Design of a Modular 4 Degree of Freedom Robot for Peripheral Venous Access

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Abstract

With an estimated **2.7 million lines drawn each day**, venipuncture is the most prevalent invasive procedure in the United States. **Failure rates** are reported to occur in **20-45%** of attempts, costing the U.S. healthcare system an estimated **$4.7 billion/year**. The current gold standard for venipuncture involves a trained phlebotomist visually inspecting and manually palpating for veins in the anterior forearm (for intravenous therapies) and the inner elbow (for blood draws); however, the success of the procedure is in large part determined by human variability. To improve the success rate of venipuncture in the clinic, we are developing a **robotic device** that **performs the procedure autonomously**. The device uses image guidance to position a needle into the peripheral vein. To date, we have validated a functioning prototype on several human imaging trials and *in vitro* cannulation studies. The goal of the work described here is to improve the precision and reliability of the prototype in preparation for *in vivo* validation. To this end, we have incorporated several advancements, including a **modular device design**, a 4 degrees-of-freedom (DOF) robot mechanism, an automated camera positioning platform, an optical shell, and closed-loop motor feedback software based on potentiometric readouts.

Design Requirements

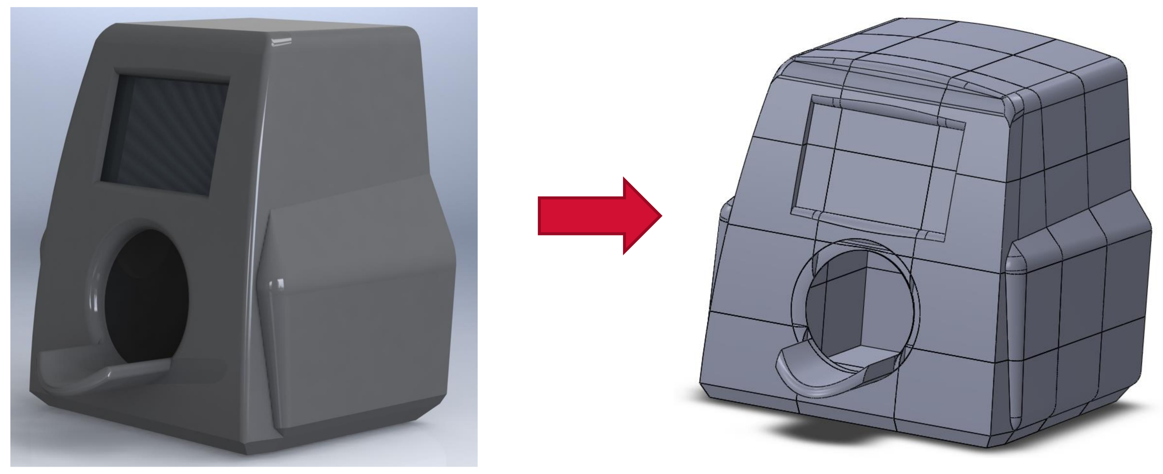
1. Device should **autonomously** detect and select an appropriate vein in agreement with an attending clinician
2. Device must have **precision** to target and cannulate **2.5 – 3.5 mm** diameters veins in adults and **0.9 – 2.4 mm** diameter veins in children
3. Device must autonomously withdraw blood into collection vials without human intervention
4. **Imaging depth** must exceed **3 mm** (depth of superficial forearm veins in adults is 1.9±1.1 mm)
5. Device must be controlled in **real-time** in a **closed-loop** environment
6. Device should be **portable**
7. Materials cost for the device should be **less than $10k**

Robot Mechanical Design

The current prototype measures **30 x 35 x 38 cm** and weights **2.5 kg** which satisfies space constraints in the clinical setting for venous access procedures. The device combines a **2 DOF gantry system** with a **3 DOF manipulator arm** to servo the needle. The gantry system includes two linear ball-screw stages (Zaber T-LSM 100/200) providing X and Y translation. The manipulator arms contains one stepper motor (Zaber T-NM17A04) to control altitudinal rotations and a linear actuator (Zaber T-NA08-25) to drive the needle insertion. The linear stages have a peak velocity of 7 mm/s and step size of 0.0476 µm, and the rotational stepper motor provides a maximum torque of 30.7 N-cm and angular step size of 0.0191°. Both the manipulator arm and the cameras are mounted on the Z stage so that the needle always remains within the field of view. The **total workspace is 20 x 15 cm** – sufficient to scan the length of an adult forearm and elbow.

