Final Report

Motorized Fixation to Tubular Retractor in Brain Surgery

EN 601.456 Computer Integrated Surgery II

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1 Introduction

1A Background

To give the reader a clearer understanding of the origins of this project, we begin by discussing prior innovation in the field of brain surgery.

Current methods for neurosurgical retraction, such as the use of “metal blade retractors” are well-documented for imparting excessive focal pressure on the brain, leading to high risk of injury. Of the 700,000 neurosurgical cases each year in the US requiring brain retraction, about 9%, or 63,000 cases, exhibit acute retraction-induced injury [1]. Given that major complications cost roughly $50,000 for the patient and that each day spent in the hospital costs around $2,500 [2], this amounts to a $3 billion burden on the US healthcare system due to retraction-induced injury.

Figure 1.1: Tubular retractors used in industry. *The picture on the left shows Vycor Medical’s VBAS retractors[3]. The picture on the right shows NICO Corporation’s BrainPath retractors[4].*

Tubular retraction is one state-of-the-art method executed to access deep-seated lesions during brain surgery, and is a safer alternative to metal blade retractors. In tubular retraction, a tube-shaped device (Fig. 1) is inserted into the brain to provide an operable corridor providing access for surgical tools. A case study series where surgeons compared the NICO BrainPath retractor (Fig. 1) to conventional metal blade retractors found a 50% reduction in length of stay, and this reduced ICU time saved critical care facilities $17,000 in direct variable costs on average per retractor use [5]. Developing a safer alternative can protect the health of patients undergoing difficult, relevant surgeries, and reduce the associated financial load on hospitals.

Prior Work

The aforementioned problem regarding increased complications and high financial burden has been targeted with a solution intended to decrease brain trauma by a Johns Hopkins startup named CortiTech. The company has successfully designed an alternative method for tubular retractor insertion (Fig. 1.2). The main objectives of this device are to target reduced trauma by providing “a minimal port of entry to minimize the risk of tissue damage and ‘brain shift’ during insertion,” as well as through “gradual radial expansion to spread pressure over time” [6].

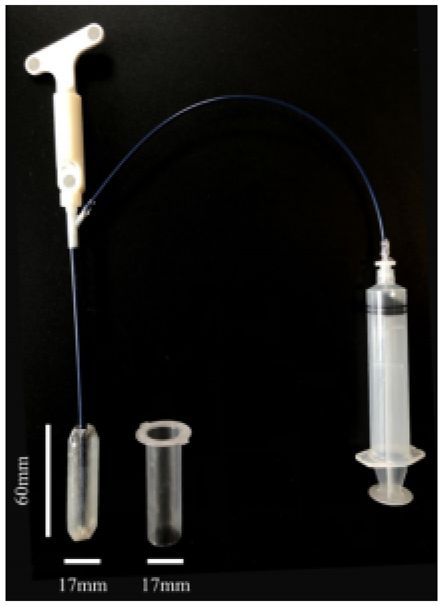

Figure 1.2. *CortiTech device*[6].

The results of animal cadaver testing showed that the “insertion step…required less force with the novel device” and “minimal bleeding” was observed. However, “there was no difference noted in the degree of operative access and optical clarity of the device sheath compared to other tubular retractors” [6], showing that the device was not necessarily any more easy to use from a surgeon’s standpoint.

1B Motivation

<u>Entrepreneurial Motivation</u>

During surgical interviews evaluating CortiTech’s solution and the general scope of the field, some surgeons mentioned issues with the ease of use of tubular retractors. This exposed a potential need to give surgeons a better reason to use retractors in the first place - even if CortiTech’s technology is less traumatic, it may be too much of a hassle to relearn a new approach simply for a method that is not extremely easy to use in the first place. CortiTech may want to solve the problem of trauma, but even if this is accomplished, surgeons have to want to use the technology. As it turns out, the feasibility of solving a clinical problem may depend on a market problem that needs to be fixed.

Clinical Motivation

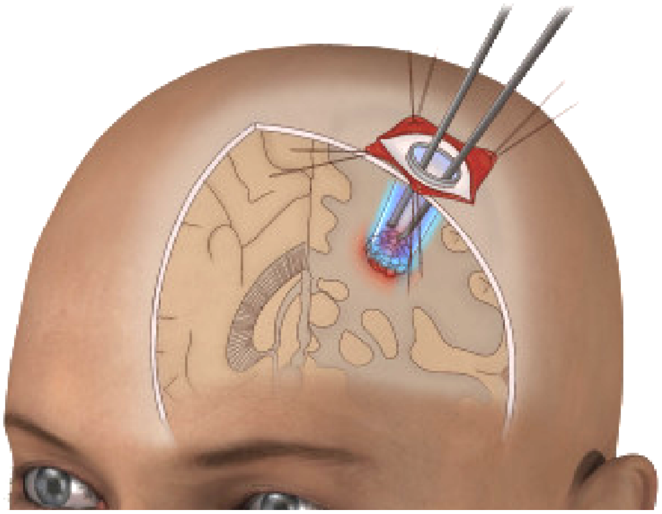

Figure 1.3: Tubular retractor "floats" in the brain[7].
Inserted tools may come in contact with retractor walls and cause the retractor to shift.

When looking into solutions that improved ease of retractor use, the team noticed the issue that tubular retractors are unconstrained inside the brain (Fig. 1.3), which can allow unintended movement and lead to excess brain trauma or inconveniences during procedure. So, the team found a dual problem - usability was an issue as expected, and trauma was a potential issue, but in this case, during the operation rather than the initial insertion step of the tubular retractor. The solutions found for unconstrained retractors include manual devices used to adjust retractors, which can be shaky and unwieldy (Fig. 1.4).

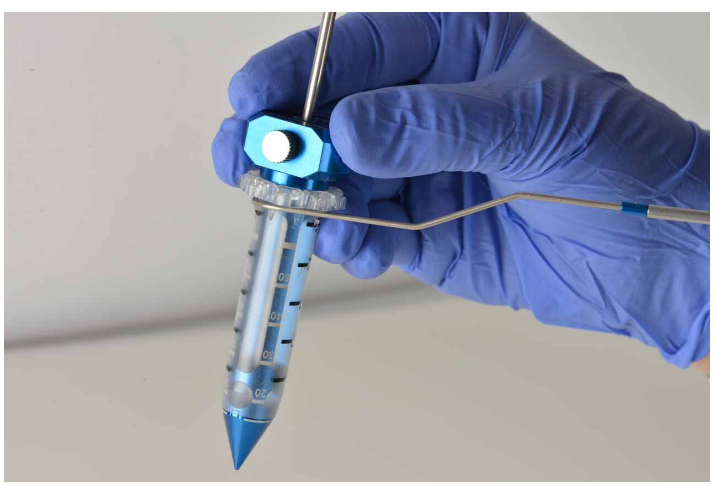

Figure 1.4. NICO Corporation's Shepherd's Hook technology[8].
The thin metal hook around the retractor is a manual stabilization device, but is difficult to use.

