Team 9 Final Report

Electromagnetic Tracking of Endovascular Catheters

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1 Introduction

This project focuses on developing a novel approach to replace the commonly used fluoroscopy during endovascular neurosurgical procedures with electromagnetic tracking to minimize radiation exposure. Specifically, we look at using electromagnetic tracking to guide surgeons in navigating their catheters during the endovascular treatment for brain aneurysm.

This project is led by Shanelle Cao, Fangjie (FJ) Li, and Huilin (Lin) Xu, who are all senior undergraduates spanning fields of Biomedical Engineering, Electrical Engineering, Chemical and Biomolecular Engineering, and Computer Science. This project is advised by Dr. Ali Uneri of the I-STAR Labs of the Department of Biomedical Engineering, and Dr. Fernando Gonzalez, an experienced neurosurgeon in the Johns Hopkins Hospital.

2 Background

2.1 Brain Aneurysms

Brain aneurysms are bulges in blood vessels in the brain primarily due to thinning artery walls. They often occur where blood vessels branch, as vessel walls are usually thinner at these locations. Brain aneurysms can either leak or rupture, which will then quickly develop into life-threatening conditions. Leaking or ruptured brain aneurysms may cause severe headaches, stroke, permanent neurological deficits, or death [1]. In the US, around 6.7 million people live with brain aneurysms [2]. Out of the 6.7 million, around 30,000 patients experience ruptured aneurysms annually, with a fatality rate of up to 50% [2].

Figure 2.1.1: Brain Aneurysms (taken from [1])

2.2 Current Treatments

With such a high fatality rate, treatments are mainly concerned with stopping further blood flow into the aneurysm to prevent or stop an ongoing rupture. Two different procedures are available for embolizing aneurysms. Microsurgical clipping, as shown in Fig.2.2.1, is where a small opening is made on the skull near the site of the aneurysm, and a clip is inserted to pinch off further blood flow into the aneurysm [3]. This method is highly invasive,

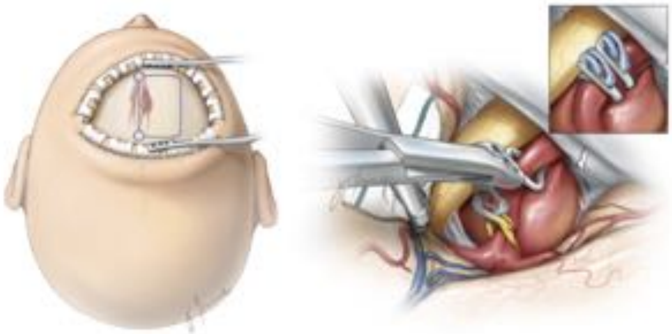

Fig.2.2.1 Microsurgical Clipping (taken from [3])

taking patients long periods of time to heal after the operation. More recently, the endovascular neurosurgical method has been developed, where a catheter is inserted from the femoral artery near the thigh of the patient and navigated to the site of the aneurysm in the brain. Once the catheter reaches the aneurysm, there are two different methods to embolize the aneurysm. One such method is coiling, where a coil of wire is inserted into the aneurysm through the catheter, causing blood clots. The other method is flow diversion, where a mesh

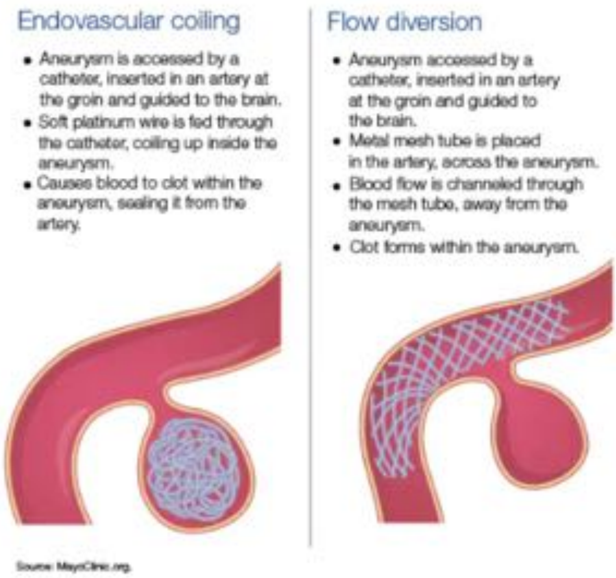

Fig.2.2.2 Endovascular Catheter-Based Surgeries (taken from [4])

tube, acting like a stent, diverts the blood flow away from the aneurysm and along the vessel. With no new blood flow into the aneurysm, existing blood inside the aneurysm will clot. Blood clotting will block further blood flow into the aneurysm, preventing or stopping an ongoing rupture. Compared to microsurgical clipping, the endovascular neurosurgical method is minimally invasive.

