Guidance for Skull Base Surgery

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1. Project Statement

The goal of our project is to improve the accuracy of computer-aided transsphenoidal skull base surgery through the use of intraoperative imaging. This would enable us to better protect critical structures such as the carotid artery during the drilling process. Improving accuracy is particularly important in children because their smaller anatomy renders the trans-sphenoidal approach dangerous and technically difficult. To do so, we build on the computer-aided surgical system developed by Xia et al.. However, experiments showed that the system is only able to achieve an average accuracy of 1-2mm, with errors up to 3mm. To achieve clinically acceptable errors of 1mm, we will use intra-operative imaging, specifically, photo-acoustic imaging (PAI), to reduce uncertainty in the registration.

2. Paper Selection

Xia, T., Baird, C., Jallo, G., Hayes, K., Nakajima, N., Hata, N. and Kazanzides, P. (2008), **An integrated system for planning, navigation and robotic assistance for skull base surgery.** Int. J. Med. Robotics Comput. Assist. Surg., 4: 321–330. doi: 10.1002/rcs.213

This paper was selected because of its direct relevance to our project. It describes an image-guided robot system to provide assistance for skull base surgeries. The goal of our project is to expand upon this system with a photoacoustic intraoperative imaging or sensing system that will improve the system's accuracy. The background, materials, and procedure are all highly relevant to our experimental and simulation design as well as our knowledge of the overall system. The paper also highlights many of the challenges that the system faces prior to clinical use. If we are to make significant improvements, we must first understand the current system and its flaws in order to successfully incorporate any useful components.

3. Paper Summary

3.1 Problem Statement and Goals

The difficulties in neurosurgery are complicated to address, due to human limitations in dexterity and performance. In skull base surgery, there are many critical structures that must be avoided. Sawaya et al. has reported neurological deficit occur in 20% of craniotomy outcomes for intraparenchymal brain tumors.[1] When bone removal is required, even more obstacles are presented. Even when following an established surgical procedure, the surgeon may still damage a variety of critical structures.[2]

Precise robotic assistance may be highly beneficial in preventing complications during skull base surgeries. Many of the current image-guided systems are used for more accurate navigation, but do not incorporate robotic assistance. By integrating a robotic system with a virtual fixture and cooperative control with CT imaging, Xia et al. hopes to address many current problems through an integrated robotic system for navigation, assistance, and control in skull base surgery.

3.2 Key Results and Significance

Xia et al. showed that the proposed system is highly feasible for clinical use, although needs a couple of improvements in accuracy. Both the average placement error and the average displacement error was 0.6mm in phantom studies. Average overcut in cadaver studies was higher, ranging from 1-3mm. The potential for such a robotic-assisted procedure is high, especially in avoiding complications caused by human error. The significance and relevance to our project is to implement this system with additional improvements using intraoperative imaging in a different skull base surgery method, through the sphenoid sinus.

4. Background

4.1 Materials

The system consisted of a modified NeuroMate robot, a StealthStation Navigation System, 3D slicer software, and a workstation running application logic and robot control.

The NeuroMate robot (from Integrated Surgical Systems) is an FDA-cleared image-guided robotic system designed for neurosurgery. The robot is originally designed solely for surgical tool placement and orientation, but was modified by attaching a six-degree of freedom force sensor (from JR3 Inc.) between the surgical drill and the final axis. The force and torque information supplied to the robot allows for cooperative control and the use of virtual fixtures. Calibration of the surgical tool gives the position of the tip of the tool in robot system coordinates.

The StealthStation system is a commercial navigation system (marketed by Medtronic Navigation). The system tracks the locations of sets of markers, with a known geometry, on rigid bodies. The reference frame is defined by another rigid body, which is placed near the operation location. This allows for a certain degree of camera movement, since the relationship between the tracked object and reference frame still holds.

3D slicer is an open-source application for analyzing medical images and data. It allows for the creation of more complex virtual fixtures and better visualization of the 3D model and tracker tool in comparison to the StealthStation software. The workstation runs the application control software, which uses the *cisst* package, and provides a method of communication between the different subsystems and software, i.e. the force sensor, NeuroMate, StealthStation, and the 3D slicer software.