There have been solutions in the general field of surgery targeting shaky movements; one big step in technology for this has been tremor reduction through surgical robotics. However, there have been many issues associated with robotics in brain surgery, the most prominent of which include issues with robotic tool usability and surgical field obstruction and reduced haptic feedback sense. Because of the many limitations, robots have not yet dominated the field of neurosurgery [9].

1C Goals

Objectives

The goal of this project is to design a motorized fixation to serve as an intermediary between the structural support arm and the tubular retractor to improve the precision and control of retractor positioning. Working towards this goal, three sets of checkpoints were made:

Minimum Deliverables:

- Hardware to allow for 2 DOF movement of the tubular retractor.*
- Rudimentary software to align a tubular retractor using motors, based on computer inputs such as set of angles.*
- Report analyzing the accuracy of our retractor realignment method.*
- Documentation of our code base. *

Expected Deliverables:

- Prototype "orientation object" for collecting orientation/movement data using IMUs.*
- Finely tuned retractor angling actuation with smooth control through positive and negative x and y axis movements.*
- Software that filters and analyzes data collected from the "orientation object" and determines the relative orientation of the object and moves the retractor to a matching orientation when a button or foot pedal is pressed.*
- Report analyzing accuracy of orientation estimation and matching.*

Maximum Deliverables:

- Surgical instrument attachment with IMUs (does not hinder functionality).
- Software that filters and analyzes the data collected from the forceps and moves in the same way as it did with the calibration object (New constraints in this system).

- Safety features to limit velocity, maximum angle, and prevent shaky movements from surgeons*

* -Indicates completion or partial completion of deliverable within the timeline

These goals, if accomplished, will remove the lack of precise adjustment from manual use of tubular retraction, this limiting hand tremors. It will also allow free use of hands without the drawback of potential traumatic motion in the brain. It will also avoid issues with robotic tools as surgeons will still use conventional tools inside the brain to operate.

2 Technical Approach

2A Mechanical Design

The preliminary design involved a rudimentary upscaled design of a 2-axis gimbal structure that was angular in shape for ease of servo attachment (Fig. 2.1). The inner structure that rotates about the inner servo axis has a hole for fitting a long rod as seen in section 4C Surgeon Feedback. This rod protrudes partially upwards and partially downwards. The downwards protrusion is useful for monitoring motion inside the brain in case the rod hits the walls of the skull hole. The upwards protrusion is useful for observing motion. The second iteration of the preliminary design involved a change to the inner structure which more closely resembled a retractor for testing with the calibration object. The limitation to this design is that it is bulky and takes up extra space in the surgical field.

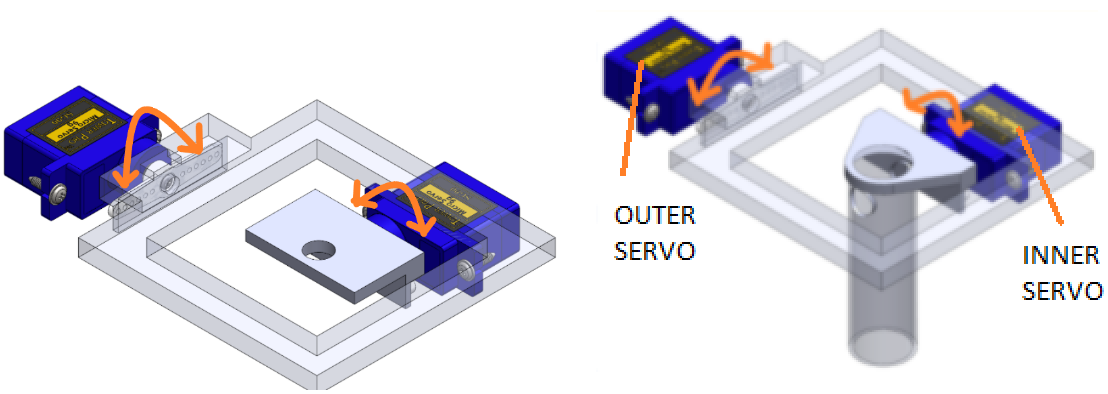

Figure 2.1. *<u>Left</u>: Original 2-axis gimbal structure for the physical attachment with angular inner platform. <u>Right</u>: Updated physical attachment with modified inner platform to resemble retractors.*

2B Actuation and Control

Actuation

The main method of actuation used in this project's design was through servomotors. The initial plan involved the use of micro stepper motors that fit into the surgical area. However, due to issues with necessary soldering materials for precise soldering of small electrical components these motors, servos were used as a replacement. Servos proved to be more precise than expected, and our clinical advisor had no issues with smallest movement resolution. This was achieved by commanding the servo to move to predetermined angles in increments of one degree.

Control

Implementation of servo actuation control was performed in stages. The first stage of development was implementing basic button step control. In this control method, each servo is moved based on positive and negative increment buttons that move the servo one degree in either direction. Stage two of motor actuation control included numerical inputs from an external machine. In this iteration, the user is required to enter desired x and y-axis orientation angles for the physical attachment to achieve. These designs were then adapted to the main task of interpreting IMU sensor information and commanding motorized components accordingly. After each iteration, feedback was received from surgical mentors (found in 4B), however this report will exclusively discuss accuracy assessments performed for the final input approach.

This final method of control was automatic synchronization based on a "calibration object," manufactured using a 3D printer (Fig. 2.2). The goal was to insert the calibration object into the retractor, tilt it, and design the retractor to tilt the same way, so that its central axis aligned with the "rod" of the calibration object. This action represents the surgeon titling a tool inside the retractor and having the retractor "follow" it. Hence, the rod of the calibration object was designed to resemble the general elongated shape of most tools that are used inside the retractor.

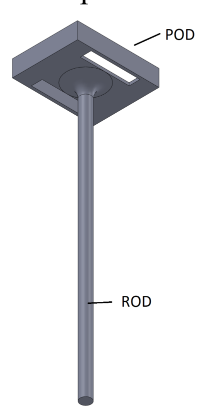

Figure 2.2. *Calibration object design.*

The “pod” of the retractor was designed to hold an IMU sensor, which was used to find the orientation of the calibration object through reading the angles with respect to the environment output by the sensor. The pod was matched in dimension to secure the sensor snugly to avoid looseness. This was important because looseness could cause the sensor to shift and lead to inaccuracies in the data. The slots in the bottom of the pod allowed the wires coming from the sensor to be directed away from the system instead of being stuck inside of the pod with the sensor.