2.3 Catheter Path

Although the endovascular procedure is minimally invasive, it is hard for the surgeons to navigate the catheter to the site of the aneurysm smoothly. Once the catheter enters the patient's body through the femoral artery, it first travels through the aorta to the heart. Along this path, one common mistake is that the catheter will enter the renal artery, which leads to the kidney. To ensure that the catheter is on the right track, fluoroscopy is used during this step. Fluoroscopy uses X-ray to obtain the real-time position of the catheter inside the patient's body. Because the aorta is relatively straight, with artery diameters in the cm range, the poor soft tissue contrast of X-ray is not a concern. Sufficient information is given to the surgeon through the relative position of the catheter to the bone structures.

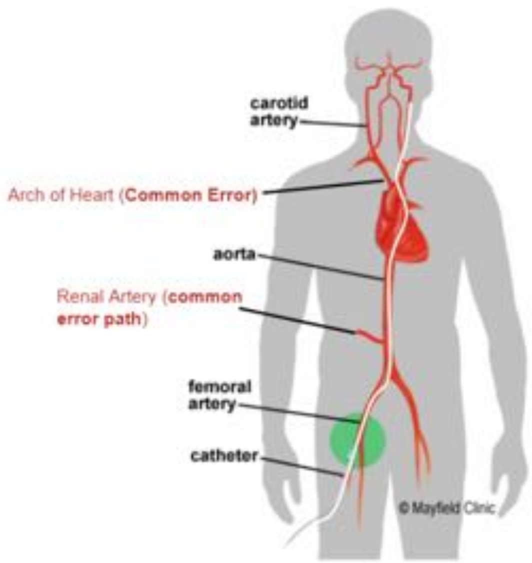

Fig.2.3.1 The arterial path taken by catheter, with common errors highlighted in red (modified from [5])

Once the catheter reaches the heart, the surgeon has to precisely determine the correct carotid artery out of the multiple branches on the aortic arch that leads to the site of the aneurysm. Additionally, the diameter of the arteries from this point on decreases to the order of mm. Due to the intricate structure of vessels in the heart and brain, a more precise imaging technique is needed. Thus, pre-operative CT angiography combined with fluoroscopy with the addition of contrast is used to increase the visualization of blood vessels and tissues.

3 Significance

As described in the background section, for endovascular techniques, fluoroscopy, and CT angiograms are used to help surgeons visualize the position of their catheter in order to navigate the catheter to the site of the aneurysm. However, this process exposes both the patient and surgeon to hundreds of mGy of X-ray radiation. At this level of radiation exposure, there are increased health risks of diseases such as cancer, cataract, non-malignant skin damage, and impaired fertility [6]. In addition, surgeons are especially at increased risk since they perform this procedure on a regular basis. Thus, there is currently a need for methods of detecting catheter position inside the patient without relying on X-ray imaging techniques, which will greatly reduce the amount of radiation that patients and surgeons are exposed to.

4 Goals

4.1 Minimum Deliverables

At minimum, the project is expected to produce a hardware catheter prototype with an embedded EM sensor at the tip. We expect the prototype to have the following abilities:

1. 5DOF Tracking with the existing Aurora EM system, with sufficient accuracy and robustness.
2. Suitable exterior diameter and rigidness for navigation in arteries.
3. Sufficient Interior catheter diameter for the delivery of tools necessary for aneurysm surgery.

The implementation of minimum deliverables can be found in the catheter design part in the **Technical Approach** section.

4.2 Expected Deliverables

The expected deliverable includes the delivery of 3D slicer modules that constitutes a software with the following abilities:

1. Real-time catheter path modeling based on the EM tracker data.
2. Registration of path data onto a patient specific, X-ray coronal image.
3. Visualization of the generated path with the X-ray coronal image.

The implementation of expected deliverables can be found in the fiducial point registration and tip visualization part in the **Technical Approach** section. The results of the algorithm are discussed in the **Result** section.

4.3 Maximum Deliverables

The maximum deliverable builds upon the software work from the expected deliverables. The deliverable will come in the form of extra software modules added to the software framework built for the expected deliverables. It will have the following abilities:

1. Registration of path data onto a pre-operative CT angiography (CTA) scan.

The implementation of expected deliverables can be found in the path-based registration part in the **Technical Approach** section. The results of the algorithm are discussed in the **Result** section.

