CIS II Team 3: Robotic Assistant for MRI-Guided Low Back Pain Injections

CIS II Project #3 Final Report

EN.601.496/656: Computer Integrated Surgery II

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1. Introduction

1.1 Background and Relevance/Motivation

Lumbar Spinal Injection is a method to deliver pain-relieving medications locally to the site of the pain source. It is typically performed in the lower back and pelvis area and requires the targeting of sub-millimeter nerves, small muscular compartments, and thin anatomic spaces. This procedure is conducted to treat lower back pain and perform nerve root injections, facet joint injection and epidural injection to treat and relieve pain caused by different aliments.

In 2020, an estimated 619 million people worldwide suffered from low back pain, making it the leading cause of disability globally. By 2050, the number of people affected is projected to rise to 843 million, a 36.4% increase, driven mainly by population growth and aging, especially in Asia and Africa. The global age-standardized prevalence rate in 2020 was 7.5% . Low back pain maintains its position as the top contributor to disability worldwide. Prevalence increases with age, peaking at 85 years. Women are more affected than men in all age groups. Regions with the highest prevalence rates are Central Europe (12.8%), Eastern Europe (11.2%), and Australasia (11.1%), while the lowest prevalence rates are found in East Asia (5.2%).

An average of 92 thousand lumbar punctures (LP) are performed annually between the year 2010 to 2018[2]. Radiologists hold the largest share of 45.7% of annually of lumbar punctures. A preliminary survey from 2015 shows that more than 40% of the patients have experienced anxiety and pain during this procedure [3]. The current methodology LP has the radiologist, initially perform the procedure without any imaging guiding, utilizing their understanding of the human anatomy. This leads to more than 45% of the patients requiring more than 3 attempts for a successful LP procedure for a viable and understandable result. After which over 10 % of the patients required X-ray guided LP due to the initial failure. The repetitive failure rate is sure to cause frustration for both the radiologist and the patient. While X-ray guided LP has a higher successful rate this is not logistically feasible due to the large number of patients and the healthy radiations limits that radiologists are required to maintain.

1.2 Significance

Looking at the logistical constraints of X-ray based LP surgeries and the estimated increase in lower back pain which would require Spinal injections, it would be great incentive to find an alternative method of imaging that would provide a greater resolution and actively updated the position of the needle without exposing the surgeon to radiation. It would also be ideal to address this issue by building a robot that is able to repeat this procedure repeatably and effectively. One of the current imaging technologies that would satisfy this condition would be MRI imaging. While it satisfies all the required conditions, it also places a few major constraints, such as the workspace limitations of the robot and, hence, the overall size of the robot. It also limits the materials used in the robot. Hence, each individual component utilized in the robot must remain MRI compliant. For example, the usage of a traditional motor itself is a constraint; the manufactured robot must not contain metal.

	Item	Specifications
4-DOF Needle Alignment Robot	Workspace	Medial/Lateral: ± 40 mm Superior/Inferior: ± 30 mm
	Position accuracy	<1 mm. (Needle tip in free space)
	Orientation (Rx, Ry)	±30°
	Angular accuracy	±1°
1-DOF Needle Driver	Insertion Depth	115 mm
	Insertion Accuracy	0.5 mm
Robotic Assistant	MRI compatibility	MR-Conditional
	Weight	1.5 kg
	DOFs	5

Table 1: Robot Technical Specifications

The next step would be to design a robot that matches all the specifications mentioned in Table 1. Hence, the final goal is to design a 5 Degree of Freedom robot that matches MRI space constraints while having the ability to accommodate a variety of patient sizes. The robot should be able to have a virtual Remote center of motion.

1.3 Prior Work & Project Goals

Our team builds upon the robot F.L.I.M.P.Y (Five DOF Lumbar Injection MRI Compatible System), which addressed the recent exploration of body-mounted systems with the goal of minimizing the robot's footprint and weight.

Our team has three main goals, namely, to evaluate robot transmission and needle tip accuracy. We would also like to develop the software suite required for motion tracking and testing. The next step would be to redesign the robot harness to allow for safer mounting of the patient. It should also accommodate various patient sizes while allowing for quick detachment of the robot for safety purposes. The mounting should also be such that the robot can reach the targeted workspace. The next goal would be the overall rigidity of the robot by possibly increasing the rigidity of the members of each robot linkage.

2. Technical Approach

2.1 System Workflow

The system workflow can be broken down into three separate sectors that all depend on one another to achieve the desired results and satisfy the goals stated previously. These separate sectors are software interface, mechanical design, and robot accuracy. The team started with a working robot the year prior. The team utilized the working robot, optical trackers and dial indicators, and Galil to test the accuracy and repeatability of the existing robot's ability to function and accurately reach the locations it is executed to reach. The team also had independent tasks that did not require support outside their skillsets, such as profile analysis, 3D slicer integration, and development of a lower body mount.

2.2 Motor Accuracy Testing

One of the teams' first steps in pursuit of accomplishing their goals is to first test the accuracy of the actuation subassembly and ensure that the motors and limit switches are bringing the robot to the correct positions via Galil. The team will test their motors first by their homing capabilities as well as their accuracy of its movement. The students intend to test these attributes by using a Noga BG61003 Magnetic Base Dial and Test Indicator Holder. This has allowed them to have readings at the micron level, record the data from multiple repetitions of a singular movement, and analyze their results. The students will then use all analysis and error determined at the motor to determine the end effector; this is discussed later in the optical tracking section. However, to understand where error may be stemming from, this information can prove to be crucial.

2.3 Robot Workspace Testing

The students need to verify that the robot is able to navigate within the maximum reachable area that is determined by their forward kinematics. By ensuring that the robot is able to operate in which the area that is defined, the team can validate that the whole mechanism has the barebones it needs to succeed. The team verified the robot's workspace by developing their own testing script in Galil that will maneuver the robot within a grid contained in the workspace. The team repeated this process multiple times while collecting data on its accuracy, the data being found from the optical trackers that will be discussed in further detail later.