To estimate the orientation of the calibration object, a 9 degrees of freedom Inertial Measurement Unit (IMU) was utilized. The 9 DoF IMU used in this project was the Adafruit Precision NXP 9-DOF Breakout Board which includes a tri-axial gyroscope, tri-axial magnetometer, and tri-axial accelerometer. Sometimes this combined sensor will also be referred to as a MARG in the literature which stands for magnetic, angular rate, and gravity sensor array. The data from this type of sensor can be fused to calculate an orientation/attitude estimate. The procedure for doing this with the Madgwick and Mahony filters is described in section 3C.

Modified Calibration Object

Figure 2.3. *Calibration object augmented design. Left to right: design iterations.*

Though the calibration object resembled a surgical tool, there were certain additions made to its design that helped resemble tools more closely. These designs are shown in Figure 2.3. The main design feature here was the “bayoneted” tool, which was inspired by similar surgical tools such as the NICO BrainLab pictured in Figure 2.4. The initial design was an added handle. The second design implemented a full bayonet. The third design moved the rod of the object to the side of the pod for better visibility. According to our clinician, the best design is a combination of the central and rightmost designs.

Figure 2.4. *Inspiration for calibration object design:NICO BrainLab. Stereotactic trajectory planning device with bayonet feature.*

2C Software

All electrical components included in the system hardware are wired to a single Arduino Uno microcontroller. This makes using Arduino software most convenient, and the majority of our codebase is written in the Arduino language making use of Servo and Adafruit Sensor libraries. All code must be uploaded to the microcontroller with use of Arduino Studio, but the user can choose to run the system independently of a personal computer if interaction with the Serial Monitor is not required. The final iteration of our software as discussed in this report aims to use IMU readings to motivate servo motor movement.

In order to generate accurate motor commands, both the sensor inputs and motor outputs needed to be calibrated. This was done using several experiments outlined in the following section. The data was then analyzed using Python.

Note that our code is currently being stored on a private repository on Github for the protection of IP that may be useful for our sponsors, CortiTech. To access our code repository, please send a message to Caroline so access can be granted.

3 Experimental Setup

3A Servo Motor Alignment

While Servo motors are popular due to their low cost and simplicity of control, they tend to lack precise angle actuation. To combat this inaccuracy, trials were run to determine the error margin of angle actuation, and to derive error offset equations.

Each Servo motor was tested at 5 degree increments spanning their full range, using a weighted protractor attachment as shown below in Figure X. Images of the protractor in each position were imported into MATLAB and analyzed using the image analysis protractor tool (Find Documentation Here). Once overall error of the raw readings was computed, simple linear and quadratic error mitigation equations were derived using the SciPy Optimize Library. Experiments were repeated, altering the angle inputted into the Servo motor using each mitigation equation, and the average absolute error was again computed.

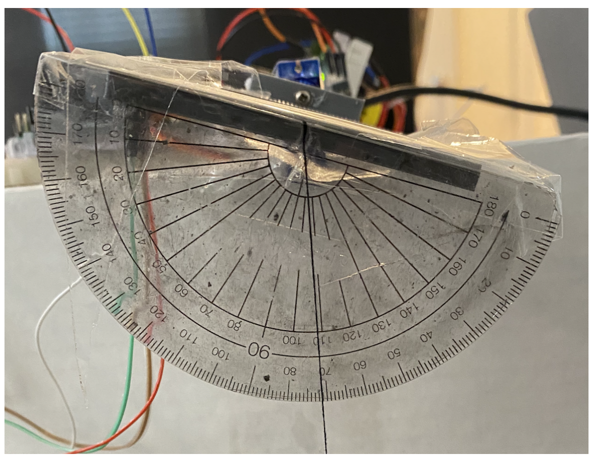

Figure 3.1. *Outer Servo Motor Accuracy Testing*

For the x-axis Servo motor (outer ring of physical attachment), the raw average absolute error was found to be 7.46 degrees. Offsetting the inputted angle via the equation $f(x) = 0.868x + 0.0008x^2 - 4.38$ yielded an improved average absolute error of 1.46 degrees.

For the y-axis Servo motor (inner ring of physical attachment), the raw average absolute error was found to be 15.71 degrees. Offsetting the inputted angle via the equation $f(x) = 1.013x - 17.06$ yielded an improved average absolute error of 2.41 degrees.

We deemed both error margins as within an acceptable range for our purposes, though this is a potential area of improvement in future iterations of the design. However, while the accuracy and resolution of the positioning of the retractor with the servo motor setup is within an acceptable range, we see a major issue being the smoothness of movement and control. We plan to eventually use DC motors in our design to help with this issue, but due to the malfunctioning of our 3D printer, this goal was pushed back.

3B Magnetometer Calibration

Magnetometer readings are necessary to limit the drift error of the gyroscope readings in the IMU sensor. However, during the manufacturing process, these readings tend to collect an offset error that can be eliminated by calibration. We performed this calibration through hard iron offset calculation, aided by the Adafruit Sensorlab Library mag_hardiron_simplecal code (Find documentation here). The hard offset trial was run several times and averaged to find an approximate offset value for each axis.

After determining the hard offsets in each axis, these numbers were uploaded to the Ardino microcontroller ROM for future use. This procedure was performed once for each IMU used in the system.

3C Orientation Static Trials

One of the most common issues with estimating orientation or position with IMUs is that the readings tend to drift. Drift can be defined as the low frequency change in a sensor with time. However, if a sensor is found to be smoothly drifting the sensor can be corrected for drift [12]. To determine the drift present in the IMUs used in our experimental setup, we placed the IMU at on the desk and collected the orientation being read out over 5 minutes. Throughout the trials, we tested two filters for estimating orientation: the Madgwick Filter and the Mahony filter. The two algorithms operate very similarly but with some important differences. We will now briefly summarize the algorithms and their differences.

The Mahony Orientation Filter is an estimator proposed by Robert Mahony et al [10] that incorporates readings from a gyroscope, accelerometer, and magnetometer to produce an attitude estimate (orientation estimate). The main benefit of the Mahony filter is it is much more computationally efficient than the Madgwick filter making it better for running on the low power Arduino UNO's used in our setup. A brief description from AHRS describes the Mahony filter as a "deterministic kinematic observer on the Special Orthogonal group SO(3) driven by an instantaneous attitude and angular velocity measurements.".

