Robot for Remote Catheter Guidance through Blood Vessel Models

Final Design Report Template

Gray Becker – Project Manager & Logistics Manager

Joshua Hernandez – Financial Manager & Manufacturing Engineer

Joshua Parra – CAD Engineer & Test Engineer

Fall 2024-Spring 2025

Project Sponsor: Steven Schwartz, Jesse Wells

Faculty Advisor: Reza Razavian

Sponsor Mentor: Tim Becker

Instructor: David Willy

DISCLAIMER

EXECUTIVE SUMMARY

The purpose of this project is to design, build, and test a robotic system that can translate and rotate a catheter into a benchtop blood vessel model using a remote control. The clients work in the Bioengineering Devices Lab at Northern Arizona University on treatment of brain aneurysms in the circle of Willis. This project will allow testing of catheters in an environment with high-powered x-rays. To achieve this, the system must function using a remote control. Dr. Becker is the project sponsor, providing a budget of $5,000. An additional $500 will be raised by the end of the year, with $350 currently raised.

The project has a functional decomposition with inputs such as catheter mounting, energy and power, rotational motor, translational motor and outputs of a real-time display, translational force, and rotational force. The system can be broken into subsystems of translation, rotation, microcontroller, sensors, power supply, and controller. Through mathematical modeling and insights from previous literature, the preliminary designs of the translation and microcontroller subsystems have been verified with an initial prototype.

The translation system has four rollers, where the catheter will run between the top and bottom roller pairs. One roller is attached to a stepper motor and will drive the catheter, while the other three are idler rollers. The subsystem must be capable of translating a catheter over two feet. Stepper motors were chosen for more precise motion of under a millimeter per step. For the rotation subsystem, two rollers squeeze a catheter along its axis. Both rollers are driven by a stepper motor attached to a gear box. Due to the sensitivity of force measurements required for this project, the sensor subsystem will consist of a shaft with a moment arm resting on a load cell. The components of translation and rotation were tested in prototypes to prove they were capable of working. They have been fully assembled with final system testing being done. Purchases have been completed as of the final assembly. The code has been done through an Arduino and will run the whole system. The lead screws will be raised or lowered depending on the action followed by the related motor running. All system forces are recorded by the load cell in the sensor device and exported back to the Arduino. All in all, this report covers the design process, design selection criteria, calculations, and prototyping and assembly of the system in full.

TABLE OF CONTENTS

Contents

1 BACKGROUND

The project description will provide context of the client proposal, budget, and importance of the project. Major deliverables, including course and client deliverables, are included in the deliverables section. For the project to succeed, success metrics including calculations and major design requirements are added.

1.1 Project Description

An aneurysm forms at a weakened segment of blood vessel, resulting in an abnormal pouch that can hemorrhage and lead to death. Additionally, blood clots can originate from aneurysms and block blood flow to parts of the brain, causing a stroke. The Bioengineering Devices Lab (BDL) at Northern Arizona University focuses on the treatment of stroke caused by blood clots and brain aneurysms. They work with biomaterials and biomedical devices related to vascular blood flow, currently testing liquid embolics, flow diverters, and aspiration catheters in the circle of Willis. [1]

The project's clients, from BDL, have asked engineers to design, build, and test a robotic system that can remotely translate and rotate a catheter into a benchtop blood vessel model [1]. The system must be capable of measuring forces, torques, and distances. By creating a remote-control system, researchers at BDL can run experiments with an x-ray machine without concern for damaging the user.

The project sponsor is Dr. Becker, who has provided $5000 for the construction and testing of the project's design. An additional $500 will be fundraised through GoFundMe and robotic part donations.

1.2 Deliverables

The first major course deliverables for this project are three different presentations, a website, and two reports to update the course instructor on the project's progress. Additionally, an analytical analysis memo, four prototypes shown in two prototype demonstrations, final testing and demonstration, and a bill of materials must be provided.

The major client deliverable is a working final product that meets the robotic system project description.

1.3 Success Metrics

Project success will be assessed via testing and calculations of the final design. These include the ability to translate and rotate the catheter and measure forces, torques, and distance to a precision specified by the client and engineering requirements. This requires distance calculations from the motors, rollers, and other components in the robot. The design must not damage the catheters or blood vessel models used with the system, as determined by stress and strain calculations. Most importantly, the final product must be controlled remotely, as the purpose of this project is to protect the user from an x-ray machine positioned next to the blood vessel model and catheter. This will be considered a success if the robot can be controlled from at least ten feet away.

2 REQUIREMENTS

This section of the report will go over requirements, including the customer requirements, engineering requirements, and house of quality. Customer requirements are pulled from the clients' project description and conversations with the clients. Engineering requirements are generated quantifiable requirements which must be met by the design to be considered ideal. These are modified customer requirements with numeric goals to reach in terms of forces, distances, and times. The house of quality shows the graded importance of each engineering requirement versus the corresponding customer requirements.

2.1 Customer Requirements (CRs)

- CR1: Translation and rotation of catheter
    - The system must be able to move a catheter with the same functionality as a person's hand. This includes moving the catheter in and out of the blood vessel model and rotating the catheter to allow it to move properly through any bends in the model.
- CR2: Pre-programmed or controlled remotely
    - The current device the clients are using uses a step-by-step programing block system which they would like the project to mimic. The clients also want the device to be controlled from a distance to run lab equipment that may be dangerous to people.
- CR3: Measure data instantaneously
    - Data acquisition is very important, the clients need to measure torques, speeds, and forces acting on the catheter. It needs to be instantaneous since data gathered will be time critical. The data will not only be recorded but will also tell the operator and the device if there is an issue with the catheter before a catastrophic error occurs, such as damaging of the model or the catheter.
- CR4: Emergency stop system
    - The emergency stop system will oversee smart decisions based on gathered data and will be able to stop the device before it causes damage to the catheter or the model. The clients would like this to be automatic, but there will also be need for a manual override which will stop the device regardless of the command instructions it is currently executing.
- CR5: Level the introducer and system to prevent kinking
    - The device must be level when operating to not induce unnecessary friction and bending on the catheter. The clients require a leveling system for the device.
- CR6: Force measurement equipment easy to replace
    - The device is expected to have a long lifetime. The ability to replace sensitive equipment such as the force measurement device is needed. Sensors must be easy to replace allowing accuracy of data and device uptime to be prioritized.
- CR7: Mechanism to prevent load cell damage
- CR8: Easy to disassemble/reassemble, transport case
    - The device will need to operate in many locations and therefore must be mobile. The ability to take apart the device and having a transport case is necessary.
- CR9: Force and distance calibrations and testing
    - For the data to be accurate during experiments, the device will need to have the ability to save a zero state for the sensors.

2.2 Engineering Requirements (ERs)

- ER1: Translation of catheter at least 2 ft
    - The catheters used will be at least three feet in length, and the blood vessel model used

for experiments has a clot and aneurysm designed inside. The path to this location is less than two feet long.

- ER2: Rotation of catheter at least 360 degrees
    - With many twists and turns in the blood vessel model, the catheter must be able to do a complete rotation, allowing it to move wherever necessary.
- ER3: Remote controlled from at least 10 ft away
    - To prevent harm to lab personnel, the device must be controlled from ten feet away.
- ER4: Sampling rate frequency between 5-30 Hz
    - The on-board computer or microcontroller must record data at a rate between five to thirty data recordings per second.
- ER5: Handle catheter sizes between 2-15 French
    - The device should be able to handle different diameters of catheters between the size of two to fifteen French. Three French is equal to one millimeter.
- ER6: Measure push resistance force between 0.1-10 N
    - The catheter will experience resistive forces which must be measured. These forces will be between one tenth to ten newtons.
- ER7: Measure displacement of catheter with resolution of at least 0.1 mm
    - The device must measure and move the catheter forwards and backwards at a resolution of one tenth of a millimeter.
- ER8: System noise/tolerance: $\pm$ 0.05 N
    - The allowed tolerance of error to be recorded from the sensors must be between the range of plus or minus five hundredths of a newton.
- ER9: Total size under 1 cubic foot
    - The total volume of the device must be under one cubic foot when taken apart and not in use. The size of the device when deployed is not given.
- ER10: Temperature below 60°C
    - The device must not cause material deformation due to high electronic temperatures

2.3 House of Quality (HoQ)

Translate catheter over distance									
Full rotation of catheter	3								
Controlled from a distance	1								
Fast sampling rate		3	3						
Handle variable diameters		1							
Measure push resistance	1			3	1				
Measure displacement resolution	9			3					
Low system noise			1	9		3	3		
Limited volume	1		1			1	1		
Moderately low temperature	3	3							

Project title:	Catheter Roller
Project team:	F24toSp25_02
Date:	3/21/25

		Technical Requirements										Customer Opinion Survey					
Customer Needs	**Customer Weights**	Translate catheter over distance	Full rotation of catheter	Controlled from a distance	Fast sampling rate	Handle variable diameters	Measure push resistance	Measure displacement resolution	Low system noise	Limited volume	Moderately low temperature	*1 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*	*Unsure*
Translation and rotation of catheter	1	9	9	1	3	3		9	3		3			A		B C	
Pre-programmed or controlled remotely	1	3	3	9			1		3		3		A			B C	
Measure data instantaneously	3	1	1		9	1	3	3	9							A C	B
Emergency stop system	2			3					1					C		A	B
Level introducer and system to prevent kinking	3						9									A	B C

Force measurement equipment easy to replace	4						3			1				A			B C
Mechanism to prevent load cell damage	3				3		3		1						A		B C
Easy to disassemble/reassemble	5			1						9		A		C		B	
Force and distance calibrations and testing	3	3	3		1	3	3	3						C		A	B
Technical Requirement Units		ft	degrees	ft	Samples/secon	F	lbf	in	lbf	ft^3	°F	Legend	System name				
Technical Requirement Targets		2	360	10	5 to 30	2 to 15	0.0225-2.25	0.0034	0.0112	<1	<140	A	MSI interventional device testing equipment 3000				
Absolute Technical Importance		24	24	21	42	15	67	27	38	49	6	B	Microbot Medical: Liberty Robot				
Relative Technical Importance		1	2	3	8	4	7	6	9	10	5	C	Autonomous Robotic Intracardiac Catheter Navigation Using Haptic Vision				

Figure 1. House of Quality [2]

3 Research Within Your Design Space

3.1 Benchmarking

3.1.1 IDTE 3000

The IDTE 3000 from Machine Solutions is commercially available tool that allows for a multitude of tests to be performed on catheters. It consists of a feeder and a water tank vein system. The feeder is modular, which allows for the variety of tests with both rotation and translation. It also contains systems for motion and torque feedback. According to the QFD, this design fits the engineering and customer requirements. However, it is not perfect for the project as it does not fit the volume or remote-controlled aspect of the criteria. [3]

3.1.2 Haptic Vision Catheter

Autonomous robotic intracardiac catheter navigation using haptic vision is a research paper following the implementation of haptic controls for a catheter navigation system. This is very similar to the current project, making it a good benchmark. The paper goes over the robotics of how the catheter is translated and rotated, computer control, and force sensors. All are topics which will are important to the subsystem breakdown of the project. Using the knowledge of this benchmark allows for smart decisions to be made while coming up with the final design. [4]

3.1.3 Liberty Robot

The Liberty Robot by Microbot Medical is a small, disposable device that attaches to a patient's thigh and inserts a microcatheter via handheld remote control. This benchmark is a good example of creating a small system, which matches the requirement of a robot within 1 cubic foot in size. The controller system allows for remote control of the catheter, representing a successful implementation of the most essential requirement of the project. Its ability to work with off-the-shelf catheters additionally demonstrates the design's flexibility, which is important to consider for the requirement to work with catheters between 2-15 French. [5]

3.2 Literature Review

3.2.1 Josh P.

LabVIEW Fundamentals [6]

The LabView Fundamentals book is a manual and tutorial on how to use LabVIEW. It covers how to use LabVIEW from a beginner viewpoint. It includes basics like menu navigation and goes up to controller integration. This will help if the team decides to use LabVIEW for programming. The clients recommend LabView for the software side and to read the data collected. This guidebook provides the information needed to meet this requirement.

