Phlebot

Team D: Phle-Bot

Intravenous Robot -Design Proposal

Mechatronic Design - Spring 2023

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1. Project Description

Opening an intravenous line for some patients can be very challenging due to difficulty in visualizing the vein. Market solutions to this problem include infrared finders and NIR based sensors which reach prices upwards of $750. This project aims to create a low budget medical device that would be capable of opening an intravenous line to simplify the venipuncture process. The value of this project aims to provide a cheap alternative to the many current visualization tools out in the market currently, which in addition has the ability to successfully perform venipuncture and open an I.V. safely without a trained healthcare professional. The final design aims to be able to autonomously determine the vein and perform the injection without any external help.

2. Design Requirements

2.1 Explicit Requirements

As this device aims to compete against market devices and autonomously complete phlebotomy, a few key tasks must be completed in order to be considered successful. The finished device should be able to disinfect, inject/draw, and safely remove the needle after every run. One key requirement that is not mentioned below as it is specific to team members as well is safety, ensuring no harm comes to the surroundings and even the training arm as well. In regards to the performance specifications for this, the explicit requirements are outlined as follows:

- Device must operate on a Geriatric IV Training Arm
- Robot must use a dedicated supply or batteries for the final power
- Project budget must not exceed $800
- Project design must be robust and portable
- Device must not damage anything it interacts with and should prioritize safety
- Robot localization and calibration must be completed in a 5 minute period before hand
- Robot must be able to visualize the veins with an acceptable error of ± 0.5mm.
- The team may be permitted to apply the tourniquet manually
- Robot must disinfect the injection region with a disinfecting wipe
- Robot must also anchor the vein by pulling the skin tight to aid in venipuncture
- Robot may pick any visible and wide enough vein to withdraw blood or inject medication with the syringe
- Robot must withdraw the needle afterwards

2.2 Implied Requirements

Even though the following criteria may not be required, they are some that are inherently required to make this project follow all of the explicit requirements. As the project progresses, more undeclared requirements may be presented at a later date to assist in the success of all other requirements. Some additional specifications that will need to be met in order to assist in the success of this project are:

- Robot must have a maximum operating time of 10 mins
- Robot must fit a small area of 2ft x 2ft in order to be considered portable
- Robot will have a simple and effective user interface for choosing commands and displaying status
- Robot must inject at an angle of 30° or less [1]

2.3 Coolness Factors

To achieve a desired coolness to the venipuncture device, the robot aims also be able to meet the additional requirements if time permits:

- Robot must apply a band-aid over the puncture point of the arm
- Robot should aim to be completing entire task within 5 minutes of deployment
- Robot should be minimally invasive to the patient, ie. it should not be bulky or uncomfortable