On the other hand, the Madgwick Orientation filter is an estimator proposed by Sebastian Madgwick [11] that, like the Mahony filter, produces an attitude (orientation) estimate based on the fusion of magnetometer, accelerometer, and gyroscope data. A brief description from AHRS describes the Madgwick filter as employing "a quaternion representation of orientation to describe the nature of orientations in three-dimensions and is not subject to the singularities associated with an Euler angle representation, allowing accelerometer and magnetometer data to be used in an analytically derived and optimised gradient-descent algorithm to compute the direction of the gyroscope measurement error as a quaternion derivative”. The main improvements here are an adjustable parameter defined by observable system characteristics, a gradient descent algorithm that works with low sample rates, a magnetic distortion compensation algorithm, and gyroscope bias drift compensation. While these may improve performance, the runtime is much higher presenting a problem for the Arduino UNO as the filter can not be called as repeatedly as with the Mahony filter.

Similarly, we tested several different starting positions for the sensor: sensor’s z-axis facing upward (Pose 1), sensor’s y axis facing upward (Pose 2), and sensor’s x-axis facing upward (Pose 3). Since the position of the IMU will be moved a maximum of 15 degrees during a procedure according to our clinical advisors, we can choose the position with the best performance as the starting state for a procedure to bolster performance.

Throughout all of the trials, we noticed an unusual trend in which the first minute or so of orientation readings produced by either filter were highly inaccurate and fluctuated within rather large bounds. An example of this sort of error is shown here:

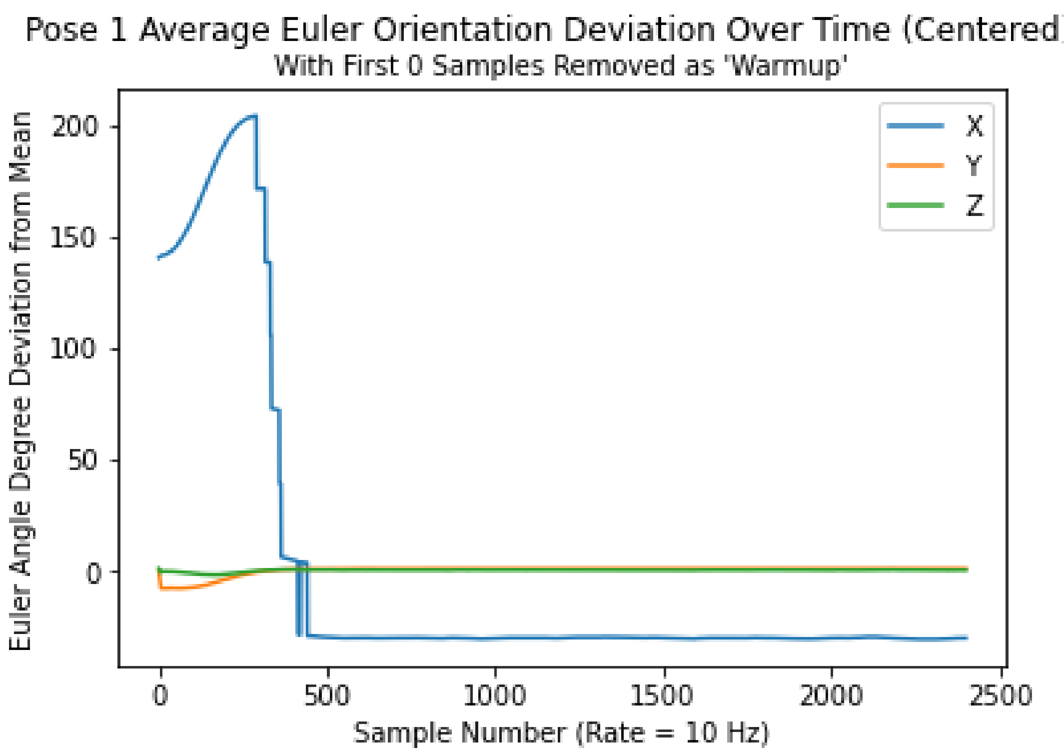

Figure 3.2. *Plot demonstrating the fluctuations in readings provided by the IMU during the first minute of sampling.*

To account for this issue with the sensor fluctuation during “warmup”, we determined that it was best to wait 580 samples or approximately 1 minute before beginning use after turning the system on.

The trials were performed first with the Madgwick filter to determine which pose was best. The mean results of the 3 poses are shown here (with the warm up samples thrown out):

