration occurs in the robot coordinate system, this tends to reduce the effect of small calibration errors which may be present in the robot itself.

In addition to the ability to drill a precisely defined access, this robot system also incorporates several distinct advantages such as a force-torque sensor which allows the surgeon to interact directly with the robot to control its motion during drilling and milling procedures. Additionally, this force sensing will allow the robot to automatically detect tissue boundaries similar to the method used by Brett et al. in cochleostomies [5, 6]. Additionally, the addition of haptic feedback control is possible which will ultimately enable surgeons to extend current minimally invasive procedures to previously unexplored opportunities.

5 References

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