2.5 Lower Body Mount Configuration and Integration

One item of high priority for this project was to develop a means to fasten the robot on the body of a human that is appropriate for low back pain injections. For the area of the lower back that the needle would need to be injected within, determining how to fasten the robot onto a person proved to be a more complex task than anticipated. The robot had to be fastened above the glutes as opposed to the back due to how a person is routinely positioned on an MRI table for these procedures. However, the robot couldn't be physically apart from the human as certain factors would demand a solution of that sort to be too demanding, such as the size of the person's glutes, breathing during the procedure, and dimensional constraints of the MRI machine itself. Therefore, the students developed a harness-like design to attach the robot to the body, by utilizing a fiducial ring and connector that runs between said ring and the baseplate of the robot, the team was able to successfully design a lower-body mount. However, testing was not able to take place, and further investigation must be done to deem their design to be under working conditions.

2.6 End Effector Relation to Motor Accuracy

As mentioned earlier, one motivation to testing, recording, and analyzing the robot's accuracy is to determine its end effector relationship via motor capabilities in moving the sliders down the lead screws. For instance, how does even a micron error on one of the motors in the actuation subassembly affect the ultimate end effector? This is a critical value the team determined as it allows for a better understanding of the robots to even attain less than a 1mm error at the needle tip. The students found their motors to have 0.07mm error at the accuracy, well below the insertion error bounds at the motor level, proving that this system can operate well within the constraints established, and further testing could take place. If the motors alone were not able to precisely control the slider to operate within 1mm accuracy, then the students would know that the system's design was flawed and a better design would have to be investigated.

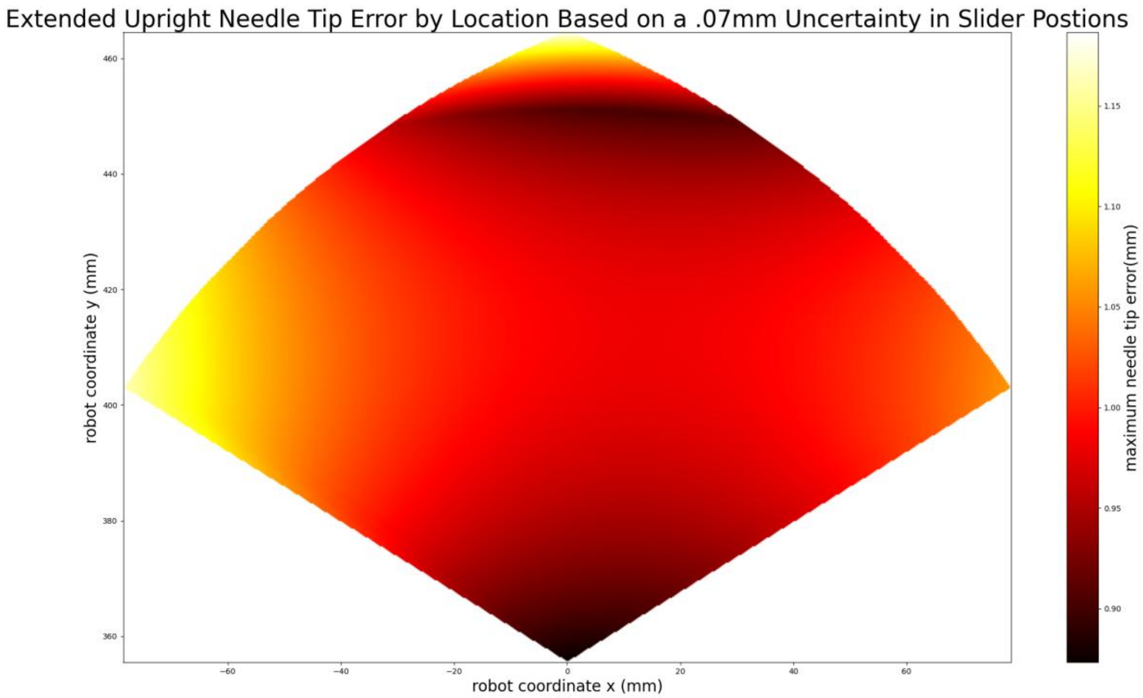

Figure 1: Robot Linkage Kinematic Workspace

2.7 3D Slicer

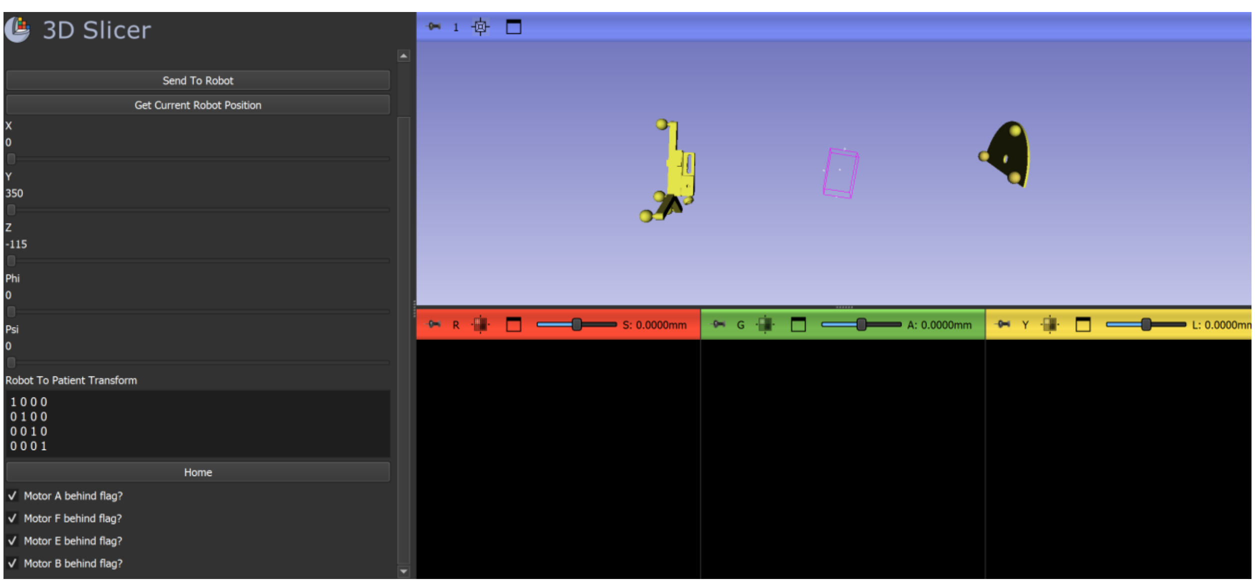

Figure 2: 3D Slicer UI Prototype

The 3D Slicer GUI was not completed due to delays in data collection because of robot debugging. The basic UI and interface have been specified. There will be communication with the control program that gets the active position of the needle. The UI will also be able to send commands to the robot based on the approach specified by the slicer UI. The angles represent a rotating around a remote center of motion using two angles, phi: the angle from the up axis, and psi: the angle from the forward axis. Using these two angles, we define an approach to the specified point. This code is already implemented on the control side.