Machinery's Handbook (pg. 754-1003) [7]

The Machinery's Handbook is a textbook that includes everything one needs to know about mechanics and manufacturing. The topics range from physics equations to how to design gears. The tooling and manufacturing section is the focus. It goes into the tools needed for different manufacturing details. This will be useful for the project which will involve working on a smaller scale and needing to learn the production methods for these parts to make and purchase.

Friction characteristics and servo control of a linear peristaltic actuator [8]

This paper discusses new ways to use pneumatics without worrying about the non-linear effects. It shows methods to move a pressurized hose. They set up a system where a pressure difference causes motion in the tube. This could be helpful if using pneumatics in the translation system. The team would be able to create a pressurized tube to induce motion on the catheter or to clamp down on the catheter.

Prevention of Servo-Induced Vibrations in Robotics [9]

Paper on how to reduce vibrational friction in the software and hardware systems of robotics. They go into how to track the motion and forces of the servo motor. In the paper, the authors describe the basics of setting up a servo control system with feedback. Although the team is using a stepper motor over a servo, this is still helpful as a guide on how to set up the motor interface. Additionally, these methods can be used to reduce unnecessary motion transferred to the catheter, as vibration and similar forces are unwanted in precise medical equipment.

Software interfacing of servo motor with microcontroller [10]

This paper is about how to control a servo motor with MATLAB and a microcontroller. It describes how to link a servo motor to a microcontroller driver and how servo motors work in a circuit. The paper also goes into writing programs for the motor in MATLAB. This applies to the project in that the team is investigating ways to control and monitor the motor as it runs. It also provides an alternative to LabView which is talked about above. With two program options, the team will be able to test and prototype multiple designs.

ISO 25539-1:2017 [11]

The standard is about tests of endovascular devices. It covers the conditions for the tests and how to report the data. These criteria apply because the team is making a device that can perform these tests. The project must allow the user to follow the standards outlined in the document.

ViVitro Labs Catheter Testing and Delivery System Testing [12]

A website that provides examples of procedures for different catheter tests. It gives some information about the test like equipment and purpose. They show the show the setup so the reader can see what is being performed. This is useful in helping organize the layout of the design, and it can be used as inspiration from how they perform each test to build components and research similar tools.

The six factors you need to consider when picking a force sensor [13]

This article lists what to consider in a force sensor. They discuss topics like environment and sensitivity. They guide you through the process mentioning crucial details within each topic. After finding all the necessary criteria, the website directs you to a page where you can purchase the best sensor. This will help in finding a sensor for the project. Some way to measure the force put onto the catheter as well as the force of the catheter on the vein system is required. By reading this article and looking through the catalog, a force sensor that is applicable in the design can be found.

ASTM-D2240-Durometer-Hardness [14]

The Durometer Hardness standard outlines the testing definitions for rubber hardness. It goes over how to test for hardness and what each designation means. The test involves pressing a metal tip into a thin slice of a material and measuring the reaction force. The metal tip varies in shape and sharpness depending on the testing standard. The hardness of the rollers is 55A which means a dulled point was pushed into the sample at a force of roughly 4.7N.

SAE J300 [15]

This is the standard for lubrication and engine oil. It designates codes for the viscosity and temperatures of the oil. These values are assigned through finding the time the oil takes to flow through a small hole. In the design, bearings that are embedded with SAE30 oil are used. This standard helps determine the properties of this lubricant and evaluate tests on the bearings.

3.2.2 Josh H.

Handbook to electric motors, 2nd ed. Chapter 2: types of motors and their characteristics [16]

The book contains in depth information on everything about electric motors. With majority of the information is more tuned for motors in industry use. However, much useful information can be gained from particular chapters and sections. Section 2.5 of the book goes over motors for special applications, talks in depth about stepper motors their uses and how to decide which motor is best suited for your project based on your needed characteristics. The information was useful to narrow down what motors on the market would work in terms of power and torque.

NEMA standard for stepper motors [17]

The NEMA standard is a commonly used standard pertaining to motor size and dimensions. The standard is about the size of the motors face, stepper motors on the market are referred to as 'NEMA' followed by a number pertaining to its size class. For example, the NEMA seventeen has a face plate of one point seven by one point seven inches. The length of the motor is not included in the standard meaning you can get a NEMA seventeen motor which has different characteristics, usually more powerful equals longer in length.

Electromate stepper motor catalog [18]

Catalog with information on all motors using the NEMA standard. Many different NEMA motors of many sizes with different characteristics will be useful to reference to get a feel of what is available on the market allowing for a proper design to be made based on the characteristics listed. It is worth mentioning that just because this is a catalog by a company which manufactures and sells these stepper motors the idea in using this is to have an easily accessible 'list' of all the possible stepper motors which can work for the application.

Selection of Microcontroller board and stepper motor driver for FDM 3D printing to reduce power consumption [19]

This paper goes over microcontrollers and drivers for stepper motors. The article mostly focuses on power consumption which will not be a major issue for this project, however power consumption is always a concern. The main gain of information from this article is in microcontroller and stepper motor drivers. A microcontroller will be needed to control and run the motors and selection of one that is able to handle multiple motors is important. There will be a need for a stepper motor driver which will power the motors based on the commands sent to in by the microcontroller. This is another area of design decisions so information on this topic is needed. Finally, the article touches on power supplies, these will be needed to power the device and must be capable of running all the electronics reliably.

Handbook to electric motors, 2nd ed. Chapter 3: Motor Selection [20]

Section 3.1: Standards, goes over standards of motors and helps you understand and use these standards showing how said standards can apply to a range of different motors. It contains the NEMA standard but goes into more details for motors talking about types, lengths, and power classes instead of just face plate size. This is helpful in identifying certain motors with some motors being better for the task at hand than others.

Tech tip: How to choose and use stepper motor power supply from automationDirect [21]

An online video which helps with general rules of thumb to choose and appropriate power supply. Includes info about voltage and current at different rpms and what power supply is best. With power supplies being a main subsystem of the design, much consideration must be given. This is especially true when some market power supplies are better than others and when connecting power supplies isn't always simple and there needs to be assurance that the power supply will deliver the correct amount of voltage and amps.

Selecting the best power supply for your stepper motor or servo motor application [22]

An online article going over the different types of power supplies in technical detail. Will be very helpful in choosing the correct type of power supply based on characteristics needed for the application. Like the other power supply related sources this one overpowers supplies in a more application specific way.

A design of the automatic anti-collision system [23]

Goes over embedded systems design to help with 'anti-collision,' in our case it can be repurposed for telling us when to emergency stop the machine before it breaks our artery model. The usage of interrupts can be used to allow for time critical events to take place at a priority to other code which is currently running. Being able to detect trends and fail conditions is very important to having the microcontroller make smart decisions. Helpful in showing the best way to set up a system which can reliably work and prevent damage.

Arduino tutorial: serial inputs [24]

A web article going over all information pertaining to serial inputs. Information that was found helpful was how to set one up, send to and read from serial ports. The page also touches on how to do things with input. This means setting up a string parser and having the inputs affect the Arduino.

Arduino interrupts tutorial [25]

A web article that goes over Arduino interrupts. Interrupts is a priority system built into the processor. There can be software or hardware interruptions. If an interrupt gets triggered the Arduino will drop what it is doing no matter where it is in the code and handle the interrupt. This can be helpful with time critical events.

3.2.3 Gray B.

Theory and Design for Mechanical Measurements 7th Edition [26]

This book covers measurements and uncertainties and their calculations. It also discusses the mechatronics of sensors, actuators, and controls. The information will be useful in determining how to obtain accurate data collection as required by the client.

Shigley's Mechanical Engineering Design 11th Edition Chapter 19 [27]

This book chapter discusses finite-element analysis of different geometries to find loads and torques. Finite-element analysis will help identify components of our design that may be subjected to high loads or torsion.

Modeling and Estimation of Tip Contact Force for Steerable Ablation Catheters [28]

This article analyzes catheter shaft curvature to determine contact force with the catheter tip. This will be helpful in determining how to measure the reaction force of the catheter tip indirectly.

Force Calibration for an Endovascular Robotic System with Proximal Force Measurement [29]

This article describes an indirect force measurement of the catheter tip forces via motor transmission. This is another method that can be used to determine reaction force at the tip of the catheter.

Accurate Estimation of Tip Force on Tendon-Driven Catheters Using Inverse Cosserat Rod Model [30]

This article provides an equation that determines the relationship between catheter curvature and contact force. This provides a third method that relies heavily on calculation using the Cosserat rod model to determine catheter tip forces indirectly.

ISO 10555-1:2023 [31]

This standard gives requirements for kink, torque, and tensile forces on catheters. This will be useful for informing our design requirements for components interacting with the catheter.

ZwickRoell Horizontal Testing of Catheter Systems [32]

This website discusses a test machine to determine catheter coefficient of friction and breakaway torque. As an example of indirectly measured insertion force, track force, and lubricity, the machine's processes could be adapted to determine reaction forces on the catheter.

Nanoflex Robotics Advanced Magnetic Technology [33]

This website introduces a method that uses magnetism to position and guide a catheter tip through blood vessels. The method provides an example of external robotic manipulation to guide the catheter through a patient, rather than a direct remote-controlled process.

Fatigue and Tribological Properties of Plastics and Elastomers [34]

This book provides information on plastics, polymers, and elastomers. This includes the formulae for hoop stress. The properties and equations are important for understanding how a catheter will respond to clamping.

LabVIEW Programming Reference Manual [35]

This manual provides detailed information on LabVIEW's different functions and references. This will be used to connect LabVIEW to Arduino to allow control and communication between the two platforms. The section on VISA functions is most useful towards achieving this connection.