3. Functional Architecture

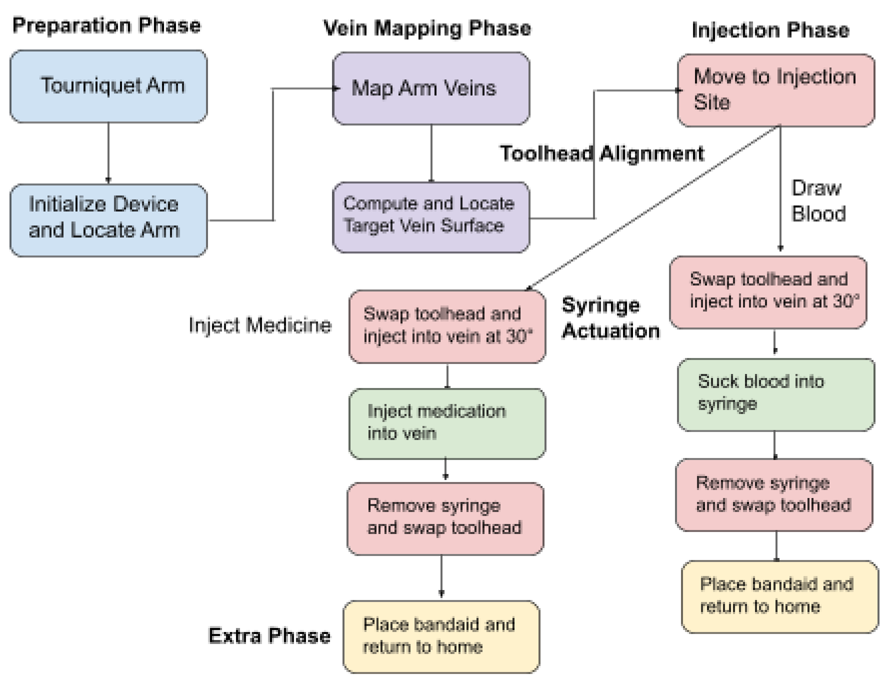

Figure 1: Flow Diagram of the Functional Architecture of Venipuncture Robot

The venipuncture robot's major functions and flow can be seen in Figure 1. The process will begin with the user inserting their arm into the robot in order to create an alignment that we can then follow. An external operator would then tourniquet the arm to stimulate blood flow and the robot will then localize and center itself after locating the notch of the arm.The sensing and computer vision processing occurs here as sensors in the form of cameras would be used to locate the vein for puncturing. The actuation phase begins here as the robot navigates to the appropriate toolhead and moves to the location of the vein. According to the desired output, the robot will anchor at this position and swap toolheads to complete each desired action such as disinfecting, injecting, removing, and bandaging the entry.

4. Design Trade Studies

4.1 Vein Identification

The market solutions for vein finding fall into three broad categories: transillumination lamps, IR Vein Finders and ultrasound.

Transillumination products are the cheapest category, and generally involve a small visible or IR spectrum light source held close to the patient's skin. The penetration of light through the skin enhances the contrast between the veins and the surrounding tissue. Trained medical personnel then visually identify the veins. There are many commercially available options online. Price range is on the order of $100. One example is the VeinLite LED+ product [2].

IR vein finders are a group of recent devices that use Near Infrared (NIR) illumination and cameras to penetrate skin and locate deep veins. They also project the segmented image onto the skin using calibrated projectors to visually aid medical professionals. These range in price from $1200 to $5200. Examples include the Accuvein 500, VS-400 and PBENO [3][4][5].

Ultrasound setups use ultrasound to map the subcutaneous structure of the arm. These are usually applied in cases of difficult cannulation cases, where the patient has collapsed veins, dark skin or deep veins. They require a trained technician to operate and the ultrasound equipment is also expensive, around $1000 for a basic model [6].

None of the existing options will serve our project through purchase. Even with transillumination, we will need to solve the perception problem. Instead we assessed the following options:

1. RGB-D Cameras: Products such as the Microsoft Kinect and the Intel RealSense return color and depth maps. These cameras project an IR speckle pattern to improve depth sensing on low-texture surfaces. The RealSense 435f offers <2% depth error at 2m. When employed at the minimum ideal range of 0.3 m, assuming the same accuracy holds, we have < 6 mm error. The depth stream has a resolution of up to 1280 x 720 at a rate of 90 fps. The cost is $350.

2. NIR Cameras: These cameras sense NIR light, which can synergize with an NIR light source to enhance the contrast of veins. The camera will cost $300 while a basic lamp will cost $30 (Amazon)
3. RGB Cameras: These are regular high-resolution cameras that can interface with embedded computers. A 12 megapixel camera will cost $30 (Amazon).

We selected the RGB cameras to begin with. Because the mapping strategy is much the same between the different camera types, switching will be a matter of changing the camera's mounting structure and code. We decided to first assess if the cheapest option: RGB cameras can produce the required mapping accuracy and quality.

Using NIR cameras is a common approach to vein mapping in the academic literature [7]. This is because the contrast in the NIR spectrum exceeds the visual contrast. This makes the task of image segmentation easier. However, given the large upfront cost and given that all our assessments will be performed on the simulated arm, it was decided to delay the purchase until the RGB solution was assessed. Furthermore, the literature is focused on room-scale scenery, and COTS sensors have been designed for larger range applications than we are using.

The RealSense Camera can potentially offer more accurate 3D structure than either of the projective sensors above. However, again, given the upfront cost and the fact that we are operating on a well-textured phantom arm, the RGB cameras may be a sufficient solution, pending testing.

