COMPUTER INTEGRATED SURGERY II
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# DaVinci-Assisted Continuum Robot Navigation and Manipulation System
## Final Report

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# Contents

# 1 Introduction

(a) (b)

Figure 1: Commercial surgical robots: (a) 6-DOF DaVinci surgical robots[1]. (b) Ion Inc.’s Endoluminal System which has a continuum robot end[2].

The DaVinci robot arm is a state-of-art surgical robot that offers 6-DOF translational and rotational joint control. Tendon-driven continuum robots, on the other hand, use flexible, curving structures to navigate tight spaces and perform delicate tasks (shown in Fig. 1). They have several advantages over traditional rigid robots, including improved accuracy, flexibility and reachability.

This project has wide application in surgical domains. Taking the lung biopsy as an example which previously need manual insertion of catheter by surgeons. After a continuum robot catheter was introduced to the lung biopsy field, ”the pulmonary nodule biopsy resulted in an 83% diagnostic yield, which represents the likelihood that tissue samples obtained during the procedure will provide physicians with information needed to establish a diagnosis.”[3]

Furthermore, our proposed robot system builds on these technologies by combining the accuracy, flexibility and reachability of the dVRK robot arm with the unique capabilities of a tendon-driven continuum robot end. By doing so, we aim to build a new design of dVRK and a corresponding navigation system that overcomes the limitations of traditional rigid robots and offers improved reachability in surgical robotics systems.

## 1.1 Background

As shown in Fig. 2, the inspiration for this project was drawn from the ION surgical robot, which has demonstrated the potential of flexible and accurate robotic catheter ends for minimally invasive solutions in lung biopsy[3]. With continuum robotic end such as ION, surgeons can access small lesions located deep within the lungs, which is made possible through distal tip articulation which helps target catheters to small areas outside of the airway. Preliminary studies have also shown a relatively low incidence of pneumothorax that requires medical intervention.[3]

As for the development of dVRK system, We aim to leverage the available resources of the DaVinci platform and dVRK resources at Johns Hopkins University[4], and will receive technical training from Anton Deguet in the Laboratory for Computational Sensing and Robotics (LCSR) to develop our

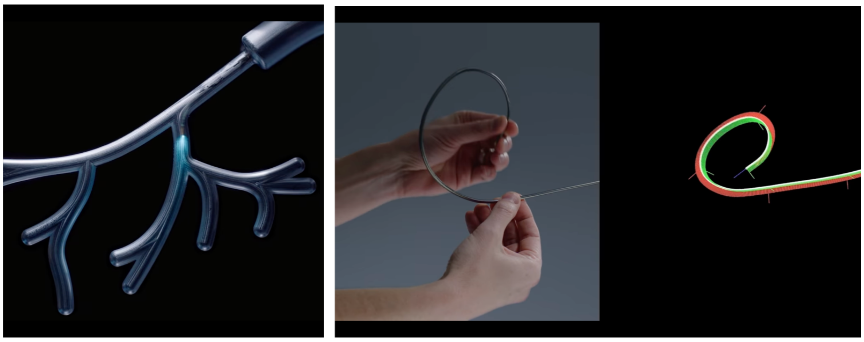

(a) (b)

Figure 2: Ion Inc.'s Endoluminal System[3].

navigation and manipulation algorithm.

Although there exists a good dynamic model of the tendon-driven catheter, the limited practical application of flexible catheters on the dVRK system has created a compelling opportunity for us to fully develop our project and expand the scope of flexible catheter applications in surgical robotics.

### 1.2 Goal

The primary goal of this project is to develop a continuum robot navigation and manipulation system that combines the advantages of accuracy and reachability of the dVRK robot arm and the unique flexibility of a tendon-driven continuum robot end. To achieve this goal, we will first generate a new design of dVRK with flexible endoscope, and then build a corresponding system of navigation and remote actuation, where we will re-identify the workflow of the continuum dVRK starting from `IO` and `PID`. Throughout the whole design and development procedures, we will especially focus on adapting various surgical catheters[5] to our continuum dVRK. The teleoperation between `ARM` and `MTM` is our highest expectation in the end.

### 1.3 Significance

As a comprehensive project with novel design, where we make our own continuum dVRK and build corresponding navigation system from the bottom. The project could lead further enhancement to dVRK platform.

The significance of our proposed system also lies in its potential impact on the field of surgical robotics. By offering better reachability and dexterity in delicate surgical procedures, our proposed DaVinci-assisted continuum robot navigation and manipulation system has the potential to improve surgical robotics and patient outcomes.

## 2 Technical Summaries

### 2.1 Workflow

In this section, the technical approach for developing a new continuum robot end effector for surgical applications will be presented. The proposed workflow consists of mechanical design, experimentation, computer integration, and potential applications, as shown in Figure 3.