3.3 Mathematical Modeling

3.3.1 Catheter Deformation (Josh P.)

For my mathematical model, I analyzed how a catheter would deform inside of the vein system. To do this I used the equations for column deformation. The assumptions I made are ignoring rotation and the effects at the ends. Assumptions were made about the values in the calculations. I set the value of the catheter to a diameter of 3 mm as it is the average size of system will need to test. The distance between the catheter and the vein is 1 mm. A length of 2 ft was used because it is the total length of the vein network. Finally, the modulus of elasticity of Pebax is 260 MPa. With these values the deformation can be found. The critical load is the maximum force before the column bends. The calculation for this is:

$$P_{cr} = \frac{\pi^2 \frac{\pi(R^4 - r^4)}{64} E}{L^2} = \frac{\pi^2 * \frac{\pi(1.5^4 - 1^4)}{64}\left(\frac{1\,m}{1000\,mm}\right)^4 * 2.6 * 10\text{^}8Pa}{0.6096^2\,m^2} = 0.0014\,N \ \ [30]$$

As a catheter can and is made to bend, I looked at what this bending looks like. By using the above values and the equation of deformation:

$$X = Csin\left(\sqrt{\frac{P}{EI}}Y\right) = 0.001m * sin\left(\sqrt{\frac{P}{5.185 * 10^{-5}}}Y\right)$$

where P was made to be 0.1N(left) and 0.5N(right) that produces the graphs shown in Figures 2 and 3:

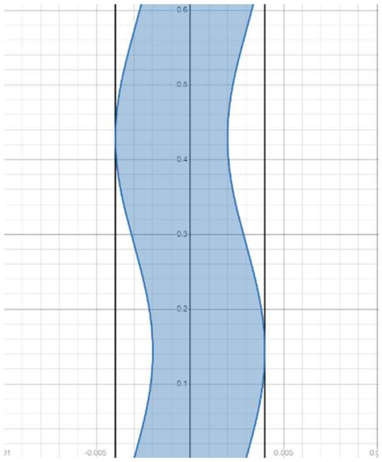


Figure 2. Deformation when P = 0.1N

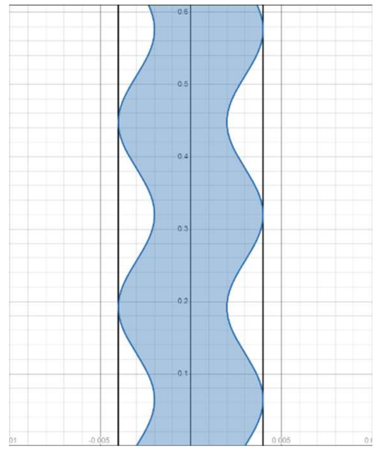


Figure 3. Deformation when P = 0.5 N [31]

The conclusion taken from this is how the catheter acts when pushed without rotation. As the catheter is pushed with nowhere to go it is only able to distribute the load throughout itself and the vein. From the graph, one can see that load over 0.5N can damage the system. Therefore, force must be carefully controlled along with a balance of rotation and translation. Although the data used in this calculation is slightly inaccurate due to the assumptions, it does give data on how to measure and calculate the push resistance.

3.3.2 Power supply and Motor Calculations (Josh H.)

The motors will need to be able to step at the correct resolution to meet customer requirements. For the translation this comes to a step resolution of 0.1 mm and for the rotation there was no customer requirement less therefore an assumed 0.5 degrees is chosen. For the translation system using the equation below,

$$S = r \cdot \frac{\pi}{180} \cdot \deg$$

will give the step based on the radius of roller being used. Due to limitations with what rollers are available a twenty-five-millimeter roller was chosen; this is because it was the smallest roller to accommodate the shaft diameter being eight-millimeters. Running the calculation gives point-thirty-nine-millimeters per step when what is needed is point-one-millimeter per step. Dividing the current step size by the required step size gives a ration of three-point-nine to one. Therefore, to get an acceptable step size there would need to be a reduction in step size of a four to one magnitude (rounded to four). This can be done with a gear reduction system. Looking at the market the only gear ratio available was five to one, ultimately giving a step size of 0.079 millimeters per step. The motor is a 'NEMA 17 5:1 planetary gear' paired with a twenty-five-millimeter roller. The next motor is the rotation motor. The step size of the motor is by default one-point-eight-degrees this will need to be reduced to point-five-degrees. Unlike the translation motor having its reduction done by a gear system the reduction for the rotation motor will be done with a sub step setting set using the stepper motor driver. The reason for this is sub stepping can be inaccurate, and it was more critical that the translation system had its needed resolution thus the physical reduction. For the rotation what needs to be looked at is how much the catheter rotates based on the roller rotating. The roller in question is a thirty-millimeter roller which rotates the catheter based on the ratio of their respective diameters. The smallest catheter is point-seven-millimeters in diameter creating a ratio of one to forty-three dividing the point-five degrees by forty-three gives a 0.012 degree per step and dividing the motors one-point-eight-degree by the newfound degree per step this gives us a stub step of 150. This isn't available for the stepper motor driver; the smallest sub step is 128. Dividing one-point-eight by 128 gives 0.014 degrees per step and multiplying this by forty-three gives the catheters rotation per step, point-six-degrees per step. This is acceptable. The motor used for the rotation is a NEMA 11 for its small size.

Next is the power supply, this will need to power all of the electronics within the system. This was selected by finding a working voltage to run the system at and then finding the required amps of each component. Before getting into calculations there must be a definition for what will consume the power within the system. The flow of power will look something like this, Fig.1 Power Flow Breakdown Here we see the flow of power from the power supply to the different power consuming components. The initial focus will be on the motors and motor drivers as they will consume the most power out of the entire system and therefore will dictate what motor supply will be chosen. Within the design there are two motors, a NEMA 17 with a rated voltage of two-point-eight volts and one-point-sixty-eight amps, a NEMA11rated at six-point-two volts and point-sixty-eight amps. This may point to the answer to which power supply, however there is another driving factor to this problem. That being the stepper motor driver. The stepper motor driver has the task of taking inputs from the controller and sending the power supply energy to the motor in a way that is needed by the controller. Stepper motor drivers can be found ranging from eight volts to thirty-two volts, all of which are above the rated voltage of our stepper motor. This turns out to be okay as stepper motors do not need to run at their rated voltage as the stepper motor drivers will limit the amount of current going into the motor. According to research stepper motors are typically okay with voltages twenty times higher than rated. The only possible issue would be heat generation. The motors won't be running continuously or at a heavy load which essentially negates this issue. Higher voltages are advantageous to stepper motors as they allow for faster response times and higher performance. This leaves the voltage of the power supply to fall onto other factors. For the drivers there is the A4988 for the NEMA 17 motor and the DVR8434 for the NEMA 11 motor. The reason we use the DVR8434 for the NEMA 11 is because it offers a 128-sub step size which is needed to reach the resolution of movement needed from the rotation. The NEMA 17 does not share this issue as it gets its step size resolution from a 5:1 gear ratio attached to its shaft. Using this we can find the amps needed. For the stepper motor drivers will take in a reference voltage from our microcontroller which allows it to limit the current to the motor's specifications.

$$V\,ref = Imax\ (8 * 0.068)$$

This is the equation to find the reference voltage for the A4988, Imax is the rated current of the NEMA 17. However, reading the data sheet we find that the max current must be set to forty percent higher than the rated current. Solving gives us a reference voltage of one-point-three volts. Forty percent over the stepper motors rated current gives us two-point-four amps, this is significant as it is above the drivers rated current of two amps. Although the datasheet describes additional cooling in the form of a heat sink will allow for safe operation of the driver. This coupled with the fact the motors won't run under load or continuously is sufficient to allow us to use this driver despite being over current. Next, we do the DVR8434,

$$V\ Imax = ref\ 1.32$$

This gives us a reference voltage of point-nine volts. These two reference voltages can be supplied by our microcontroller. We now move onto calculating the power draw of each motor by using the power equation.

$$Power = Current * Voltage * 2$$

There are two in the equation since these are bipolar stepper motors meaning there are two phases inside which will each need powering. This means the NEMA 11 will need around eight-point-four watts and NEMA17nine-point-four to thirteen-point-four watts. The reason the NEMA 17 is a range is due to the higher current which may be to run through it as described by the stepper motor driver data sheet. We will only use the higher power consumption so be sure we have the needed power. Now, we will jump to the microcontroller and sensors as they will be power consuming components. Here we mainly want to see if we can find a workable voltage as these components will require minimal current to run but will actually need a specific voltage. Knowing the microcontroller we intend to use is an Arduino. We can look at the data sheet and see what voltage constraints we are working with. Through this we can see the Arduino can handle up to twelve volts. This falls within our voltage range for the stepper motor drivers so twelve volts will be chosen for the system. In fig.1 there is a component labeled "step-down," it turns out the Arduino has one (up to twelve volts) built in, this simplifies the design and allows the sensors, microcontroller and motors to run off the same power supply. Calculating total current draw,

$$Current = Power\ Volts$$

The stepper motors will be supplied with twelve volts, even if just for a moment, dividing the calculated stepper motor required power by the twelve volts we get the current being drawn by the motors. NEMA 17 draws one-point-one amp and the NEMA 11 draws point-seventy-eight amps. The Arduino will run at a max of 500 milliamps or point-five amps. Now summing all the current together as these systems run in parallel gives a value of two-point-four amps total. Adding in our safety factor of fifty percent we get a final value of three-point-six amps

3.3.3 Catheter Clamping Forces (Gray B.)

This mathematical model determines the cross-sectional area required for a clamped catheter to remain undamaged under certain conditions. Assuming the worst-case scenario, the catheter would experience a push force of 10 N, and the surface of the rollers is assumed to be wet, with an arbitrary coefficient of friction of 0.1. Using the normal force equation below and plugging in these values results in a normal force of 100 N.

$$F_N = \frac{F_f}{\mu}$$

Catheters are often made of Pebax, a material with a yield stress of 12 MPa. Rearranging the stress equation for cross-sectional area and solving for diameter, the minimum French size of the catheter can be found.

$$A_c = \frac{F}{\sigma}$$

$$d = 2 * \sqrt{\frac{A_c}{\pi}}$$

Based on these calculations, the minimum diameter to resist deformation would be 3.26 mm, or a 10 F catheter. Since our robot must handle catheter sizes as small as 2 F, maximum push force must be reduced, the coefficient of friction must be increased with our choice of rollers, or a mandril would be needed to support the catheter.