Table 1: Camera Comparison

	Option 1: RGB Camera	Option 2: RGB-D Camera	Option 3: NIR Camera
Cost	$30	$350	$300
Reconstruction Quality	Varies	< 2% depth error (prior to fusion)	Varies
Segmentation Quality	51.29% [8]	51.29% [8]	98.1% [9]
Computation Cost (Reconstruction/Segmentation)	40s (300 images on Nvidia Titan X) [10] / TBD	Real-time [11] / TBD	TBD / 32.9 ms (NVIDIA GeForce MX250 GPU) [9]

4.2 Mechanical System Architecture

We could not find systems of the market that would perform vein cannulation autonomously. The closest comparison is surgical robots.

The most prominent example of surgical robots is Intuitive's set of surgical robotics products. These are multi degree-of-freedom robot arm platforms that use revolute and prismatic joints to provide a large range of motion in the workspace. Advantages include fine control over precise movement, which is necessary for performing minimally invasive surgeries, visual feedback from the toolhead and custom manipulators for various applications. Disadvantages include high complexity required for controls, higher cost, and large size.

Another example of physical architectures for replacing precision handwork is gantry systems as seen in Figure 2, which are common on FDM 3D printers, laser cutters and other advanced manufacturing machines. Advantages include ease of design, the structure for a machine of this type is well documented and relatively low cost due to this simple structure and the ubiquity of the required actuators. The drawbacks of taking this approach fall on patient comfort, with the large structure requiring patient maneuvering, and the difficulty when reaching the desired insertion angle.

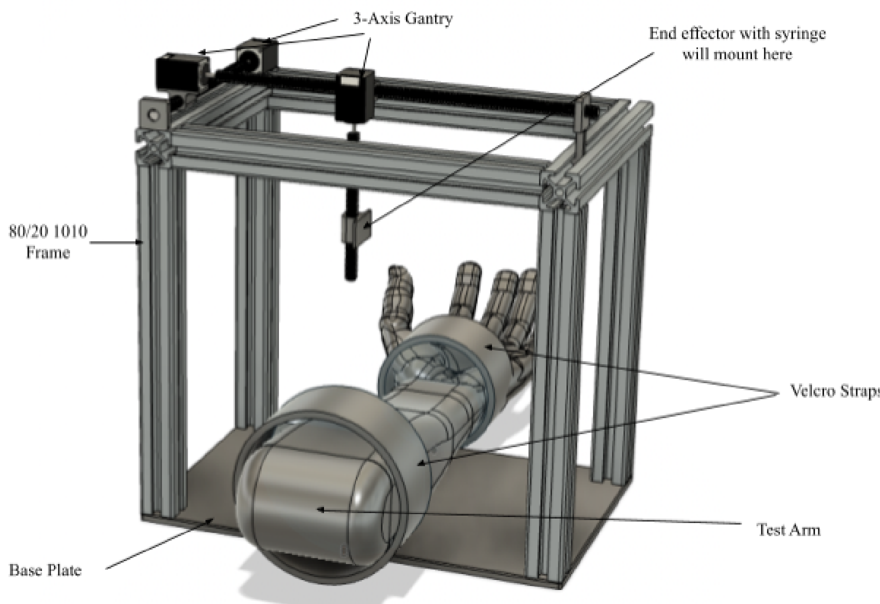

Figure 2: Previous design taking the gantry approach

The last system architecture to consider would be a purpose built solution for vein finding and autonomous injection. The proposed solution would include a curved rail which “clamps" the patient's forearm down into an arm rest. A toolhead would then travel along this rail, thus being a set height off of the forearm. The toolhead will be responsible for sanitizing the arm, scanning it to find a suitable point of injection, and venipuncture. The concept system is depicted below in Figure 3. The blue object represents the primary toolhead for insertion of the needle and interfaces with the patient's skin, the yellow is the cross arm rail to allow for the transportation of the toolheads into position, the green is the carriage rail to allow for positioning along the arm and the gray is the Y-axis carriage.