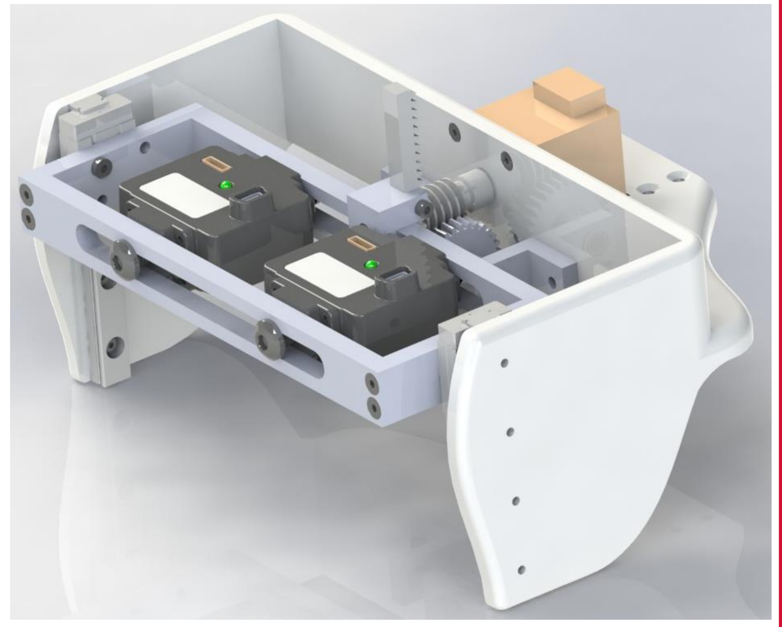
Exterior Optical Shell

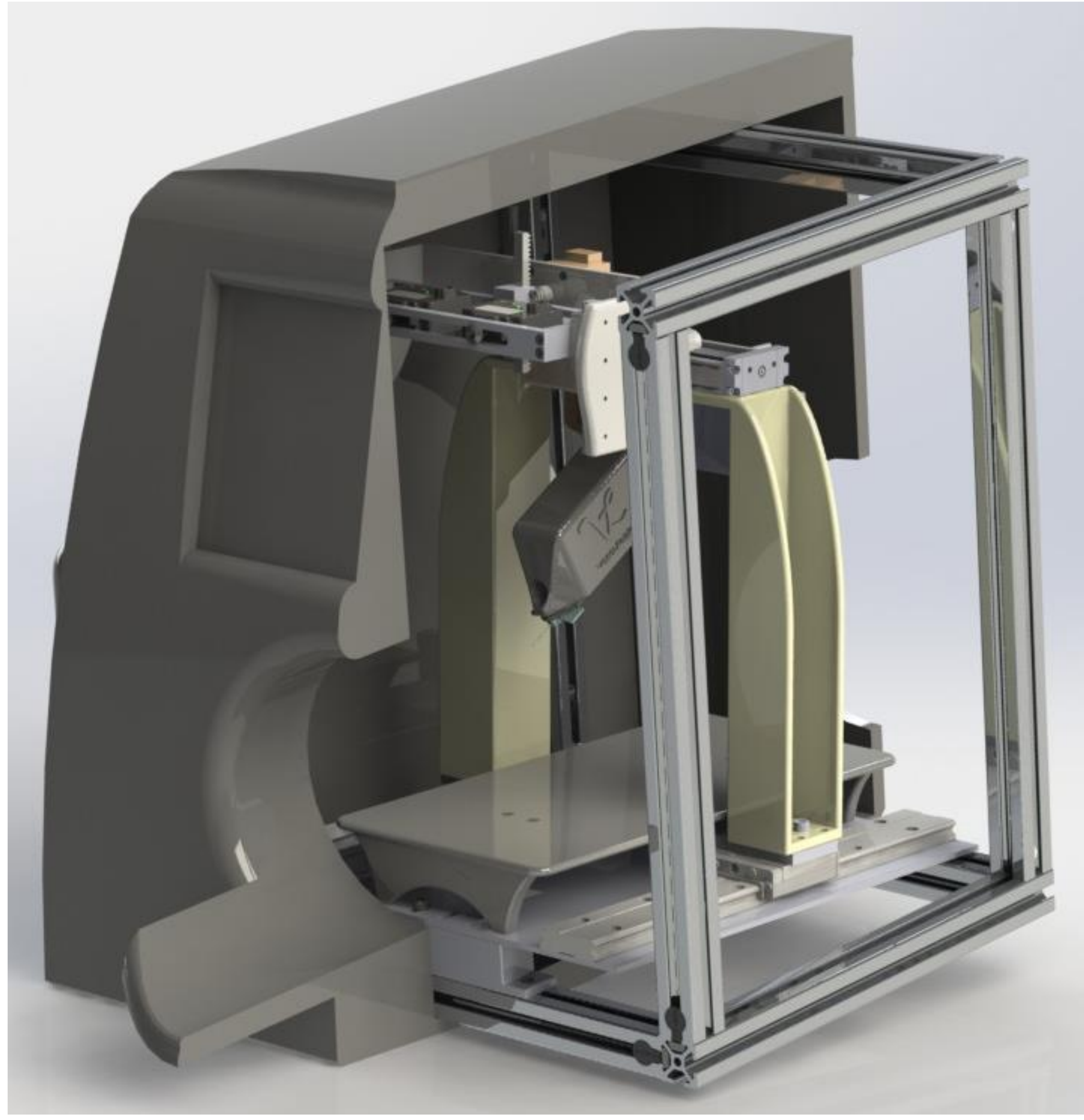
The current exterior shell was designed to enclose the robotic mechanism and provide a housing for the optics system. It was **sectioned into 36 parts suitable for 3D printing** with ABS plastic, and the parts lock together via a lock and key mechanism. The robot is surrounded by a **structural framework consisting of t-slot aluminum** to allow for easy attachment to the shell. The near-infrared (NIR) lighting system is attached to the structural framework to image superficial veins. The whole device has a **modular design**, meaning the robotic mechanism, structural framework, and exterior shell are all separate entities that can easily be attached or separated.