5 Prior Work

Our project builds off of some modules that have been already developed for this purpose. Both a module that performs basic registration between the sensor and X-ray frame, and a visualization module that tracks the path of the catheter already exist. However, we have identified some major weaknesses.

5.1 Registration

For the registration module, the original idea was to perform fiducial point registration between the sensor and a non-patient specific rough model X-ray. However, the results were poor. Because the original algorithm assumed isotropic scaling, it failed to adjust to different body sizes, resulting in non-informative or even misleading image guidance. In addition, the algorithm used to compute the transformation was very simplistic. The user defines two sets of superior and right vectors that correspond to each other in the sensor and CT frame. Then, the algorithm aligns the two vectors with a simple scaling to perform registration. These factors combined led to the poor performance of the registration module, which can only handle simple transformations.

Thus, after discussion with our mentors, we've decided that instead of using a non-patient specific X-ray, we would use a patient-specific X-ray. Although in reality this information is not readily available, we determined that the tradeoff between accurate registration and additional steps to obtain such information is worth it, especially since a single full body X-ray image is not complicated to obtain. In order to make the registration algorithm more rigorous, we opted to first adopt fiducial point registration with Arun's method. Then, if time allows, we would implement path-based registration, since identifying fiducial points on the patient body is difficult.

5.2 Path Visualization

For the path visualization module, live tracking of the catheter was already implemented. As the user moves the catheter along the vessel, points are plotted to reflect the path taken by the catheter, and registration is used to overlay this path onto the X-ray image.

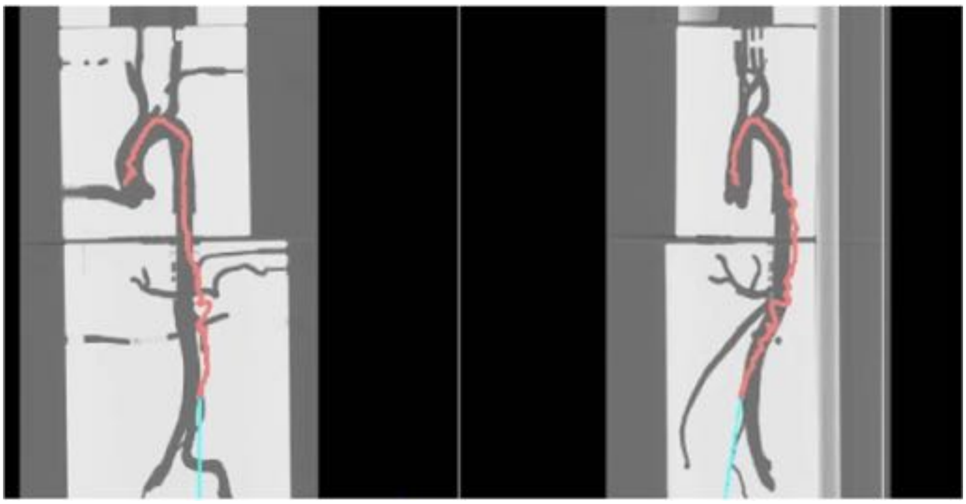
Figure 5.2.1 Previous path visualization

In addition, a deletion algorithm was implemented. In order to accurately provide image guidance, we want the tracking to reflect the truthful path of the catheter. Thus, when a surgeon retracts the catheter, points corresponding to the retracted portion that was previously plotted needs to be accurately deleted. This has been implemented by previous work. However, we have identified some improvements needed for the module. The existing tip visualization estimates the orientation and velocity of the tip based on recently tracked sensor motion. The estimation system was very crude, which led to tip orientation visualization with large errors. This was particularly problematic in that the length of the visualized tip model was dependent on the velocity estimate, and varied widely due to poor estimation quality. It severely degraded the usability of the tip visualization during operations, especially for guiding navigation during tight turns, such as at junctions. Therefore, firstly, we need to more accurately display the tip orientation using the available sensor information. Additionally, because the catheter tip is curved so that it can assist surgeons in turning the catheter into a branched vessel. Thus, it is important to know the orientation of the catheter tip (i.e. which way the curve is pointing) for effective navigation. The current module lacks this functionality. Lastly, the module GUI can be updated for better image guidance and smoother user experience.

6 Technical Approach

6.1 Overview

For the hardware, we will redesign the catheter to attach the 5-DOF EM sensor with protection. Detailed design information can be found in section 6.3.