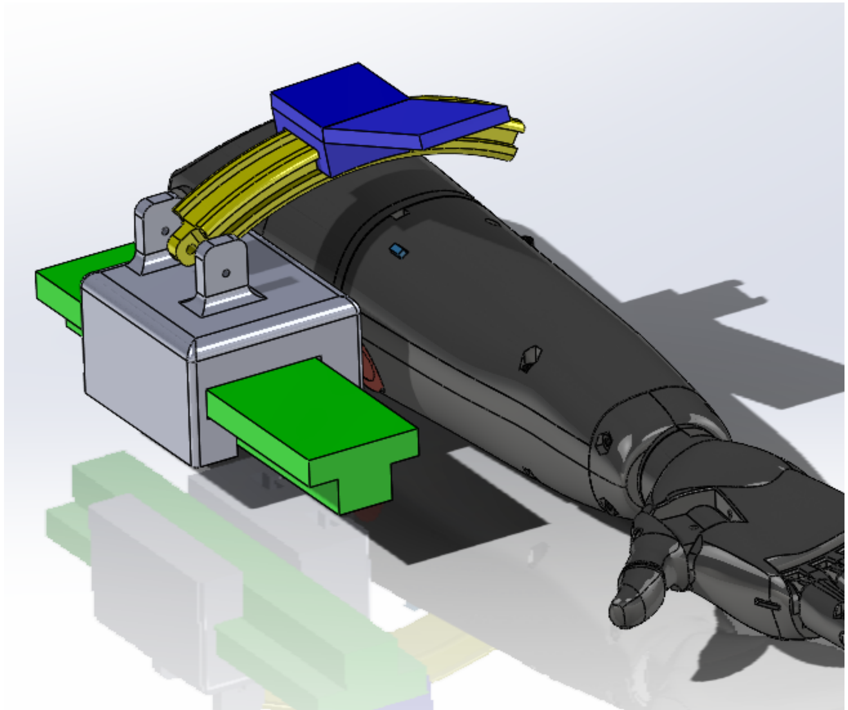

Figure 3. CAD mockup of the system design

The advantages to designing a purpose built solution is the ability to produce a minimally invasive solution, less complex controls and the potential for better performance. The primary disadvantage to taking this kind of approach is the higher required engineering time and effort and the potential failure of the system due to unforeseen design complications.

4.3 Choice of Actuators

For the conceptual design for the venipuncture robot, there were a few key features that needed to be considered as the type of actuator was decided. The main types of actuators that may have worked in the design are servos, steppers, pneumatics, and DC actuators. The team opted to add weights to each requirement according to what we deemed most important and the results can be seen in Table 2 below. The final decision was to implement pneumatic actuators in the system as it gave us the power needed to inject and more.

Table 2: Actuator Decision Table

Criteria	Weight	Stepper	Smart Servo	Servo	DC	Linear Actuator	Pneumatic
Toolhead and Carriage							
Cost	3	5	4	5	5	2	3
Force bandwidth	1	1	3	1	2	1	5
Position bandwidth	4	5	5	3	2	4	1
Size	2	3	3	4	2	1	5
Totals		42	41	36	29	25	28
Clamping							
Cost	3	..	..	..	..	..	..
Force bandwidth	5	..	..	..	..	..	..
Position bandwidth	2	..	..	..	..	..	..
Size	2	..	..	..	..	..	..
Totals		36	43	34	33	21	46
Insertion							
Cost	2	..	..	..	..	..	..
Force bandwidth	3	..	..	..	..	..	..
Position bandwidth	3	..	..	..	..	..	..
Size	5	..	..	..	..	..	..
Totals		43	47	42	32	24	49

5. Cyber Physical Architecture

The system cyber physical architecture between the entire system can be seen in Figure 4 below. The proposed system shows the steps in integrating both the hardware and software for the venipuncture robot.