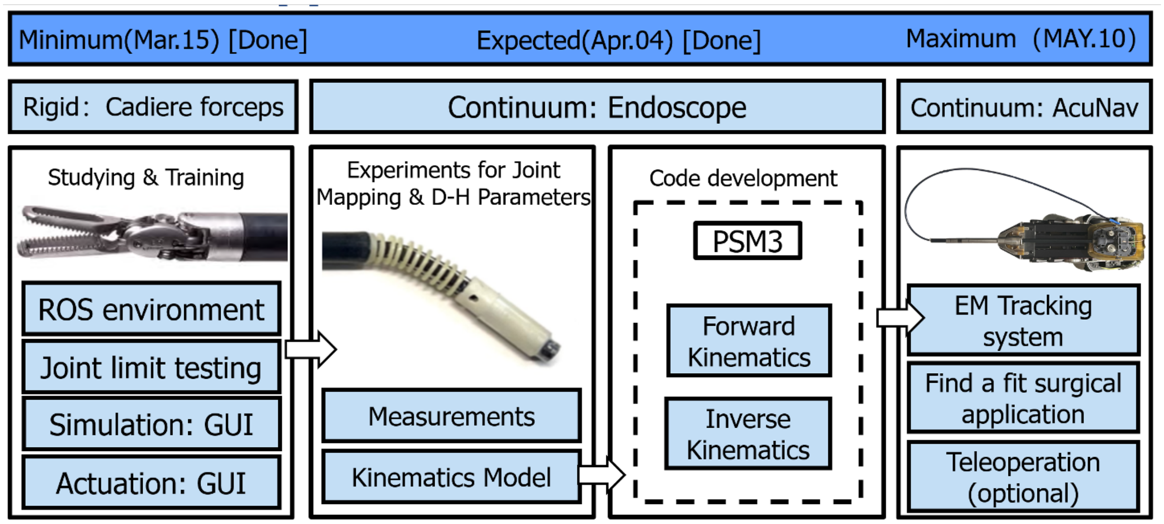


Figure 3: Basic workflow.

The first phase of the approach involves designing a new continuum robot end effector that incorporates the desirable characteristics of the available endoscope catheter and Acunav catheter. The team has compared the available actuators, mechanisms, and materials, and identify suitable components for the new end effector. In the end, we have designed a endoscope mechanism to assemble the Acunav catheter into the dvrk baseplate. Basic actuation on dvrk has also been achieved to ensure that the hardware design is functional.

The second phase of the approach involves conducting experiments to obtain the necessary results for identifying endoscope parameters using the DaVinci platform actuation. The team has applied NDI Aurora EM tracking system to the designed experiments. These experiments will provide the necessary data for the identification of the continuum endoscope and dVRK, such as remote center of mass location as well as relevant frame transformation. These parameters were used to develop the code for forward kinematic actuation on PSM.

The third phase of the approach involves building real-time kinematics model of continuum robot. At the beginning of this phase, the team learned how to actuate the robot arm and catheter using GUI and terminal, and then detect the actuation via Python and ROS commands. In order to manipulate and navigate the continuum robot catheter on the patient side manipulator, a dynamic model will be developed. The team calculated the d-H parameters based on the parameters identified in the experimentation phase, as well as developed customized json configuration files for the continuum dVRK end effector. The dynamic model is finally developed to control the movement of the Acunav catheter.

The fourth and final phase of the approach involves identifying a suitable surgical application for the new continuum robot end effector, as well as transforming the developed method from continuum endoscope to prototyped Acunav catheter. The team designed experiments and validated our design. Different surgical procedures are selected that requires the usage of a continuum robot catheter.

## 2.2 Mechanical Design

In this section, we will show the assembly of the integrated continuum robot and the tendon-wrapping mechanism. the figure below is the break view of our integrated continuum robot

Figure 4: Break view of AcuNav-dVRK robot.

Firstly, we designed a few adaptors and retainers. The adaptors are used for connecting two cannulas to extend the length of the tubes. The retainers are designed to centralize the AcuNav catheter and make it roll with cannula operation. The main design principle is to find a proper inner and outer diameter for a valid tolerance and friction so that we can improve the rigidity of the whole cannula.

Besides, we made three iteration designs by adjusting the geometry, diameter, and print orientation, the figure below is the CAD drawing of our latest adapters and retainers.

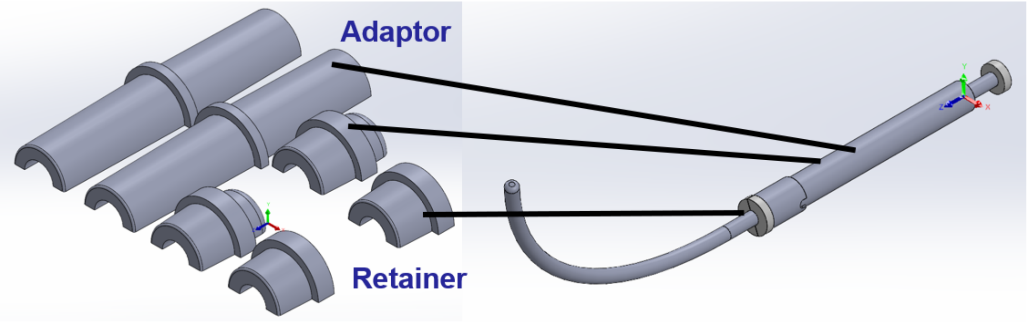


Figure 5: Latest iteration of adaptors and retainers.

As the wrapping mechanism, the figures below illustrate the difference in mechanism between our endoscope catheter and the Acunav catheter. For the endoscope, each pulley on the dVRK baseplate controls 1 DOF( Degree of Freedom) motion. So we can control the bending in pitch(1 DOF) and yaw(1 DOF), and rolling(1 DOF) via rotary joints on the baseplate. For the Acunav catheter, each pulley on the dVRK baseplate controls 0.5 DOF motion. So we can control the bending in pitch(0.5 DOF+ 0.5 DOF), and yaw(0.5 DOF+ 0.5 DOF) via rotary joints on the baseplate. Finally, we tried wrapping the tendons of the AcuNav catheter as the same way as the endoscope catheter, after a few days of testing, it is basically functional, but considering the difference between the material of the tendons, the AcuNav tendon will generate a little slack when it is not tensed, so we need to calibrate this slack in the future work to improve the accuracy of our continuum robot.