For the software, the main task is the registration problem between the catheter (i.e. the sensor frame) and the patient model (i.e. the CT frame). We implemented two workflows: fiducial points registration and path-based registration. Besides that, since the tip of the catheter is curved and we only have one 5-DOF sensor attached, we developed the algorithm to estimate the position and orientation of both the tip part and the body part of the catheter.

6.2 Experiment Setup

Aurora Field Generator generates an electromagnetic field around the phantom. The field will cause current to run through the coil in front of the Aurora 5-DOF sensor. By measuring the voltage across the sensor, the position and orientation of the catheter can be determined.

We will use a torso arterial phantom for data collection, testing, and evaluation purposes. The Aurora Field Generator will be placed above the phantom. The Aurora 5-DOF sensor is attached to the catheter.

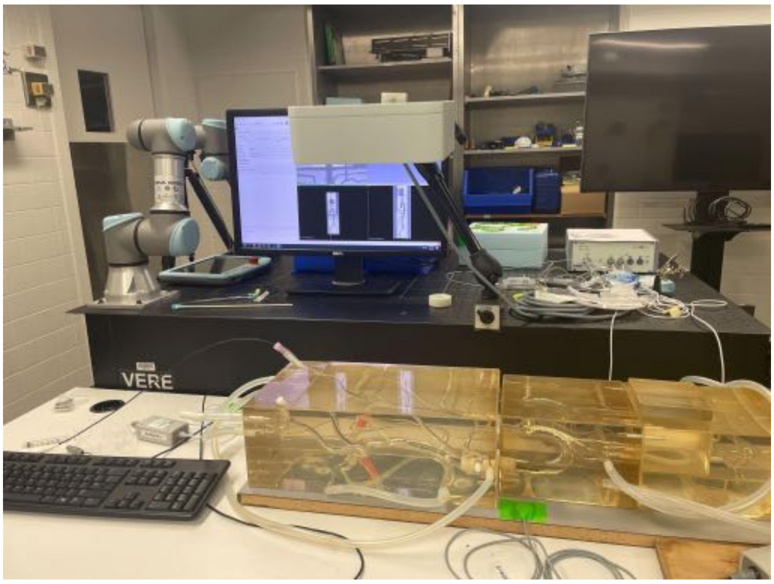

Figure 6.2.1 The setup of the Aurora Field Generator placed above the phantom

6.3 Catheter Design

6.3.1 Version 1

Figure 6.3.1.1. The Aurora 5-DOF sensor

We place the 5-DOF sensor inside the catheter. Liquid electrical tape is painted on the sensor so that the sensor can be fixed inside. The main advantage of this design is its ease of implementation. Additionally, this design adds no extra thickness to the catheter. However, the disadvantage is that it blocks the working channel inside the catheter.

Figure 6.3.1.2. The manufactured prototype for version 1

6.3.2 Version 2

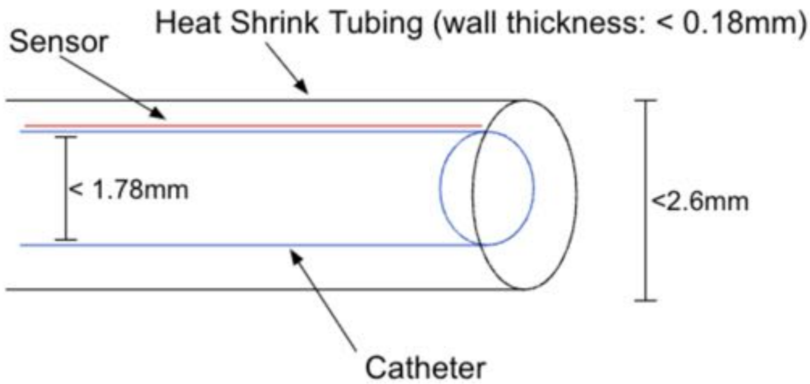

Figure 6.3.2.1. The design of prototype version 2

The 5-DOF is glued on top of the catheter using liquid electrical tape. To prevent the potential damage it may cause by doing so, heat shrink tubing is surrounded the whole system. By selecting biocompatible ultra-thin wall heat shrink tubing, 0.18mm of extra thickness will be added at most. The advantage of this design is making the working channel inside the catheter open so that other tools, such as a guide wire can be navigated through.