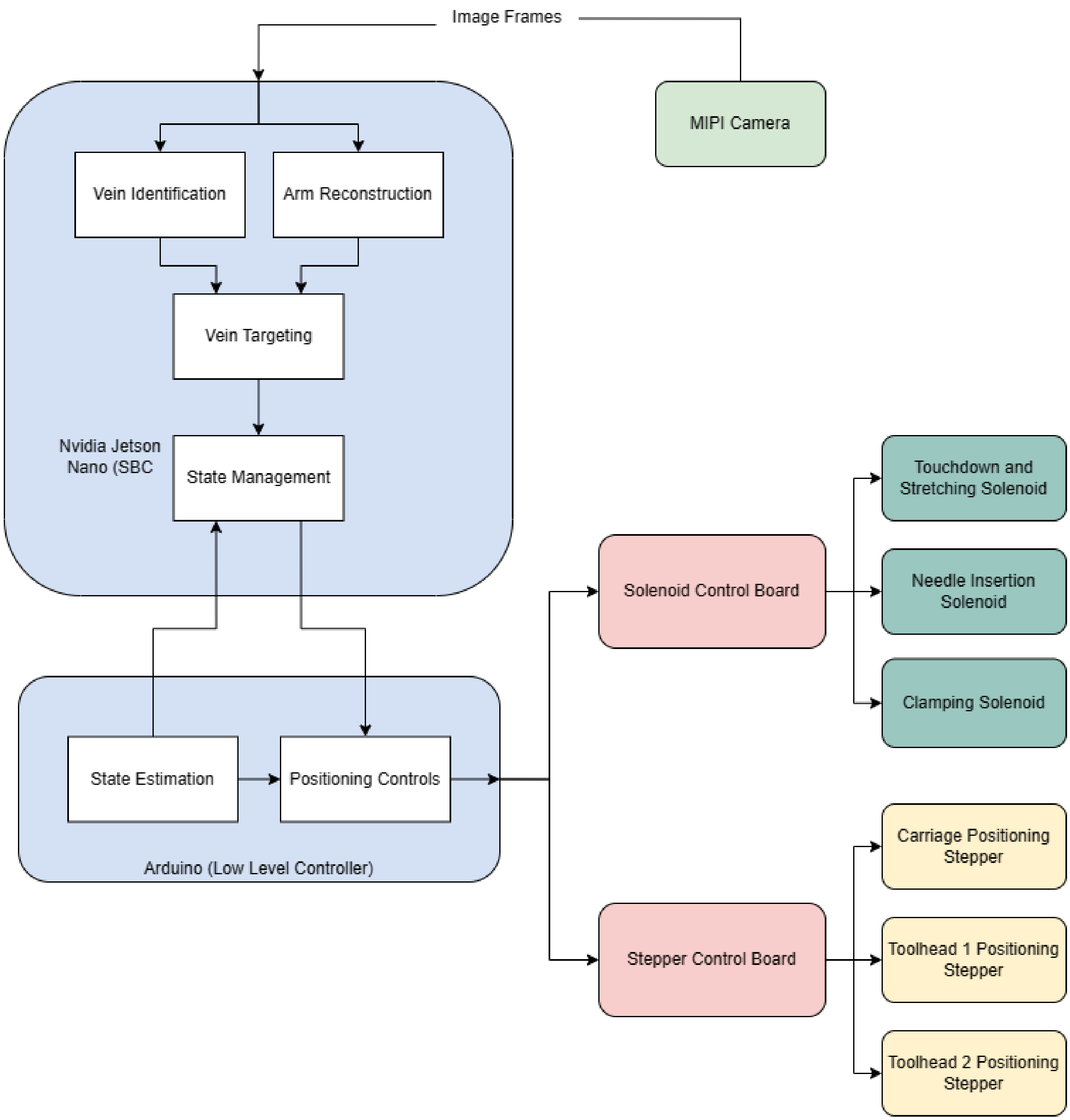

Figure 4. Cyber Physical Architecture of System

6. System Description

6.1 Perception

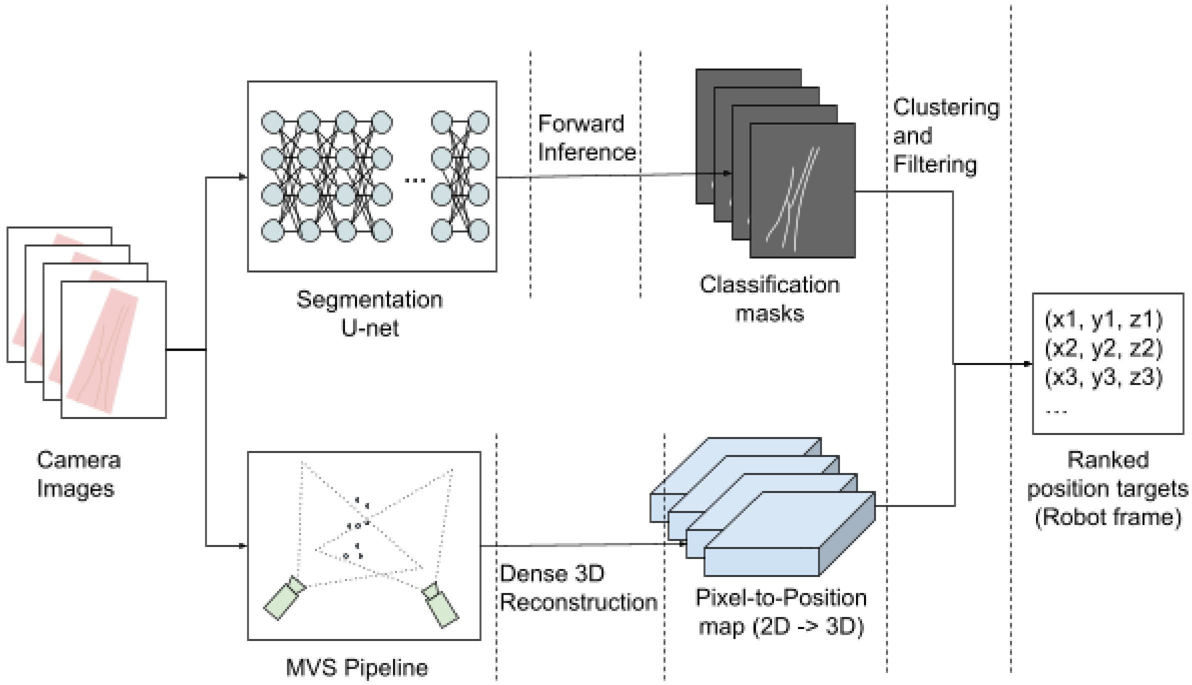

Figure 5: Perception Subsystem Description

The perception pipeline (Figure 5) is as follows:

1. The camera captures images of the work area from a variety of angles. These images are streamed to the on-board computer.
2. On the computer the images are forked to two subtasks: segmentation and stereo reconstruction.
   a. The segmentation task identifies pixels that are veins and outputs segmentation masks.
   b. The stereo reconstruction pipeline determines the 3D position of pixels on the arm and outputs a dense pixel-to-position map
3. The segmentation masks and position maps are then used to cluster vein areas during a clustering and filtering phase. The result is a ranked list of 3D position targets in the robot frame. These position targets are sent to the path planner.