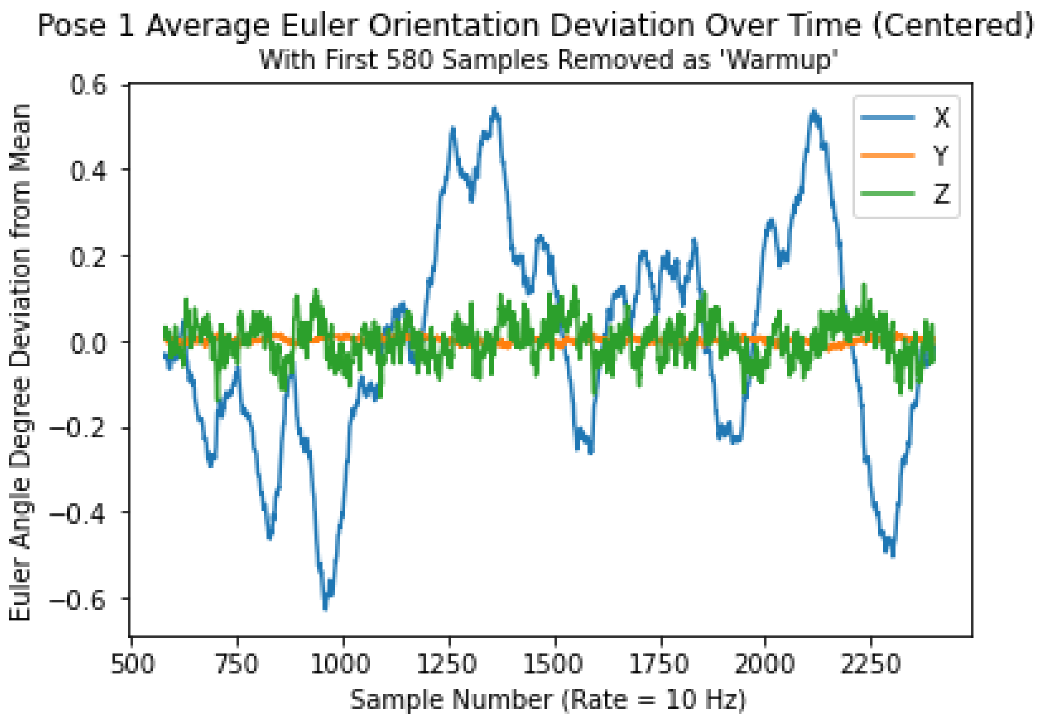

Figure 3.3. *Average Pose 1 Deviation over Time with Madgwick Filter*

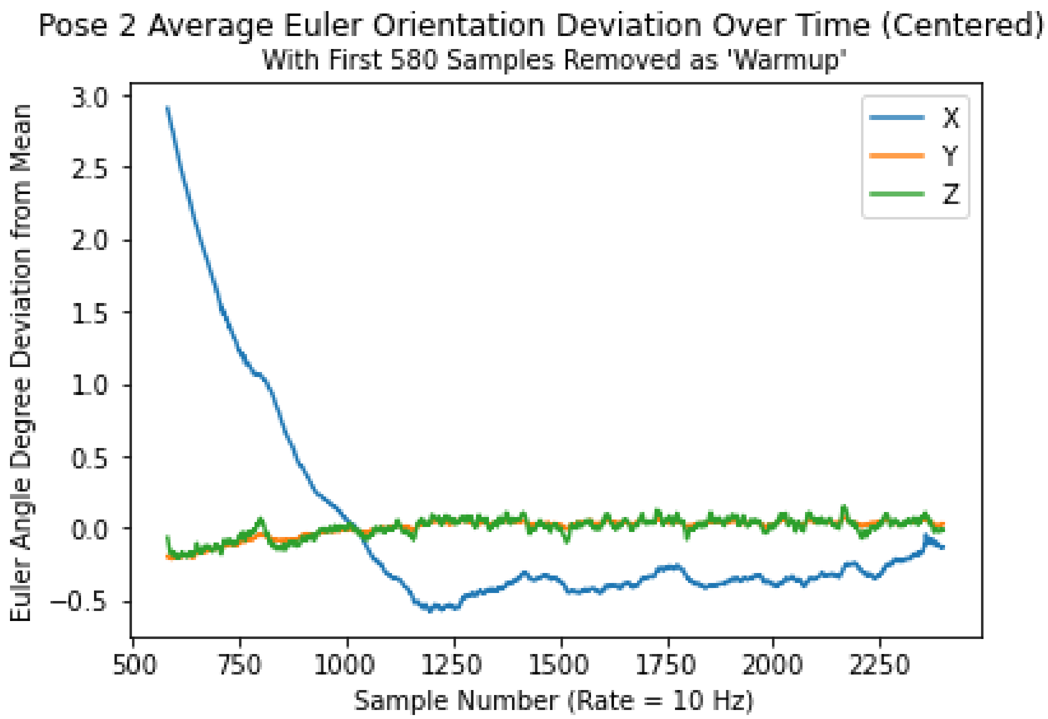

Figure 3.4. *Average Pose 2 Deviation over Time with Madgwick Filter*

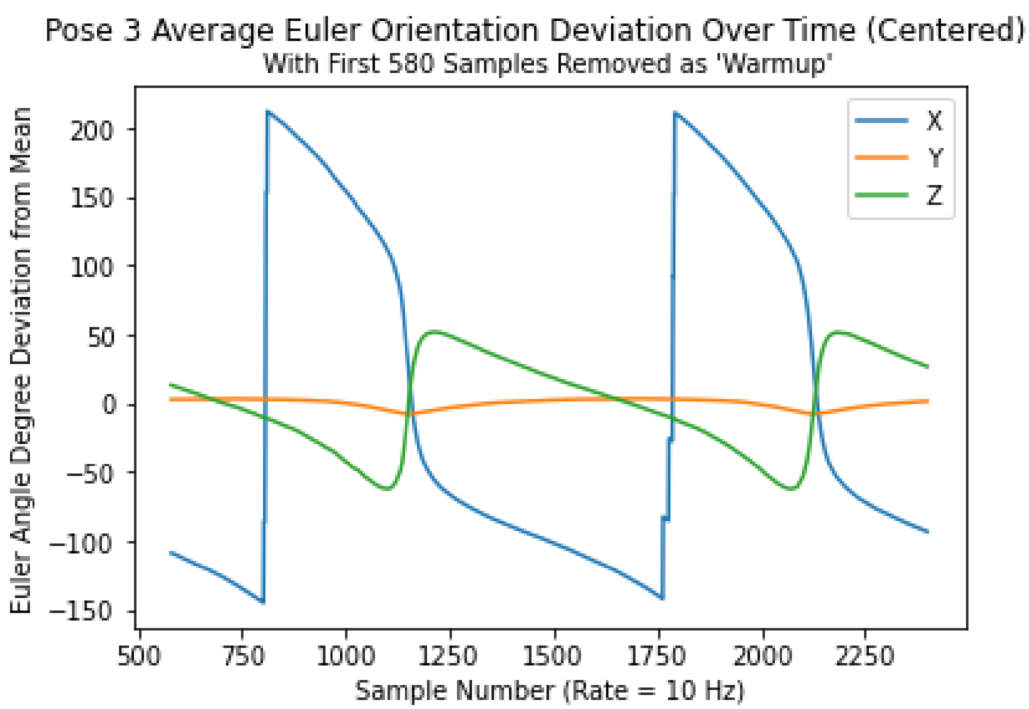

Figure 3.5. *Average Pose 3 Deviation over Time with Madgwick Filter*

Visually analyzing the plots, we can see that Pose 1 (Z-axis) facing up provides the best results, followed by Pose 2, and lastly Pose 3 reads out cyclical orientations despite the sensor being still so it is entirely unusable.

The average absolute deviations in each axis was then calculated with the results shown in a tabulated form here:

Table 3.1. Average Absolute Deviation for Madgwick Filter

Pose	Axis	Average Absolute Deviation (degrees)
Pose 1	X	0.2157
	Y	0.0054
	Z	0.0361
Pose 2	X	0.5346
	Y	0.0490
	Z	0.0532
Pose 3	X	116.0654
	Y	2.8081
	Z	28.5400

Since it was clear that Pose 1 with the Z axis facing upward would be the best position for the sensor, the trials for Pose 1 were replicated using the Mahony filter:

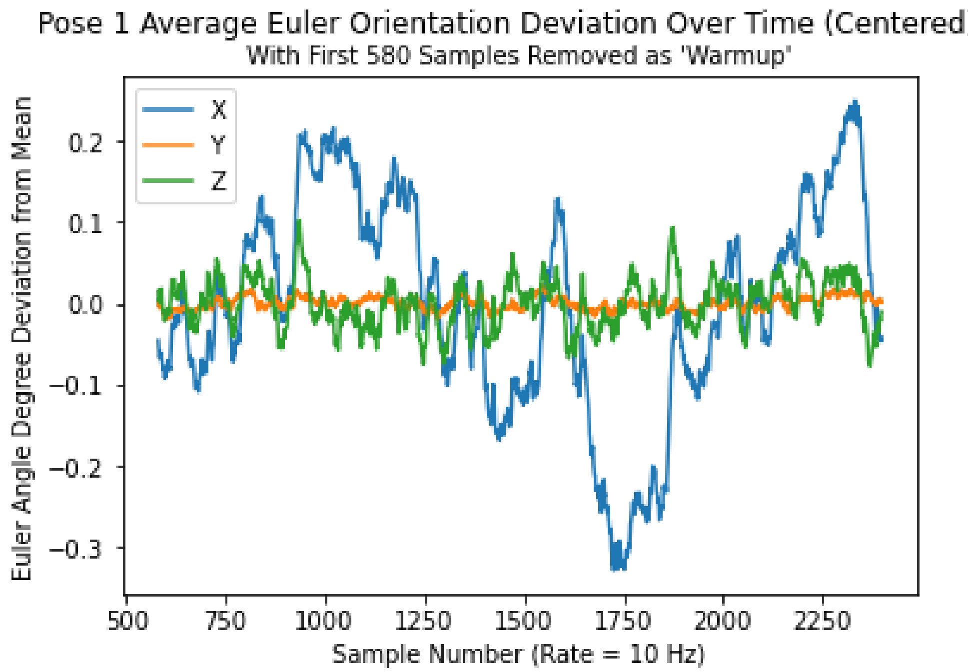

Figure X: *Average Pose 1 Deviation over Time with Mahony Filter*

The results of the average absolute deviation for Pose 1 comparing the two filters is shown in tabulated form here:

Table 3.2. Average Absolute Deviation for Pose 1

Filter	Axis	Average Absolute Deviation (degrees)
Madgwick	X	0.2157
	Y	0.0054
	Z	0.0361
Mahony	X	0.1063
	Y	0.0064
	Z	0.0246

Based on the analysis above, we see that the average absolute deviation is best for Madgwick in the Y axis, but better for Mahony in the X and Z axes. From the results, it was decided that the best course of action was to implement a design in which the IMU starts off in Pose 1 (X-axis facing upward) and uses the Mahony filter for orientation estimation.

3D Orientation Estimation and Alignment Actuation

Three dimensional orientation estimation is calculated based on IMU inputs using both Madgwick and Mahony methods as stated above. The results from static testing revealed comparable performance in the Y axis for both Madgwick and Mahony filters, but significantly increased performance in the X axis using the Mahony filter. For this reason, the Mahony filter was used for orientation angle estimation in all interactions of the system.

The final software design takes in the X and Y axis orientation of the orientation object via reading from the IMU and moves the servo motors in accordance with the relative change in orientation. This is done in the ButtonAlignmentRelative2D code. The structure of the code is as follows.

Variables

- Servo servoX: Servo motor object representing the x axis servo motor (outer ring of attachment)
- Servo servoY: Servo motor object representing the y axis servo motor (inner ring of attachment)
- Adafruit_Mahony filter: Mahony orientation filter object from the Adafruit AHRS library
- Adafruit_sensor *accelerometer, *gyroscope, *magnetometer: pointers to each of the accelerometer, gyroscope, and magnetometer objects predefined in the Adafruit AHRS library
- Int FILTER_UPDATE_RATE_HZ: rate at which the sensor location is updated
- Int stateButton: the current state of the button, 1 if pressed, 0 if not pressed.
- float roll, pitch: the current roll and pitch readings from the IMU sensor
- float startroll, startpitch: the imu roll and pitch readings directly before the button is pressed
- float diffX, diffY: the difference between the current orientation and the orientation immediately before the button was pressed
- float posX, posY: the current orientation of each servo motor
- float new_posX, new_posY: the intended new position of each servo motor

Functions

- Float limitpos(float input):
  Given an inputted float, caps the possible returned value between the ranges of 10 - 170. If the input falls outside this range the high or low number will be returned.
- Void setup():
  Attaches each servo motor object to the correct respective pin on the microcontroller, sets up IMU sensors, and assigns button state to listen to the correct pin on the microcontroller.
- Void loop():

Feeds accelerometer, gyroscope, and magnetometer data into the Mahony filter object. Calls filter.getRoll() and filter.getPitch() function to assign orientation values. Checks if button is actively being pressed. If pressed, determines the change in orientation since the beginning of the button press and moves the servo motors accordingly. If not pressed, updates the pre-button press orientation object values.

4 Results

4A Overall Accuracy

To test the overall accuracy of the system, we conducted trials in which we would use our 2D Relative Alignment code to move the retractor to different angles. We then collected the readings from the IMU, and measured the angle positioned by physical attachment with geometry to determine the overall accuracy of the system. In our series we reached a mean accuracy of:

Table 4.1. Mean Absolute Errors in Each Axis of Overall System

Axis	**Mean Absolute Error (Degrees)**
X-Axis (Outer Servo)	3.50211
Y-Axis (Inner Servo)	2.17714

In order to measure the performance of the physical attachment, a laser pointer was secured to the end effector to indicate the overall orientation angle of the device. Graph paper was positioned under the device to mark the location of the laser. With this setup, we calculated the height of the physical attachment from the table at position X = 0° Y = 0° (approximately constant height even with rotations) as well as marking the position of the laser at this orientation. The physical attachment was then moved via our alignment code. After alignment was complete, the readouts from the IMU were recorded as well as the change in position on the graph paper in the X and Y axes. The initial height of the retractor and the change in position of one of the axes makes up the sides of a right triangle. Using trigonometric properties, the angle in both the X and Y axis were calculated and then compared to the IMU readings in the table above.

4B Surgeon Feedback

The first round of surgeon feedback received was on button step control - one pair of buttons controls the heading and one pair of buttons controls the pitch. The prototype was attached to the Leyla surgical snake arm and placed over a skull model with a mock craniotomy or skull fenestration (Fig. 4.1). The initial prototype had a hole in place of the retractor so that a long object such as a stick could be inserted for better visualization of motion. After controlling the motion of the prototype with rotations about both x and y axes, our surgeon approved the resolution of the movements; however, according to him, the movements were too jerky.

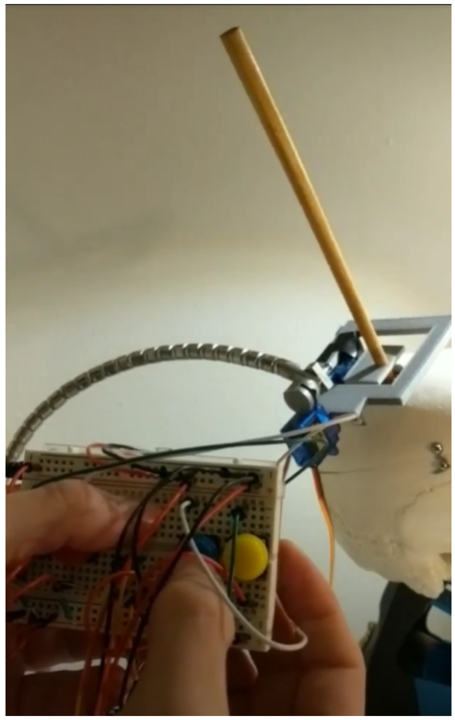

Figure 4.1. *First prototype demonstration.*

The second round of feedback was given after demonstration of our Synchronous Control. The calibration object was used in its proper fashion; however, due to some difficulties with calibration, the initial offset caused the origin orientation of the calibration object to be tilted with respect to the retractor. However, the relative synchronization was still functional and our surgeon's feedback was positive. Tilt offset was fixed and more precise control was implemented for the third round of surgeon feedback; Dr. Fouda's reaction was, once again, positive, making this the **surgeon's preferred method of alignment.** Dr. Fouda was asked to rate the overall usability based on a rubric in the categories of intuitive control (rated 4/4), precision of position selection (rated 3/4), minimizing procedure interruption (rated 4/4), and ease in mastering technique (rated 3/4). The rubric is shown in the Appendix.