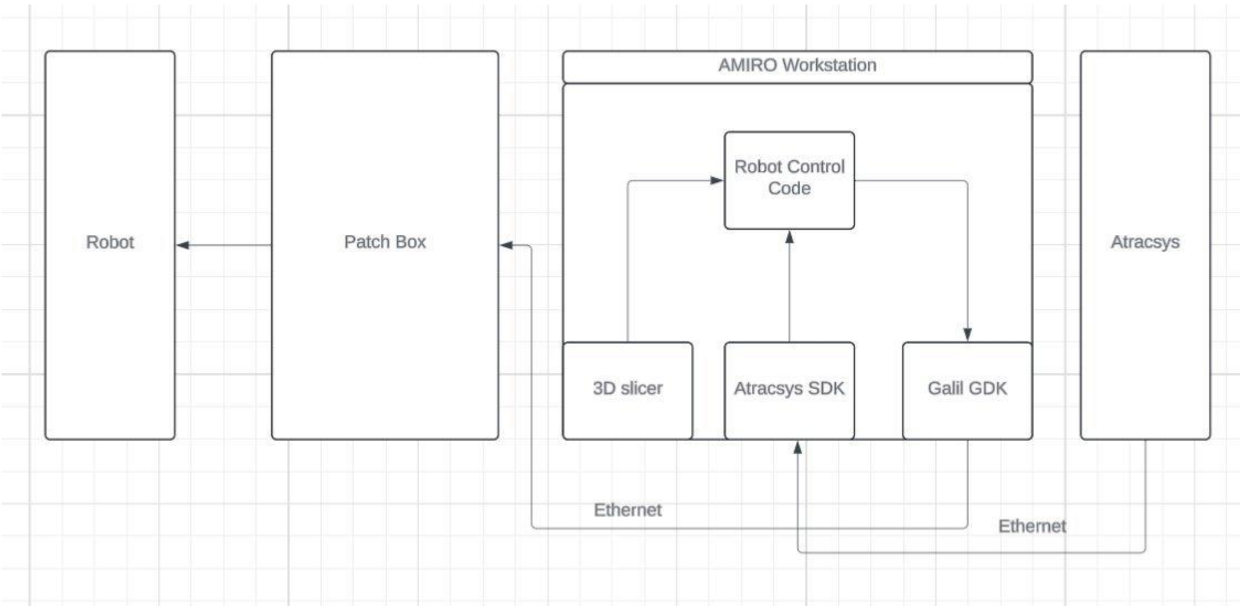

Figure 3: Software Architecture

The Atracsys SDK and the Galil GDK have been linked, but the 3D slicer UI has not been linked as planned.

2.8 Kinematics

The kinematics are fully detailed in the kinematics report section of the wiki page. Our robot has a two layered architecture with each layer having two degrees of freedom on the x-y plane. When the two layers are connected to a needle, the line formed by extending the vector from the end effector of the top layer to the end effector of the bottom layer forms a line determining the approach for the needle to take. This gives four degrees of freedom, plus the 5^{th}, needle driving degree (insertion depth).

Here is a brief labeling of core values used in the linkage kinematics:

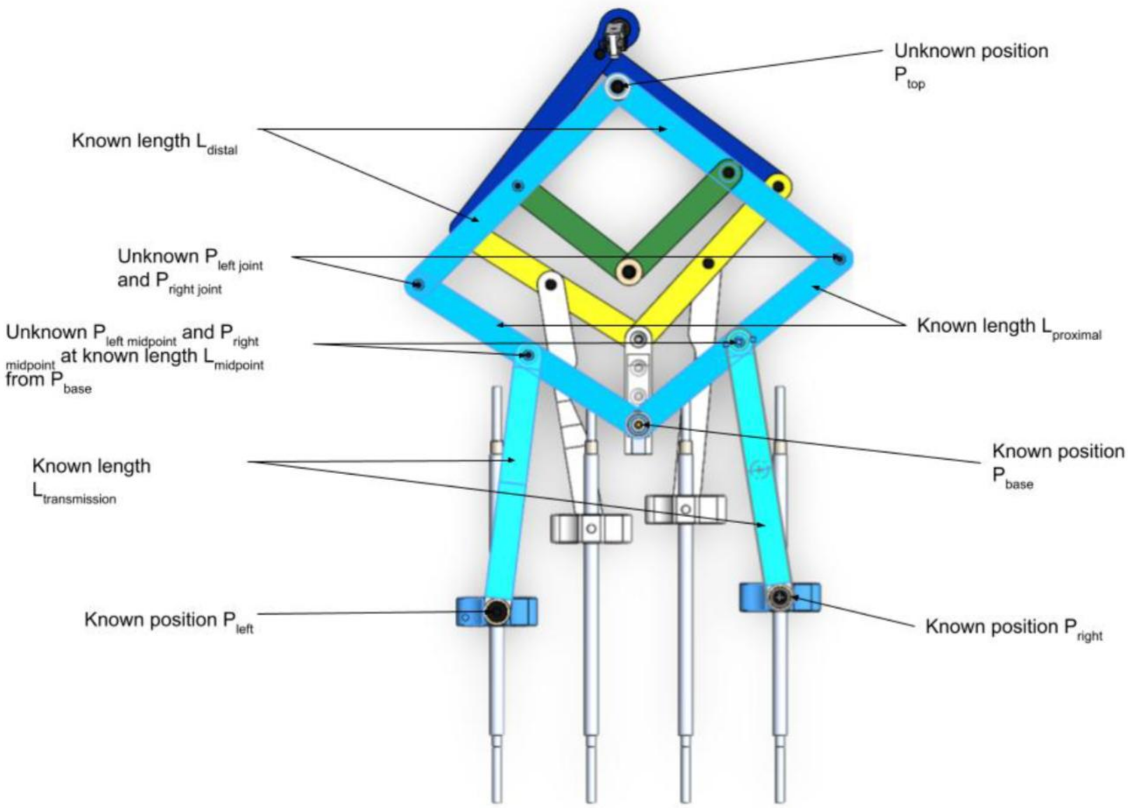

Figure 4: Robot Linkage Kinematic Labels

These are the points necessary for determining the end effector position.

