EN.530.721 MRSD
Lab 9: Soft Robot Catheter Final Project

Adithya R N, Manyu Garg, Rahul Kalpana Anwardeen, Sai Pranav Avva

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1 Project Ideas

1.1 Adithya: Navigation of Coronary Arteries

A key inefficiency in current interventional procedures for coronary arteries stems from existing catheter devices. This is due to severe limitations in terms of maneuverability. These devices are designed with fixed preset bending angles, such as 45°, 90°, or 120°, and these devices are capable of bending in a singular direction. This restrictive design is a major cause for procedural delay. This is because it requires repeatedly re-orienting the catheter to navigate through complex and variable anatomical spaces.

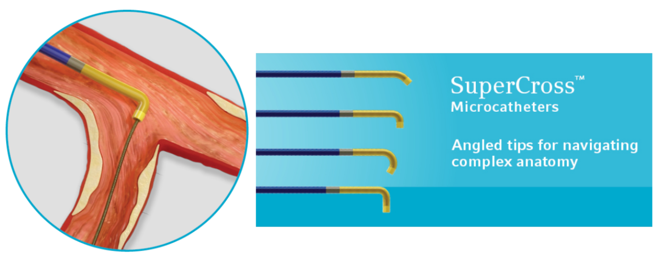

Figure 1: Existing fixed preset catheters

The proposed solution is to use a flexible catheter in place of the existing one. This would allow for improved traversability of the catheter within complex arterial environments due to its ability to bend in multiple directions. This allows it to assume variable, non fixed angles, and thus conform to the patient's unique anatomy.

1.2 Manyu: Designing a Robot for Lung Biopsy

Needle biopsy is one of the most common approaches for performing lung biopsy and is relatively one of the least invasive approaches. However, the procedure requires a needle to be inserted through the skin and then into the lung while navigating through the ribs. Due to this, the process carries potentially serious risks, such as hemorrhage or a collapsed lung.

The proposed solution is the development of a robotic system designed for safer and more precise navigation. It would involve extending a soft robot catheter, with the help of a flexible tube, to facilitate guided navigation directly to the tumor site. Another central component of the project is to employ a learning technique to train the soft robot, enabling it to navigate the complex pulmonary anatomy accurately and safely and reach the tumor.