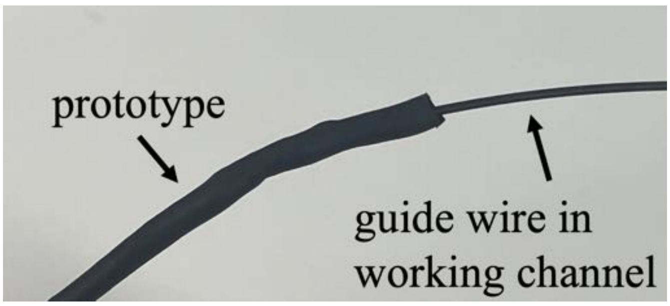

Figure 6.3.2.2. The manufactured prototype of version 2

6.4 Fiducial Point Registration

As discussed in section 2.3, for the part below the chest, a coronal X-ray image will be used as a rough model of the patient to guide the catheter insertion. The registration between X-ray imagery and the patient's body is needed. We developed a 3DSlicer module named newReg to perform this task.

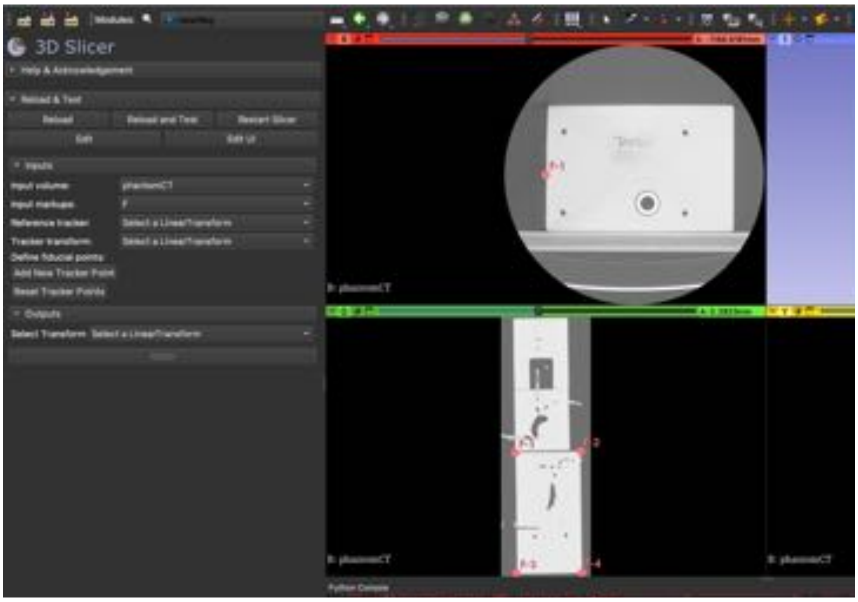

Figure 6.4.1 Module GUI for fiducial point registration showing markup points labeled on the CT volume

We first obtained a CT volume of the torso arterial phantom. Then, using the Markups module of 3DSlicer, we generated a markup point list on the CT that corresponds to the 8 corners of the phantom. This serves as our fiducial points. Then, using the catheter that we have made, we touch the catheter to each of the fiducial points in order and record their position. Finally, we used Arun's method to compute the transformation from the sensor frame to the CT frame.

6.5 Path-Based Registration

Since it is relatively difficult to perform fiducial points on real patients' bodies, the path-based registration algorithm is developed. We extract the vessel center line from the CT angiography as the ground truth. Then we map the tracker path to the center line using gradient descent. We use the sum of the mean squared distance between each sensor point and the closest point on the vessel wall extracted from the CT scan as the loss function. A rigid transformation will be found.

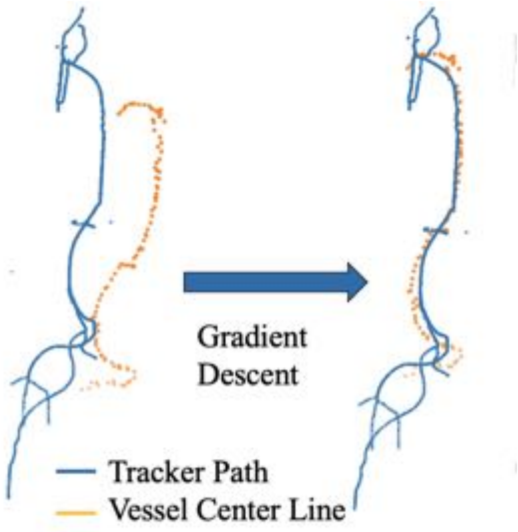

Figure 6.5.1 Path-based registration algorithm

A new 3D slicer model is developed to handle the registration. The user will first need to push the catheter forward for some distance inside the phantom. Then we will map the catheter's path to the vessel's center line using the algorithm described above.

