Force Sensing Drill - Cutter Tool for Skull Base Surgery

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Introduction

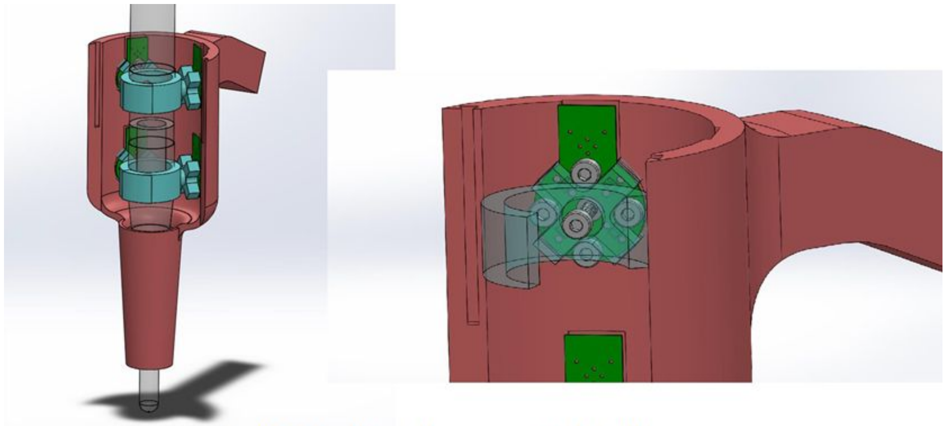
The Galen Surgical Robot is a hand-over-hand cooperative controlled surgical robotics system used for head and neck microsurgery. Currently, the Galen only sense tool-to-robot forces to reduce hand tremors and increase precision. For some applications, it is useful to measure and control the tool-to-tissue forces as well. Thus, the aim of this project is to develop a force sensing drill in order to provide physicians with more feedback and control during skull base drilling, a required step in many cranial surgeries. From 2006 to 2013, the complication rate in cranial surgery decreased from 23.2% to 14.6%, a promising but still alarming rate [1]. Many complications can occur during skull base drilling due to the complex anatomical components and the severity of damaging adjacent anatomy [2]. For example, in anterior petrosectomy for tumor excision, drilling may be within 1 millimeter of the carotid artery, facial nerve, cochlea, and venous sinuses [3].

Due to these complications, a physician's accuracy and precision are crucial in producing favorable surgical outcomes. A physician's inadvertent motions, hand tremors, and lack of feedback or safety controls from their surgical tools, however, hinder the physician's accuracy and precision during skull base drilling [4]. To solve these human limitations, we designed a drill holder that integrates multiple force sensors with a high speed surgical drill. This coupling will be interfaced with the Galen robotic system to eventually display forces and implement safety controls.

Technical Approach

<u>Mechanical Design</u>

We designed a drill sleeve capable of measuring the force exerted the tooltip on the tissue. In future work, this design principle can be extended to hold other instruments such as cutters and forceps as well. For this purpose, we used force sensors based on strain gauges available from the BLAM lab, at the Johns Hopkins Medical Institute (JHMI). We integrated these force sensors with a metal pivot which transfers forces from the drill body to the sensors.



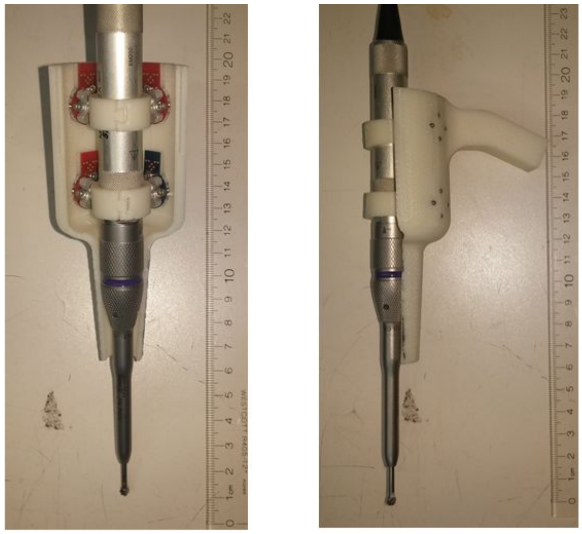
CAD Model of the assembled shell

Force Sensing

An integral component of this project is the force sensors used within the device. We intend to use a 3DOF force sensor with a small footprint. These sensors utilize four strain gauges on a printed circuit board to measure an axial Z force and 2 torques about each of the X and Y axes. The resolution of the sensors is yet to be quantified, along with its sensing limits. The data acquisition (DAQ) board for these sensors, developed by the BLAM lab, supports five sensors using multiplexing, but we only used four sensors.