4.2 Registration and Calibration

We have information starting with the preoperative CT scan. Both the StealthStation and 3D slicer can read the data, but the coordinate system between the two is different. Therefore, a fixed transformation is calculated using registration methods provided by the

StealthStation. The registration between the CT image (in StealthStation view) and the StealthStation navigation system is calculated by using fiducials placed before the CT scan. We have a set of points in the CT coordinate from the fiducials, and by touching them with a tracked probe, we can get a corresponding set of points in the navigation system. This registration is also performed using methods provided by StealthStation. The cutter tip location must also be known with respect to the robot and StealthStation coordinate systems. The NeuroMate returns the position of the end-effector and the StealthStation can return the position of a rigid body attached to the robot. In order to determine the translation from the end-effector and from the rigid body, a pivot calibration is performed simultaneously for both frames using a least-squares method. Lastly, the StealthStation navigation system is registered to the robot by using point pairs for the cutter tip in both frames of reference. A standard registration method is applied (Arun's method) using a least-squares optimization.[3] A detailed diagram is included in **appendix A**.

4.3 Virtual Fixture Definition

Using 3D slicer, the system is able to define a virtual fixture with a six-sided convex hull. Clinical input states that a "box-like" virtual fixture is sufficient for many skull base applications. However, one or two of these edges are not included to account for entrance of the drill tool. The fixture is divided into three regions: a safe zone, a boundary zone, and a forbidden zone. Movement is unrestricted in the safe zone and movement is restricted toward the safe zone in the forbidden zone. In the boundary zone, the velocity of movements toward the forbidden zone are scaled down depending on how close the forbidden zone the cutter tip is and is unrestricted for movements toward the safe zone. Mathematically, the admittance control law is given by: And d is given by:

$$\dot{q} = J^{-1}(q) \times K(d) \times G(f) \times \begin{bmatrix} F_w \\ T_w \end{bmatrix}$$

$$d_i = \frac{(C-P)\cdot N}{|N_i|}$$

The left side of the control law is the goal velocity in joint space. F_w and T_w are the measured forces and torques in the robot frame and J is the Jacobian resolved at the cutter tip. J^{-1} transforms Cartesian velocities into joint velocities. G(f) is an admittance gain that is a nonlinear function of measured force which was experimentally determined. This serves to limit noise and cut-off at high forces to keep goal velocity in a reasonable range. K(d) is a scale factor as a function of the distance to the forbidden zone. In the safe zone, this is the identity, but in the boundary zone, velocity is scaled down proportionate to d. C is the coordinates of the tip, P is a point on the virtual fixture plane, and N is the normal vector to the plane. d_i is determined for each of the x-, y-, and z-coordinates and $d = d_i/D$ for the lowest d_i value, where D is the distance of the boundary zone.

5. Methods and Results

5.1 Accuracy of Robot and Navigation Systems

Xia et al. first tested the accuracy of the robot and navigation subsystems by using a precisely machined aluminum plate with 13 small divots. The machine used had a known accuracy of 0.0127mm, which is relatively insignificant for their experimental purposes. The cutter tip was guided into each of the small divots and the points were recorded in robot frame and navigation frame coordinates. These positions were registered to the known machined positions. The fiducial registration error was **0.64mm for the robot** and **0.74mm for the navigation system**.

5.2 Accuracy of Integrated System in Phantom Studies

A phantom was created using a plastic skull with an embedded fixture that allowed for placement of foam blocks. A box-shaped virtual fixture was defined following registration, such that the distance between the cut edge and block edge is known. The foam block was cut out using the robot and distances between the edge of the foam box and cut regions were measured using calipers. This was repeated three times using the same registration and three more times using different location/orientation and registration each time.

The placement and dimensional error were measured for the x- and y-axes. The placement error is the difference between the expected center and the cut center. The dimensional error is the difference between the actual and planned cut dimensions. The total overcut is then |placement error| + (dimensional error)/2, however, this assumes that dimensional error is equal on both edges. Because the z-axis is only bounded on one side, error was not split into placement and dimensional. Detailed results are included in **appendix B**. As evident from the standard deviations, the system has good repeatability when the same registration is used (SD1 < 0.25mm for all errors), but more realistic results are reflected in the latter trials (SD2 up to 0.80mm).

5.3 Cadaver Studies

For the cadaver studies, Xia et al. took a suboccipital approach as needed to resection an acoustic neuroma on the left and right sides of three cadavers. Virtual fixtures were generated from a CT scan with 0.5mm slice spacing and were constructed to reflect actual surgical conditions. Registrations were only accepted if less than 1mm for CT to Stealth and less than 0.5mm for Stealth to robot. Postoperative CT scans were also taken to examine cut regions for overcut and undercut by transforming the preoperative virtual fixture to the postoperative image. Image results are included in **appendix C**. "O" shows overcut regions and "U" shows undercut regions. "VF" shows the defined virtual fixture. However, the typical overcut seen was 1-2mm, with some errors up to 3mm.