2.9 Optical Tracking and Workspace Testing

First, here is the experimental setup:

Figure 4: Experimental Setup

The Robot is secured to the table. The Atracsys optical Tracking system is mounted on a Tripod. There are two optical markers attached to the robot linkages, giving data on relative motions.

The lower linkage optical marker used a pivot calibration to determine its relationship to the lower linkage. The resulting vector of the pivot calibration was determined to have an error magnitude of +/-.011mm.

The optical Tracker has an accuracy of 0.17 mm with a 95% Confidence interval up to 2.0 meters [4].

2.10 Improving Rigidity of Robot

2.10.1 Carbon Fiber Members

The robot initially was manufactured using PLA linkages, while this was sufficient for proof of concept, we required a more rigid robot to address the restoring forces experienced by the robot while performing needle insertion. The whole robot can be treated as a cantilever beam, and each member is a simple cantilever, which in a series-parallel combination accounting for the rigidity of the robot. Now, improving the rigidity of each beam would allow for an overall increase in the rigidity of the robot. Without changing the kinematic linkage and workspace, improving the rigidity of the robot is possible by changing the material of the robot's members.

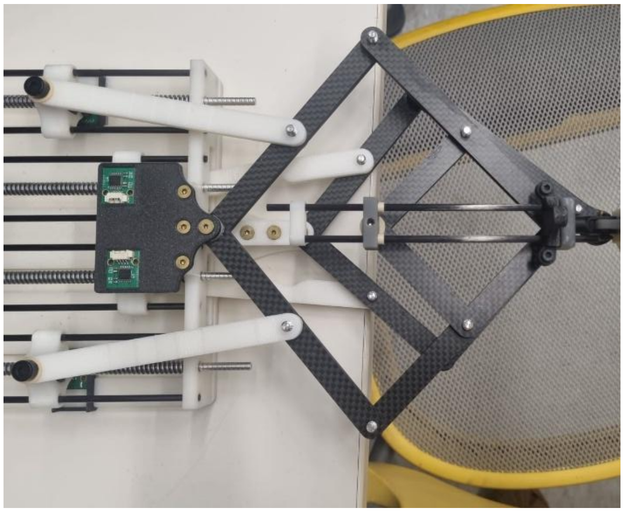

Figure 5:Carbon Fiber Robot Linkages

While this would improve the overall rigidity of the robot, Carbon fiber(Figure 6)is known to be MR conditional rather than MR compatible. Carbon fiber might have possible heating effects in an MRI field.

2.10.2 Redesigned PLA and ABS-based robot members

A simple FEA analysis on 6 mm and 5 mm thick carbon fiber linkages for a 5 N loading condition provides the following results.

Carbon Fiber Thickness	Deflection under 5 N Loading (micron)
5 mm	30
6 mm	15

Table 2:FEA Results for Carbon FIber

Addressing the MR compatibility issues of Carbon fiber, it was decided to design some 3D printable profile members using PLA and ABS that would reach the same stiffness as that of carbon fiber without changing the kinematics or the overall robot workspace.

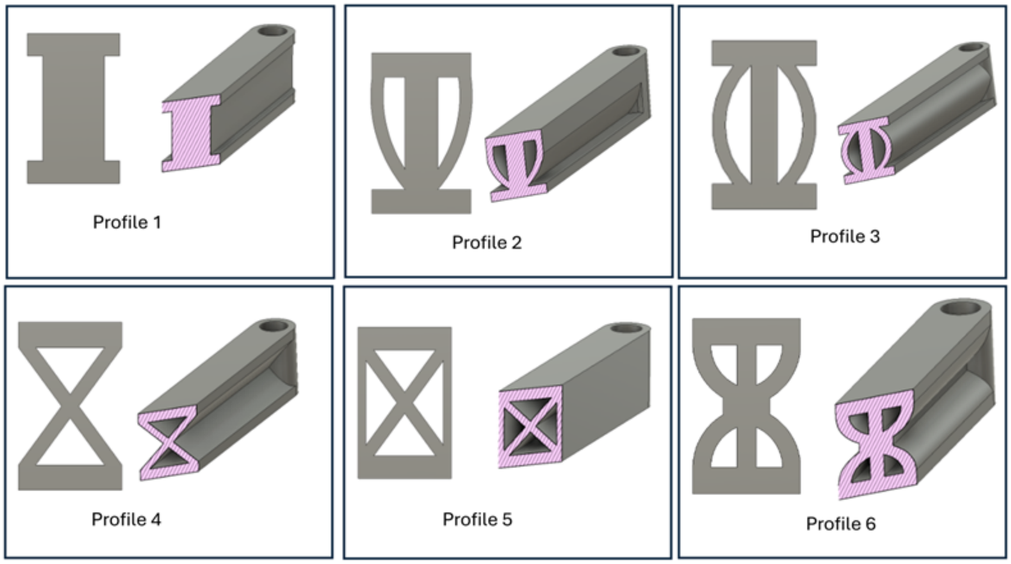

Table 3: Various Beam Profiles

To determine which profile is ideal, a fixed height and width were considered to keep the parameters constant for comparison. The ideal profile is one with the highest second moment of inertia and least self-weight. When each profile was compared with this ratio, as shown in Table 4, we noticed that the I-beam profile is the most optimal one. The material used for this simulation was ABS and under 5N loading similar to a cantilever beam.

