Design of a Robotic System for Ultrasound-Guided Central Line Placement

EN.601.656 Computer-Integrated Surgery II
Final Report
Team 22

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Team Mentors: Dr. Axel Krieger, Lidia Al-Zogbi, Dr. Vinciya Pandian
Dr. Mathias Unberath, Wenhao Gu

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1 Introduction

This report discusses the detailed design of a lightweight and patient-mountable robotic system for ultrasound-guided central line placement. It outlines the high-level and low-level design specifications of the system, including its mechanism and workflow design. Furthermore, the details of the implementation of the system is discussed, along with plans for future improvements. By presenting our design, we hope to contribute to the ongoing efforts to improve the safety and accuracy of central line placement.

1.1 Background

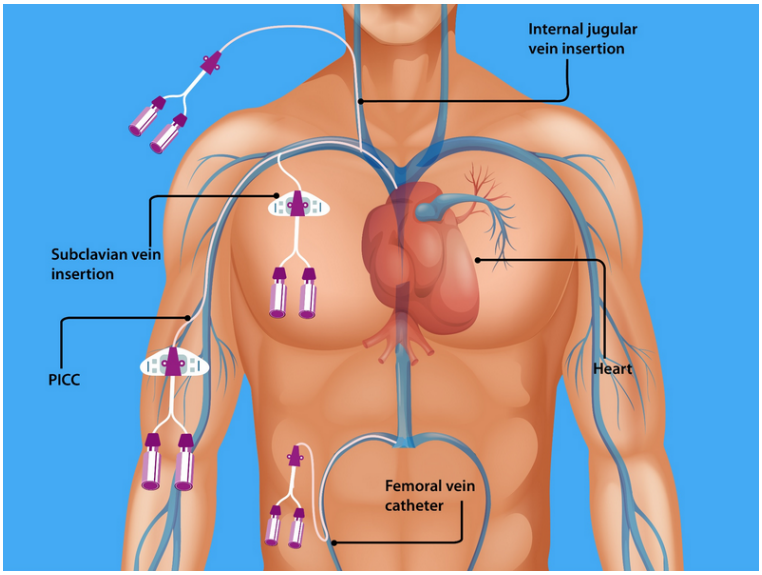

Figure 1: Different access points for CICCs ([1])

Central line placement is a critical procedure that is commonly performed for a reliable, short-term or long-term intravenous vascular access. A central venous catheter is a type of catheter that is inserted into a large vein in the body, typically in the chest or neck, to provide easy access for medical treatment, monitoring, hemodialysis, emergency venous access, blood draws etc. There are several types of central venous catheters, including Centrally Inserted Central line Catheters (CICCs), which are inserted into a central vein and then threaded through the vein until the tip of the catheter is located near the heart. The procedure has 4 standard access points (refer to [3], [1]) as depicted in Fig. 1: jugular, subclavian, femoral and arm veins. The different kinds of CICCs (see [2], [4]) may be listed as follows (refer to Fig. 2):

1. Non-tunneled CICC: This is the most common type of CICC and is inserted through the skin into the jugular, subclavian, or femoral vein. It is typically used for short-term access, such as for administration of medication, fluid replacement, or for drawing blood.

2. Tunneled CICC: This type of CICC is similar to a non-tunneled catheter but has an additional tunnel created under the skin from the insertion site to the exit site. The tunnel helps to anchor the catheter and reduce the risk of infection. Tunneled catheters are commonly used for patients who require long-term access, such as for chemotherapy or dialysis.

3. Peripherally Inserted Central Catheter (PICC): A PICC is a type of CICC that is inserted through a peripheral vein in the arm and threaded through the vein until the tip reaches the central veins. PICCs can be used for long-term access and are often used in patients who require frequent blood draws or administration of medications that may irritate peripheral veins.

4. Implanted Port: An implanted port is a type of CICC that is surgically implanted under the skin, typically in the chest or arm. The port has a small chamber with a septum that is accessed with

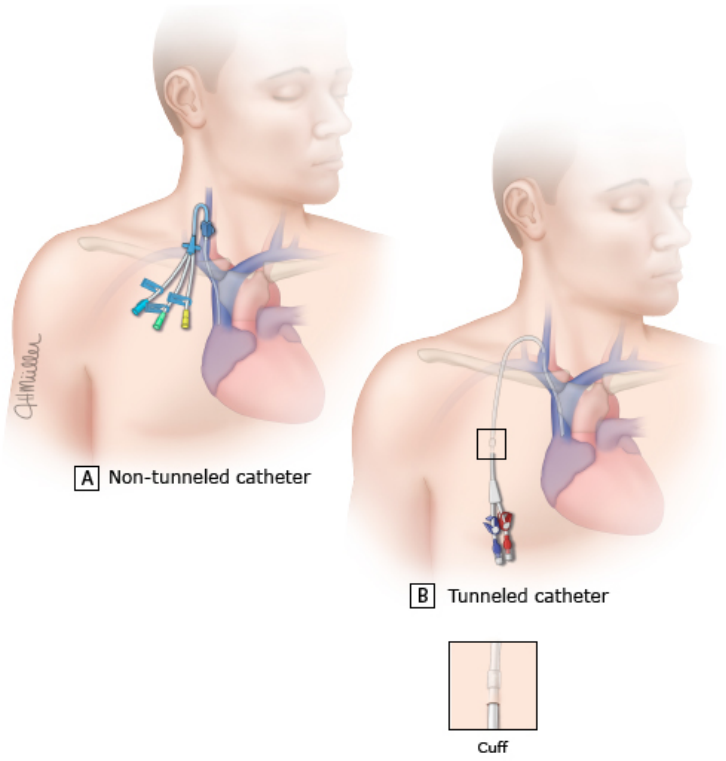

Figure 2: Tunnelled and non-tunnelled catheters ([2])

a special needle for the administration of medication, chemotherapy, or blood draws. Implanted ports are often used for long-term access and can remain in place for months or years.