6.2 Mechanical Design

The mechanical design component of the venipuncture robot can be split up into a few key components: the injection toolhead, camera toolhead, and clamping arm/rail.

6.2.1 Injection Toolhead

This subsystem is responsible for applying pressure to the skin, bringing the needle down into contact with the patient's arm, and inserting the needle into the skin. Looking at Figure 6, the toolhead floats above insertion position, drops and skin stretchers make contact with the arm. From there, the skin stretchers move along arm pulling skin taut and insertion guide makes contact with the skin, and the needle is pushed through the guide into the vein.

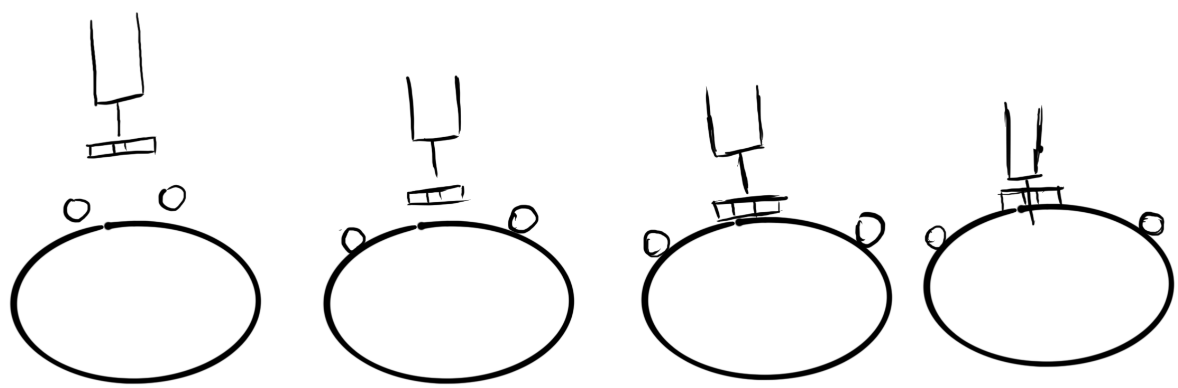

Figure 6: Toolhead touchdown sequence from right to left.