Profile	Second Moment of Inertia	Weight (kg)	Ratio (Inertia:Weight)	Deflection under 5 N (mm)
	1.55E-8	1.82E-5	8.52E-4	1.1E-4
	1.68E-8	1.76E-5	9.54E-4	1.12E-4
	1.62E-8	1.7E-5	9.53E-4	1.13E-4
	1.40E-8	1.38E-5	10.01E-4	1.3E-4
	1.59E-8	1.62E-5	9.9E-4	1.2E-4
	1.64E-8	1.73E-5	9.5E-4	1.13E-4

Table 4: Comparison of various beam profiles

The goal was to design linkage profiles that would give you around twice the rigidity of 5 mm-thick carbon fiber members. From this FEA analysis, we understand that the I-beam is the ideal beam profile. For a given width and height, the I beam can further be optimized. This is achieved by understanding the various parameters controlling the dimensions of an I beam(Figure 7). The strongest theoretical I-beam is one where the web thickness is zero. This is not practically feasible; hence, to ensure fixed web thickness material, the ratio of web height to web thickness is governed by the AISC code to ensure there is enough material to withstand the loading conditions. This is given by the formulation:

$$\frac{h}{tw} \leq 3.76\sqrt{\frac{E}{F_y}}$$

Where:

h: Web height E: Young's Modulus

Tw: Web Thickness   Fy: Yield Strength.

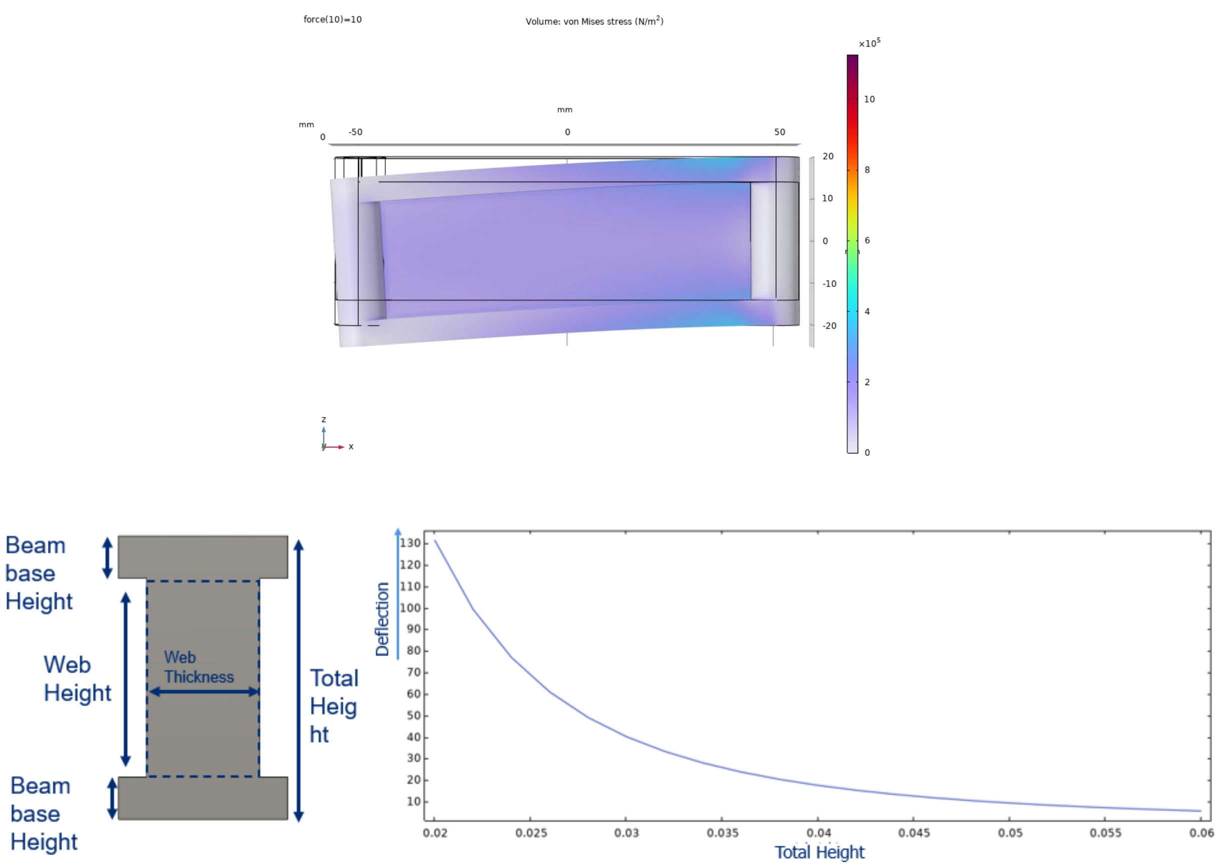

Figure 7: I-Beam FEA result(Top), I- Beam parameter(Bottom Left), Deflection vs Total Height(Bottom RIght)

Looking at the FEA analysis, deflection vs total height, we find that an I beam with the parameters given in Table 5.

Parameter	Dimension (mm)
Total Height	48
Web Height	33.6
Web Thickness	4.2
Beam Base Height	7.2

Table 5: Ideal I-beam Parameters

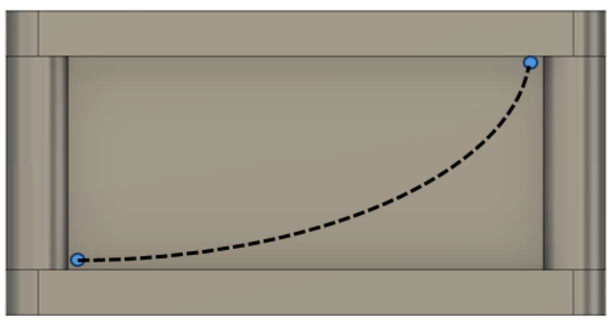

Figure 7: The curve along which the I-beam was further optimized

To further optimize the I-beam profile, we fixed the height of the profile at 48mm and t hen further varied the curvature. It was ensured that the curve was varied according to a second-order equation. Finally, Figure 7 shows that the profile managed to reach the same deflection as the Carbon fiber. While it reached the required rigidity, it only allowed for a 2% weight reduction, which is not significant.

3. Results

3.1 Optical Tracking Results

We conducted Five Optical tracking experiments:

3.1.1. **Workspace Coverage test**

This test brought the robot to every position on the upright grid, confirming its theoretical range.