6.6 Tip Visualization

The 5 DoF sensor, which is aligned with the tip, has sufficient information to display the tip orientation with a high degree of accuracy. However, the challenge is to estimate the pose of the body, which we do not have direct sensor data of. Therefore, we relied on an assumption for body pose estimation: the catheter is sufficiently rigid for a short span of length. As a result, the catheter pose will resemble the trajectory composed of recent sensor readings. Therefore, we fitted a linear vector to the sensor readings closest to the current sensor position, (1 cm within current location) using PCA based computations. Then, this orientation is attached to the current sensor tip transform, with a small translation offset that is predefined by the user to best reflect the actual geometry of the catheter tip shape.

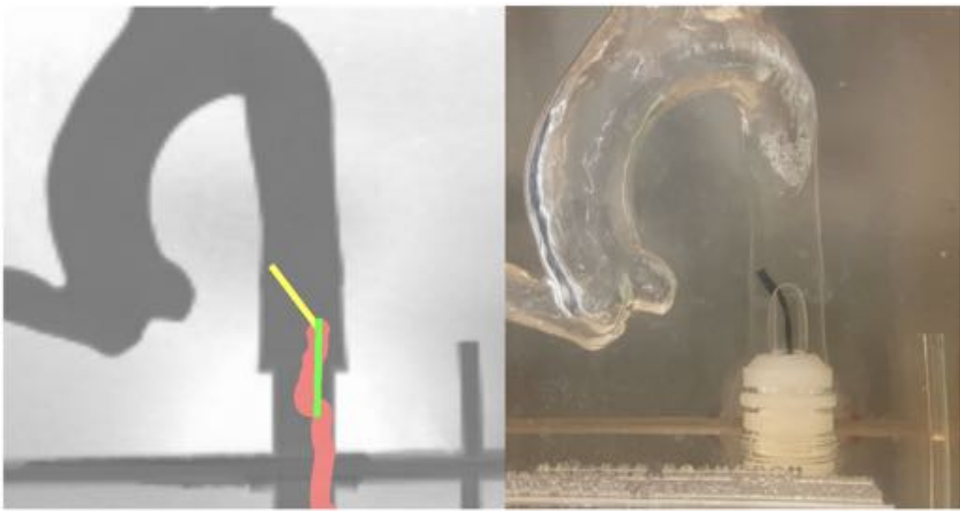
Figure 6.6.1 (left) Catheter tip visualization in module, (right) actual catheter tip in phantom

7 Results

7.1 Fiducial Point Registration

We mainly assessed our registration results through visualization. As shown below, after applying the computed transformation, the tracked path matches closely with the phantom X-ray.

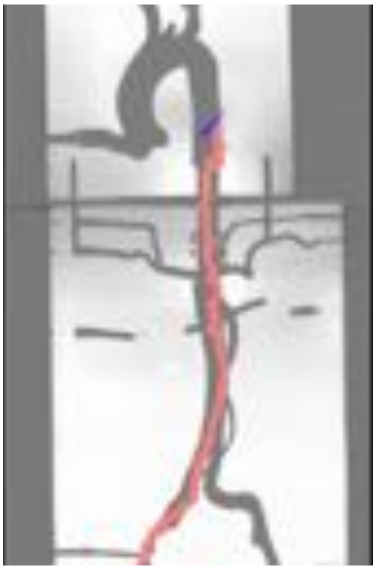

Figure 7.1 Tracked path overlaid onto X-ray image using fiducial point registration

7.2 Path-Based Registration

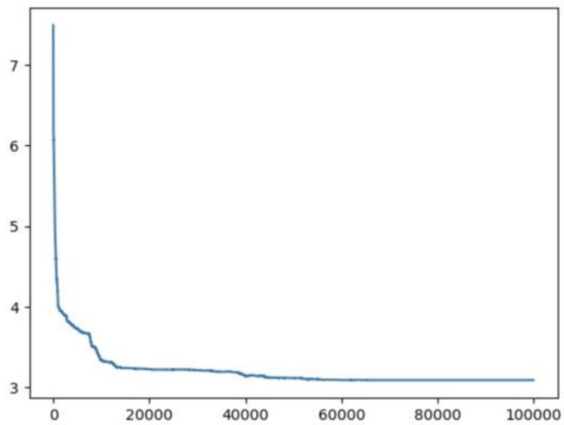

Figure 7.2. The loss function of the gradient descent result

The algorithm can be done in roughly 1 minute on Macbook Pro with an Intel Core i7 CPU and 16 GB memory. The loss function is shown below, where the horizontal axis is the number of iterations and the vertical axis is the loss in millimeters. Based on the graph, the loss can be reduced to within 3mm after roughly 30000 iterations.