6.2.2 Sanitizing Wipe & Camera Toolhead

This subsystem is responsible for preparing the patient's arm in the general area of injection. It serves the additional function of translating the camera along the arm to allow for multiple vantages and improve detection and localization of veins.

6.2.3 Clamping Arm and Toolhead Rail

This subsystem is responsible for the lateral and vertical movement of the two toolheads. It will lightly clamp down onto the arm with a curved rail shape which the toolheads can travel across. This will allow each toolhead to move laterally along the arm for positioning. The positioning of toolheads will be critical for wiping the skin during sanitization, scanning the skin during vein finding, and injection.

6.2.4 Y-Axis Rail

This rail will carry the clamping arm subsystem so that it can move longitudinally along the arm. This will allow for more precise positioning in the case that the initial position of the arm in the machine does not give a suitable needle insertion location within the initial workspace.

7. Project Management

7.1 Project Schedule

Table 3 below describes the goal for each checkpoint in regards to subsystem progression and integration. Along with that, Figure 7 below shows how many days are to be dedicated to each phase over the entire semester.

Table 3: Schedule and Goals for Each Deadline

Dates	Assignment	Goals
1/30/23 - 2/9/23	Design Proposal	Proposal Submitted. Includes basic parts planning in budget
2/1/23 - 2/13/23	Mock Up Demo	Basic 3D CAD models and schematics for theoretical electronics completed
2/8/23 - 2/22/23	System Demo #1 / Website Check #1	Show completed build for each individual subsystem and maybe some motion. Website should include details from this document
2/22/223 - 3/2/23	System Demo #2	Show completed electronic subsystem interaction and some CV reading of vein
3/2/23 - 3/15/23	System Demo #3	Show integration of mechanical and electrical systems together
3/15/23 - 3/22/23	Mid Semester Presentation I	Proof of concept must be ready to show during demos
3/15/23 - 3/22/23	Mid Semester Presentation II / Peer Evaluations I	Update any errors from previous demo and redo presentation
3/22/23 - 3/29/23	System Demo #4 / Website Check #2	Refine precision of motor movement with CV readings. Website should include mid semester demo information
3/29/23 - 4/5/23	System Demo #5	Implement extra coolness factor toolheads and keep testing
4/5/23 - 4/12/23	System Demo #6	Increase puncturing accuracy
4/12/23 - 4/19/23	System Demo #7	Increase precision and speed for puncturing
4/19/23 - 5/3/23	Final System Demo	Demo robust final design of device
4/24/23 - 5/5/23	Final Report	Complete report, updating all sections
5/4/23 - 5/8/23	Peer Evaluations II / Website Check #3	Update final version of website for entire project

Key notes about the semester schedule is that the aim is to have each subsystem fairly functional relatively soon as the aim is to dedicate as much time as possible to increasing accuracy of puncturing. This also will allow us to have enough time to create and brainstorm any additional toolheads that may be required for the success of the device.