3.3.4 Rotation Calculations (Josh H.)

The calculations done for the rotation system are to find if there is a better way to produce friction between the catheter and rollers to allow for a complete and seamless rotation. The first thing done was to find the moment of inertia of the catheter. This was an estimate since the density of the catheter is variable and a very well-kept secret for companies. This is found with the equation,

$$I = \frac{1}{2}Mr^2$$

which will then be converted to:

$$I = \frac{1}{2}p\pi r^2 L r^2$$

The length L was given to be two feet as designated by the engineering requirements as the max sized catheter needed to be handled. The radius range of the catheter must be between point-thirty-five to two-point-five-millimeters. This was then plugged into the torque equation,

$$T = aI$$

Where a is angular acceleration and I is moment of inertia found above. This will tell us the required torque to rotate a catheter which is small. Almost any motor will be able to supply this. However, the question is the friction needed. This depends on the normal force and the friction coefficient. The max friction force must equal the max force required to get the required torque. This will give a ballpark answer for how much the catheters would need to be 'squeezed,' or rather the normal force acting upon it. Below is a figure where the calculations were run in mass. Something of note is the angular acceleration is a design choice variable. In Figure 4, there can be seen a wide range of angular accelerations. These were based on how long it would make logical sense for a catheter to rotate.

plate:			1 rev = rad	Catheter diameter sizes		inertia Large:	1.87E-11	kgm^2	Mass of plate	6.52	g
smallest	15.7	mm	6.283185307	0.7	mm	Inertia Small:	7.18E-15	kgm^2	Normal force:	0.064	N
Largest	31.4	mm		5	mm	density:	1	const.	Worm (d):	8	in
							Friction plate rotation				
Velocity:			Acceleration		Toruqe_L	Torque_S	Force_L	Force_S			
time	rad/s	mm/s	rad/s^2	mm/s^2	Nm	Nm	N	N			
1	6.283185307	15.7	6.283185307	15.7	1.18E-10	4.51E-14	4.70E-08	1.58E-17			
2	3.141592654	7.85	1.570796327	3.925	2.94E-11	1.13E-14	1.18E-08	3.95E-18			
3	2.094395102	5.233333333	0.6981317008	1.744444444	1.31E-11	5.02E-15	5.22E-09	1.76E-18			
4	1.570796327	3.925	0.3926990817	0.98125	7.34E-12	2.82E-15	2.94E-09	9.87E-19			
5	1.256637061	3.14	0.2513274123	0.628	4.70E-12	1.81E-15	1.88E-09	6.32E-19			
6	1.047197551	2.616666667	0.1745329252	0.4361111111	3.26E-12	1.25E-15	1.31E-09	4.39E-19			
7	0.897597901	2.242857143	0.1282282716	0.3204081633	2.40E-12	9.21E-16	9.59E-10	3.22E-19			
8	0.7853981634	1.9625	0.09817477042	0.2453125	1.84E-12	7.05E-16	7.34E-10	2.47E-19			
9	0.6981317008	1.744444444	0.07757018898	0.1938271605	1.45E-12	5.57E-16	5.80E-10	1.95E-19			

Figure 4. Angular Accelerations for Varying Catheter Sizes

Overall, the normal force required for this will be around 0.064 newtons. This is assuming the friction coefficient is one which is a real-world value of some rubbers which is what the material-on-material interaction was assumed to be based on firsthand experience with catheters. This means if it is a material less fractionable than rubber more force will be needed to have the catheter move while max force is applied.

4 Design Concepts

4.1 Functional Decomposition

For the functional decomposition, our system has three main functions and four main sensor readings. These are represented in Figure 5. First, the design must adjust to the catheter size, then the system will either translate or rotate the catheter. As a result, translational or rotational force and velocity will need to be recorded, respectively. Since the system cannot rotate and translate at the same time due to limitations created when clamping the catheter, this functional decomposition tracks the necessary measurements associated with the decision to move or rotate the catheter.

Inputs to the system are energy supplied to the motors and signals sent from the user via remote system to activate the motors. Outputs include motor motion and the resulting recorded data from that motion. Figure 5 also illustrates the recorded measurements associated with motor activation.

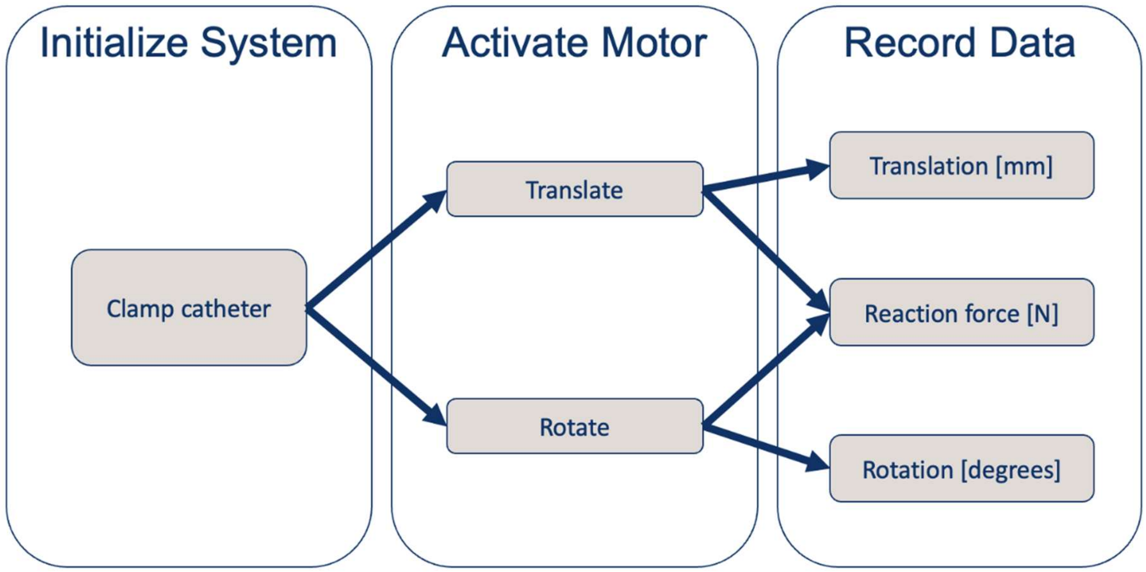


Figure 5. Functional Flow Model

4.2 Concept Generation

4.2.1 Translation

The translation component will control the forward and reverse motion of the catheter. From our research, we have found that an extruder-based design with a set of rollers above and below the system are best way to do this. The rollers would be separated on different halves connected by a threaded column that can change the distance between them. This result comes from our SOTA systems and other research. We have considered and calculated concepts other than this, but none produced competitive results. To make our own version of this design without direct copying, we investigated different ways to arrange the rollers in the above arrangement.

One idea is to have the rollers organized in a square layout. One of the rollers would be attached to a motor with the rest idling freely on bearings, shown in Figure 6. This is the most like the current systems though it is unique in the way it is adjusted vertically. No other model uses the threaded rods changing the height. The advantage of this design is that it is easier to manufacture as the top and bottom braces are very similar. However, the design will need to be larger to allow space for the rollers and motor.

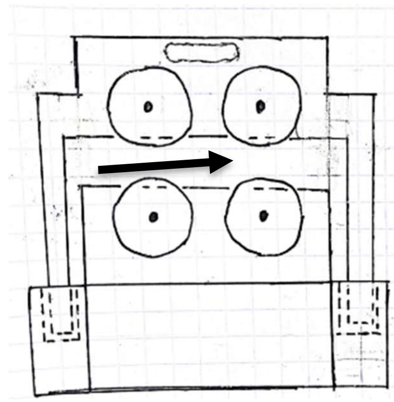


Figure 6. Square Design

Another idea is to place the motor roller on the bottom plate and have three smaller rollers on the top. The three top rollers will be free rolling on a bearing, seen in Figure 7, similar to the above design. With this orientation, the motor can provide a larger push on the catheter. The advantage of this layout is it more compact. The disadvantage of this layout is that a larger motor will need to be larger to produce the same effects and more distinct parts are needed.

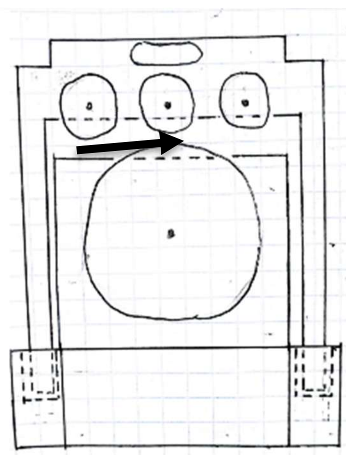
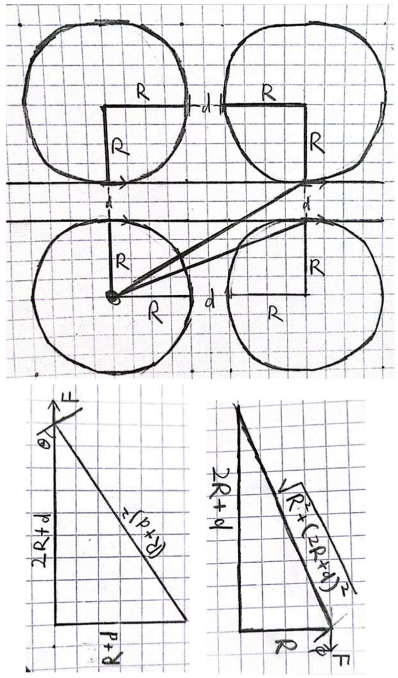


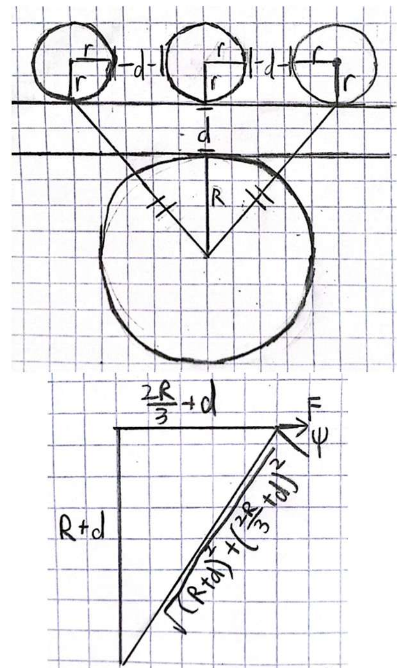
Figure 7. Triangle Design

To determine the best layout for the rollers, the team looked at which design requires more torque from the motor. By choosing the axle of the motor as the center of mass, the sum of moments can be evaluated along with the magnitude of force needed to roll all the rollers and push the catheter. The assumptions made for this calculation are that the rollers in the square roller design are all equal. And for the triangle setup, the smaller rollers are a third of the diameter of the larger one which is equal to one of the square rollers. This information was used to derive the equations that were put into MATLAB. We found that to produce a 10N force, the motors require almost equal moments. Changing the values and relationships caused switching in which motor was better. Figures 8 and 9 illustrate the moment diagrams for each design.



$$\varphi = \tan^{-1}\left(\frac{2R + d}{R}\right) \qquad \theta = 90 - \tan^{-1}\left(\frac{R + d}{2R + d}\right)$$

Figure 8. Square Design - Moment Diagram



$$\psi = 90 - \tan^{-1}\left(\frac{R + d}{\frac{2R}{3} + d}\right)$$

Figure 9. Triangle Design - Moment Diagram

After talking with our clients about the better design they recommended going with the square design for prototyping and making the triangle design if it does not work.

4.2.2 Rotation

The rotation explored two methods of rotating the catheter. The first was a plate design where two plates were to squeeze the catheter and move linearly perpendicular to the catheter. This was to mimic the movement of a hand and is how people will rotate catheters in the real world. The design was very complex but had the benefits of very good friction and smooth rotation for the catheter. This design used multiple components and multiple stepper motors to allow for the plates to move up and down as well as left to right. These designs are illustrated in Figure 10.

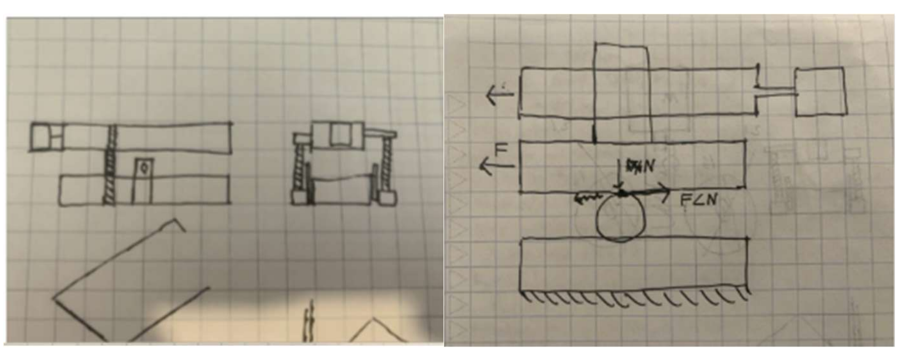


Figure 10. Plate Rotation Device

The next design was simplistic, only utilizing one motor and two rollers. These were positioned vertically in a housing where the catheter will be fed in-between the rollers and will rotate as the motor roller rotates. This design runs the potential that the rotation will not be uniform since there will be the curve of the roller. Also, there is a chance that the catheter would slip out of its position and not be directly in-between the rollers as intended.