The choice of CICC depends on the individual patient's needs and medical condition. The medical team will work with the patient to determine the most appropriate type of catheter for their specific situation.
The following is a general outline of the workflow for central line catheter placement (refer to [3], [5]):

- Preparation: Before the procedure, the patient will be prepared by cleaning the skin over the intended insertion site with chlorhexidine solution and administering any necessary medications, such as antibiotics or sedatives. The clinician and the workspace will also be sterilized.
- Prepare ultrasound: Insert the ultrasound probe into a sterile sheath, and use sterile ultrasound gel during the procedure. Identify the jugular vein and carotid artery to ensure a proper entry site.
- Anesthesia: Local anesthesia is administered to numb the area where the needle will be inserted.
- Needle insertion: The clinician will insert a needle and follow the needle trajectory with ultrasound until the vein is entered and blood enters the syringe.
- Guidewire insertion: Remove the syringe and advance the guidewire through the needle. Let the guidewire go along the blood flow. Once the guidewire is ready, the needle is removed. It is essential to always maintain a grip on the wire throughout the procedure.
- Dilation: Insert a dilator and then remove it to extend the entry hole to the width of the catheter.
- Catheter insertion: The catheter is then threaded over the guide wire and advanced into the vein. Once the catheter is in the proper position, the guide wire is removed.

- Secure placement: Flush all ports with saline. The catheter is secured in place with sutures or adhesive, and a dressing is applied over the insertion site.
- X-ray confirmation: In some cases, an X-ray may be used to confirm that the catheter is properly positioned.
- Post-procedure care: The patient will be monitored for any complications, such as bleeding, infection, or pneumothorax (collapsed lung). The catheter will also be flushed with saline or heparin to prevent clotting.

Overall, central line catheter placement is a complex procedure that requires careful preparation, skill, and attention to detail to ensure successful placement and minimize the risk of complications.

1.2 Motivation

The central line catheter placement procedure may involve the following complications, that may occur during catheter placement or post the procedure:

1. Pulmonary complications including pneumothorax, air embolism.
2. Cardiac complications including arrhythmia and cardiac arrest.
3. Vascular complications including arterial puncture, venipuncture and hematoma.
4. Delayed complications may include catheter-related bloodstream infections, device dysfunction and central vein stenosis.

Central line infections are a serious concern in healthcare settings. While the central lines are used to administer medication, nutrition, and fluids directly into a patient's bloodstream, they can also introduce bacteria and other microorganisms that can cause infections. According to the Centers for Disease Control and Prevention (see [1]), central line-associated bloodstream infections (CLABSIs) can result in prolonged hospital stays, increased healthcare costs, and even death. Therefore, a robotic system for central line placement can minimise the risk of infection, help improve patient outcomes and reduce healthcare costs.

Furthermore, the procedure of central line placement can be physically and mentally demanding for clinicians. Performing the procedure requires a steady hand, precise movements, and the ability to maintain focus over a prolonged period of time. Clinicians may experience physical fatigue and discomfort, as well as mental fatigue and burnout. Hence, a robotic system can assist clinicians with these tasks, not only helping alleviate their burden but also improving the efficiency and safety of the procedure.

Ultimately, by addressing these two key issues, a robotic system for central line placement could reduce the time required for the procedure, increase accuracy, and potentially reduce complications associated with the placement of central lines.

1.3 Prior Work

In the development of a lightweight body-mountable robotic system for automating needle insertion, guidewire, and catheter advancement procedures for central line placement, it is essential to review the prior work in this field. Various compact robotic systems have been designed and implemented for needle insertion and other medical applications.

The first paper, "Body-Mounted Robotic System for MRI-Guided Shoulder Arthrography: Cadaver and Clinical Workflow Studies," emphasizes the need for a robotic system for ultrasound-guided needle insertion (see [6]). However, the system is bulky and tackles only femoral access. This work demonstrates the potential benefits of using a robotic system to assist in needle placement procedures, but its bulky nature and limited application make it less suitable for our project's goals.

The second paper is "An MRI Coil-Mounted Multi-Probe Robotic Positioner for Cryoablation."(see [7]) This paper proposes a compact and patient-mountable robotic system to insert multiple probes under MRI monitoring. The design architecture of this system helps divide the problem into subtasks, and it is inspiring in the way it performs multiple object insertions. However, unlike inserting three identical probes, catheter and guidewire have different stiffness and dimensions from the needle. The arc design and the sliding design of the carriage are also inspiring for our project. The ease of sterilization problem is also addressed in the paper, which is a problem to be solved in our project. However, this system only performs the adjustments of the orientation of the probes, and the clinicians still need to insert the probes manually after the adjustment. Our project aims to cover all angle adjustments and insertion procedures.

Another paper, "Design of a Percutaneous MRI-Guided Needle Robot With Soft Fluid-Driven Actuator," presents a novel design for a percutaneous needle robot that can be guided by magnetic resonance imaging (MRI)(see [8]). The robot is intended for use in minimally invasive medical procedures, such as biopsy and brachytherapy, where high accuracy and precision are required to minimize damage to surrounding tissue. This paper describes a robotic system for needle insertion that uses a soft, flexible actuator. While the specific application of the system is different (MRI-guided needle placement versus ultrasound-guided central line placement), the use of a flexible actuator could provide similar benefits in terms of safety and navigational capabilities.