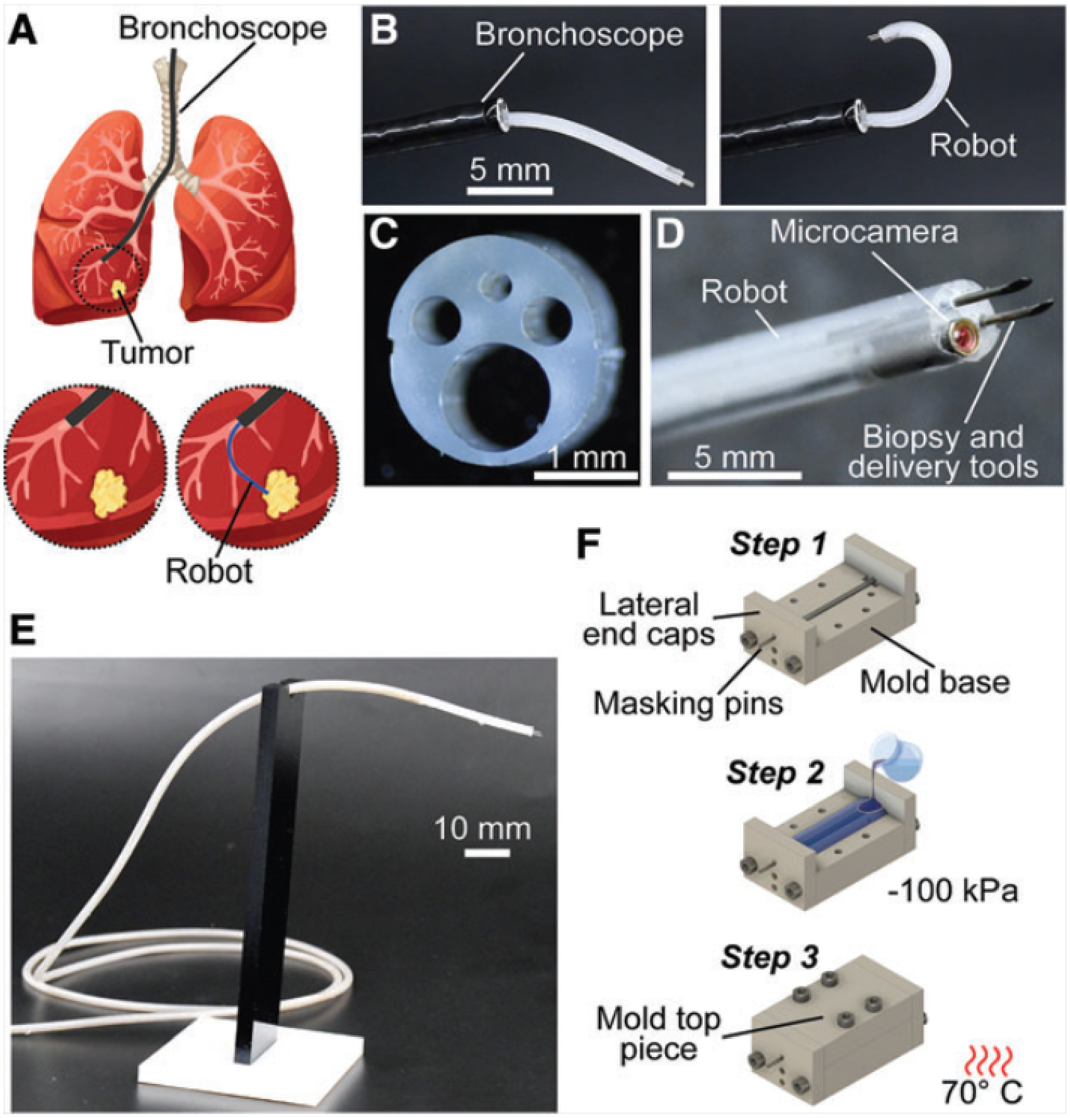

Figure 2: Soft robot for Peripheral Lung Cancer Diagnosis (Image taken from paper)

1.3 Rahul: Anesthesia Delivery in the Eye for Extended Surgery Durations

A substantial amount of manual effort is required to maintain effective local anesthesia during lengthy ophthalmic procedures. Moreover, once the procedure goes beyond the typical duration, to maintain continuous supply of local anesthesia, it is delivered by a flexible catheter. But this demands constant attention of both the surgeon and the anesthesiologist, who have to place, hold, and feed the catheter to ensure constant injection.

Figure 3: Local Anesthesia Delivery in the Eye

The proposed solution combines a UR5 with a catheter. The UR5 would ensure accurate, fixed, and stable overall positioning of the catheter, while the flexible catheter would leverage its own control to navigate and precisely deliver the anesthetic directly to the sight.

1.4 Sai Pranav: Laser Treatment for Tumor Resection

There is a key geometric and mechanical constraint in the existing robotic mitral valve surgery. It is that the possible regions for inserting the robotic arm into the patient's chest are strictly limited by the mechanical Remote Center of Mass (RCM) of the robotic arm. This reduces the surgical access points and restricts accessibility.

The proposed solution involves attaching specialized surgical tool tips not directly to the robotic arm, but to the end of a flexible catheter. This simple modification allows the entire system to be inserted from a wider range of areas, thus expanding available surgical access points for the robotic arms.

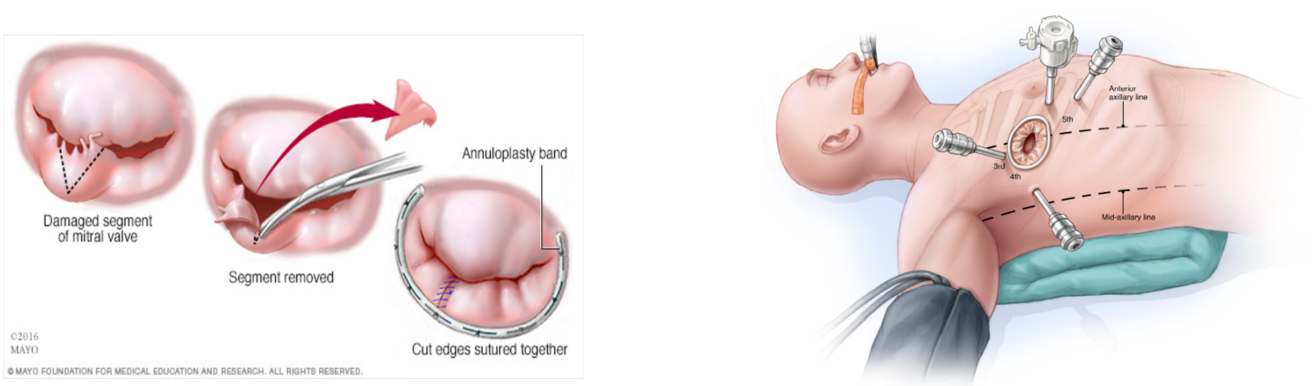

Figure 4: Representative Image of Mitral Valve Surgery

2 Project Selection

Based on the rough ideas for each project mentioned in the previous section:

- The anesthesia delivery project for extended eye surgery felt like it would need extensive coordination between the UR5 and the flexible systems, making a demonstration difficult within the given time.
- The coronary artery navigation proposal, while an interesting project to pursue, would require extensive setup and validation data, to show variable angle bending and bidirectional control.
- The mitral valve surgery project had a lot of potential to address the RCM constraints, but would require integrating tool tips with the flexible catheter, and then demonstrating the surgical task execution. This made the problem a little more complex and with the given time, it would be difficult to produce a tangible result.

Considering the timeline and the skill set of the group members, the decision was made to develop a proof-of-concept for a lung biopsy soft robot.

3 Project Implementation

3.1 High Level Specifications

- Improve control of the soft robot through both software and hardware means.
- Increase range of current soft catheter robot

3.2 Low Level Specification

- Develop a data-driven method to model and control the robot
- Design and build enclosure to ensure ideal and repeatable conditions for data collection.
- Introduce additional rotational and translational stages to the robot

4 Enclosure

The design of the enclosure was inspired by the working principle of surgical lights that utilize sparsely placed LED's with over-lapping sections utilizing the principle of shadow dilution.

In the design of the enclosure we went with LED strips to achieve the effect of multiple light sources and to have parallel light beams. We placed a few overhead lights on the top of the enclosure with sufficient distance from the camera mounting point to ensure that there is no apparent glare.

There are a set of lights evenly placed along the 4 sides of the enclosure, this is to ensure that there is even light across the overall length of the enclosure.This also helps to ensure that there are no dark regions present in the enclosure.

Finally, there are three sets of lights, one facing top down, one from across the bottom edge of the enclosure, and finally one pointing towards the top of the enclosure. This prevents overcast shadows from being caused by the overhead lighting. The surfaces of the enclosure were roughened with sand paper to reduce the amount of reflections and reduce the reflective property of Prusament PLA Galaxy Silver, which was used to print the enclosure.

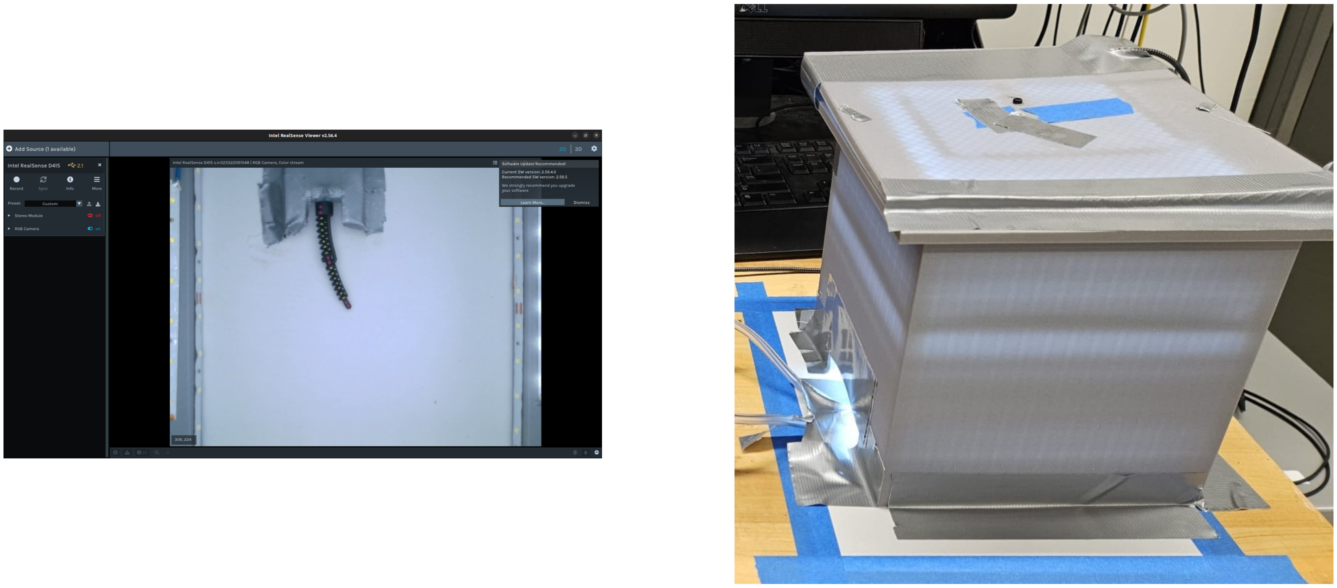

Figure 5: The internal and external view of the enclosure

5 Improving Range of Motion

Maxon combination motor 464703 was mounted on a Nema-17 driven linear stage. This allowed for the addition of translation and rotation to the soft catheter increasing the range of motion as shown in the images below and attached video:

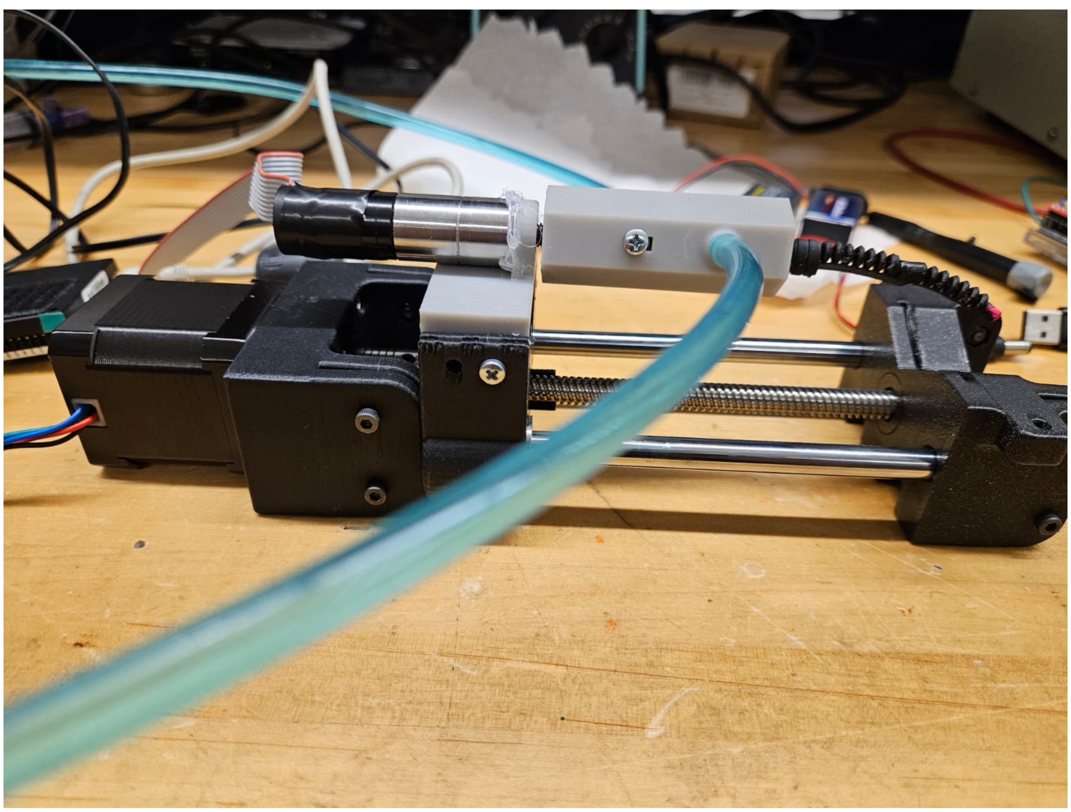

Figure 6: Setup for increased RoM

6 Neural-network based modelling

6.1 Overview

Soft robots are inherently non-linear and also exhibit hyseteresis, making their mathematical modelling particularly difficult. Data driven methods, particularly neural networks, provide a viable alternative for the understanding and prediction of system behavior. We focused on re-implementing the ”Hysteresis-Aware Neural Network Modeling and Whole-Body Reinforcement Learning Control of Soft Robots” paper by Z.Chen et. al. Their work focused on making the neural network aware of hysteresis, by adding change in pressure in each timestep as inputs to the neural network. Since we dont have pressure sensors in our current setup, the network was slightly simplified and adjusted. The inputs to the neural network consist of the pump displacements and their direction of movement. The outputs of the neural network consist of the 2 joint angles (base-waist and waist-tip). The parameters of the neural network are as follows:

6.2 Data Collection

In total, 2208 data samples were collected. The samples were a mix of smooth movement, as well as randomized motions. The randomized motions were added in to fully model the hysteresis behavior of the soft robot.