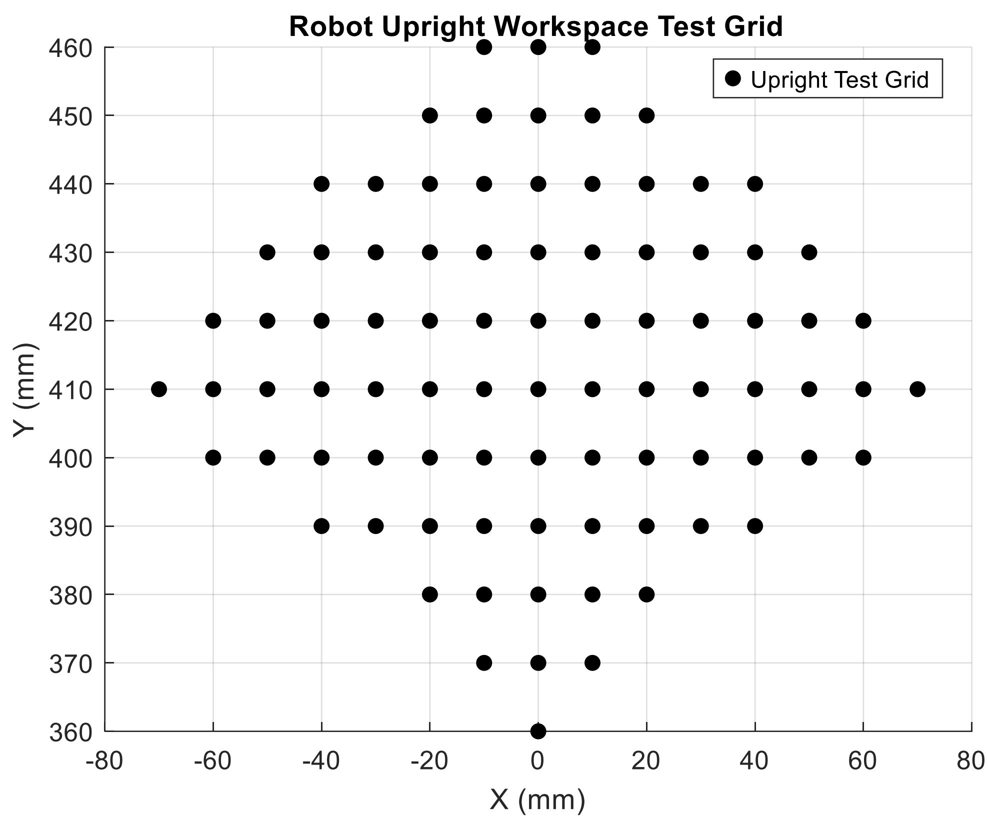

Figure 8: Workspace Grid

2.9.2 Y Direction Accuracy Test

For the next four tests, accuracy is determined as a distance from the home position. For positions, it is measured distance - expected distance. For angles it is arccos(expected z axis ● measured z axis). This works because this is the axis of the needle, and therefore the relevant one to measure angular error in.

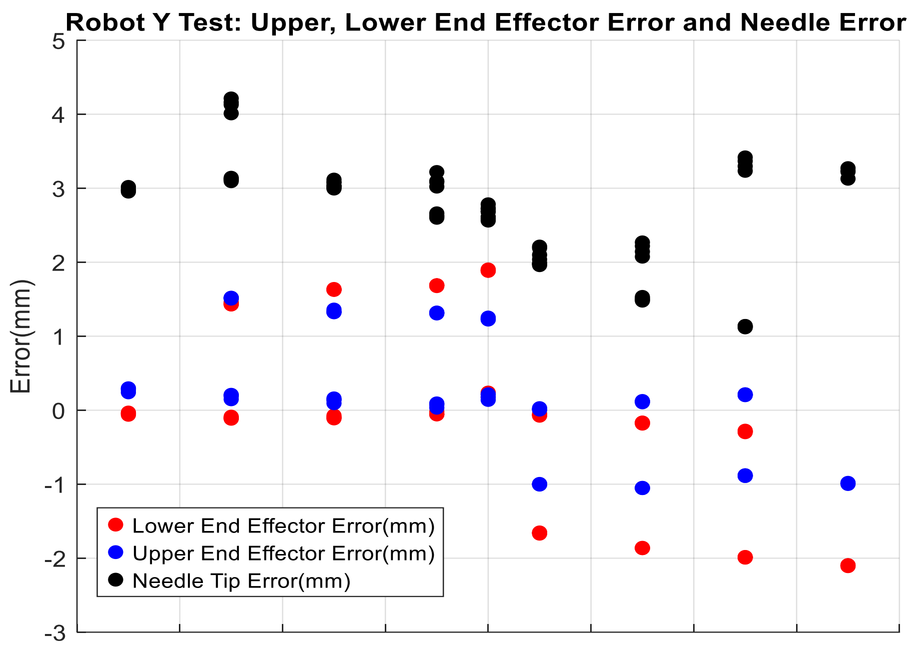

Figure 9: Y Test Graph

The Y accuracy test went 5, 15, 25, and 35 mm from home in both directions. Going back and forth to those increments. Home was taken as (0, 410). The lower end effector errors were as follows. The backwards (-y direction) motions were taken without backlash and the forwards (+y direction) motions had backlash. Backwards motions had an average error of 0.125+/-0.015mm. Forwards Motions had an error of 1.782+/-0-036. The upper end effector errors are as follows. The non-backlash error averaged 0.147+/-0.015mm. The backlash error averaged 1.166+/-0.037mm.