To conclude, the past decade has witnessed research on compact, i.e., hand-held or body-mounted, robots for needle insertion for various medical applications. While these prior works provide valuable insights and potential design inspiration, they also have limitations that make them less suitable for our specific project goals. Therefore, there is a need to develop a lightweight body-mountable robotic system for automating the needle insertion, guidewire, and catheter advancement procedures of central line placement, thereby bridging the research gap in design and applications.

1.4 Objectives

The objective of this project is to design and develop a robotic system for ultrasound-guided central line placement that can enhance the accuracy and safety of the operation. The goals of this project are as follows:

1. Develop a prototype of a robotic system for untunnelled central line catheter placement through the jugular vein. The system would automate the following procedures:
    - Needle insertion
    - Guidewire insertion
    - Catheter insertion
2. Provide documentation and support for the system to ensure that it can be integrated into clinical practice and used effectively by healthcare providers.

Overall, the proposed system aims to improve patient safety and outcomes by providing a more accurate and reliable method for central line placement. By achieving the goals outlined above, we believe that the system will be a valuable addition to clinical practice and will have a significant impact on patient care.

2 Technical Approach

This section presents the technical approach we used to develop our robotic system for ultrasound-guided central line placement. It begins with a discussion of the assumptions we made during the design process. We then describe the high-level and low-level design specifications. The details of the robot mechanism design are explained, along with the operation workflow design that describes how the system is operated and controlled and interacts with the patient. By detailing our technical approach, we aim to provide a comprehensive understanding of the design and development process of our robotics system.

2.1 Assumptions

The following assumptions were made during the design and development of the robotic system:

- **Clinician's role:** The clinician will scan the region using ultrasound and decide on the insertion site and angle, ensuring the robot's focus is on the insertion process.
- **Guidewire type:** The guidewire used will be straight without a J-tip, simplifying the design requirements for the guidewire advancement mechanism.
- **No dilators:** Dilators will not be used in the insertion process, reducing the complexity of the robotic system.
- **Manual retraction:** The clinician will manually retract the needle and guidewire, allowing the robot to concentrate on insertion tasks.
- **Detachable syringe:** The syringe will be detachable from the needle without the need for a twisting motion, easing the robot's needle insertion mechanism design.
- **Clinician's assistance:** The clinician will load the guidewire and catheter onto the robot system, simplifying the design requirements for object handling.

2.2 High-Level Design Specification

The high-level design specification is as follows:

- **Core functions:** The robot should be able to perform needle insertion, guidewire, and catheter advancement, automating key aspects of central line placement.
- **Patient adaptability:** The robot should be able to adapt to variations in patient anatomy, ensuring compatibility across different individuals and increasing its applicability.
- **Infection mitigation:** The robot should be able to mitigate the risk of infections by incorporating sterilizable components into the system design, enhancing patient safety.
- **Ultrasound integration:** The robot should be able to integrate with a wireless ultrasound probe, facilitating real-time guidance during the procedure.

2.3 Low-Level Design Specification

The low-level design specification is as follows:

- **Angular workspace:** The robot should have an angular workspace of around 10 degrees to 45 degrees relative to the skin, ensuring a suitable range of insertion angles.
- **Degrees of freedom:** The robot should have 2 rotational degrees of freedom and 2 translational degrees of freedom, enabling precise positioning and movement during the procedure.
- **Precision and accuracy:** The robot should have a precision of at least 1mm in all movements with an accuracy of 90%, ensuring reliable and consistent performance.
- **Needle insertion parameters:** The robot should be able to insert an 18-gauge needle at an angle of 30-40 degrees (see [9]) and a depth of 2-6 cm (refer to [10]), conforming to standard central line placement guidelines.
- **Guidewire advancement:** The robot should be able to advance about 10-15 cm of a 50 cm guidewire (see [11]), ensuring proper placement within the target vessel.
- **Guidewire compatibility:** The robot should be able to insert a guidewire with a diameter of 0.035 inches (see [9]) through the needle, accommodating standard guidewire sizes.
- **Catheter compatibility:** The robot should be able to insert a catheter with a size 8.0 French (refer to [9]), conforming to standard central line catheter sizes.
- **Remote center of motion indication:** The robot should be able to indicate the remote center of motion, providing guidance and ensuring proper alignment during the procedure

2.4 Robot Mechanism Design

The robotic system consists of five parts: the base, the arc, the carriage, the needle insertion actuator, and the guidewire & catheter advancement actuator, as shown in Fig. 3. It has 2 rotational degrees-of-freedom (DoF) and 2 translational DoF. The angular workspace of insertion is 13 degrees to 50 degrees relative to the skin, and the depth workspace is 19.8 mm to 67.4 mm. The mechanical remote center of motion (RCM) is 8.5 mm above the skin.

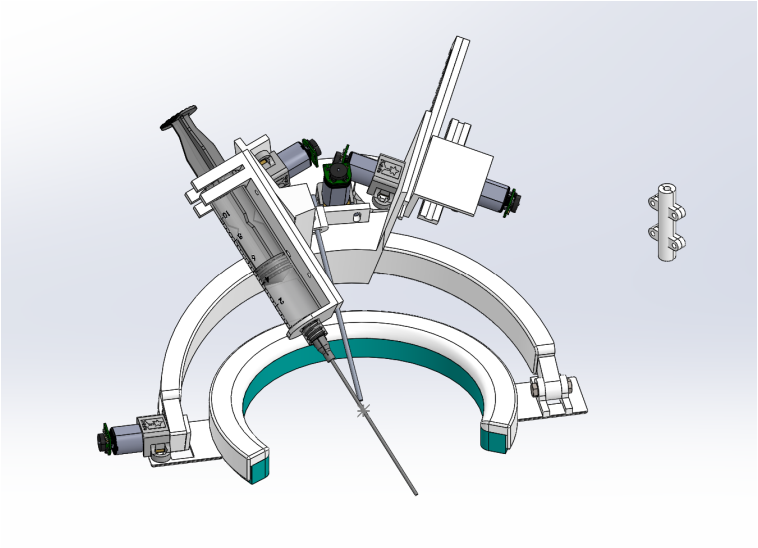

Figure 3: Isometric view of the overall design

The base includes a GelPort and a rigid base, as shown in Fig. 4.