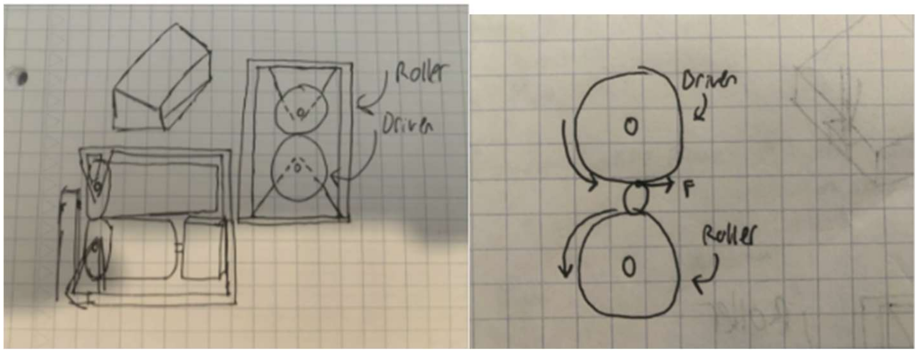


Figure 11. Roller Rotation Device

4.2.3 Sensors

One of our customer requirements is to collect and record how the system reacts to the forces we are applying. For the above components to work properly, we need a way to measure their effects. Without any feedback, the motors or plates could break the catheter or the vein system. There are many ways to apply feedback to a system like this. We have considered and tried multiple of these and came to two final ideas.

The first way to measure feedback is with a load cell. A load cell is a device that is put through a certain force and can provide that force to a computer. They are helpful in designs where a force is needed but the strength of that force is unknown. When the rollers move in each system, a negative force will be produced that pulls on the support structure. By placing the system on wheels and connecting it to a load cell, that negative force can be measured and recorded. The advantage of this design is higher accuracy from load cell measurements. However, this approach is more expensive and results in a larger and more complex design since it requires additional infrastructure. This method is illustrated in Figure 12.

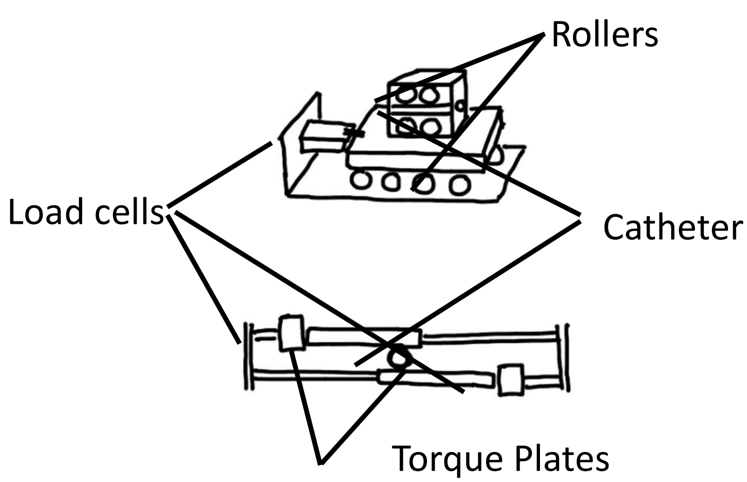


Figure 12. Load Cells for Translation and Rotation

Another method for collecting feedback is with an RPM sensor or tachometer. When a wheel or roller spins, each part of that wheel spins once per rotation. By marking a place of the wheel with tape and pointing a laser at it, the rpm can be found. The laser will record how many times the line is reflected per minute and turn it into rpm. With the speed and radius of the wheel known, one can find the force being produced. This design suffers from lower accuracy since the motors used in our system do not have a 100% efficiency. However, this design is simpler to implement and will not complicate the size and structure of the design. This method is shown in Figure 13.

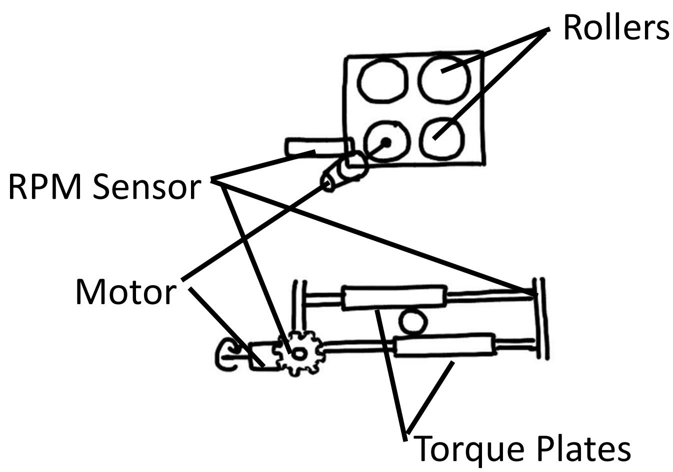


Figure 13. RPM Sensors for Translation and Rotation

4.3 Selection Criteria

4.3.1 Translation

The above calculations led the team to compare them under different conditions. From the concept generation, the square design seemed to be more efficient and easier to produce as both the top and bottom plates have identical layouts. To manufacture this design, the housing will be needed to contain all components. It will have housing for the motor leading into a shaft for the driver roller. The shafts and bearings will be placed between two walls on both the top and bottom parts. Columns will be built into the housing for the top section to sit on. The columns will give the system variable height. It will also have a locking mechanism to keep the top section off the system while the translation component is not in use.

4.3.2 Rotation

Originally the calculations and the selection criteria for rotating a catheter led to the plate design being chosen. However, after further analysis, the roller design was chosen. The plate design has the benefits of uniform friction, it was eventually deemed too expensive and complex. The design alone needed multiple stepper motors which will all have to be accounted for driven by a stepper motor driver and controlled by a microcontroller. There were also many different materials and components which would all have to come together on a relatively small scale for this design to work. For this reason, the roller rotation design was chosen. The roller rotation is simplistic and easy to manufacture. Needing minimal components, it won't break and will also be easy to replace a part that does fail. The negatives of the catheter not sitting right and slipping out will be answered in prototyping as this design will need to be tried and tested. To add on if needed the catheter could be held into place by two thin plates which will rest alongside the catheter. This will negate the risk of the catheter falling out and thus making this the optimal design.

4.3.3 Sensors

The load cell system provides more accuracy, but its construction requires more components. The RPM sensor offers a simpler alternative. Due to the complexity of the load cell design, the clients preferred the RPM sensors. However, this design only works if the motor is constantly rotating, which will not be the case in the translation and rotation systems since they use stepper motors. After extensive research and conversations with other engineers, a rotary torque sensor or reaction torque sensor was recommended. The cost of the rotary torque sensor is around ten times greater than a reaction torque sensor, and its wiring could get caught. Reaction torque sensors were also examined, but these sensors do not have the sensitivity to pick up small catheter translation or rotation without the presence of an amplifier, as discovered after individual analysis. Thus, the team must create a reaction torque sensor with high sensitivity through a design variation of the load cell system. Instead of adding rollers to the entire system, a shaft can be attached to the motor and bearings to allow the motor one degree of freedom, and a moment arm resting on a load cell will allow for the measurement of forces and torques. This concept is newer and still in development.

4.4 Concept Selection

We placed the above designs into a morphological matrix where the components make two full designs. Taking these designs and the equations calculated above we can find the best design for our project.

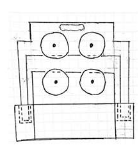
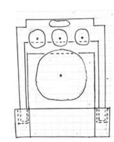
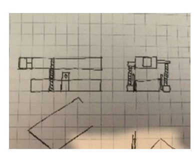
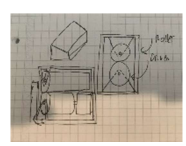
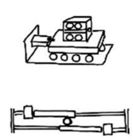
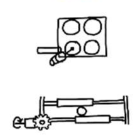
Subsystems	1	2
A. Translation		A2 
B. Rotation		
C. Sensors		C2 

Figure 14. Morphological Matrix

For the translation component, the best choice is the square design. This is due to the ease of manufacturing and the catheter feed angle. As the bottom and top plates are mirrors, when making the parts, the CAD does not need many changes. Additionally, the square design allows for the catheter can remain straight as it is fed. Catheters do not have much structure, so they need to be supported. In the triangle set up, the catheter will roll along the motor roller and get stuck under the system. The square design offers more support to the catheter and help to keep that straight motion.

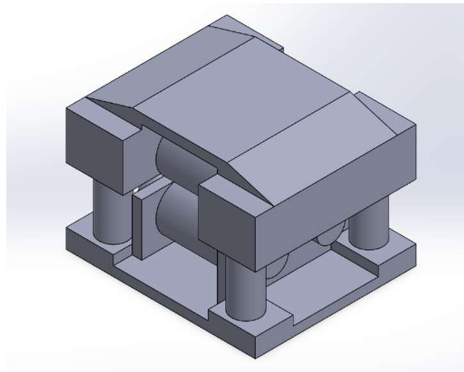


Figure 15. Square Design (SOLIDWORKS)

Originally, the better rotation component was the two plates. The wheel design, like the triangular translation design, will not be able to maintain contact with the catheter. As the wheels rotate the catheter can easily fall off or get tangled. The plate design, although more complex, allows for cleaner motion and has less room for mistakes. However, after consideration of the values of the project a complete 180 of the project happened.

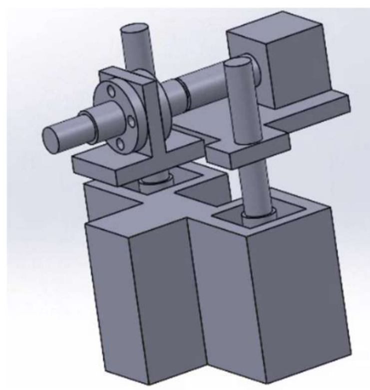


Figure 16. Rotational Design (SOLIDWORKS)

The design which is being used is two roller designs. The concern that the catheter will not stay in place has a solution where two thing plates can hold the catheter into place. This design was the simplest and cheapest. Which is why it was chosen.