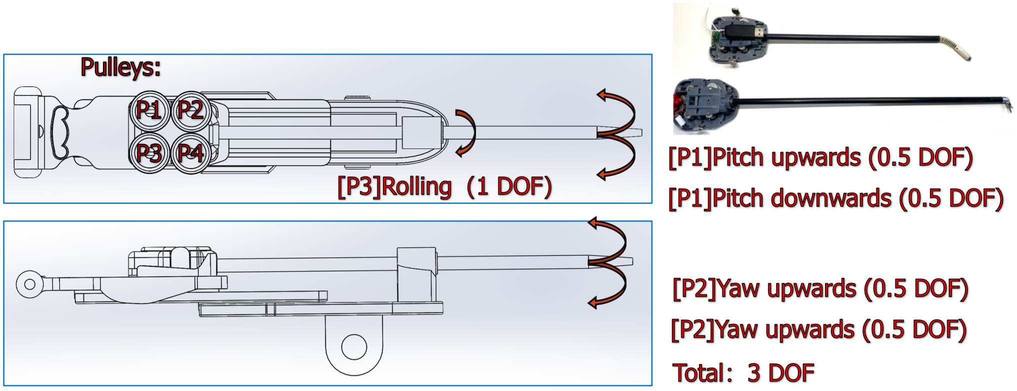


Figure 6: Motion control principle of the Endoscope catheter.

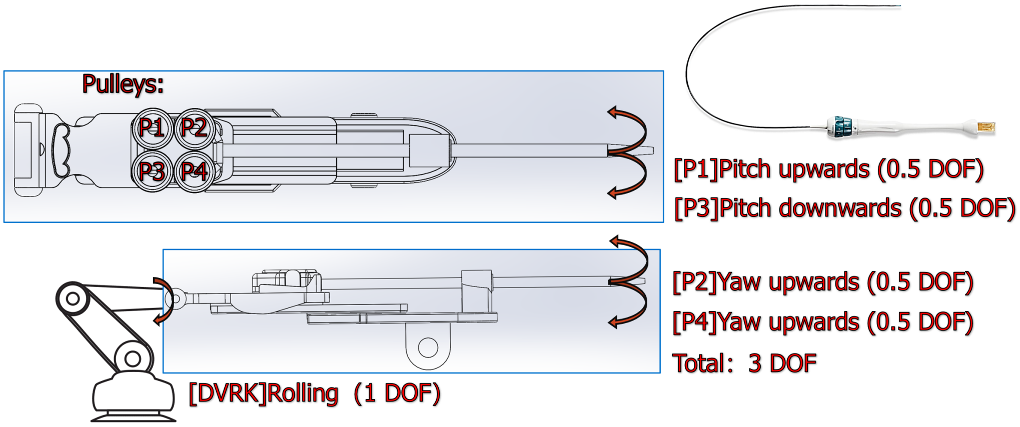


Figure 7: Motion control principle of the Acunav catheter.

## 2.3 Real-time Calibration of Continuum End Effector Using NDI

### 2.3.1 Calibration Methodology

The NDI Aurora Tracking System is used for the continuum dVRK's motion control process. 2 electro-magnetic trackers are attached to the base and continuum tip of the dVRK, thus know the corresponding transformation in frame of NDI Aurora. Therefore, a calibration from NDI tracking system to dVRK is required to find the corresponding transformation, and complete the whole frame transformation from dVRK's base frame to continuum end-effector tip, which is shown in Figure 8.
The calibration process takes advantage of the Da Vinci Robot's remote center of mass (known as RCM point) on PSM arm. During PSM arm's movement, the RCM point will remain fixed, which gives us convenience in performing calibration procedure from EM tracker base to the RCM point (shown in Fig. 9).
The mathematical approach to calibrate the RCM point C is shown below while corresponding python files are attached in the next section.

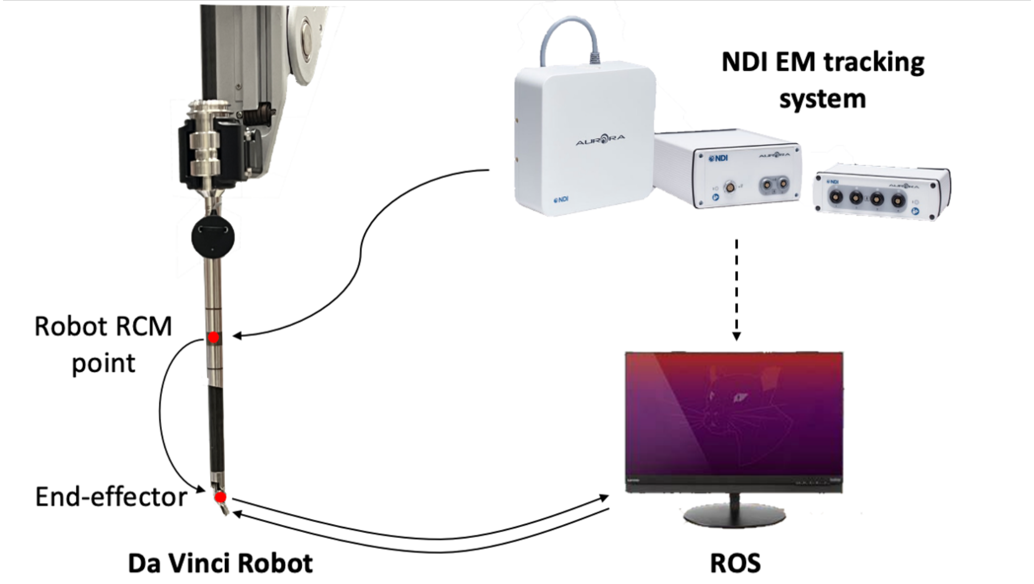


Figure 8: System diagram of the frame transformation.