7.3 Visualization Improvements

7.3.1 Module GUI

We have updated the user workflow for the EM tracker module. Shown below is the updated module GUI. On the left, we allow users to select the input coronal and sagittal X-rays. We would then automatically configure the view windows on the right, an improvement from the old manual configuration. The top left panel is a zoomed view that follows the current catheter tip. This was adopted from surgeon feedback that a zoomed in view is needed for accurate navigation. On the top right panel is the tracked path in empty space, where the user can have a 3D view of the path. The bottom two panels are the tracked path overlaid on the full coronal and sagittal X-ray respectively. This allows the user to gain full context of where the catheter currently is.

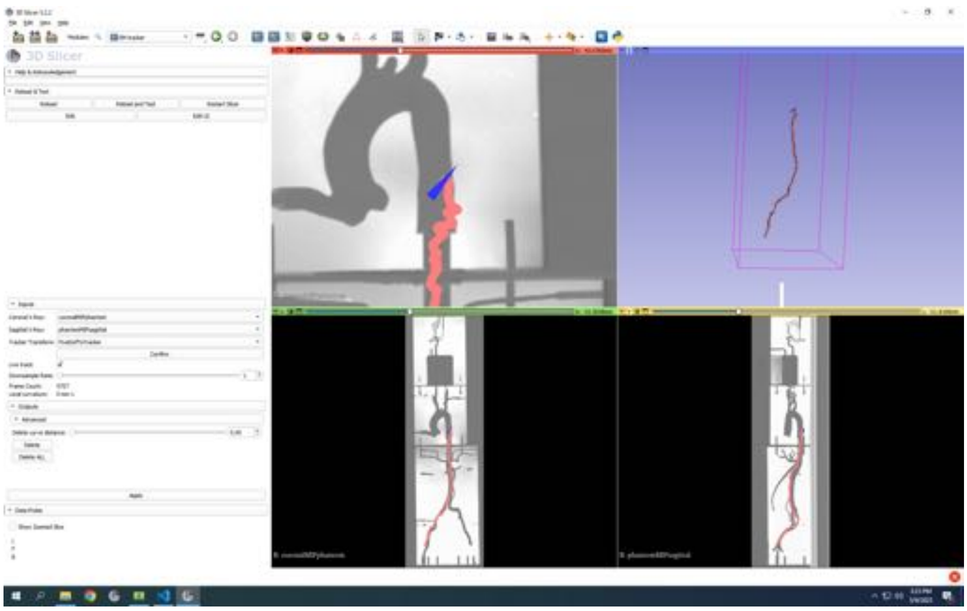

Figure 7.3 Module GUI for Path Visualization

7.3.2 Tip Visualization

We developed two versions of tip visualization. For iteration one, we displayed the tip orientation directly based on the sensor data. It leads to accurate tip pose display, as evidenced in figure 6.3.2. However, the version lacks any body body estimation. As a result, the display is suboptimal for guidance during sharp turns at vessel junctions.

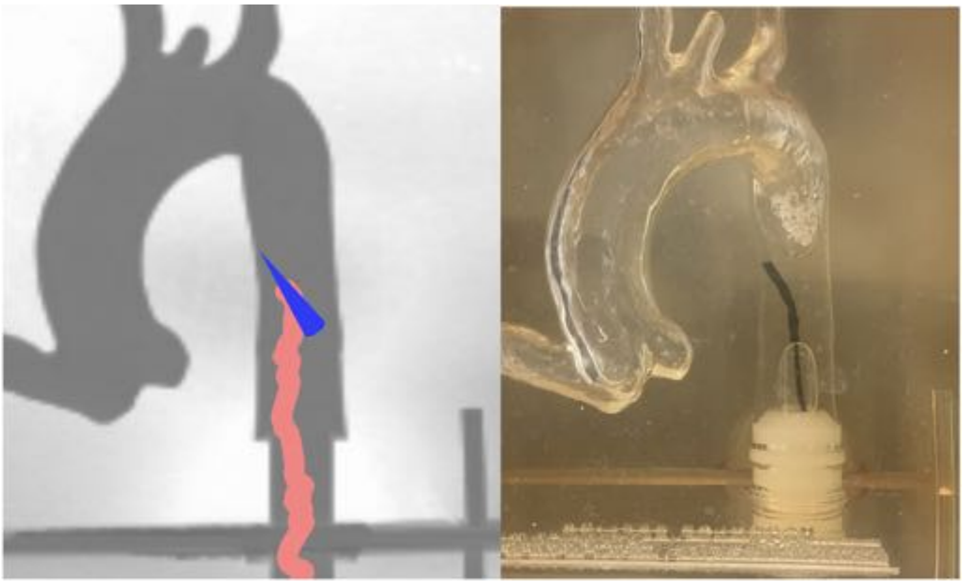

Figure 7.3.2.1 The first iteration of tip visualization. It displays the tip orientation with good accuracy, but without showing any body pose estimation information

Afterward, we developed the second iteration of tip visualization. It now displays both the tip and tool body pose estimations, shown with improved models. This results in an accurate representation of the frontal section of the catheter. This is extremely helpful for navigating in small vessel junctions, such as the aorta-carotid artery junction shown in Figure 6.3.2.1..