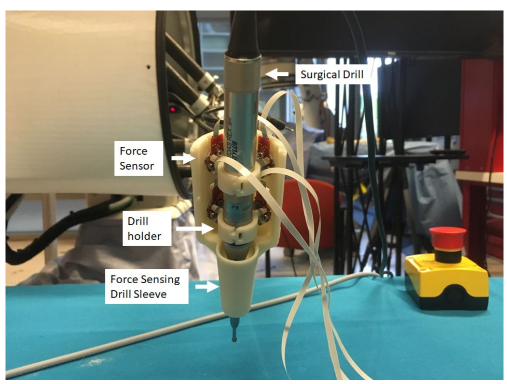
Mechanical Drill Sleeve Design

The drill holder design consists of three major components: (1) Four force sensors placed perpendicular to the axis of the drill. Each of these force sensors provides a 3DOF output force of an axial Z force and 2 torques about each of the X and Y axes. (2) A 3D printed ABS sleeve hold these sensors with slots for wiring the sensors and a quick release tool attachment to the Galen surgical robot. (3) A 3D printed cover ensures that no forces apart from the ones from the drill tool tip are exerted on the sensors. This also protects the sensors and their wiring within the drill. The overall focus of the design has been to reduce the drill profile as much as possible for ergonomic use by the surgeons.



3D printed and assembled drill holder

The present iteration of the drill sleeve was noted to have the following issues: The overall diameter is still large which adds a fair amount of bulk to the drill body; the 3D printed parts attaching to the tool holder are not durable enough for repeated use which causes wear of screw profiles within the holder. Some improvements that can be made are using Hall effect force sensors for a smaller force sensor design, which reduces the bulk of drill. The Hall effect force sensors are also better at detecting shear forces. Furthermore, using a metal tool holder attached to the end of the drill sleeve can resist wear when attaching to the Galen robot.

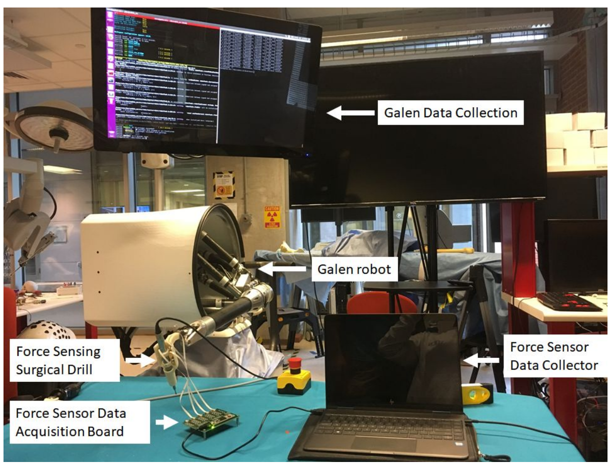


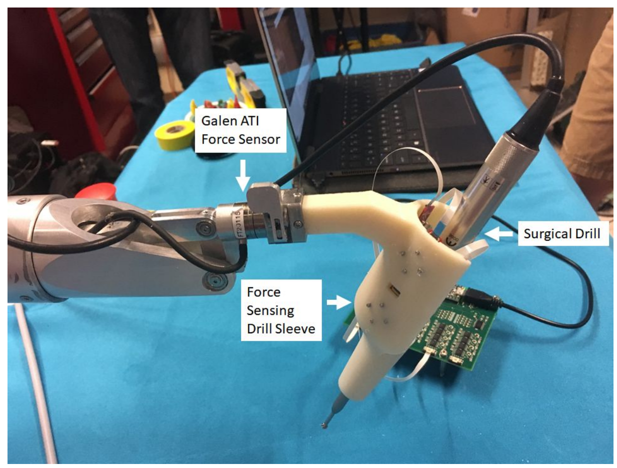
<u>Calibration</u>

Once the mechanical drill sleeve was completed and assembled we could begin the calibration procedure. The first step in calibration was the data collection phase. We used the DAQ board developed by the BLAM lab to obtain uncalibrated X, Y, and Z force readings for each of the four sensors affixed to the drill sleeve. This data was visualized using Plotosaurus, a visualization software developed by the Alex Forrence at the BLAM lab, to ensure that the forces were registering. In addition, we used Plotosaurus to output a TXT file that included timestamps with each line having the following format:

Time (s)	FS1 Fx (N)	FS1 Fy (N)	FS1 Fz (N)	FS2 Fx (N)	FS2 Fy (N)	FS2 Fz (N)	FS3 Fx (N)	FS3 Fy (N)	FS3 Fz (N)	FS4 Fx (N)	FS4 Fy (N)	FS4 Fz (N)	FS5 Fx (N)	FS5 Fy (N)	FS5 Fz (N)
430.90629	0.03049	0.70177	0.94833	-0.00353	0.71084	1.00589	0.02156	0.7017	1.05449	0.04219	0.64667	0.95183	-0.69003	0.72281	1.84735
430.90729	0.0299	0.7015	0.948	-0.00346	0.71097	1.00601	0.02153	0.70184	1.05429	0.04292	0.64549	0.95192	-0.69006	0.72282	1.84755
430.90828	0.0306	0.70131	0.94775	-0.00309	0.71098	1.00691	0.02114	0.70199	1.054	0.04298	0.64552	0.95116	-0.69006	0.72282	1.84712
430.90929	0.02969	0.70172	0.94824	-0.00316	0.71084	1.00667	0.0212	0.70195	1.05447	0.04272	0.64677	0.95181	-0.69005	0.72281	1.84756

We attached the drill apparatus to the Galen robotic arm. The Galen robot has a built in six degree-of-freedom ATI force sensor that detects forces exerted on the robot handle. The force at the drill tip could be easily resolved from handle force assuming there was no external force on the drill sleeve. These force and torque readings were outputted with timestamps in a TXT format. The figure on the left shows the configuration in the Mock OR where the calibration was performed and the figure on the right shows the attachment of the drill sleeve apparatus to the Galen robot.





We collected data from the Galen's ATI force sensor while using the DAQ board to simultaneously collect force sensor data from the sensors on the drill sleeve. From this, we obtain a TXT file for the force data of both systems. While both systems were simultaneously collecting data, force was applied in multiple directions using our finger. The first step was to initiate a mechanical trigger, meaning a force that will be displayed clearly in both datasets. This trigger will be used to synchronize the datasets by allowing us to determine an offset between the datasets. The sides of the drill tip were pressed on in different radial directions. Force was also applied on the underside of the drill tip to simulate normal force applied when pressing on tissue.

Once this data was obtained the next step was to preprocess it. The time offset between the collection initialization of the Galen and the DAQ board was determined by first plotting one of the components of one of the sensors and also plotting a component of the Galen force sensor. The X force component of the first force sensor was plotted with the X torque on the Galen force sensor. There was a clear portion of the plots that appeared show the same behavior that was likely caused by the mechanical trigger. To verify this, in MATLAB we examined the plots to observe that the time of both of these applied forces were approximately equal. Then we found the starting time of the applied force on each of these plots and used the difference as the offset. This difference was used to adjust the timestamps on the drill force sensor data since the Galen data collection was started first. After the starting points of the data were lined up, the next step was to filter the data to match sampling rates. The ATI force sensor on the Galen samples at 200 Hz while the DAQ board collects readings from the force sensors at a rate of 1 kHz. To account for this the MATLAB function *resample()* was applied to the drill sleeve sensor data to adjust the sampling rate to ⅕ of the original rate (1 kHz to 200 Hz). Two matrices were created from 30 seconds of this data.

There are twelve total force readings from the force sensors on the drill sleeve labeled as follows:

$$f_{x1}, f_{y1}, f_{z1}, f_{x2}, f_{y2}, f_{z2}, f_{x3}, f_{y3}, f_{z3}, f_{x4}, f_{y4}, f_{z4}$$

Where f_{y3} represents the y component of the force sensor connected to port 3 on the DAQ board. Using a similar notation for the forces from the Galen's built in ATI sensor resolved at the drill tip these are:

$$t_x, t_y, t_z, t_{x\_torque}, t_{y\_torque}, t_{z\_torque}$$

Therefore, let S be the n by 12 matrix for drill sensor readings and G be the n by 6 matrix for corresponding drill tip forces recorded by the ATI sensor.