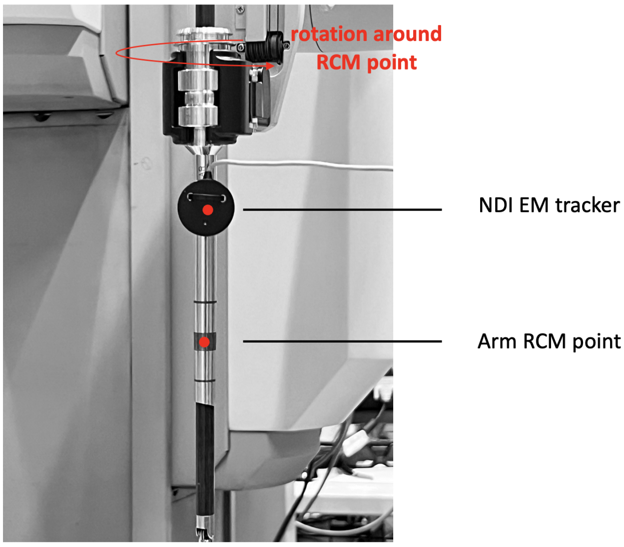


Figure 9: RCM point on PSM arm.

a. **Get reference frames:** The two reference frames is fixed on the same rigid body: frame B is the EM tracker and frame C is the RCM point.

b. **Acquire frame sequence data:** the PSM arm is rotated with respect to RCM point C while acquiring EM tracker data, thus give us a sequence of the frame, $\{F_{B_1}, F_{B_2}, ..., F_{B_n}\}$:

$$F_{B_i,B_{i+1}} = F_{B_i} \cdot F_{B_{i+1}}^{-1}$$
$$R_{B_i,B_{i+1}} = F_{B_i,B_{i+1}}[0:3, 0:3]$$

c. **Calculate rotation axis $\bar{r}$:** the rotation axis sequence $\{\bar{r}_1, \bar{r}_2, ..., \bar{r}_{n-1}\}$ of adjacent $F_{B_i}$ is calculated to perform RCM point calibration in EM tracker's frame using Rodrigues' rotation formula [6]:

$$R = I + \hat{k} * \sin\theta + \hat{k}^2 * (1 - \cos\theta)$$
$$\theta = \cos^{-1}((trace(F_{B_i,B_{i+1}}) - 1)/2)$$
$$\bar{r} = \frac{1}{2\sin\theta} * (R - R^T)$$

d. **Calculate RCM point C:** the RCM point C is calculated by applying least square optimization on the rotation axis sequence $\{\bar{r}_1, \bar{r}_2, ..., \bar{r}_{n-1}\}$:

$$\bar{r}^* = \arg\min_{\bar{r}} \sum_{i=1}^{n-1} \left\| R_{B_i,B_{i+1}} \cdot \bar{r} - \bar{r}_i \right\|^2$$
$$F_C = F_{B_1} \cdot \bar{r}^*$$

e. **Calculate transformation from EM tracker to RCM point:** the transformation from EM tracker to RCM point is calculated by:

$$F_{B,C} = F_B \cdot {F_C}^{-1}$$

### 2.3.2 Software Implementation

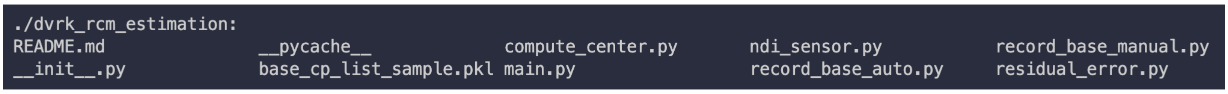
The calibration process is implemented in Python, which has been wrapped up in a package named `dvrk_rcm_estimation`. The package is available at `https://github.com/SP23-CISII-dvrk`. The package is tested on Ubuntu 18.04 with ROS Noetic and Python 3.6.9. The package is dependent on the following packages: The program structure is shown in Fig. *. The package contains 5 functions:

| Package | Version |
|---|---|
| numpy | 1.24.2 |
| scipy | 1.10.1 |
| PyKDL | 1.4.0 |
| rospy | 1.16.0 |
| crtk | 0.0.25 |

Table 1: Dependent packages

`ndi_sensor.py` defines a class of NDI Aurora EM tracker which can be called from NDI GUI, which is based on `crtk` packages; `record_base_auto.py` and `record_base_manual.py` subscribes ROS topic from NDI sensor and records a sequence of sensor frame data; `residual_error.py` defines the residual error function for least square optimization; `compute_center.py` calculates the RCM point C and transformation from EM tracker to RCM point, which use `scipy` package to perform least square method.

The calibration process and results are described with details in Validation section.



```
./dvrk_rcm_estimation:
README.md             __pycache__            compute_center.py      ndi_sensor.py          record_base_manual.py
__init__.py           base_cp_list_sample.pkl main.py               record_base_auto.py    residual_error.py
```

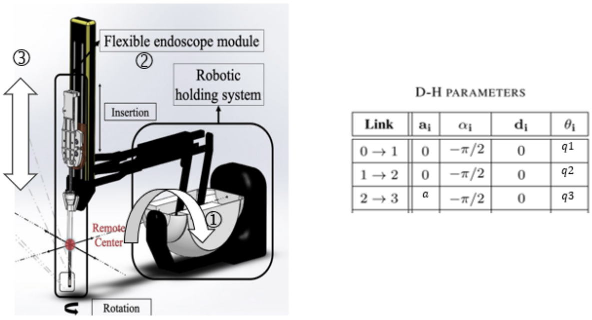
Figure 10: Program structure of `dvrk_rcm_estimation` package.