Automated Camera Positioning

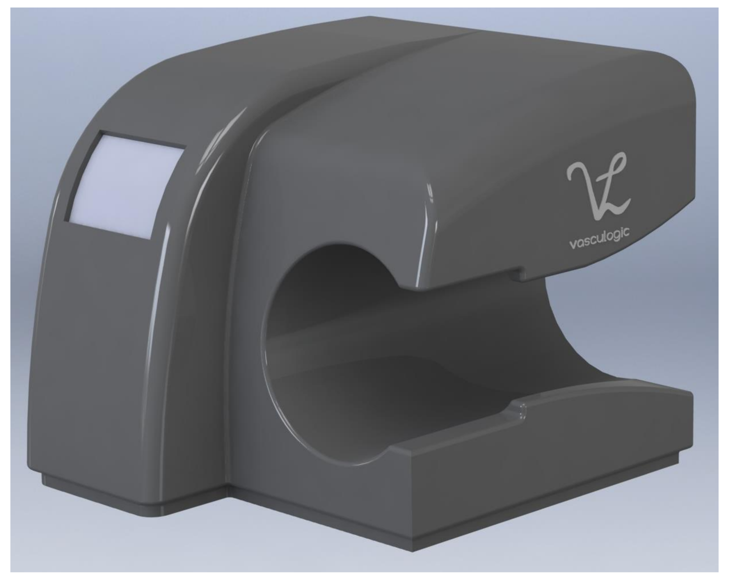
A motorized camera positioning system was designed to enhance and **automate the camera calibration process**. A stepper motor (Zaber NM11A07S) provides a maximum rotational torque of 6.8 N-cm. This rotational motion is converted to linear motion via a simple drive train that includes a **worm and rack/pinion gearing system**. The worm and mating worm gear were designed to increase the output torque using a **gear ratio of 20:1** to meet the torque requirements to lift the camera assembly. The worm gear system was also chosen due to its self-locking mechanism, meaning the camera height can be held in place without running a hold current through the motor. A rack/pinion system with a 1:1 gear ratio was then implemented to convert the rotational motion of the worm gear to linearly move the camera assembly up and down.