6. Conclusions and Review

6.1 Discussions and Relevance

Overall, the system maintains many benefits in skull base surgery. Although the accuracy of the system needs improvement, it is relatively close to the desired clinical threshold. Furthermore, the ergonomic benefits provided to the surgeon are also important. The tool will not move if it is let go and the surgeon has the added security of the virtual fixture.

The system described in the paper is directly relevant to our project. We want to incorporate a new imaging subsystem to improve the accuracy of the current system. We must first understand how the system works in order to improve its functionality. In this sense, the paper is more relevant not in its results and discussion, but more in the materials and methods. It is important to understand the mathematics and registrations that are taking place. The paper also shows us some limitations of the system, which we are trying to address. Overall, this is key background knowledge for our project. The paper describes that it is a feasible system and that our project is an attainable goal. However without this foundation to build upon, making any progress would be very difficult.

6.2 Limitations (Positives and Negatives of the Study)

The paper was very clear and well written. The details of the system can get complicated, but for the most part, they were very well explained. The rationale behind the study was also well thought out and detailed in explanation. The paper also used a variety of experiments to show that the system is accurate under optimal conditions and even under more realistic settings, has the capability to be very useful.

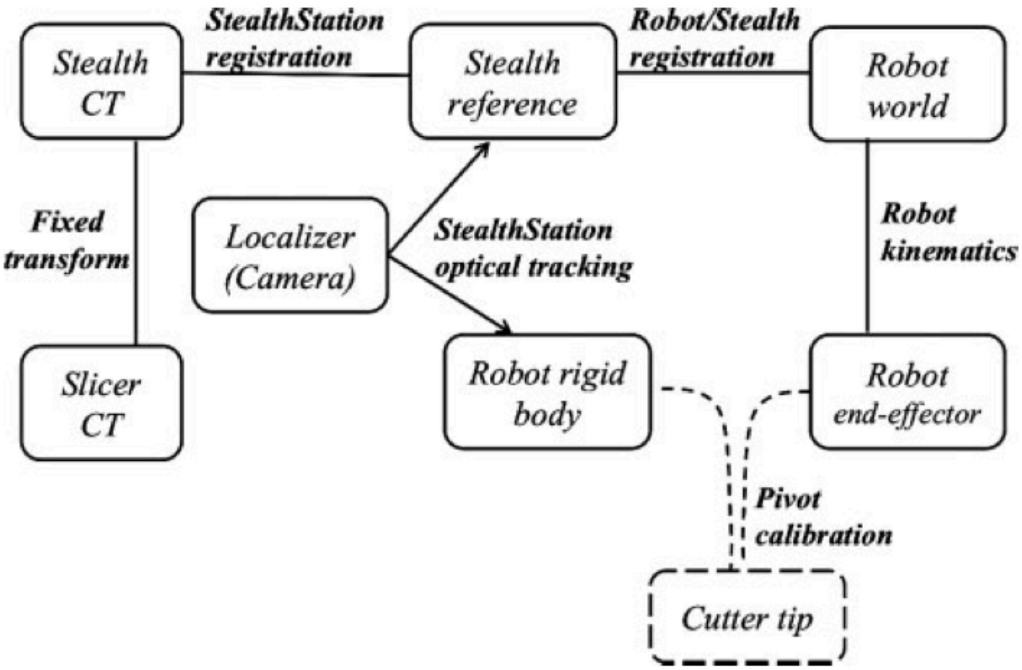
However, there were also limitations. There were not many trials done for either of the experiments. Only six trials were performed for the phantom experiments and three out of five data sets were used for the cadavers, making it difficult to show statistical significance between groups. Also, there was very few numerical data for the set of cadaver experiments. Measurements of overcut were done more or less qualitatively and lacked a more detailed quantitative basis. A more accurate method in measurement will be needed. In the actual system, there are also some limitations in the virtual fixture definition. Because the velocity is set to very low close to the boundary, it is difficult to move tangential along the boundary. Also, the equation they used to calculate total overcut error in the phantom experiments assumes that dimensional error is spread out evenly on both borders of the box. This may not always be the case and would yield a smaller overcut than in actuality.