3.1.3 X Direction Accuracy Test

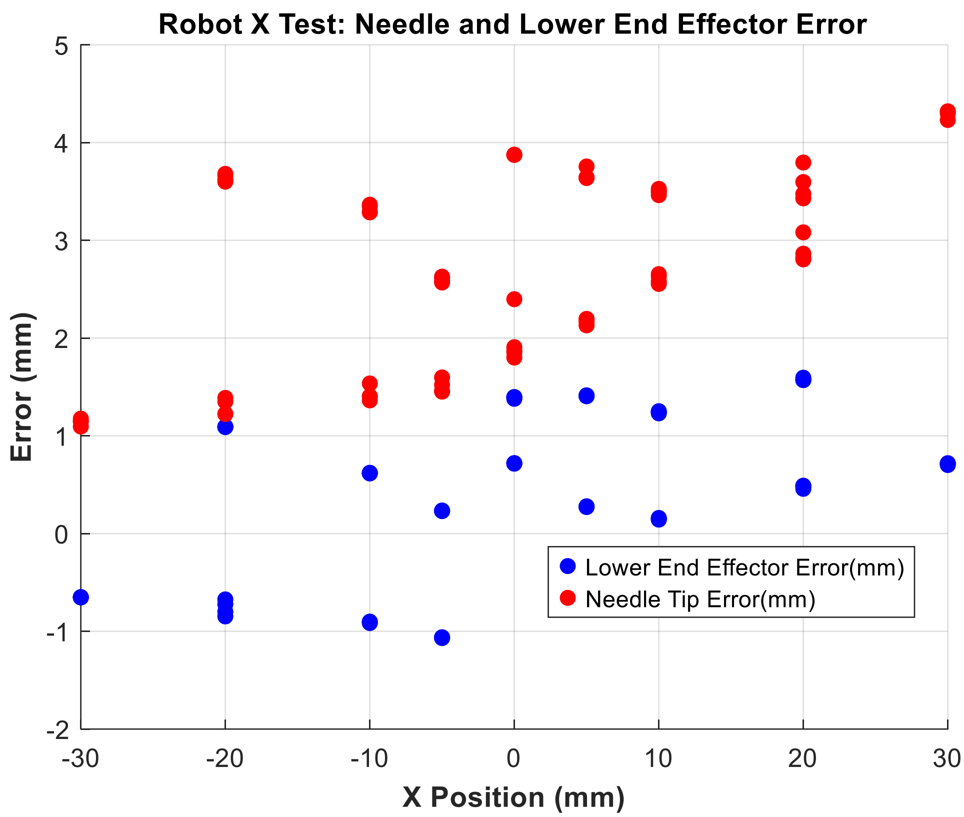

Figure 10: X Test Graph

The X axis test was conducted by moving the lower end effector in a horizontal line 5, 10, 20, and 30mm away from the center line in both directions.

Average Lower End Effector Error Magnitude: 0.832+/-0.055mm

Average Needle Tip Error Magnitude: 2.687+/-0.127mm

3.1.4 Pitch and Yaw Tests

For this test, the needle was rotated with +/- 0. 5, 10, and 15 degrees of angulation around a remote center of motion in the center of the workspace. Yaw had higher errors. These were likely because the motors were spinning in opposite directions. We also see backlash as a factor in our error here, causing the separation in the data. Our highest recorded angular error was an undershot of 3.02 degrees. This is well above our < 1 degree requirement.

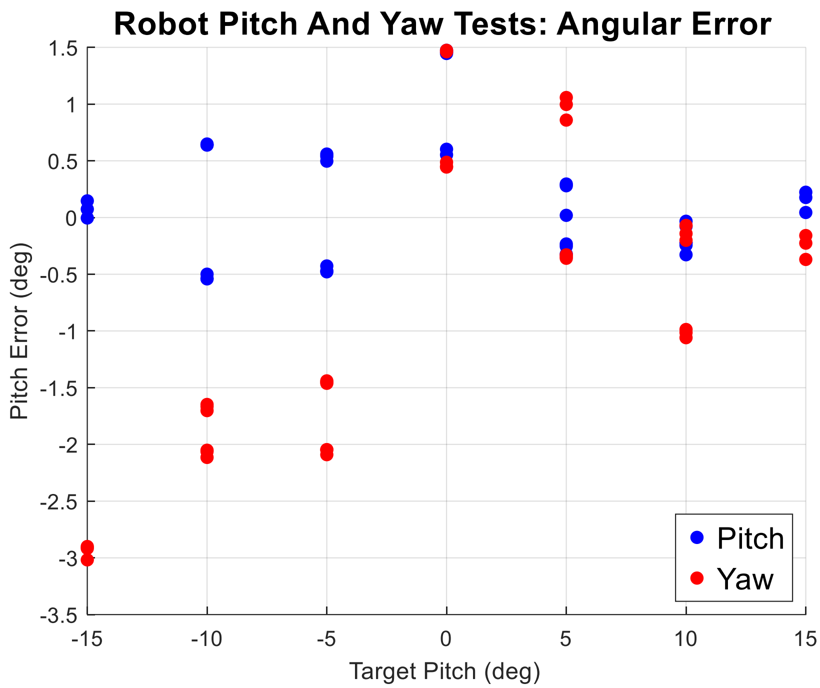

Figure 61: Pitch and Yaw Test Graph

3.3 Bending Test

We performed a bending test by mounting the profiles according to the test setup in Figure 12. We tested the 6 mm carbon fiber profile and each of the printed profiles by loading them to 5, 10, and 15 N of force. To ensure that we were getting the proper bending moment, the member was weighed across 8 equidistant points and their deflection was measured at the free end.

We found that the 3D printed profile managed to match the carbon fiber profiles, like how FEA had predicted. While the deflection of the 3D printed profile and Carbon fiber matched the expected outcome, the values didn't match with the FEA model. Upon further investigation, it was identified that there is a stark difference between the Young's modulus provided by the data sheets and the true Young's modulus found through experimentation. Adjusting the FEA model with the experimentally found Young's modulus showed deflection similar to the bending test.

Figure 12: Pitch and Yaw Test Graph

The Young's modulus found in carbon fiber, according to the datasheet, was 240 GPa, and under 10 N of loading, the expected deflection was around 60 microns for a 6 mm-thick carbon fiber member. The deflection was close to 300 microns. This matches with the FEA results, when the Young's modulus of Carbon fiber is 45 GPa, and the experimentally calculated Young's modulus is 45 GPa.