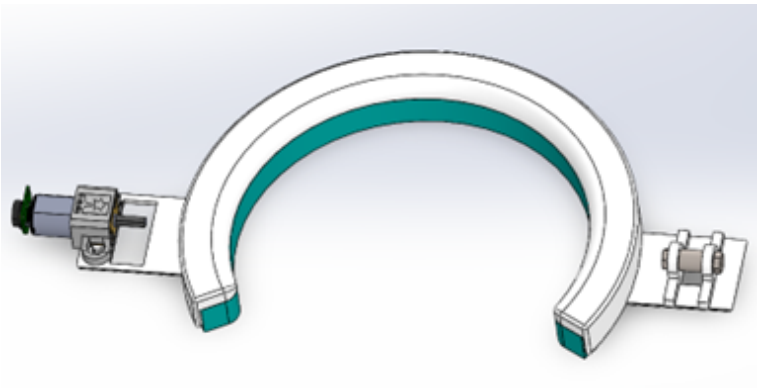

Figure 4: Details of the base

1. GelPort, a sticky soft material generally used in laparoscopic surgery, holds the robot on the patient.
2. The rigid base sticks on the GelPort, which connects the GelPort and supports the arc.

The arc is connected to the rigid base and is driven by a step motor attached to the rigid base to provide one rotational DoF along the y-axis, as shown in Fig. 5. The teeth on the arc are matched with the gear on the carriage, providing restrictions on the motion of the carriage.

The carriage uses a circular rack and pinion gear mechanism to slide over the arc, as shown in Fig. 6. There is a small gear on the carriage driven by a step motor on the back to provide one rotational

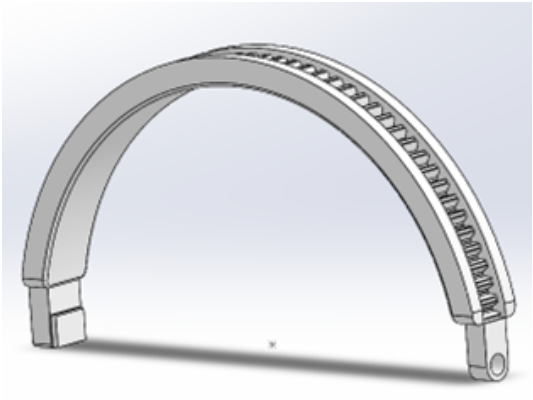

Figure 5: Details of the arc

DoF along the x-axis. There is a laser pointer bucket at the bottom of the carriage, holding the laser pointer to indicate the RCM when rotating. There is a motor on each side of the carriage, driving the needle insertion actuator and the guidewire & catheter advancement actuator separately to provide two translational DoF. As both actuators use a rack and pinion gear mechanism to move along the carriage, there are pinions attached to the shaft of the motors and sliders matched with the racks on the actuators to provide restrictions on the motion.

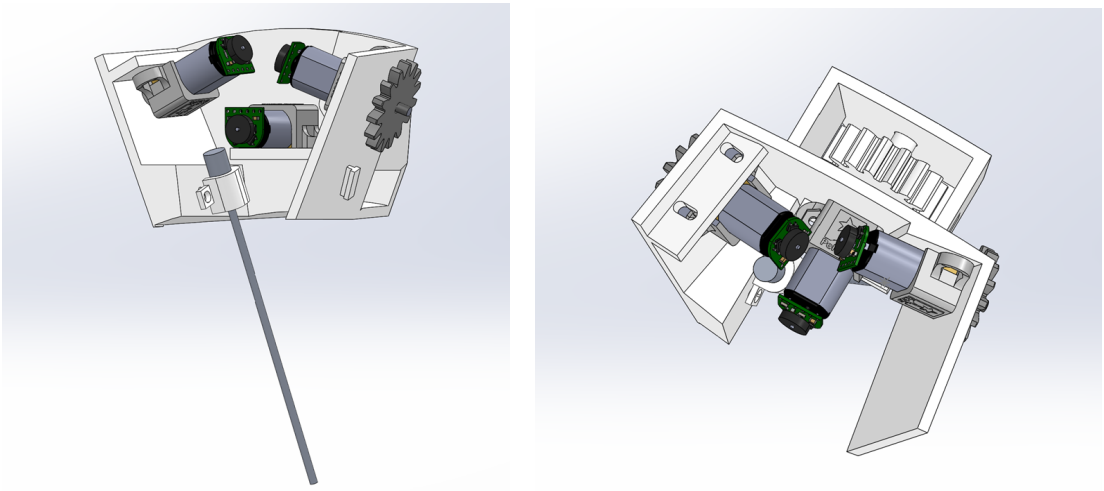

Figure 6: Details of the carriage

The needle insertion actuator is a holder of the needle syringe, as shown in Fig. 7. There is a rack on the back of the holder, which is coordinated with the pinion on the carriage. There is a guide rail on the rack, which is coordinated with the slider on the carriage.

The guidewire & catheter advancement actuator is shown in Fig. 8. Similar to the structure of the needle insertion actuator, there is a rack on the back of the actuator, which is coordinated with the pinion on the carriage. There is a guide rail on the rack, which is coordinated with the slider on the carriage. A detachable guidewire & catheter feeder is held on the actuator, allowing the guidewire and catheter to go through and restricting the direction of their movements. The feeder is coordinated with a roller driven by a step motor to advance the guidewire and catheter.