6.3 Future Work

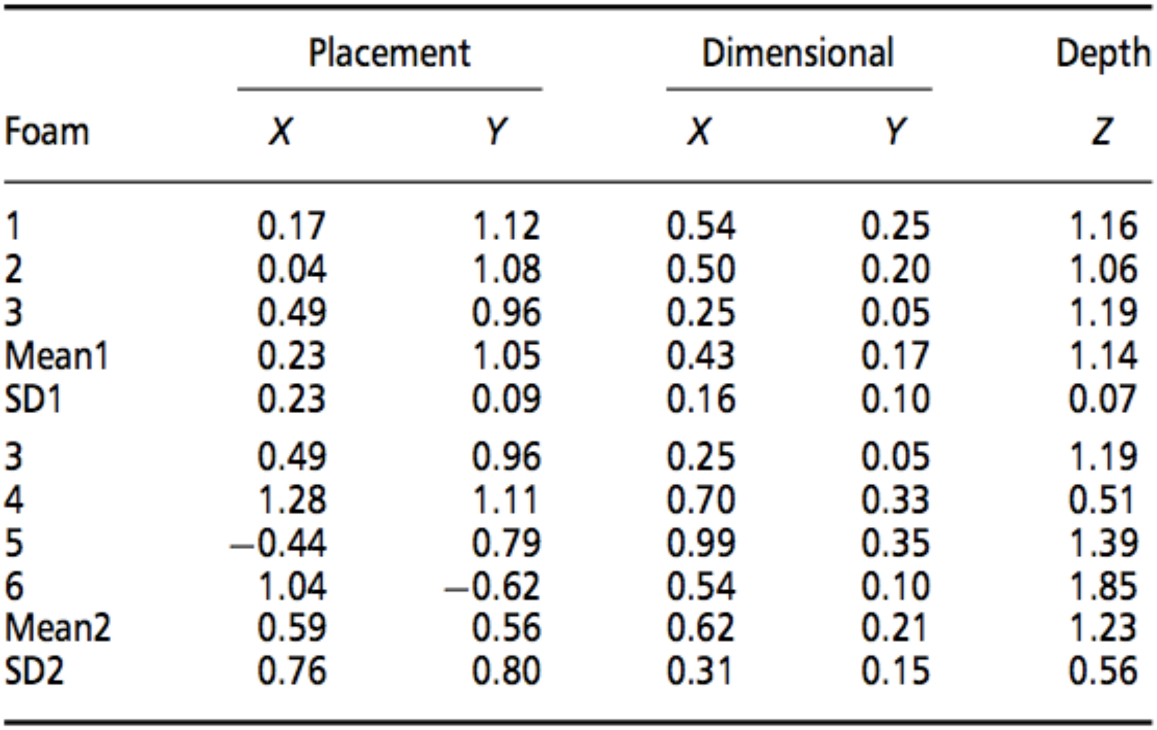
The project that we are currently working on is one type of the future work that is being conducted on this system. Because the system relies on one preoperative CT image, there is potential for errors throughout the procedure. By introducing a method of intraoperative imaging, we can improve the system's accuracy, such as by improving registration or adjusting the virtual fixture introperatively. Our project is to simulate an ultrasound photoacoustic system that will be implemented with the system.

Other future work that can be done include updating the virtual fixture algorithm. Conducting more experiments would also be highly beneficial in more precisely reflecting the accuracy of the system through more trials. Another suggestion would be to use telemanipulation as this will reduce errors from the measured forces and torque of the surgeon. However, this would be a very long-term project and one of the limitations is that that the surgeon will not feel fully in control.

Appendix A:

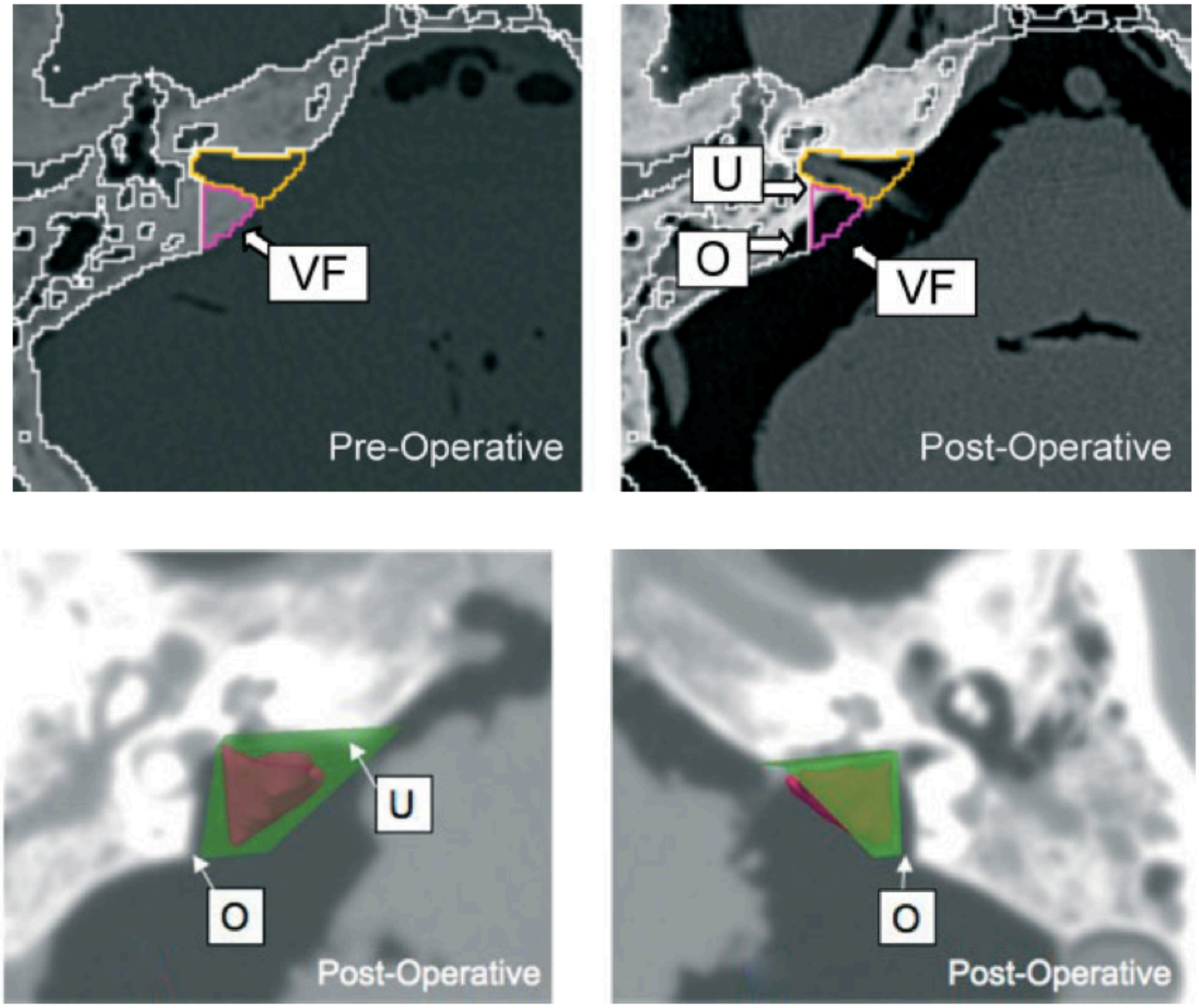


Appendix B:



	Placement		Dimensional		Depth
Foam	X	Y	X	Y	Z
1	0.17	1.12	0.54	0.25	1.16
2	0.04	1.08	0.50	0.20	1.06
3	0.49	0.96	0.25	0.05	1.19
Mean1	0.23	1.05	0.43	0.17	1.14
SD1	0.23	0.09	0.16	0.10	0.07
3	0.49	0.96	0.25	0.05	1.19
4	1.28	1.11	0.70	0.33	0.51
5	−0.44	0.79	0.99	0.35	1.39
6	1.04	−0.62	0.54	0.10	1.85
Mean2	0.59	0.56	0.62	0.21	1.23
SD2	0.76	0.80	0.31	0.15	0.56

Appendix C:


VF
Pre-Operative
U
O
VF
Post-Operative
U
O
Post-Operative
O
Post-Operative

References:

[1]Sawaya R, Hammoud M, Schoppa D, *et al.* Wildrick neurosur- gical outcomes in a modern series of 400 craniotomies for treatment of parenchymal tumors. *Neurosurgery* 1998; **42(5):** 1044 – 1055.

[2]Machinis T, Fountas K, Dimopoulos V, *et al.* History of acoustic neurinoma surgery. *Neurosurg Focus* 2005; **18(4):** e9.

[3]Arun KS, Huang TS, Blostein SD. Least-squares fitting of two 3D point sets. *IEEE Trans Pattern Anal Machine Intell* 1987; **9(5):** 698 – 700.