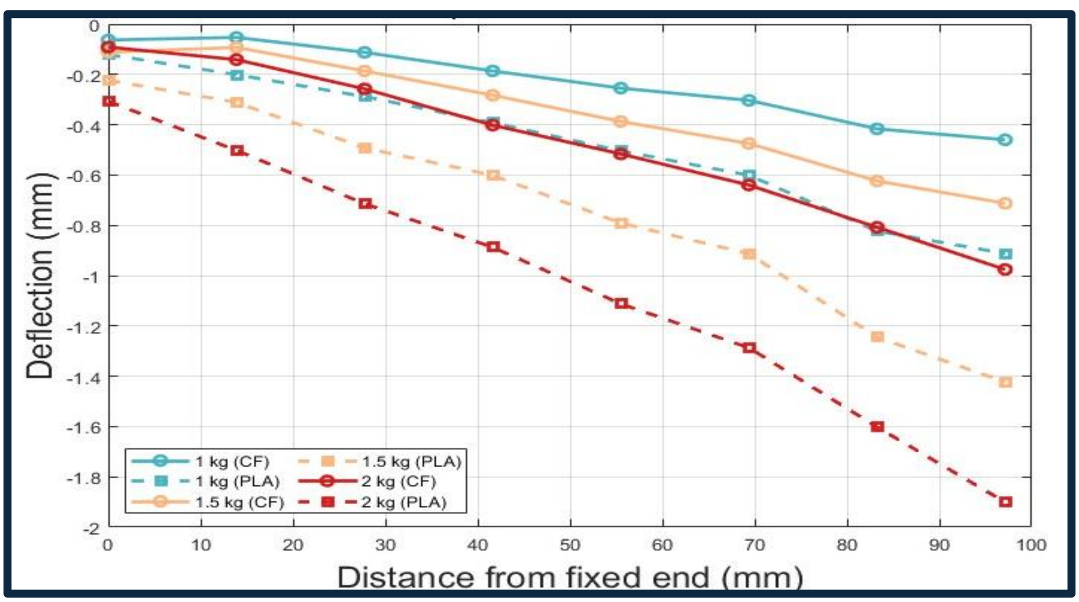

Figure 13: Pitch and Yaw Test Graph

3.4 Setbacks

The team had a substantial number of delays in their ability to collect data due to circumstances that weren't predictable. The main issue they faced was with their robot. The students faced issues with their motors, encoders, and wiring. Additionally, some issues were also faced when it came to software. Considering this robot was picked up from the year prior, it's understandable that things were knocked around or information was not properly translated over. This resulted in hour-long sessions of debugging that pushed back many of the deliverables that the students wished to accomplish.

3.5 Next Steps

The students, considering their setbacks, would like to ensure that all information is translated to the team that picks up this project next. This includes creating comprehensive documentation regarding their code, set-up, procedures, miscellaneous parts, etc. This documentation would include references to explicit tests conducted, photo and video demonstrations, a well-composed GitHub repository that details their scripts, procedures well-typed out, and any other additional piece that might be relevant to the project.

The robot must also integrate backlash compensation, kinematic compensation, and the new profiles to demonstrate improved accuracy in order to meet our targets.

4. Management Summary

4.1 Deliverables

The minimum deliverables for this project are:

- Evaluation of the working prototype on benchtop test. ☑
- 3D Slicer UI that displays the robot's pose and current configuration within the environment of a phantom lumbar spinal scan. ◍
- Comprehensive documentation for future research. ☑

Expected deliverables are:

- A robot for lumbar spinal injections that meets the workspace and accuracy requirements. ☑
- Modified optical encoder wiring/controller box patch panel such that it is functional and organized. ✖

- Real time tracking with fiducials so that the robot's pose relative to the patient is known. ☑
- A mount that can secure the system on a patient. ☑
- A GUI to implement path planning so the surgeon can view paths from multiple angles, with integrated 3D registration and patient scan data (robot to phantom registration, and lumbar spinal phantom scan). ◍

The maximum deliverables are:

- An advanced experimental evaluation of robotic system on lumbar spinal phantom (targeting experiments for an IEEE 6-page conference paper). ✖
- An MR-compatible robot. ☑
- A concept of design for 6DOF Robot (+1DOF in the needle driver). ✖
- A redesigned robot if the mechanism if targets are not met in testing. ☑
- Integrated MRI tracking markers so that the robot can be tracked in an MRI machine. ◍
- Software safety features like a software adjusted approach or automatic stopping if the patient moves. ◍

The team has utilized a green check, yellow circle, and red "x" to signify completed, in progress, and will not complete, respectively. Though the team is upset that not all expected deliverables were met, the team had previously decided, with advice from their mentor, to remove the modified optical encoder deliverable. The team is pleased with their progress on their maximum deliverables. The team wishes they could've done the IEEE 6-page maximum deliverable the most but due to many errors with the robot has malfunctions and setbacks.

4.3 Individual Responsibilities

The team has decided to split up the tasks of the project per individual's skill set. The team intends to be informed on everyone's progress and current work as well as help troubleshoot any issues that may arise during the semester. Sai worked on finite element analysis (FEA) simulation to determine new profiles. Tyler was the lead on all software-related items such as development, documentation, and interfacing. Tyler also operated the optical tracker and designed all testing procedures. Diana oversaw all CAD related items, was the main lead to help debug robot malfunction related to operation, motors, encoders, etc. Diana also worked on developing a lower body mount for the robot to be fastened onto, assisted with the optical tracker, and was the main lead for data analysis and documentation.

4.4 Communication Platforms & Meetings

For communication, the team will have a few different avenues on how they plan to discuss project items with one another. For general communication amongst the entire time, including both mentors, the team decided to use email, this was reserved for critical updates or additional meeting times. To communicate on day-to-day activities or updates, the team would text amongst one another and often with their mentor, Aabhas. Lastly, for all file sharing or import data that needed to be shared, the team would use teams. Teams were also the main platform for all filesharing. In terms of meeting times, the team had bi-weekly meetings with the entire team on Fridays at 1pm in Dr. Iordachita's office. Diana and Tyler also met weekly in the second half of the semester to discuss optical tracker items. Aabhas would also routinely meet with the team, minimum of 3-4x a week most weeks. The team would attempt their hardest to meet at least once a week with one another.

5. Technical Appendices

5.2 References

[1]https://www.who.int/news-room/fact-sheets/detail/low-back-pain

[2] Trunz LM, Gandhi AV, Karambelkar AD, Lange SM, Rao VM, Flanders AE. National Trends in Lumbar Puncture from 2010 to 2018: A Shift Reversal from the Emergency Department to the Hospital Setting for Radiologists and Advanced Practice Providers. AJNR Am J Neuroradiol. 2021 Jan;42(1):206-210. doi: 10.3174/ajnr.A6870. Epub 2020 Nov 12. PMID: 33184070; PMCID: PMC7814782.

[3] Scotton WJ, Mollan SP, Walters T, et al. Characterising the patient experience of diagnostic lumbar puncture in idiopathic intracranial hypertension: a cross-sectional online survey. BMJ Open. 2018;8(5):e020445. Published 2018 May 30. doi:10.1136/bmjopen-2017-020445

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