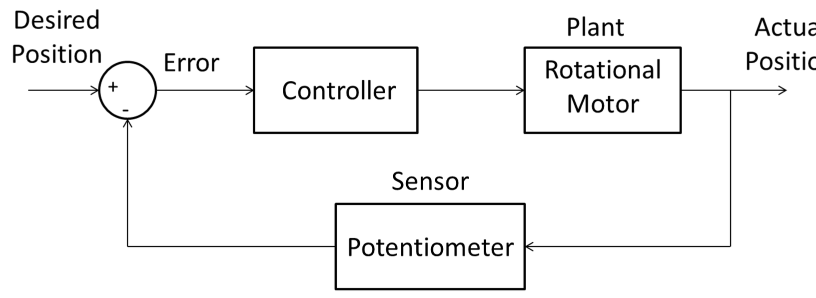
Alternative Concept

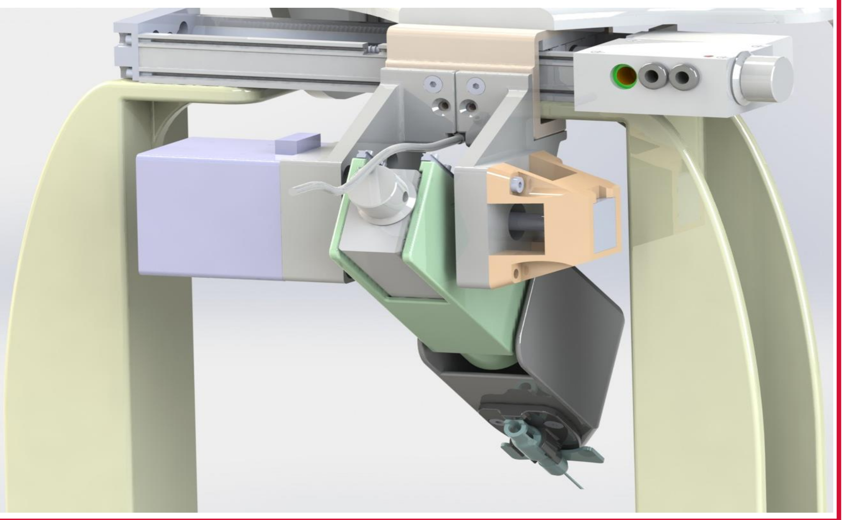
An alternative concept design is pictured to the right that incorporates a system to analyze blood samples at the point of care. This device will not only consist of an imaging system for superficial vein selection and a robotic arm for vein cannulation, but it will also include a microfluidic system to screen a broad range of hematopathologies, and a heurisitc computer decision support system for automated diagnosis of blood disorders. Disposable microfluidic assays will be developed that use label-free immunophenotyping via protein biomarkers for cell separation. This approach will allow us to use semiconductor light sources and detectors in place of large and expensive lasers that are commonly used in immunoscreening devices. Then, we will develop an automated system to facilitate the diagnostic interpretation of the microfluidic readouts. This system will consist of medical logic modules that use a heuristic statistical learning algorithm and a knowledge-based rules set based on patient data.



Potentiometer Feedback Loop

A 10 kΩ potentiometer was attached to the altitudinal stepper motor to create a **closed loop positioning system**. The potentiometer is interfaced with a **LabView compatible Arduino board**. As the potentiometer rotates with the motor, it produces an analog voltage output. By correlating the rotational voltage output signal of the potentiometer with the motor step angle, we were able to create a positioning feedback control system as depicted in the figure above. A standard controller was used to adjust the error signal between the desired and actual motor position.





Future Work

With the completion of the second prototype, future work will focus on improving the precision and reliability of the device for the purpose of extending our current *in vitro* and *in vivo* studies. This involves developing a new 2 DOF gantry system to allow for improved positioning control, and a miniaturized 4 DOF manipulator arm to servo the needle. The micromanipulator arm will control up-down rotation, right-left swivel, Z positioning, and needle injection via micro piezoelectric motors. It will be designed to reduce the weight and size of the current device to better satisfy size and weight design constraints. In addition to the future mechanical designs, we will also be implementing ultrasound in the device to go along with NIR imaging for vein imaging. Combining NIR and ultrasound to produce a photoacoustic imaging system will also be explored in future studies.

Acknowledgements

- John Petrowski and Joe VanderVeer (MAE Department)
- Jeremy Mush
- This material is based upon the work supported by the National Science Foundation Graduate Research Fellowship under Grant no. DGE-0937373.