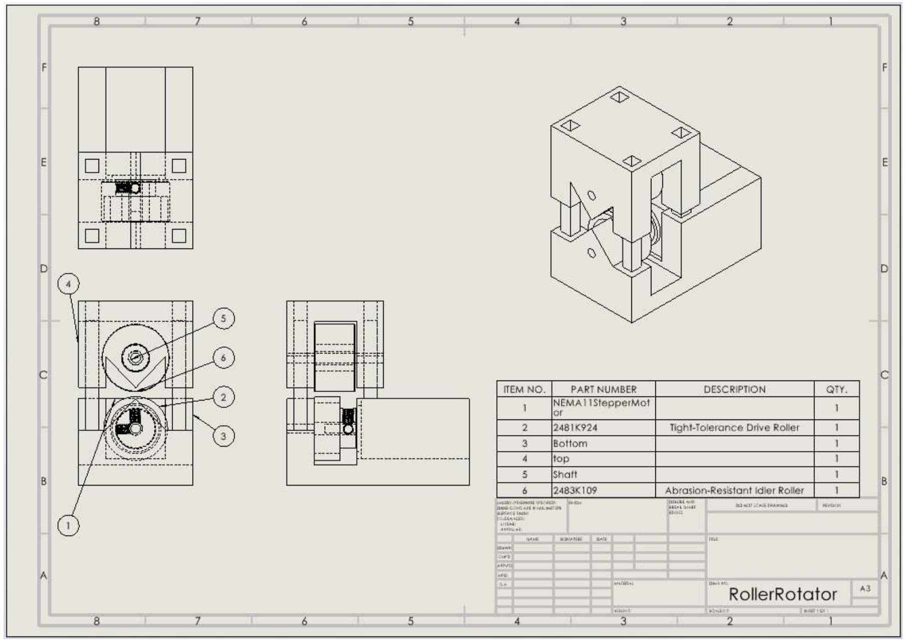


Figure 17. Drawing of rotation system CAD (SolidWorks)

The first sensor idea with the load cells was rejected by the client due to its added complexity to our robotic system. Our RPM sensor idea was well received by the client, but our advisor has indicated that the system may be too inaccurate for our client's needs due to motor efficiency adding an unexpected variable to our power and force equations. Additionally, RPM sensors work best for constantly rotating objects, while our system would only conduct minute rotational adjustments.

5 Schedule and Budget

5.1 Schedule

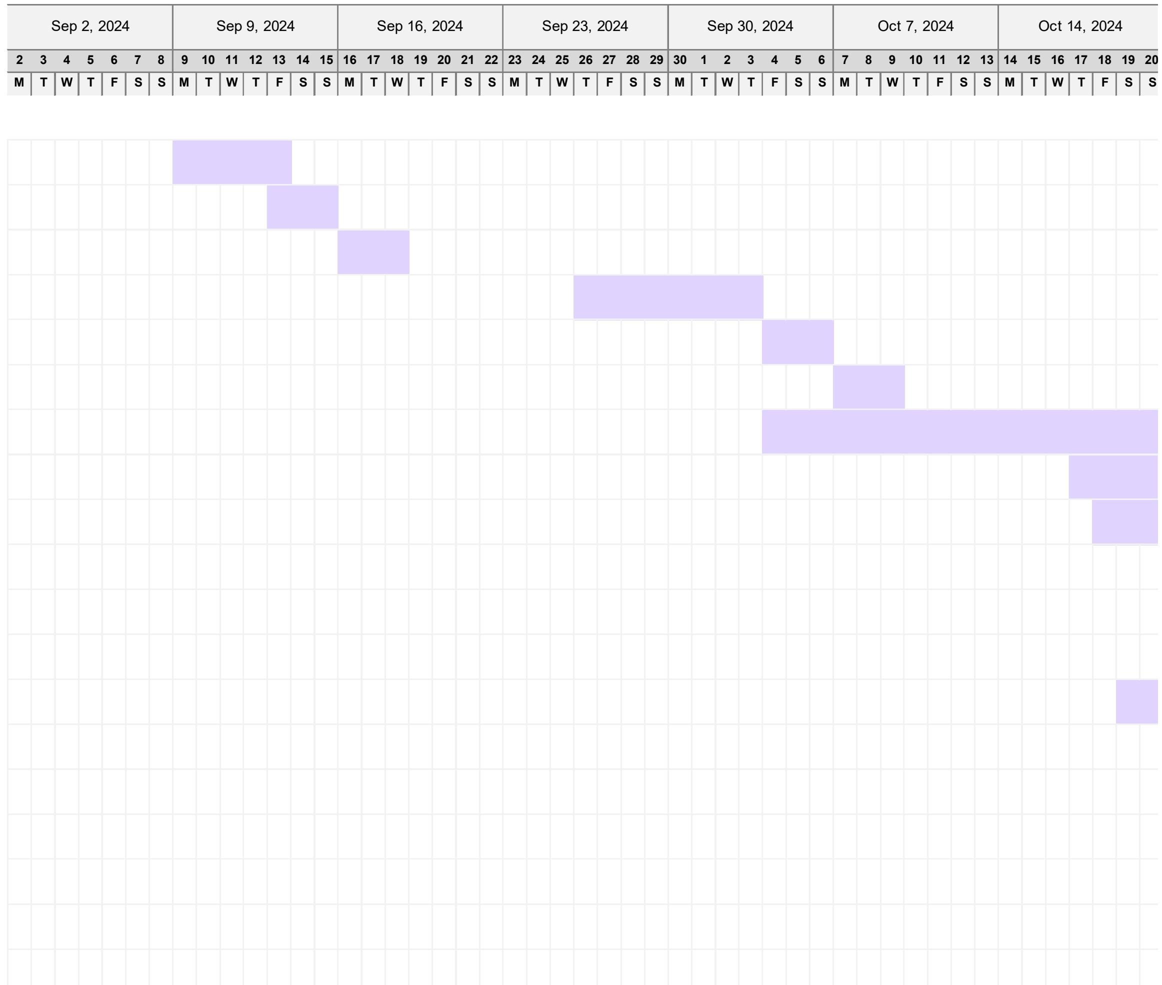
A Gantt chart, shown in Table 1, was created to keep track of course deliverables, such as prototypes and presentations. Presentations involved slides, practice, and revisions to update the course instructor and other capstone teams, while reports included cumulative progress of the capstone.

F24toSp25_01 Gray Becker

Display week: 1

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

TASK	ASSIGNED TO	PROGRESS	START	END
Course Deliverables (Fall 2024)				
Presentation 1 Slides	All	100%	9/9/24	9/13/24
Presentation 1 Practice	All	100%	9/13/24	9/15/24
Presentation 1 Revisions	All	100%	9/16/24	9/18/24
Presentation 2 Slides	All	100%	9/26/24	10/3/24
Presentation 2 Practice	All	100%	10/4/24	10/6/24
Presentation 2 Revisions	All	100%	10/7/24	10/9/24
Report 1	All	100%	10/4/24	10/20/24
Website Development 1	All	100%	10/17/24	10/24/24
Analytical Analysis Memo	All	100%	10/18/24	11/1/24
Presentation 3 Slides	All	100%	10/24/24	10/31/24
Presentation 3 Practice	All	100%	11/1/24	11/3/24
Presentation 3 Revisions	All	100%	11/4/24	11/6/24
Prototype 1 Demo	All	100%	10/19/24	11/15/24
Report 2	All	100%	11/12/24	11/26/24
Final CAD	All	100%	11/18/24	12/2/24
Final BOM	All	100%	11/18/24	12/2/24
Prototype 2 Demo	All	100%	11/10/24	12/1/24
Project Management	All	100%	11/25/24	12/5/24
Website Development 2	All	100%	11/29/24	12/6/24



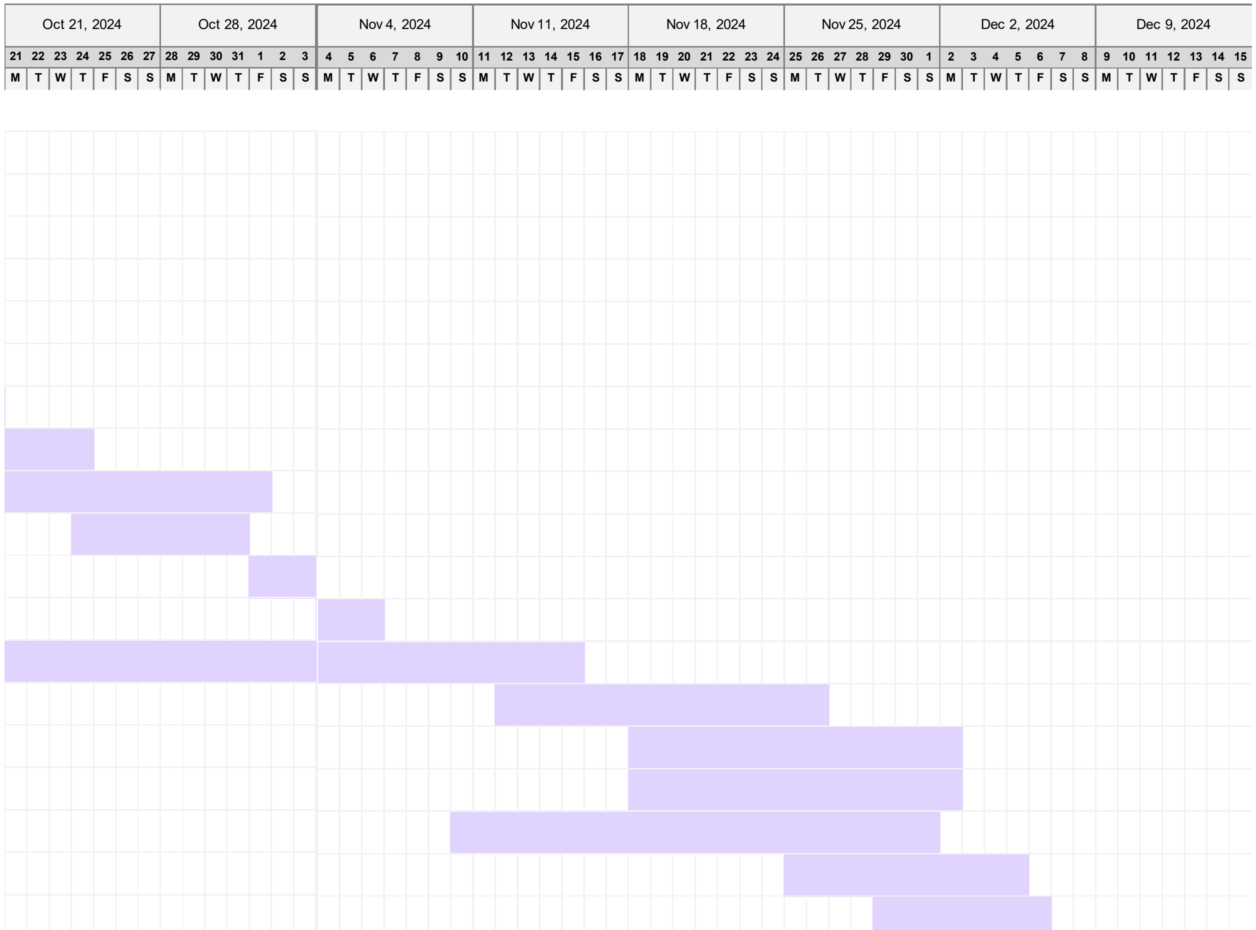


Table 1. Fall 2024 Catheter Roller Gantt Chart

Table 2 shows the Gantt chart for the second semester, including course deliverables and UGRADS requirements.