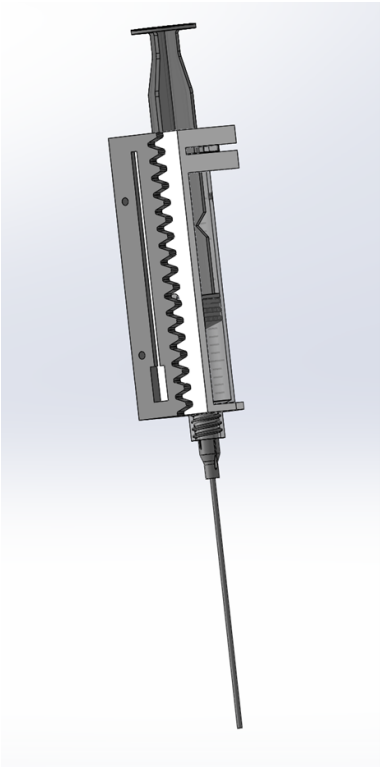

Figure 7: Details of the needle insertion actuator

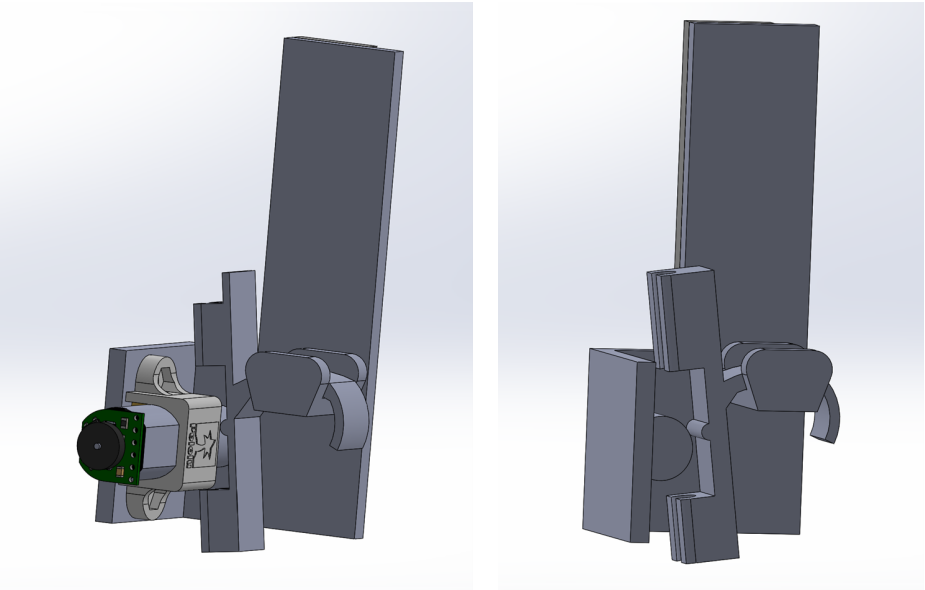

Figure 8: Details of the guidewire & catheter advancement actuator

2.5 Workflow design

The operation workflow design follows the Seldinger technique, a medical procedure that provides safe access to blood vessels and other hollow organs. The team modified the insertion part to include the robot system in the procedure. The following is a summary of the workflow:

1. The clinician sterilizes themselves and the patient.

2. The ultrasound probe is placed on the area of interest by clinicians, and the ultrasound image is displayed on a screen. The clinician finds the target point and decides on the needle insertion site and angle on the image. This information is then transformed from the image frame to the robot frame.

3. The arc and the carriage move to the appropriate position according to the insertion information, ensuring the RCM of the robot, which is indicated by the laser pointer, coincides with the insertion point. The needle syringe, which is preloaded on the carriage, is actuated and the needle is inserted into the skin by 2-6 cm. After ensuring the success of the needle insertion, the needle is clamped by the clinicians using surgical clamp scissors, and the

4. The carriage moves along the arc, ensuring the advancement direction of the preloaded guidewire coinciding with the insertion angle of the needle. The guidewire is then actuated and advanced through the needle into the vein by 10-15 cm. After ensuring the success of the guidewire advancement, the guidewire is clamped by the clinicians using surgical clamp scissors, and the needle is retracted by the clinicians.

5. The catheter tip is loaded to the end of the guidewire via the adapter. The guidewire feeder on the carriage is taken off and replaced by the catheter feeder by the clinicians. The catheter is then actuated and advanced along the guidewire into the vein. After ensuring the success of the catheter advancement, the guidewire is retracted by the clinicians, and the catheter is sutured onto the skin.

By following this process, the clinicians only need to touch the needle and guidewire by hand once during the retraction, which is a much easier task than insertion and can reduce the possibility of infection as they touch less equipment. The optimized workflow design ensures the efficient use of the robot system and provides a safe and reliable way to access blood vessels.

3 Result

Throughout the project, we successfully designed and assembled the primary structure and components of the robotic system, including the base, arc, carriage, needle insertion actuator, and guidewire and catheter advancement actuator. These essential elements have demonstrated significant progress towards our goals of improving the safety and accuracy of central line placement procedures. As we encountered challenges related to assembly, such as component alignment and clearances, and motor control issues like synchronization and smooth motion, our team worked diligently to optimize the design through iterative problem-solving and improvements.