## 2.4 Real-time Kinematics Model of Continuum Robot

### 2.4.1 Forward & Inverse Kinematics Methodology

A. Forward Kinematics

The PSM of the da Vinci consists of an arm and a tool component. Due to the parallelogram structure of the arm, the remote center can be seen as the mounting base, as shown in figure 11. Joint1 performs a yaw motion about the remote center, while Joint2 pivots the instrument in a pitching motion about the same center. The home position, defined as zero joint 1 and joint 2 angles, aligns the insertion axis perpendicular to the PSM mounting plate. The insertion moves the instrument along the axis of its shaft into or out of the patient. The arm's Denavit-Hartenberg parameters and forward kinematics ($T_1$) are built based on these premises, as shown in Eq.1.



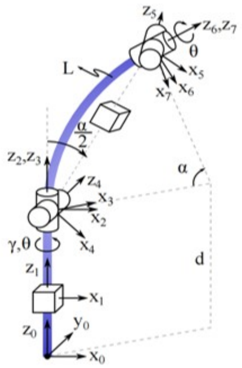
D-H PARAMETERS

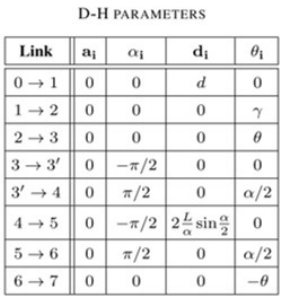
| **Link** | $\mathbf{a_i}$ | $\alpha_i$ | $\mathbf{d_i}$ | $\theta_i$ |
|---|---|---|---|---|
| $0 \rightarrow 1$ | 0 | $-\pi/2$ | 0 | $q1$ |
| $1 \rightarrow 2$ | 0 | $-\pi/2$ | 0 | $q2$ |
| $2 \rightarrow 3$ | $a$ | $-\pi/2$ | 0 | $q3$ |

Figure 11: Arm and DH parameters, a is length of the Insertion[1].

$$\begin{bmatrix} -\sin(q_1)\sin(q_2) & -\cos(q_1) & \cos(q_2)\sin(q_1) & -\cos(q_2)\sin(q_1)(a-q_3) \\ -\cos(q_2) & 0 & -\sin(q_2) & \sin(q_2)(a-q_3) \\ \cos(q_1)\sin(q_2) & -\sin(q_1) & -\cos(q_1)\cos(q_2) & \cos(q_1)\cos(q_2)(a-q_3) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The tool component uses different DH parameters for different end-effectors. For the continuum end-effector, special DH parameters have been constructed, as shown in figure 12. The pitch and yaw of the continuum tip have been replaced with the Bending angle $\alpha$ and the Bending plane angle $\theta$, and $\gamma$ represents the Rolling angle by rotation. These variables describe the shape of the continuum tool. The transformation matrix, $T_2(\gamma, \theta, \alpha)$, describes the pose of the continuum tool tip in base coordinates. By combining the forward kinematics of the arm and tool, the instrument's forward kinematics $g$ can be obtained.




D-H PARAMETERS

| Link | $a_i$ | $\alpha_i$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| $0 \to 1$ | 0 | 0 | $d$ | 0 |
| $1 \to 2$ | 0 | 0 | 0 | $\gamma$ |
| $2 \to 3$ | 0 | 0 | 0 | $\theta$ |
| $3 \to 3'$ | 0 | $-\pi/2$ | 0 | 0 |
| $3' \to 4$ | 0 | $\pi/2$ | 0 | $\alpha/2$ |
| $4 \to 5$ | 0 | $-\pi/2$ | $2\frac{L}{\alpha}\sin\frac{\alpha}{2}$ | 0 |
| $5 \to 6$ | 0 | $\pi/2$ | 0 | $\alpha/2$ |
| $6 \to 7$ | 0 | 0 | 0 | $-\theta$ |

Figure 12: Continuum tool and DH parameters, L is length of the bending section[8].

$$\begin{bmatrix} \sin(\gamma+\theta)\,\sin(\theta)+\cos(\gamma+\theta)\,\cos(\alpha)\,\cos(\theta) & \cos(\gamma+\theta)\,\cos(\alpha)\,\sin(\theta)-\sin(\gamma+\theta)\,\cos(\theta) & \cos(\gamma+\theta)\,\sin(\alpha) & -\frac{L\,\cos(\gamma+\theta)\,(\cos(\alpha)-1)}{\alpha} \\ \sin(\gamma+\theta)\,\cos(\alpha)\,\cos(\theta)-\cos(\gamma+\theta)\,\sin(\theta) & \cos(\gamma+\theta)\,\cos(\theta)+\sin(\gamma+\theta)\,\cos(\alpha)\,\sin(\theta) & \sin(\gamma+\theta)\,\sin(\alpha) & -\frac{L\,\sin(\gamma+\theta)\,(\cos(\alpha)-1)}{\alpha} \\ -\sin(\alpha)\,\cos(\theta) & -\sin(\alpha)\,\sin(\theta) & \cos(\alpha) & d+\frac{L\,\sin(\alpha)}{\alpha} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

## B. Inverse Kinematics

The idealized mapping from task space to configuration space begins with g and calculates q1, q2, q3, $\alpha$, $\theta$, and $\gamma$. The spatial manipulator Jacobian is defined as:

$$J^s = \left[ \left( \frac{\partial g}{\partial q_1} g^{-1} \right)^{\vee} \dots \left( \frac{\partial g}{\partial q_n} g^{-1} \right)^{\vee} \right]$$