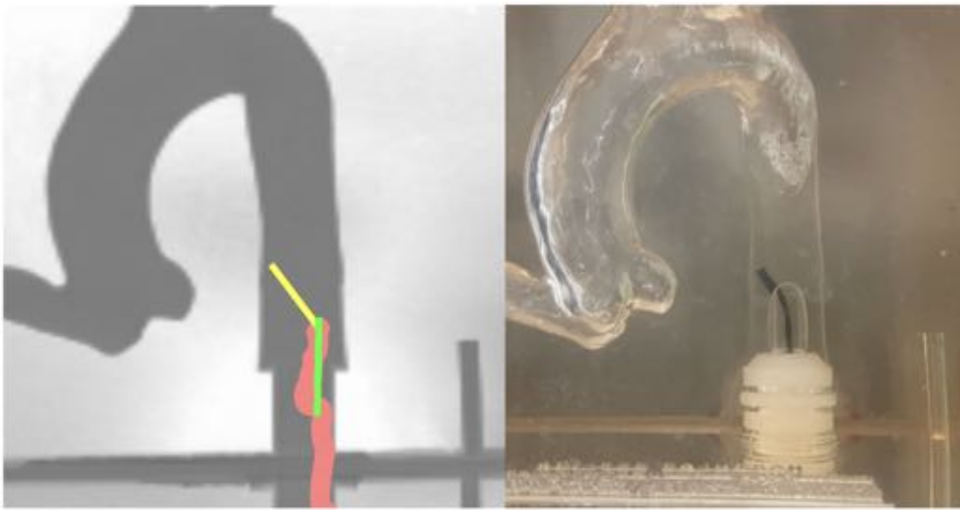

Figure 7.3.2.2 The second iteration of tip visualization. It now displays both the tip and body pose orientation. This can be very helpful for navigating the catheter at vessel junctions, such as the aorta-carotid artery junction, as pictured at the top of this figure.

8 Discussion

8.1 Current Limitations

1. When the catheter tip is pointing downwards toward the table or upwards from the table, the current tip visualizes in 2D looks identical, making it hard to differentiate. One possible solution is adding color indications for the direction.
2. For path-based registration, our current algorithm is finding the transform between the tracker path and the centerline of the vessel with the assumption that the path will follow the centerline most of the time. However, this assumption is not valid when the catheter is turned, especially in the arch of the heart – the catheter will more likely go along the wall of the vessels instead of the center line. This may cause difficulties in curve fitting and lead to inaccurate registration results.

8.2 Future Work

1. A quantitative method to evaluate the error of the registration is needed.
2. A user study will be performed to evaluate the usability of the whole system.

9 Conclusion

Overall, we created a proof-of-concept system where it is possible to replace fluoroscopy with EM tracking. We achieved high accuracy registration and clear visualization of catheter navigation in vessels. However, the project currently views the problem from more of an engineering perspective, and more detailed needs to be flushed out for application in a medical environment

Reflecting on the project, we were happy with the progress that we have achieved, and learned a lot more about computer integrated surgery by applying our theoretical knowledge.

10 Management

10.1 Progress Evaluation

All dependencies were resolved by the set deadline. During implementation, although some deliverables (mainly path visualization) were delayed due to changing expectations, we were able to achieve all deliverables, including the maximum, in the end.

10.2 Role Distribution

Huilin Xu was responsible for manufacturing the prototype catheter and evaluating it. In the second half of the term, since the catheter prototypes were finished, she worked on path-based registration.
Shanelle Cao was responsible for registration along with Huilin Xui. She completed fiducial point registration. In the second half of the term, she moved to working on improving the tracking module GUI.
Fangjie Li was mainly responsible for path visualization. He completed improving the tip visualization. In the second half of the term, he moved to working on path-based registration with Huilin Xu.

10.3 Weekly Meeting

The team met with the mentors every Thursday at 3:30 pm, in the lab space to discuss progress and plans.

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