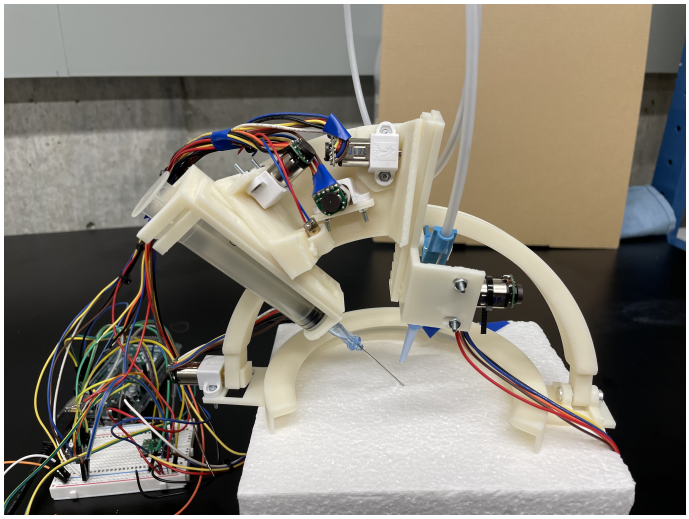

Figure 9: Needle insertion performed by the system

By addressing these challenges, we have effectively laid a solid foundation for the system, enabling precise needle insertion (see Fig. 9) and guidewire (see Fig. 10) and catheter advancement (see Fig. 11 and 12) with 2 rotational and 2 translational degrees of freedom. This groundwork paves the way for future refinements and functional testing to ensure the system's effectiveness in streamlining central line placement procedures and enhancing patient safety.

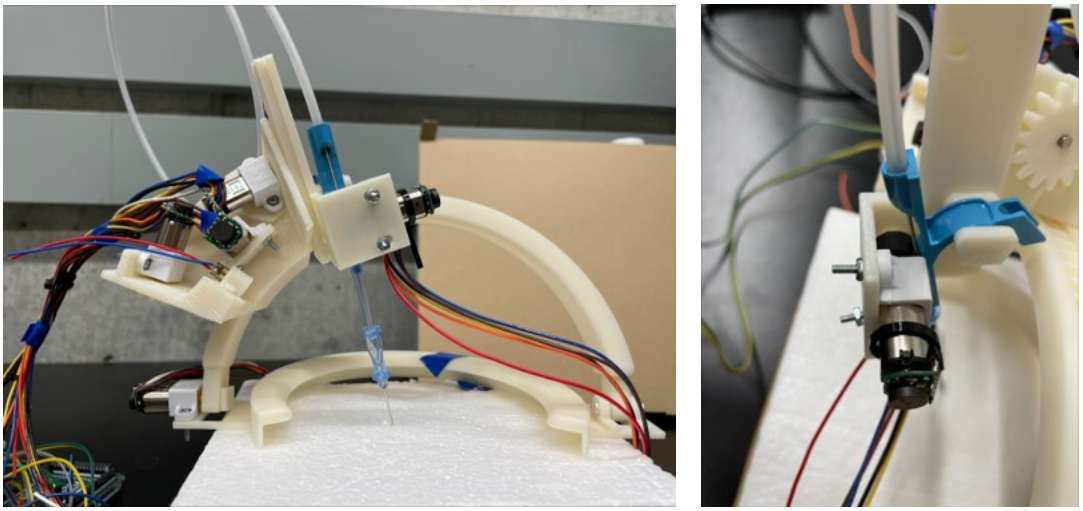

Figure 10: Guidewire advancement performed by the system

Figure 11: Adapter used for placing catheter over guidewire

Furthermore, our team's innovative use of the sticky GelPort material combined with the rigid base for stable attachment to the patient, as well as the arc and carriage mechanisms for smooth, controlled movement, showcases our dedication to creating a practical, feasible system that takes real-world clinical situations into account. By focusing on the specific needs and challenges of central line placement, we have made substantial progress towards achieving a functional robotic system that can ultimately transform the way this critical procedure is performed, benefiting both patients and clinicians alike.

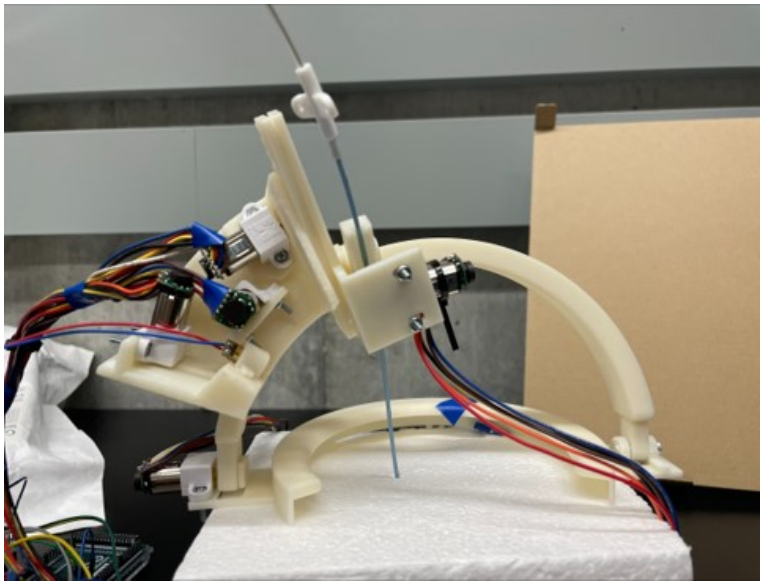

Figure 12: Catheter advancement performed by the system

4 Future Work

In the future, we aim to further improve our robotic system for ultrasound-guided central line placement by considering several potential enhancements. One such improvement is size optimization, which entails making the mechanism smaller and adjustable to fit the different anatomies of patients. Additionally, we plan to design the robotic system to move the ultrasound probe during scanning to find the insertion point and hold the probe during the needle insertion process, improving ultrasound probe motion control.

Another area of improvement involves enhancing the robotic system's object clamping capabilities, enabling it to clamp various objects, including the needle and guidewire. Furthermore, we plan to work towards full automation of the process, as the current procedure requires manual operations. A crucial step in this direction is completing the registration between the ultrasound probe and the robotic system, allowing for the integration of the robotic system with the ultrasound system to enable accurate and efficient insertion.