Catheter Roller

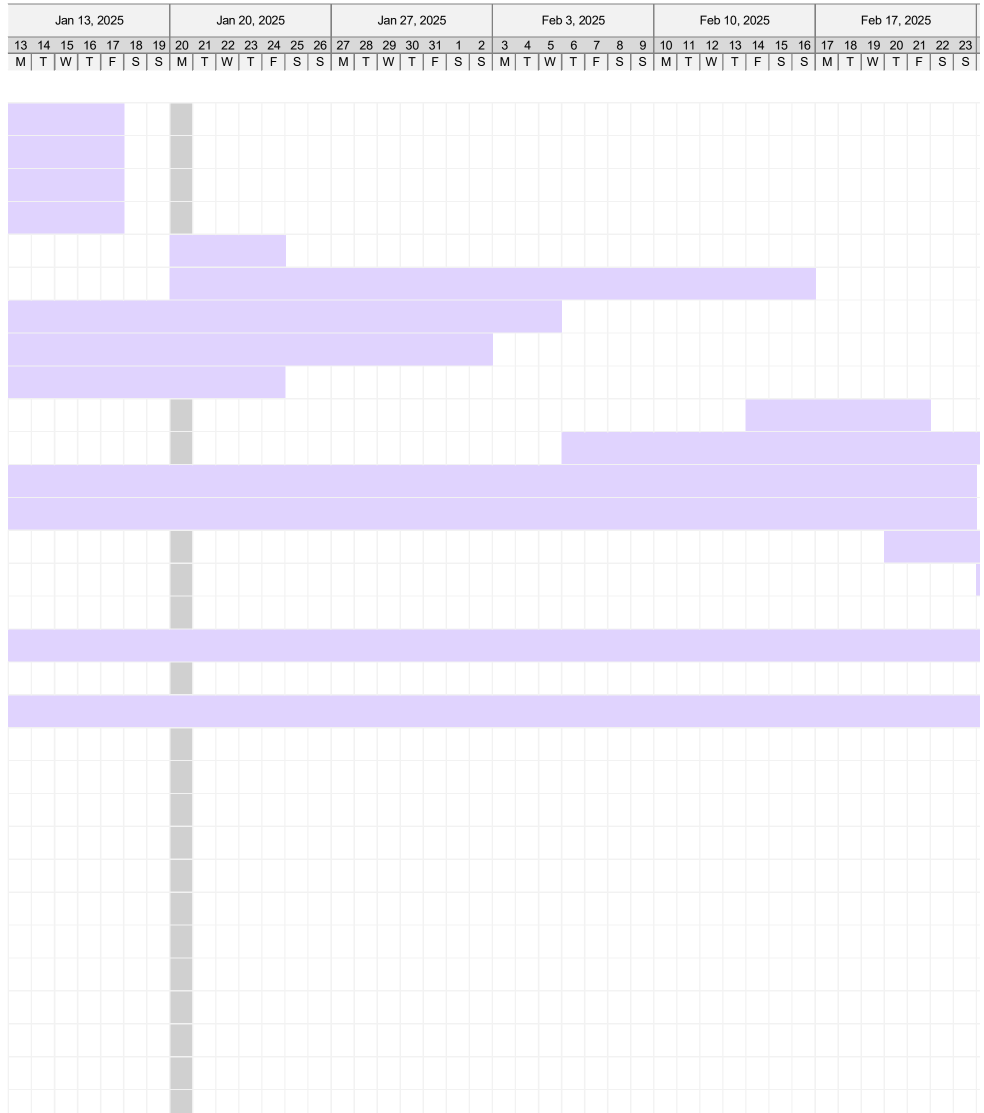
F24toSp25_01 **Gray Becker**

Project start: **Mon, 1/13/2025**

Display week: **1**

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

TASK	ASSIGNED TO	PROGRESS	START	END
Course Deliverables (Fall 2024)				
Project Management	All	100%	1/13/25	1/17/25
Gantt chart/WBS	Gray	100%	1/13/25	1/17/25
BOM	Josh H.	100%	1/13/25	1/17/25
Manufacturing	Josh P.	100%	1/13/25	1/17/25
Engineering Calculations Summary	All	100%	1/20/25	1/24/25
Self-Learning/Individual Analysis	Individual	100%	1/20/25	2/16/25
Hardware Status Update - 33%	**All**	**100%**	**1/13/25**	**2/5/25**
Wiring System	Josh H.	100%	1/13/25	2/2/25
Sensors CAD design	Gray	100%	1/13/25	1/24/25
Website Check 1	Josh P.	100%	2/14/25	2/21/25
Hardware Status Update - 67%	**All**	**100%**	**2/6/25**	**2/26/25**
Translation System (shafts, sleeves, and housing)	Josh P.	100%	1/13/25	2/23/25
Motor Mount and Load Cells System	Gray	100%	1/13/25	2/23/25
UGRADS Registration	Gray	100%	2/20/25	3/6/25
Finalized Testing Plan	Gray	100%	2/24/25	3/21/25
Hardware Status Update - 100%	**All**	**100%**	**2/27/25**	**3/26/25**
Rotation System (shafts, sleeves, and housing)	Josh P.	100%	1/13/25	3/23/25
Frame System	All	100%	2/27/25	3/23/25
Arduino Code	Josh H.	100%	1/13/25	3/23/25
Electronics Box	Gray	100%	2/27/25	3/23/25
UGRADS Poster Draft	All	100%	3/8/25	3/28/25
Initial Testing Results	All	100%	3/21/25	4/9/25
UGRADS Final Poster and Presentation	All	100%	3/17/25	4/11/25
Final CAD Packet	All	100%	3/17/25	4/13/25
Product Demonstration	All	100%	4/2/25	4/16/25
Final Testing Results	All	100%	4/9/25	4/16/25
Final Report	All	50%	4/4/25	4/18/25
Website Check 2	All	50%	4/12/25	4/19/25
UGRAD Symposium	All	0%	4/25/25	4/25/25
Spec Sheet/Operation Manual	All	0%	4/16/25	4/30/25
Client Handoff	All	0%	4/28/25	5/2/25
	Total Completion	87%		



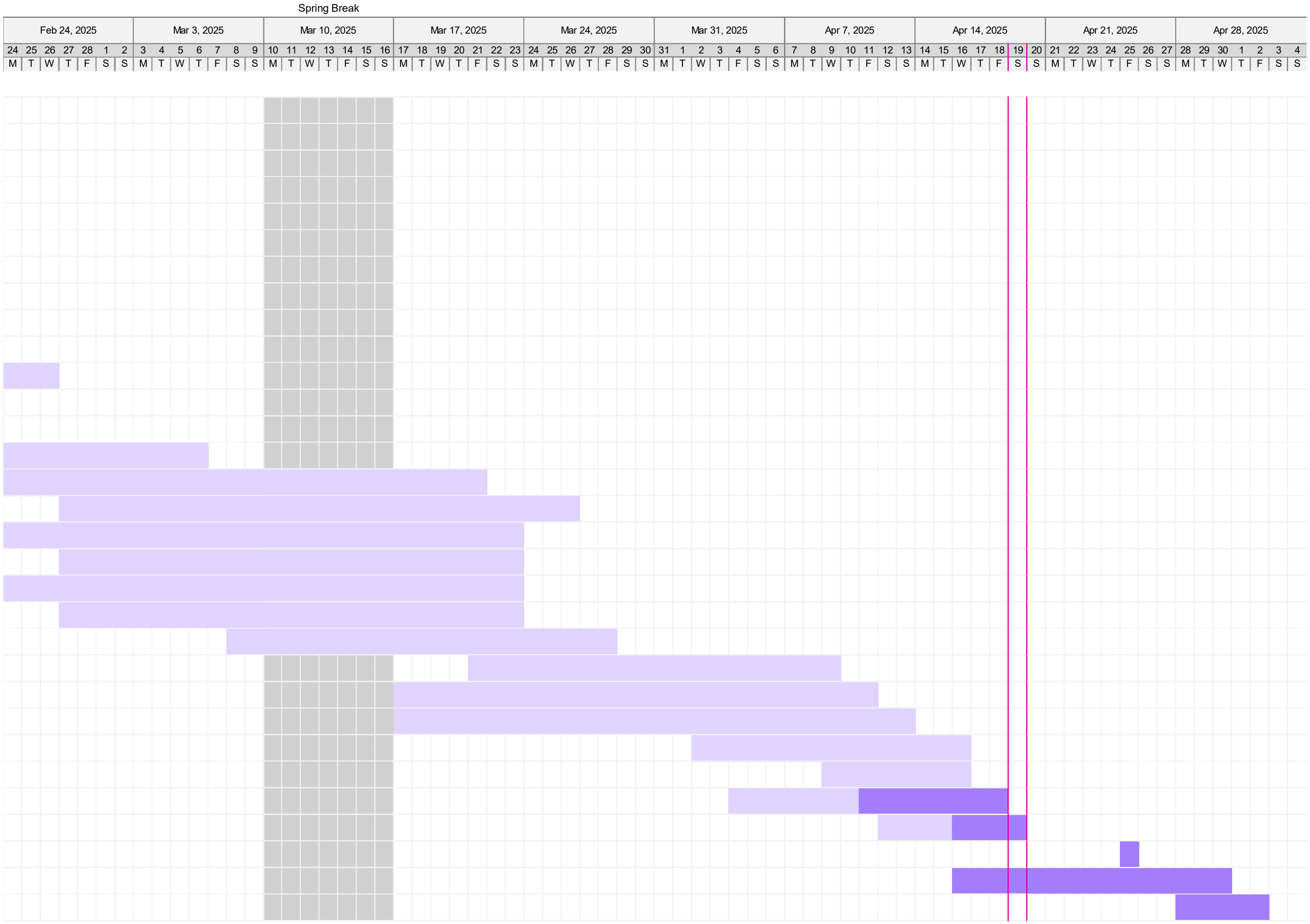


Table 2. Spring 2025 Gantt Chart

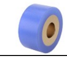
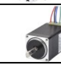
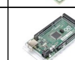
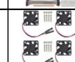
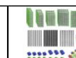
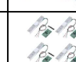
5.2 *Budget*

Figure 18 shows the full budget for the project. This includes prototyping, final assembly, and testing repairs. The total price for the project came out to be 1759.27. 32.88% of our given budget was used.