Based on the calculated Jacobian, an algorithm for calculating the inverse kinematics is demonstrated below:

```
\begin{algorithm}
\caption{Run Inverse}
\begin{algorithmic}[1]
\REQUIRE Initial matrix $TH$, target matrix $g$
\ENSURE $TH$
\STATE Compute target value from $g$
\STATE Initialize scaler and loop counter
\WHILE{not converged}
    \IF{error is small enough}
        \STATE Print current state
        \BREAK
    \ENDIF
    \STATE Compute Jacobian matrix
    \STATE Compute current state
    \STATE Compute error
    \STATE Compute change in $TH$ (dTheta) as the dot product
    of the pseudoinverse of $J$ and $Err$
    \STATE Increment loop counter
\ENDWHILE
\RETURN $TH$
\end{algorithmic}
\end{algorithm}
```

C. Joint Mapping
The continuum tool's desired configuration space motion can be mapped to the corresponding joint space inputs as:

$$
\begin{aligned}
&\phi_1 = 2R_c\alpha\cos\theta/D_{knob}\\
&\phi_2 = -R_c\alpha\sin\theta/D_{knob}\\
&\phi_3 = \gamma
\end{aligned}
$$

Figure 13: joint mapping of continuum tool.

where $R_c$ is the radius of the continuum tool body and $D_{knob}$ is the diameter of the pulley inside the dvrk base-plate.

### 2.4.2 Software Implementation

The forward kinematics and the Jacobian matrix are derived using Matlab in a file named `dvrk_function.mlx`. These mathematical formulas are then implemented in Python for the inverse kinematics. The file `formula.py` contains the derived forward kinematics and Jacobian formulas, while `Inverse.py` uses these formulas to implement the inverse kinematics algorithm. The file `dvrk_psm_test.py` integrates the inverse kinematics into the da Vinci Research Kit (dVRK) and includes a sample motion. In addition, a JSON file named `CONTINUUM_400200.json` is created, which contains the joint mapping parameters for the continuum tool. All these files can be found in the `dvrk-ros` package on GitHub.

# 3 Experimental Evaluation and Validation

## 3.1 RCM Point Calibration

The calibration process is performed on a dVRK system with a PSM (shown in Fig. 9) and a NDI Aurora EM tracker (shown in Fig. 14). The EM tracker is mounted on the PSM's metal guide pipe. The PSM is rotated arbitrarily for 10 seconds while acquiring EM tracker's poses with sampling frequency of 10 Hz. During the experiments, the EM tracker's position was changed multiple times to test the robustness of RCM calibration. In total, the calibration process was performed using 20 sets of data, with each set consisting of 100 recorded frames. A statistical analysis was performed on the recorded Remote Center of Motion (RCM) points. As a result, the detailed statistical results are tabulated in Table 2 where the mean positions indicates a consistent central location across all measurements and the standard deviations for the X, Y, and Z coordinates reflects a high degree of precision in the positioning of the RCM points. The spatial distribution of the RCM points is illustrated in Fig. 16. These quantitative results provide strong evidence of the accuracy and reliability of the calibration process.

Table 2: Mean and Standard Deviation of RCM positions

| | Mean | Standard Deviation |
|---|---|---|
| x | 0.108243 | 0.006693 |
| y | 0.016046 | 0.002830 |
| z | -0.303135 | 0.001908 |

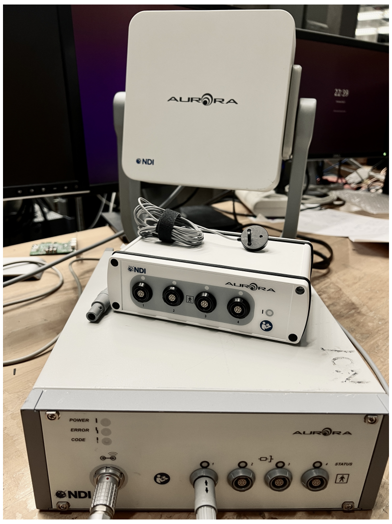


Figure 14: NDI Aurora EM tracking system.

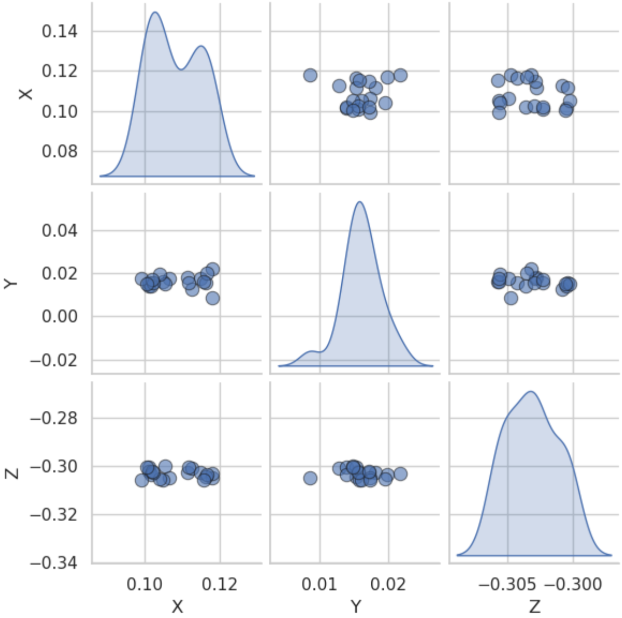


Figure 15: Pairwise relationships of RCM points.