Implementing a feedback system to track the position of the needle, guidewire, and catheter during the operation will also be an important enhancement. We also intend to develop a graphical user interface (GUI) for clinicians to input the angle and position, as well as provide feedback on the results of insertion tasks.

Lastly, it is essential to conduct functional testing to ensure that the robotic system can perform necessary movements and actions accurately and reliably. Performance testing, in a laboratory or simulated clinical environment such as phantoms, will be carried out to ensure that the robot can perform central line placement accurately and consistently while identifying and responding to any issues that may arise. By implementing these potential improvements, the robotic system for ultrasound-guided central line placement can become more efficient and reliable, reducing the risks associated with manual procedures.

5 Management Plan

The management plan is divided into seven parts: a brief introduction of the mentors, team members and their responsibilities, deliverables, dependencies, the timeline of the tasks, the communication methods, and a comparison between the initial plan and the achieved milestones.

5.1 Mentors

The mentors consist of:

- Dr. Axel Krieger (axel@jhu.edu)
- Lidia Al-Zogbi(lalzogb1@jhu.edu)
- Dr. Vinciya Pandian (vpandia1@jhu.edu)
- Dr. Mathias Unberath (unberath@jhu.edu)
- Wenhao Gu (wgu11@jhu.edu)

5.2 Team Members and Responsibilities

The team consists of:

- Kesi Liang (kliang19@jhu.edu)
  MSE BME Student, first-year
  Responsible for the CAD model design of the robotic system, the workflow development, the 3D printing of the parts, and the documentation.
- Pranathi Golla (pgolla1@jhu.edu)
  MSE ME Student, first-year
  Responsible for the mechanism design, ordering electronics, motor control using Arduino and assembly of the prototype.
- Xuanning Liu (xliu226@jhu.edu)
  MSE ME Student, first-year
  Responsible for the CAD model design of the robotic system, the workflow development, the 3D printing of the parts, and motor control using Arduino.

5.3 Deliverables

The deliverables of the project are shown below in Fig. 13.

	Deliverables
Minimum	• Design document with the high-level and low-level specifications of the robotic central line placement system, which can perform needle insertion, guidewire advancement, and catheter advancement through the subclavian vein. • CAD model of the robotic system.
Expected	• Prototype and functionality demonstration of the system, which can perform central line placement automatically with image guidance. • Documentation of the functioning of the system.
Maximum	• Experimental evaluation of the accuracy and safety of the system on phantoms. • Submission of the work to a peer-reviewed venue.

Figure 13: The minimum, expected and maximum deliverables of the project

5.4 Dependencies

The dependencies of the project are shown below in Fig. 14.

Dependency		Need	Status	Follow-up	Contingency Plan	Deadline
Prototyping/ Fabrication	3D printer and laser cutting	To do model prototype	Resolved	N/A	N/A	3/25/2023
	Ultrasound probe	Used as the sensor of the system	Resolved	Will be provided by Lidia	N/A	3/15/2023
	Hardware (Arduino board, motors, screws, and nuts)	To assemble the system	Resolved	Few parts already available; will purchase rest on McMaster-Carr	Purchase new ones if necessary, or borrow from Prof. Axel Krieger's lab	4/11/2023
Software	Arduino IDE	For communication with the Arduino board	Resolved	N/A	Other team members' laptop	3/25/2023
	SolidWorks	To build CAD model	Resolved	N/A	Other team members' laptop	3/15/2023
	ROS	Simulate and control the robot system	Resolved	N/A	Other team members' laptop	3/07/2023
Testing	Lab space (B08G)	For testing	Resolved	Two team members have access; other member will request Ashley soon	Other team members' access	3/07/2023
	Testing equipment (catheter kits)	For testing	Resolved	Will request Dr. Vinciya Pandian soon	N/A	4/11/2023
Financial support		To purchase necessary hardware	Resolved	N/A	If insufficient, need to borrow hardware from other labs	3/25/2023

Figure 14: Dependencies

5.5 Timeline

The timeline is shown in Fig. 15.