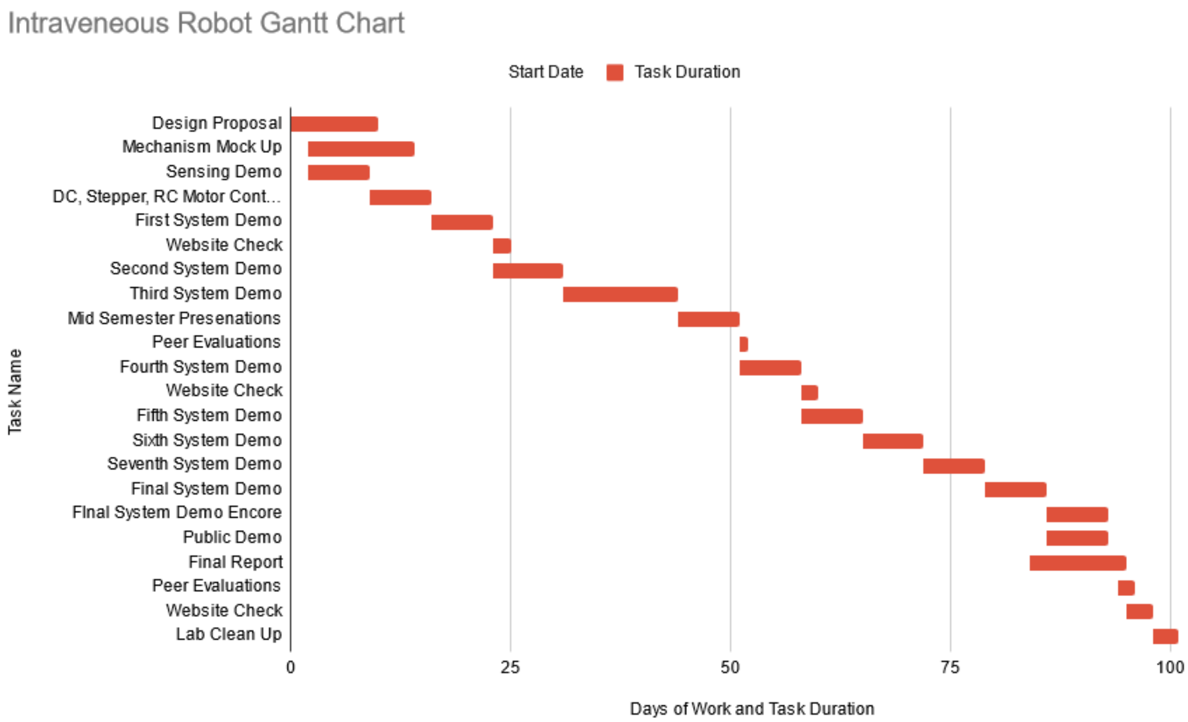

Figure 7: Gantt Chart for Number of Working Days Per Phase

7.2 Team Member Responsibilities

Even though there are team leads who are present for each subsection of the project, each member of the team will also be able to contribute in other areas if needed and to also use it as an opportunity to learn more about each topic. The four main subsystems and leads are:

Table 4: Subsystems and Leads

System	System Lead
Control Vision / Perception	Kevin Liu
Mechanical Design	Eric Jenny
Electrical Design	Sidney Nimako-Boateng
Controls / Project Management	Srividya Gandikota

7.3 Budget

A tentative bill of materials for the venipuncture robot, Phle-bot, can be shown in Table 5 below. With the current part estimations, the budget reaches a total cost under $650. However, this may change throughout the semester with each iteration.

Table 5: Subsystems and Leads

Item	Cost	Qty	Category/Desc	Total: $622	Vendor
Jetson Nano OBC	$100	1	Electrical	$100	Personally owned
RGB Camera	$30	1	Electrical	$30	Personally owned
3D Printing Costs	$100	1	Mechanical	$100	Various
AC-DC Power Supply	$20	1	Electrical. Power OBC & actuators	$20	Amazon
Micro Pneumatic Cylinders	$20	3	Pneumatic	$60	McMaster
Swing Arm Cylinder	$21	1	Pneumatic	$20	Amazon
Pneumatic Solenoid Manifold	$40	1	Pneumatic	$40	Amazon
Pressure regulators	$15	4	Pneumatic	$60	Amazon
Stepper motors	$14	2	Actuators/Control	$28	Adafruit
Stepper Motor Controller Board	$29	1	Actuators/Control	$29	Amazon
PTC Pneumatic Kit	$18	1	Pneumatic	$18	Amazon
Linear Rail System	$80	1	Mechanical	$80	Amazon
Arduino Mega	$20	1	Electrical	$20	Amazon
Disposable Tourniquet	$17	1	Mechanical	$17	Amazon

7.4 Risk Management

There is a large amount of risk based around the fact that we are designing a novel mechanism for the insertion and clamping system. As a result of the large number of unknowns in this process, it is important that we prototype to develop multiple iterations towards designing a successful mechanism. Another mitigation is that the project can be split into two independent areas of development: vein sensing and mechanical design. If the mechanical development is stalled, the vision pipeline for the vein sensing can still be developed independently. The last mitigation we will implement is frequent testing. Last year's group did not test with needles until the final stages of the project to avoid damaging the training arm. However, during the final evaluation they found that the prototype could not penetrate the skin and vein. Reflecting on their experiences, we have decided to prioritize full trials to ensure the physical difficulty of cannulation was taken into account in our design cycle. To mitigate damage to the training arm, we will use the excess tubing sticking out of the arm. If those are too damaged, they can be snipped off, provided we don't use too much of the length.

8. References

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