### 3.2 Real-time Kinematics Model of Continuum Robot

The trajectory plot is based on the integrated dVRK. The preset trajectory is a square with a side length of 0.14m at a constant height. The instrument's end is always kept vertically downward. This preset tests the performance of the integrated dVRK's navigation and manipulation capabilities. Meanwhile, the EM tracker records the tip's rotation and position to verify accuracy. The preset and actual trajectory plots are shown in Fig. 16.

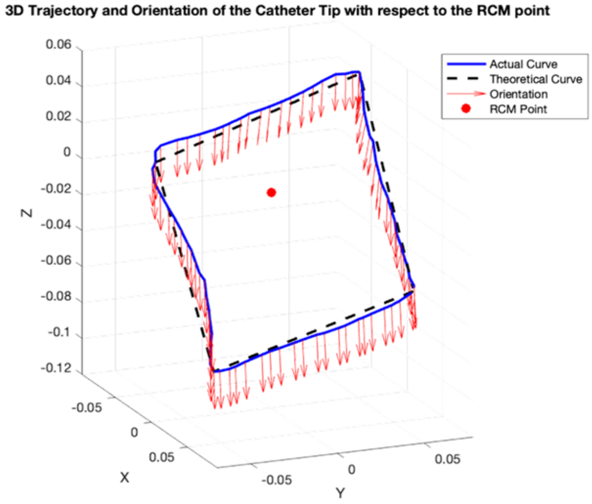


Figure 16: Trajectory of catheter tip.

From the plot, it can be seen that the end effector's trajectory is largely in line with expectations. In this trajectory, the maximum positional error is 4.6mm, and the maximum rotation error is 3.2°. These data strongly attest to the accuracy of this DaVinci-Assisted Continuum Robot Navigation and Manipulation, demonstrating that the team's current goals have been perfectly achieved.

## 4 Surgical Application

We have searched for surgical procedures that can benefit from the proposed approach. Lung Biopsy[3], Liver Surgery, and Cholecystectomy[*] are potential surgical procedures which can take advantage of advanced surgical robotics, such as the DaVinci robot arm and tendon-driven continuum robots. These robots can improve the precision, flexibility, and reachability of surgical instruments, which can lead to better patient outcomes.

a. **Lung Biopsy:** A lung biopsy is a procedure to obtain a small sample of lung tissue for examination. It is usually performed to diagnose lung diseases or abnormalities, such as cancer or infection. The use of continuum robotic-assisted systems, like the tendon-driven continuum robots, can improve the accuracy of needle insertion, reduce the risk of complications, and minimize the invasiveness of the procedure. As mentioned above, the diagnostic yield of a pulmonary nodule biopsy using such robotic systems can be as high as 83%.

b. **Liver Surgery:** Liver surgery, such as liver resection or liver transplant, involves the removal of a portion or the entire liver. Robotic-assisted liver surgery has gained popularity in recent years due to the improved precision and dexterity offered by robotic systems like the DaVinci robot arm. These systems can minimize blood loss, reduce the risk of complications, and shorten recovery times for patients undergoing liver surgery.

c. **Cholecystectomy:** Cholecystectomy is the surgical removal of the gallbladder, usually performed to treat gallstones or other gallbladder-related diseases. Robotic-assisted cholecystectomy has become an increasingly popular alternative to traditional laparoscopic cholecystectomy. The use of advanced continuum robotic systems like the DaVinci robot arm provides better visualization, improved dexterity, and greater precision, which can lead to a lower risk of complications and faster recovery times for patients.

In conclusion, the combination of the dVRK robot arm and tendon-driven continuum robot technology has the potential to significantly improve surgical outcomes in various procedures, including lung biopsy, liver surgery, and cholecystectomy. These systems offer improved accuracy, flexibility, and reachability, which can ultimately lead to better patient outcomes and reduced complications during surgery.

# 5 Management summary

## 5.1 Responsibilities

This is a comprehensive project where all team members should try their best to engage in both literature research, design, coding as well as documentation. Several major work and responsibilities are listed based on the team member's skill set.

| **Member** | **Major work** |
|---|---|
| Jaspor Jiang | ROS, dVRK platform, NDI EM tracking system, documentation |
| Heyun Wang | Forward kinematics, configuration, motion planning, experiment |
| Chenhan Zhang | Mechanical design, integration of Acunav and dVRK, literature review |

## 5.2 Future works

We will continue our project this summer with a focus on several key areas:

a. Achieving precise control over the integrated dVRK-AcuNav catheter system.

b. Enhancing our abilities to manipulate the continuum robot via teleoperation.

c. Implementing and testing ultrasound imaging on a suitable phantom.

## 5.3 Deliverable

a. **Minimum: (Expected by 3.15, 4 weeks)** (Done)

- **Preliminary research**
- **Mechanical design enhancement and designs innovation**
  Connection mechanism design
  AcuNav-dVRK adaptor CAD design
- **Verify the basic actuation function of dVRK with continuum end-effector through ROS and GUI**
  Training and getting access to DaVinci operation
  Actuating the dVRK with continuum end-effector

b. **Expected: (Expected by 4.12, 4 weeks)** (Done)

- **Obtain experimental results needed for identifying catheter parameters**
  D-H parameter calculation of endoscope catheter
  Building joint mapping function
- **Code development and forward kinematics actuation based on catheter parameters**
  Constructing the initial state of forward kinematics
  Integrate algorithms enable precise actuation of continuum effector