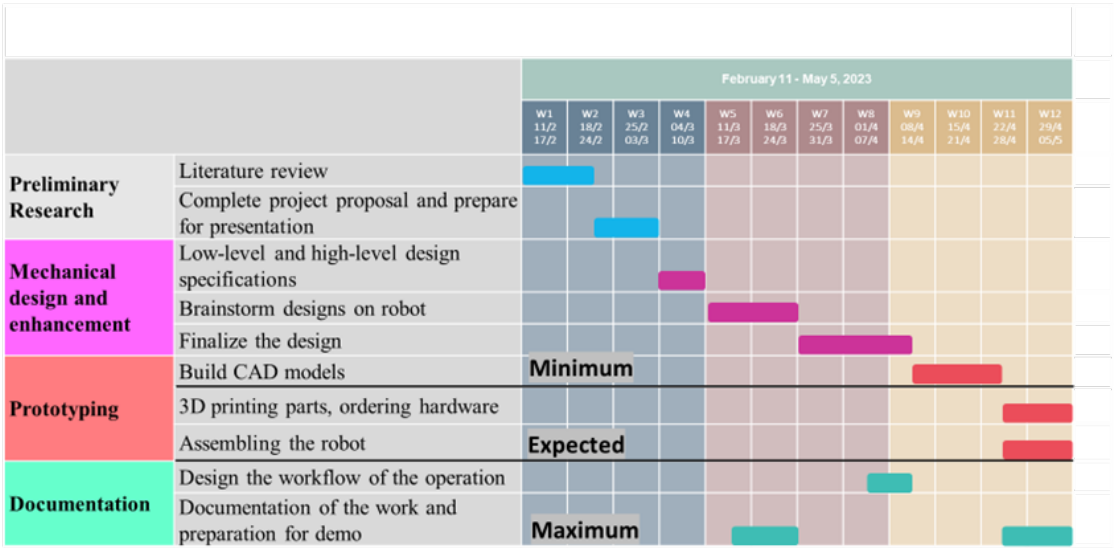

Figure 15: Timeline of the tasks

5.6 Communication

- Meeting
  - Mentor meeting
    Time: Tuesday 10:00 - 11:00
    Location: Zoom or Hackerman 116
    Weekly meeting scheduled with Lidia Al-Zogbi and Wenhao Gu, Dr. Axel Krieger attended the meeting biweekly
  - Group meeting
    Time: Thursday 10:00 - 11:00
    Location: Zoom or Hackerman 136
    Weekly meeting scheduled for three group members
- Communication platform
  Slack, Zoom, Overleaf, Dropbox, Email

5.7 Initial Plan VS Achieved Milestones

The dependencies of the project are shown below in Fig. 16.

Item		**Initial Plan**	**Achieved Milestone**
Design Specifications	Minimum Workspace	10cm x 10cm	Angular workspace: 15 °to 50° relative to the skin
	Degrees of Freedom	3 rotational 1 translational	2 rotational 2 translational
	Minimum Precision	1mm	3 mm
	Needle Insertion Depth	2-3 cm	2-6 cm
	Guidewire Advancement Length	18 cm	10-15 cm
Deliverables	Minimum	Design document with the high-level and low-level specifications	Completed
		CAD model	Completed
	Expected	Prototype and functionality demonstration of the system	Completed
		Documentation of the functioning of the system	Completed
	Maximum	Experimental evaluation	Not completed
		Submission of the work to a peer-reviewed venue	Not completed

Figure 16: The comparison of the initial plan and the achieved milestones

6 Conclusion

In conclusion, this project aimed to develop a lightweight, patient-mountable robotic system for ultrasound-guided central line placement in order to enhance the accuracy and safety of the operation. The primary goals of the project were to develop a prototype for non-tunneled central line catheter placement through the subclavian vein and provide comprehensive documentation to guide the clinician to employ the robot.

Throughout the project, we successfully designed a robotic system that automates key procedures in central line placement, including needle insertion, guidewire advancement, and catheter advancement. By incorporating the Seldinger technique in our operation workflow design and modifying it to integrate the robot system, we have created an optimized process that minimizes clinician contact with equipment and reduces the risk of infection.

The significance of this project lies in its potential to improve patient outcomes and safety in central line placement procedures. By automating critical steps and reducing the need for manual dexterity, the robotic system has the potential to decrease the risk of complications such as pneumothorax and infection. Additionally, the system may reduce procedure times and increase efficiency, leading to cost savings for healthcare providers.

Throughout the course of the project, our team gained valuable insights into the design and development of robotic systems for medical applications. We learned the importance of approaching design from a clinical perspective, designing a robot that is easy to use for clinicians, starting the design process with the clinical requirements of the applications of the robot, and how the design assumptions have to be carefully made. Furthermore, we realized the significance of developing an effective operation workflow to enhance the overall efficiency and safety of the procedure.

Overall, the project has contributed to ongoing efforts to improve the safety and accuracy of central line placement, with the potential to greatly impact patient outcomes and healthcare practices. By sharing our design and development process, we hope to inspire further innovation in the field of medical robotics.

References

[1] Y. Haddadin, P. Annamaraju, and H. Regunath, "Central line associated blood stream infections," in *StatPearls*, StatPearls Publishing, 2017.

[2] V. Chopra and I. Davidson, "Central venous access: Device and site selection in adults," in *UpToDate*, UpToDate Publishing, 2022.

[3] A. Tse and M. A. Schick, "Central line placement," in *StatPearls*, StatPearls Publishing, 2022.

[4] E. Cheung, M. O. Baerlocher, M. Asch, and A. Myers, "Venous access: a practical review for 2009," *Canadian Family Physician*, vol. 55, no. 5, pp. 494–496, 2009.

[5] J. R. Roberts and J. R. Hedges, *Roberts and Hedges' clinical procedures in emergency medicine E-book*. Elsevier Health Sciences, 2013.

[6] N. Patel, J. Yan, G. Li, R. Monfaredi, L. Priba, H. Donald-Simpson, J. Joy, A. Dennison, A. Melzer, K. Sharma, *et al.*, "Body-mounted robotic system for MRI-guided shoulder arthrography: Cadaver and clinical workflow studies," *Frontiers in Robotics and AI*, p. 125, 2021.

[7] F. Y. Wu, M. Torabi, A. Yamada, A. Golden, G. S. Fischer, K. Tuncali, D. Frey, and C. Walsh, "An MRI Coil-Mounted Multi-Probe Robotic Positioner for Cryoablation," *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2013*, 08 2013.

[8] Z. He, Z. Dong, G. Fang, J. D.-L. Ho, C.-L. Cheung, H.-C. Chang, C. C.-N. Chong, J. Y.-K. Chan, D. T. M. Chan, and K.-W. Kwok, "Design of a Percutaneous MRI-Guided Needle Robot With Soft Fluid-Driven Actuator," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2100–2107, 2020.

[9] H. E. Wang and T. A. Sweeney, "Subclavian central venous catheterization complicated by guidewire looping and entrapment," *The Journal of emergency medicine*, vol. 17, no. 4, pp. 721–724, 1999.

[10] A. Tse and M. A. Schick, "Central line placement," in *StatPearls [Internet]*, StatPearls Publishing, 2022.

[11] A. C. Heffner and A. Cochran, "Overview of acute and emergency central venous access in adults,"