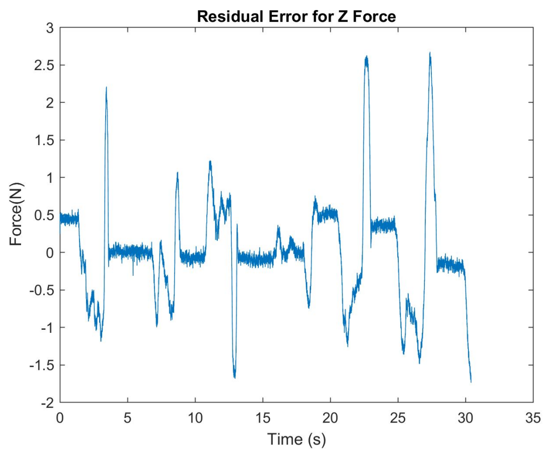
$$S_{(n \times 12)} = \begin{pmatrix} f_{x1,1} & f_{y1,1} & \cdots & f_{z4,1} \\ \vdots & \vdots & \ddots & \vdots \\ f_{x1,n} & f_{y1,n} & \cdots & f_{z4,n} \end{pmatrix} \quad G_{(n \times 6)} = \begin{pmatrix} t_{x,1} & t_{y,1} & \cdots & t_{z\_torque,1} \\ \vdots & \vdots & \ddots & \vdots \\ t_{x,n} & t_{y,n} & \cdots & t_{z\_torque,n} \end{pmatrix}$$

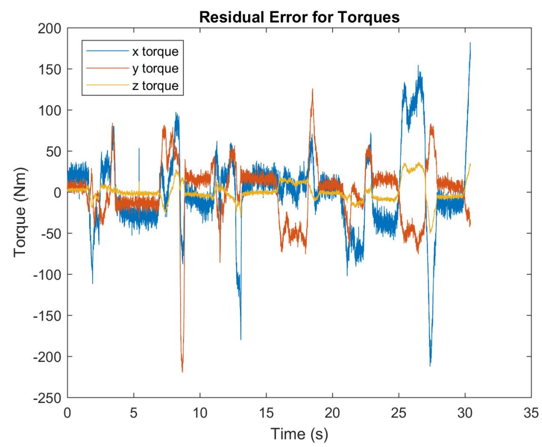
A Singular Value Decomposition (SVD) approach to solving linear least squares problems was used to find X in the matrix equation $SX = G$. This X matrix represents a computed transformation from drill sleeve sensor forces to known drill tip forces and torques.

Results

After obtaining the matrix X that transforms the readings from the drill sleeve sensors to tip force readings, we evaluated the fit. It is first important to note that we were unable to fit a linear model to the X and Y linear tip forces. This is likely due to the fact that the ATI force sensor on the Galen was not registering these forces because there was no direct shearing on the bottom of the tool tip. For the remaining data, we evaluated fit by determining an R-squared value for the Z force, X torque, Y torque, and Z torque. They are shown below along with plots for residual error:

Component	Z Torce	X Torque	Y Torque	Z Torque
R-Squared Value	0.7100	0.6064	0.7226	0.4761





Given that the R-squared value was low and the residual error plots displayed intervals of large error, the model that was fit is not conclusive. There are several factors that could account for this. With regard to the strain gauge sensors, the BLAM lab is in the process of calibrating output to correct Newton forces. However this was incomplete before our application so the individual sensors were uncalibrated. Furthermore, we encountered some issues with hysteresis. In the plots for individual force components as well as when visualizing drill sensor data during calibration, we were able to observe force readings not returning to baseline. This could explain periods of high residual error as shown in the plot above since the Galen ATI sensor demonstrated minimal hysteresis and adjusted to the baseline as compared to the strain gauge sensors on the drill sleeve. Additionally, the strain gauge sensors did not measure linear shear forces in the x and y directions, only torques. Thus without shear force sensing capability for the sensors contacting the drill sleeve, different applied tooltip forces become more difficult to model.