4C Usability Assessment

Usability was assessed using the synchronous control method only. This was decided based on surgeon feedback from Dr. Fouda. While meeting with him, he said that synchronous control would be the most suitable for clinical use.

To test usability of the system, participants were enlisted to complete trials with our system. Each participant was given brief instruction on the system controls and allowed a single practice run in which they were instructed to trace a preprinted circle. Their performance was then measured by recording the location of the laser pointer at select points sampled around the circle. The root mean squared error of the subjects tracing was calculated with measurements to the closest 0.5 mm.

The mean distance from the circle over all participants and sampled points was calculated to be: 2.6667 ± 1.6560 mm

Although not directly measured through our trials, there was clearly a trend that performance improved with the time a participant had to practice with the device.

Once participants completed their circle tracing trial, each was asked to select how intuitive the usability of the system was using the same scale as shown in the Appendix, but only with the "Intuitive Control" category. All participants in our study selected 4 on the usability rubric, suggesting extremely intuitive control, and reinforcing the idea that for a surgeon who is used to applications in brain surgery will likely find this even more intuitive than a regular participant.

5 Progress Evaluation

5A Dependencies

The only dependencies that presented issues for us throughout the course of development were the 3D printer and the Hardware (Arduino, IMUs, wires).

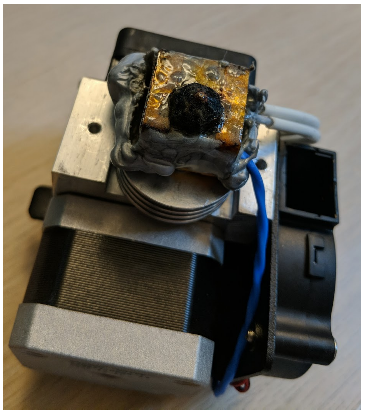

Figure 5.1. *Poor printing platform adherence led to filament oozing over the nozzle; during excess filament removal, undetermined damage was caused, but the printer manufacturers recommended a new motherboard.*

The 3D printer designated for this project experienced several malfunctions throughout the semester, and a secondary printer had to be located. The consequence of this contingency was that our initial prints and those used for testing in this report had to be printed at a lower resolution than intended. However, the secondary printer was still reliable and was available for constant iteration. This printer had a problem as well later on involving a broken temperature sensing system (Fig. 5.1), causing the need for a new motherboard that could only be purchased overseas, delaying its printing capability past the final project deadline. Thus, a tertiary external printing service had to be located, and was not a source that was available for consistent reliable iteration.

As for the ordered hardware, we did not need to rely on the contingency plan, but the orders were delayed which pushed back some of our deliverables making some of the maximum deliverables not achievable.

As a result of delayed coordination with the Johns Hopkins Hospital, we did not have the chance to perform testing with surgical tools so the need for that dependency never arose.

Dependency	**Need**	**Status**	**Followup**	**Contingency Plan**	**Deadline**
Leyla Retractor	Base for robot	Acquired	Put in Request through Dr. Cohen	Have a partially functional Leyla	2/28 Complete
3D Printer	Manufacturing	Acquired	N/A	If broken, look to use one owned by school	2/1 Complete
Arduinos and Motors	Robot Design and Data Collection	Acquired	Purchase ASAP, CortiTech budget	If breaks, need to purchase more ASAP (Also have extras)	2/24 - Ordered 3/15 - Complete
9 DoF IMUs, wires, breadboard, and USB port	Robot Design and Data Collection	Acquired	Purchase ASAP, CortiTech budget	If breaks, need to purchase more ASAP (Also have extras)	2/24 - Ordered 3/15 - Complete
Space Benchtop models	Testing	Preliminary models acquired	Request from CortiTech later if need better models	Will test for movement without brain model	4/5
3D Printer Films	Robot Design	Need to Request ASAP, but using a different printer	Request from CortiTech later if need more film	Right now we are going to be using a friend's 3D printer while we wait for more film	3/31
Surgical Tools	Retrofitting forceps and Testing	Need to Request ASAP	Request from Dr. Cohen or Dr. Fouda	Request from Cortitech	4/20

5B Adherence to deliverables

See above section 1C for a complete list of the project deliverables that will be referenced in this section.

All of the minimum deliverables listed in Section 1C were completed on time. A report documenting the results of the minimum deliverable is available on our course website.

All of the expected deliverables listed in Section 1C were completed on time. This report documents the results of the expected deliverables.

Due to the unforeseen issues with production involving the breaking of our main 3D printer, and our shipments being delayed, some of the maximum deliverables were unable to reached in the timeline of this semester, but there are plans for future work on these deliverables by Mark and the rest of the CortiTech team.

There was progress made with respect to the Maximum Deliverable:

- Safety features to limit velocity, maximum angle, and prevent shaky movements from surgeons.

We implemented certain features to restrict the maximum angle which the physical attachment can move, however additional work must be done to better refine the maximum angle. Speed limiting was implemented, but only on one motor axis as opposed to our double axis gimbal structure. However, this design was approved by our surgeon and has thus been shown to be of use and a worthwhile future endeavor.

5C Management Summary

Caroline and Robby were responsible for the software, while Mark was responsible for the mechanical design. More specifically, the responsibilities for each person are listed here:

Caroline:
- Sensor Calibration
- Coordinate Based Motor Movement
- Relative Alignment Software
- Usability Testing
- Overall System Testing

- Deliverable Reports

Robby:

- Sensor Calibration
- Orientation Estimation Software
- Static Testing
- Alignment based off of Orientation
- Relative Alignment Software
- Usability Testing
- Overall System Testing

Mark:

- Design (CAD) and manufacturing of the physical attachment (including actuation)
- Design (CAD) and manufacturing of the calibration object
- Button Step Control implementation
- Surgeon Feedback

6 Conclusion

6A Discussion

Overall, we are happy with the progress made and greater implications of our system on the future of robot assisted retractor positioning. Our system design includes intuitive controls that have been proven to allow the user precision within 3mm after incredibly brief training. We received largely positive feedback from our surgical mentors, indicating the potential for our system to be useful in the future after additional iterations of engineering.