Table 1: Neural Network Hyperparameters and Configuration

Parameter	**Value/Setting**
Input Dimension	4
Output Dimension	2
Hidden Layers	4
Hidden Size (Neurons per Layer)	64
Activation Function	ReLU
Optimizer	Adam
Learning Rate	1×10^{-3}
Batch Size	64
Total Epochs	10,000
Training/Validation Split	0.9
Loss Function	Mean Squared Error (MSE)

7 Neural Network Prediction Error Analysis

A smooth test sample was collected and the neural network predictions was compared against the collected data. The output is seen below in Fig.7.

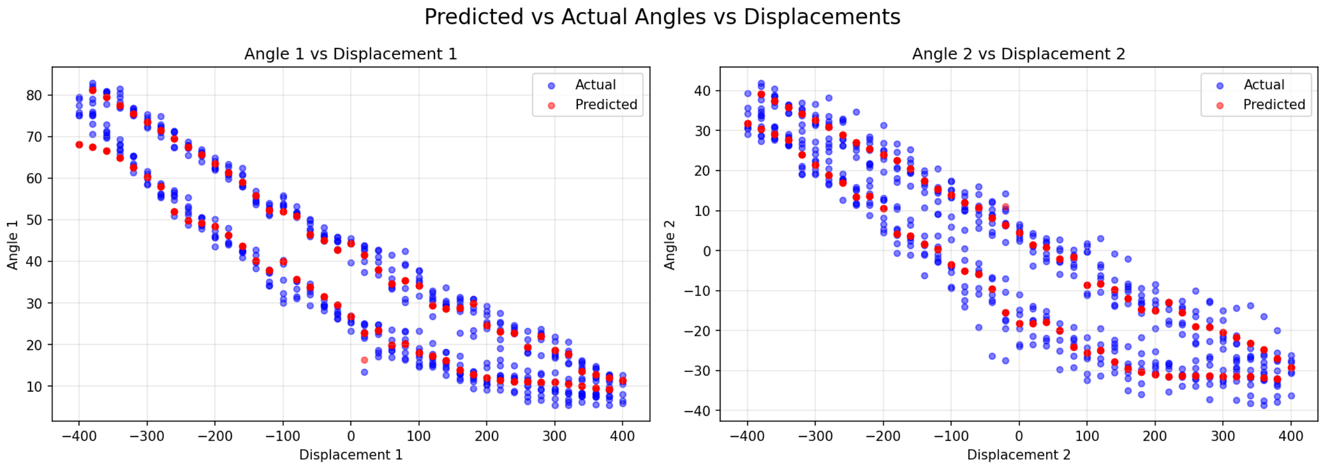

Figure 7: Predicted vs actual values

Table 2: Prediction error

Angle	Mean error (deg)	Std. Deviation (deg)
1	9.72	28.320587
2	15.418288	34.050037

Looking at the plot, we make the following observations

- The neural network does a good job of predicting the general smooth trajectory of the robot
- The neural network is able to model hysteresis accurately
- suggesting that the FK model sometimes **underestimates** the y-position more significantly.
- The high standard error mean and standard deviation is likely due to errors/noise in the camera tracking system

8 Results and observations

8.1 Results

Through the error analysis and the implementation, we have been successfully in showing a proof of concept of a 4 DoF catheter for lung biopsy application.

8.2 Observations

The following are our observations with respect to the sources of error:

- Temperature: We noticed that for the resin we have utilized to print the catheter, the data sheet specification mentions that as the ambient temperature drops below 10 degree Celsius, the elasticity decreases. This was also observed over the course of our tests, as the range of motion of the robot varied depending on the ambienttemperature.
- Syringe Piston Position: Another source of error was the lack of repeatability factor of the syringe, as the lack of an encoder never ensured the return of the syringe to the exact mentioned position, hence the error could easily accumulate over long operation durations.
- Maxon Motor Constraint: We noticed that the Maxon motor that was utilized did not have a large load bearing capacity. We reduced the payload weight by switching to a lighter tubing for the payload.

9 Future

From our observations, we believe these would be the next set of steps in the continued development of the robot:

- Currently, the robot does not utilize pressure sensors. Due to the uncertainity caused by compounding errors in the pneumatic system, we believe attaching pressure sensors to these systems would provide a more reliable method of system modelling.
- Integrating Model Predictive Path Integral Control (MPPI) or Model Predictive Control (MPC) for obstacle avoidance.