With regards to the drill sleeve design, there were no drill holes in the printed sleeve to attach the quick release tool attachment between the sleeve and the Galen so we had to manually drill holes. This led to the drill being unstable and not fixed during experimentation which could have cause forces registering on the drill sleeve sensors but not the ATI sensor on the Galen. In addition, some of the screws that connected the strain gauge sensors to the drill sleeve had heads that were too wide. This interfered with the force sensors' PCB contacts. To solve this problem, electrical tape was added to cover the contacts. This worked ostensibly, but may have affected our readings.

Conclusion/Significance

We developed a solution to measure and display the tool-to-tissue contact forces while drilling using a tool holding sleeve integrated with force sensors. This initial prototype can be improved in many ways, however, it provides a feasible solution for tooltip force sensing.

We learned that the strain gauge sensors are not useful for our purposes, thus future work can include using Hall effect based force sensors or a different type of force sensor for better sensing and a smaller tool profile. Other improvements include using a nonlinear model for better calibration of drill sleeve forces to reference ATI sensor forces. A better visualization of the forces is also needed, which can be displayed on the Galen system dashboard.

Management Summary

Member Contributions

Within the project, Prasad completed the mechanical design and its design reviews for ergonomics. He also completed the manufacture of the prototypes, their assembly and testing. For the purposes of documentation, Prasad also completed the CAD model design sheets for all parts, along with parts list.

Brandon worked closely with the BLAM lab with all things related to the force sensors and the DAQ boards. In addition, he troubleshooted problems related to the force sensors and DAQ boards. Brandon also modified Plotosaurus to display forces instead of strain gauge voltages and to output a TXT file with timestamps and forces.

Nick and Brandon handled the experimentation, data collection, and data fitting and analysis. Experiments and data collection were performed in the Mock Operating Room with the help of Paul Wilkening. After experimentation, they performed the data fitting and Nick performed the linear least-squares calibration and error analysis in MATLAB. In addition, Nick and Brandon prototyped a Hall effect sensor for the next design iteration.

Planned vs. Accomplished Tasks

We initially wanted to develop sensing capabilities and provide a visualization for the calibrated force measurements. Along with this, we also had the idea of integrating virtual fixtures with these measurements to provide additional safety to the surgeon drilling it. Due to the amount of time the drill sleeve prototype took, we were not able to begin collecting data as early as we planned, thus we were not able to explore these possibilities. In addition, we found the force sensors were not accurate enough to be used in our applications. We concluded that our time would be better spent focusing on the drill calibration and evaluating which sensors to use next.

Therefore, the goal of the project was shifted from integrating more features to improving the drill calibration and working on alternative force sensing methods such as one utilizing Hall effect sensors for higher accuracy. After shifting our goals, we were able to complete the drill calibration and produce a working Hall effect sensor.

Future Steps

Future work in this area would include reducing the drill profile using Hall effect sensors and calibrating according to that. In addition, we believe that the Hall effect sensors will provide better force sensing than the strain gauge sensors due to past research on the subject [5]. Another improvement would be to calibrate the drill using a nonlinear calibration model for a better fit.

Challenges & Lessons Learned

Design reviews and iterations took up a lot of time due to previous dependencies and a focus on smaller design profile from the start. This could have been avoided if we worked on printing and testing a part before its redesign. For example, the screws that connected the force sensors to the drill sleeve had too wide of a head which interfered with the force sensors' PCB connections. In addition, the drill sleeve did not have screw holes to be attached to the quick release tool attachment that connects to the Galen robot. We ended up drilling holes into the drill sleeve to accommodate for this, but the drill was still unstable and not rigid during our experiments. These issues would have been resolved if we printed, tested, then revised in tandem to revising our design based on feedback on the CAD models. We learned that although it is important to garner feedback on designs, it is equally important to get a prototype as fast as possible to see what issues arises and revise based on these issues.

We experienced issues with the force sensor, particularly hysteresis and lack of initial calibration. The BLAM lab is currently working on a calibration routine for the strain gauge force sensors, but this was not done before our applications. In addition, there were assembly issues that led to hysteresis in the sensors. We were able to conclude that these sensors were not as applicable to our project as we thought. We learned that one should not use the first readily available component, rather one should carefully assess all other options. If we did an evaluation of force sensors initially, we could have designed the sleeve for the Hall effect sensor as opposed to designing the sleeve for the strain gauge sensors that were faulty.

References

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