While we believe the current error in angle actuation is passable for our purposes, we would prefer to have each axis show error below 1 degree. Upgrading the hardware to more advanced motor and localization systems may allow for much greater precision, minimizing error between the commanding motion and the motor movement. This may also contribute to greater smoothness of motion and speed control, which is difficult to control using inexpensive servo motors.

6B Next Steps

There were several features which were implemented or designed towards the end of the semester, and as a result, we did not have time to verify and validate the designs with proper testing. We have included the partial results of these advancements in this section.

<u>Future Mechanical Design</u>

A new iteration of the physical attachment setup was designed to improve upon our current design. The design was created in CAD, but due to manufacturing constraints mentioned in our Dependencies section (5A), the design was not able to be printed and tested. As part of our next steps, we will be printing and testing this new model.

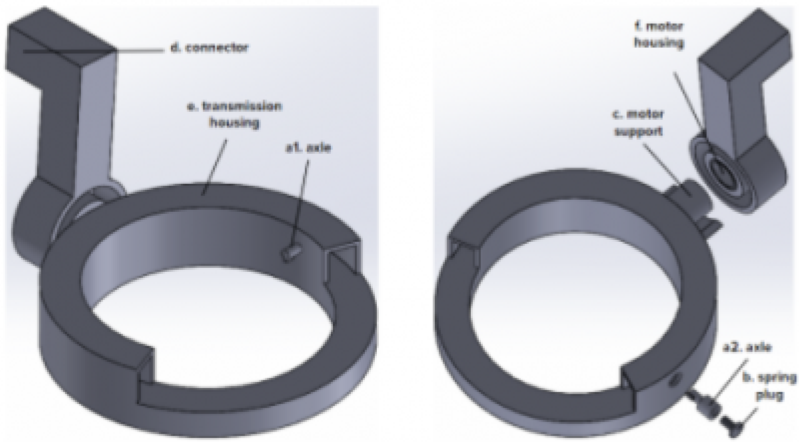

Figure 8. Mechanical Design CAD.
The retractor will be inserted into the ring, with which its circular cross-section will be concentric.

Figure 6.1. *CAD Model of Future Physical Attachment. The retractor will be inserted into the ring with which its circular cross-section will be concentric.*

An issue that did arise with servo motors was the jerky control experienced that could lead to extra brain damage. Because the basic version of software compatibility of the servos used did not include speed control, plans were made to switch to DC motors with encoders for closed-loop control.

<u>Maximum Deliverable: Alternate Method of Control</u>

Another method of control was implemented in which a joystick was used to control the pitch and heading of the retractor. This method gives the surgeon an option to direct a visual object (the joystick itself) in the desired direction in which the retractor would point, granting more intuitive control over the angle and direction of the central axis of the retractor as compared to button control. However, the drawback is that the exact ending position of the retractor under this form of control is not easily predicted as this requires good hand-eye coordination. To implement this, x and y deviations of the joystick from the center were read in as analog Arduino values, then converted to servo angles. Brief surgeon feedback included a recommendation to slow down retractor motion corresponding to joystick angulation. Due to time constraints, there was not sufficient time to properly test and evaluate this method of alignment. Next steps include laser-point testing of aiming the retractor towards the desired location.

Maximum Deliverable: Limited speed with Derivative and Proportional control

One last method of control that was implemented was manual control with force limiting. In this method, the surgeon can manipulate the positioning of the retractor by pushing on the inner walls of the retractor with the surgical tool, providing haptic feedback for the surgeon. To limit the speed to ensure slow and smooth movements, protecting the wellbeing of the patients, a DC motor was used to apply increasing resistance to the motor proportional to the speed of the motor. Closed-loop control of the system was achieved through optical encoders.

A proposed method for future calibration of speed control was outlined and planned, but not completed due to time constraints. These steps include walking surgeon through proportional and derivative gain tuning until comfort zone is reached (specifics omitted), testing forces at which tool presses on retractor within this comfort zone, and implementing future control based on maximum force. Force testing will be performed in benchtop brain models with our clinical advisor Dr. Fouda. There are several issues with the current setup that may inhibit the trials involving the mismatch of shapes of the sensor and retractor that still need to be worked out. Figuring out these issues and conducting proper tests with Dr. Fouda are part of our next steps.

Continuation of Project

The system along with all code and documentation will be provided to our sponsor, CortiTech for the project to be continued. Mark is a part of the CoritTech prototyping team and will be working on this effort. Fully completing the partial implementations listed above will be the immediate priority of the prototyping team. After this is complete, we plan to begin retrofitting an IMU onto a pair of surgical forceps to replace the calibration object and simulate a more realistic surgery setting. We also plan to try incorporating the operation of our device through the lens of a surgical microscope as was recommended by our clinical advisor, Dr. Fouda, after seeing our device. Lastly, we will look into implementing a PID controller to improve the accuracy of our overall system.

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Appendix

Overall Usability Rubric

Category	4	3	2	1
Intuitive Control	The system is incredibly intuitive to control, and takes nearly no time for new users to navigate successfully. Movements can be made smoothly and effectively.	The system is overall intuitive and takes little time for a new user to navigate. Smooth movements come after quick learning.	The system is not intuitive but can be learned after a period of adjustment. After some time, movements are somewhat smooth but not perfect.	The use of the system is not intuitive, and is difficult to control for even the intermediate user. Movements are sharp and unpredictable.
Precision of Position Selection	The surgeon is able to achieve positioning with the desired level or precision without any problem. Small and precise movement can be achieved.	Overall precise movement can be achieved but with small flaws in accuracy.	The desired positioning can be achieved but movement is often imprecise.	The system shows little effectiveness in achieving a desired position, and can only go within inches of the desired orientation.
Minimizing Procedure Interruption	The system feels as though it can likely be used without shifting view from surgical microscope. creates no interruptions in surgical workflow	System takes slight attention away from surgical workflow but can be used with minimal distraction.	System takes the surgeon's view away from the surgical microscope, but can quickly be reestablished with short interruption to procedure.	The system is disruptive to procedures and requires complete focus, drawing the surgeon away fully from the surgical field.
Ease in Mastering Technique	Surgeon feels comfortable operating system with a few minutes of training before use.	Surgeon would feel comfortable operating system with several test runs before use.	Surgeon would only feel comfortable operating system with multiple extensive training sessions, but learning is overall achievable.	Mastering system controls is nearly impossible. Desired result is not dependent on skill, but on chance.