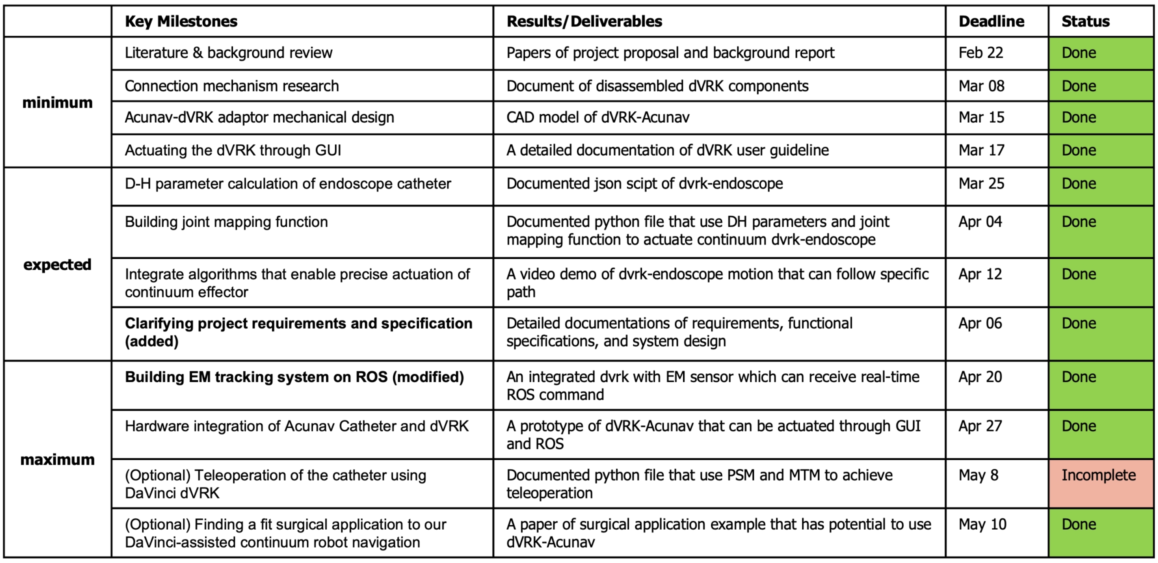
c. **Maximum: (Expected by 5.10, 4 weeks)**

- **AcuNav-dVRK integration** (Done)
  Building EM tracking system on ROS
  Prototyping & testing of Acunav Catheter
- **Find a fit surgical application**
  Find a fit surgical application to our DaVinci-assisted continuum robot navigation (Done)
  (Optional)Teleoperation of the catheter using DaVinci dVRK (Incomplete)

We have completed all aspects of our project, except for the optional part, and we plan to finish that during the summer.

## 5.4 Accomplishment and Plan

Overall, we have finished all of minimum and expected deliverables, as well as most of maximum deliverables shown in Fig. 17. In terms of timeline, we spent 4 weeks on the minimum part of the project, during which we worked on mechanical design and test the catheter with the dVRK. The expected part took four weeks, during which we designed experiments to obtain performance data for the RCM point calibration and build a complete forward kinematic for precise control of the endoscope's tip with the dVRK. The maximum part of the project involves integrating NDI tracking system with dVRK and ROS, as well as finding a suitable surgical application for our surgical system. The teleoperation as well as phantom test have not been finished within the course scope. We plan to finish it in the coming summer, if the mentor decide to continue this project.



| | **Key Milestones** | **Results/Deliverables** | **Deadline** | **Status** |
|---|---|---|---|---|
| **minimum** | Literature & background review | Papers of project proposal and background report | Feb 22 | Done |
| | Connection mechanism research | Document of disassembled dVRK components | Mar 08 | Done |
| | Acunav-dVRK adaptor mechanical design | CAD model of dVRK-Acunav | Mar 15 | Done |
| | Actuating the dVRK through GUI | A detailed documentation of dVRK user guideline | Mar 17 | Done |
| **expected** | D-H parameter calculation of endoscope catheter | Documented json scipt of dvrk-endoscope | Mar 25 | Done |
| | Building joint mapping function | Documented python file that use DH parameters and joint mapping function to actuate continuum dvrk-endoscope | Apr 04 | Done |
| | Integrate algorithms that enable precise actuation of continuum effector | A video demo of dvrk-endoscope motion that can follow specific path | Apr 12 | Done |
| | **Clarifying project requirements and specification (added)** | Detailed documentations of requirements, functional specifications, and system design | Apr 06 | Done |
| **maximum** | **Building EM tracking system on ROS (modified)** | An integrated dvrk with EM sensor which can receive real-time ROS command | Apr 20 | Done |
| | Hardware integration of Acunav Catheter and dVRK | A prototype of dVRK-Acunav that can be actuated through GUI and ROS | Apr 27 | Done |
| | (Optional) Teleoperation of the catheter using DaVinci dVRK | Documented python file that use PSM and MTM to achieve teleoperation | May 8 | Incomplete |
| | (Optional) Finding a fit surgical application to our DaVinci-assisted continuum robot navigation | A paper of surgical application example that has potential to use dVRK-Acunav | May 10 | Done |

Figure 17: Updated project milestones.

### 5.5 Lessons Learned

The Importance of Precise Control and Registration: Surgical robotics require a high level of accuracy, and our project reinforced the significance of precise control and registration. This project reaffirmed the necessity of maintaining stringent control over every element of a surgical robot's function to maximize effectiveness and safety.

Project Planning and Dependencies: We learned that thorough planning and ensuring the availability of all dependencies before beginning work are vital for the smooth execution of the project. This includes understanding the dependencies and constraints of our technical systems and software tools.

Collaborative Teamwork: The project highlighted the importance of effective teamwork in developing complex systems. We found that dividing tasks according to individual strengths and maintaining clear, open communication channels were key to our project's success.

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