Income			
From Sponsor			$5,000
From Fundraising	$500	Current:	$350.00
Total:			$5,350
Expenses			
Order Number	Description		Cost
Order 1	Idle and driver rollers for translation		$110.96
Order 2	NEMA 17 stepper with gear ratio 5:1		$43.84
Order 3	NEMA 11 stepper motor		$26.31
Order 4	driver roller 25mm		$43.84
Order 5	Stepper motor drivers		$27.13
Order 6	30mm driver roller		$74.89
Order 7	Translation 3D print 1		$39.40
Order 8	Rotation 3D print 1		$18.44
Order 9	Nema 17 back 3D print 1		$34.64
Order 10	Nema 17 back 3D print 2		$30.24
Order 11	Nema 11 back 3D print 1		$26.06
Order 12	Translation 3D print 2		$21.20
Order 13	Translation special 3D print 1		$116.58
Order 14	Translation 3D print 3		$55.28
Order 15	Shafts, frames, load cells		$108.60
Order 16	Screws and USB		$26.08
Order 17	Bearings and snap rings		$21.12
Order 18	Arduino and electronics		$186.76
Order 19	Screw terminals and H bridges		$18.54
Order 20	Idler roller		$25.30
Order 21	Rotation 3D print 2		$23.24
Order 22	Translation special 3D print 2		$137.64
Order 23	Sensor parts final		$30.79
Order 24	Electrical box print 1		$50.96
Order 25	Electrical box print 2		$92.00
Order 26	Rotation motor angling		$369.43
Total Expenses:			$1,759.27
Budget Left:			$3,591
Percent used:			32.88%

Figure 18. Current Budget (Final)

5.3 *Bill of Materials (BoM)*

Part	Details	Status	Link	Supplier	Price per Unit	Quantity	Total Price	Picture
Translation Idler Roller	3/4in roller	Delivered	https://www.mc	Mc-MasterCarr	$20.73	3	$62.19	
Translation Driver Roller	25mm roller	Delivered	https://www.mc	Mc-MasterCarr	$31.81	1	$31.81	
Rotation Driver Roller	30mm roller	Delivered	https://www.mc	Mc-MasterCarr	$31.93	1	$31.93	
Translation Stepper Motor	NEMA 17 with 5:1 gear ratio	Delivered	https://www.an	Amazon	$40.15	1	$40.15	
Rotation Stepper Motor	NEMA 11	Delivered	https://www.an	Amazon	$24.10	1	$24.10	
Motor Driver	DVR8483 stepper motor driver	Delivered	https://www.po	Pololu	$9.95	4	$39.80	
Arduino Mega	Arduino Mega 2560 REV3	Delivered	https://www.an	Amazon	$52.34	1	$52.34	
Arduino Mega terminal block sheild	screw terminal block breakout module for Arduino Mega	Delivered	https://www.an	Amazon	$32.37	1	$32.37	
Arduino basic starter kit	Arduino basic starter kit LEDs, resistors, buttons, capacitors, transistors, diodes, wires, breadboard, power	Delivered	https://www.an	Amazon	$10.81	1	$10.81	
5V mini fan	4pcs 30mm 5V fans	Delivered	https://www.an	Amazon	$10.81	1	$10.81	
DC 12V relay module	4pcs DC 12V relay module	Delivered	https://www.an	Amazon	$7.57	1	$7.57	
PCB board kit	82 pcs PCB board kit with connectors	Delivered	https://www.an	Amazon	$12.98	1	$12.98	
22 gauge wire	33ft/10m wire	Delivered	https://www.an	Amazon	$14.06	1	$14.06	
Micro lead screw	4mm 5V 2-phase 4-wire stepper motor micro lead screw	Delivered	https://www.an	Amazon	$5.92	4	$23.68	
Load cell kit	4 sets 1kg load cells and HX711 boards	Delivered	https://www.an	Amazon	$15.49	1	$15.49	
Roller Shafts	4.5in x 1/4in stainless steel shaft	Delivered	https://www.mc	Mc-MasterCarr	$6.86	2	$13.72	

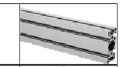
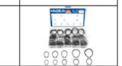
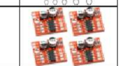
T-slotted frame	1ft T-slotted framing rail	Delivered	https://www.mc	Mc-MasterCarr	$7.57	1	$7.57	
Idler Roller	1 1/2in roller	Delivered	https://www.mc	Mc-MasterCarr	$55.77	1	$55.77	
Load cell bearings	4pcs 15x35x11mm deep groove ball bearings	Delivered	https://www.an	Amazon	$8.33	1	$8.33	
Snap rings	145pcs external retaining rings 15-28mm	Delivered	https://www.an	Amazon	$12.79	1	$12.79	
H bridges	4pcs mini L298N 2 channel H bridge DC motor driver board with MX1508 chip	Delivered	https://www.an	Amazon	$7.99	1	$7.99	
USB cable	USB cable type A male to B male, 20ft	Delivered	https://www.an	Amazon	$13.99	1	$13.99	
M4 screw kit	300pcs M4 hex socket head cap screw assortment with nuts and washers, 6, 8, 10, 12, 16, 20, 25, 30mm (black)	Delivered	https://www.an	Amazon	$8.99	1	$8.99	
PCB terminal block connectors	70pcs 2 pin & 3 pin 5mm/0.2inch pitch PCB mount screw terminal block connector	Delivered	https://www.an	Amazon	$8.99	1	$8.99	
Precision Single U-Joint	Pin and Block Joint, for 1/4" Diameter x 5/8" Deep Shaft, Acetal	Delivered	https://www.mc	Mc-MasterCarr	$40.07	4	$160.28	
Stainless Steel Ball Bearing	Shielded, Trade Number R168-2Z	Delivered	https://www.mc	Mc-MasterCarr	$5.72	8	$45.76	
Rotary Shaft	303 Stainless Steel, 1/4" Diameter, 9" Long	Delivered	https://www.mc	Mc-MasterCarr	$10.73	2	$21.46	
Press-Fit Low-Profile Drive Roller	1-1/4" Roller Diameter, 3/4" Roller Width	Delivered	https://www.mc	Mc-MasterCarr	$28.96	1	$28.96	
Metal Gear - 20 Degree Pressure Angle	Round Bore with Set Screw, 48 Pitch, 48 Teeth	Delivered	https://www.mc	Mc-MasterCarr	$28.52	3	$85.56	
Metal Gear - 20 Degree Pressure Angle	Round Bore, 48 Pitch, 12 Teeth	Delivered	https://www.mc	Mc-MasterCarr	$19.55	1	$19.55	
Ball Bearing	Sealed, Trade Number R2-2RS, for 1/8" Shaft Diameter	Delivered	https://www.mc	Mc-MasterCarr	$3.93	2	$7.86	
						Total:	$917.66	

Figure 19. Bill of Materials: Purchased Parts

Part	Details	Status	Manufacturer	Lead Time	Material	Compone nts	Manufacturing Location	Price per Unit	Quantity	Total Price
Prototype Translation Housing	Translation Housing	Complete	Josh P.	15	3D-printed PLA	1	Cline Library	$39.40	1	$39.40
Prototype Rotation Housing	Rotation Housing	Complete	Josh H.	10	3D-printed PLA	1	Cline Library	$18.44	1	$18.44
Shafts (metal)	Metal shafts for bearings	Complete	Josh P.	1	Stainless Steel	6	Engineering Machine Shop	$0.00	6	$0.00
Prototype mount for back of NEMA17	load cell housing	Complete	Josh P.	12	3D-printed PLA	4	Cline Library	$34.64	1	$34.64
Mount for back of NEMA17	load cell housing	Complete	Josh P.	28	3D-printed PLA	4	Cline Library	$30.24	1	$30.24
Mount for back of NEMA11	load cell housing	Complete	Josh P.	28	3D-printed PLA	4	Cline Library	$26.06	1	$26.06
Electronic Wiring	Circuit board wiring	Complete	All	20	Wires, solder	5	Cline Library	$0.00	1	$0.00
Prototype 2 Translation Housing	Translation Housing	Complete	Josh P.	10	3D-printed PLA	18	Cline Library	$21.20	1	$21.20
Translation Prototype Special Components	Small components or different material	Complete	Josh P.	1	Vero and Agilus	14	Bioengineering Devices Lab	$116.58	1	$116.58
Translation Final Housing	Translation Final Housing	Complete	Josh P.	22	3D-printed PLA	15	Cline Library	$55.28	1	$55.28
Rotation Final Housing	Rotation Final Housing	Complete	Josh P.	10	3D-printed PLA	12	Cline Library	$52.48	1	$52.48
Translation Final Special Components	Small components or different material	Complete	Josh P.	1	Vero and Agilus	10	Bioengineering Devices Lab	$137.64	1	$137.64
Sensor Parts Final	load cell housing	Complete	Josh P.	19.5	3D-printed PLA	8	Cline Library	$60.04	1	$60.04
Electronic Box Prototype	electronics housing	Complete	Josh P.	28	3D-printed PLA	4	Cline Library	$50.96	1	$50.96
Electronic Box Final	electronics housing	Complete	Gray	37	3D-printed PLA	4	Cline Library	$82.76	1	$82.76
Box Lid Reprint	electronics lid	Complete	Gray	4	3D-printed PLA	2	Cline Library	$9.24	1	$9.24
									Total	$734.96

Figure 20. Bill of Materials: Manufactured Parts

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

An FMEA was conducted, as shown in Table 3, and the largest source of failure was found to be the remote-control system. If the system loses connection, the robot can no longer be controlled, defeating the purpose of testing catheters from a distance and risking damage to the catheter and blood vessel model. The purpose of the emergency stop is to prevent any damage from occurring in the event of a disconnect. The last four rows of the FMEA show failure analysis from additional parts added by the original rotation plate design. The rotation roller design has similar failure scenarios to the translation system, simplifying the team's mitigation strategies.

Table 3. Failure Modes and Effect Analysis for Translation and Old Rotation Systems

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Motor	water ingress	stop operation, electrical hazard	environmental conditions	40	shield component
Motor	high-cycle fatigue	stop operation	material/component issues, fatigue	42	replace component every 5 years
Roller	fretting wear	misalignment	material/component issues, tolerances	24	replace component every 5 years
Roller	surface fatigue wear	slipping	material/component issues, fatigue	24	replace component every 5 years
Shaft	high-cycle fatigue	fracture	material/component issues, cracking	42	replace component every 5 years
Sensor	water ingress	emergency stop disabled	environmental conditions	40	shield component
Remote Control	connection loss	stop operation	environmental conditions	140	ensure stable connection conditions
Torque Plate	fretting wear	misalignment	material/component issues, tolerances	24	replace component every 5 years
Torque Plate	surface fatigue wear	slipping	material/component issues, fatigue	24	replace component every 5 years
Lead Screw	fretting wear	misalignment	material/component issues, tolerances	24	replace component every 5 years
Lead Screw	high-cycle fatigue	fracture	material/component issues, cracking	42	replace component every 5 years

6.2 *Initial Prototyping*

6.2.1 Translation

As part of the first protype demonstration, we made a complete CAD model of the translation system described in the Design Concepts section. With our calculations and requirements, we purchased the needed parts to make the system. The purchased parts were the driver and roller bearings, along with a motor with an internal gearbox. The dimensions and tolerances of these parts were put into the CAD to make it 3D printable. After the housing was printed, the system was assembled.

To test the system, we borrowed a variety of catheters from the BDL. The catheters were feed through the system and the upper roller part was lowered onto it. Unfortunately, at the time of testing, we did not have the motor system, discussed below, set up. Because of this, the motor's movement was mimicked with a hand-rotated shaft. The question we asked with this model is if the urethane rollers we purchased produce enough friction to move both dry and wet catheters with the applied force of the upper roller component.

By turning the shaft with the catheter in place between the rollers, the catheters were able to be pushed with minimal slip. We repeated the experiment with multiple catheters of different sizes and flexibilities, and they all performed perfectly.

6.2.2 Arduino Code

In the project the Arduino will need to be able to communicate with a connected computer as well as run the motors. The first prototype aimed to prove that it was in fact possible to send commands to the Arduino and have the Arduino send data back to the computer. This was done by making use of the serial monitor within the Arduino. Essentially an Arduino physically plugged into a computer can receive data being sent on the specific channel both the computer is using and the Arduino is listening too. This can happen in reverse where the connected port can instead be used for the Arduino to send data and the computer to receive it. Overall, the functionality being tested was if the Arduino can receive commands which can cause some outcome on the receiving end as well as if the Arduino can send sensor data it records to the computer for storage.

To test this a script was written for Arduino where it would observe the serial monitor until an incoming string appears. This string would be sent from the commanding computer. The string would consist of multiple parts which would dictate the Arduino's actions. The command string would always have this specific information in the form of letters and numbers the Arduino would decode using a hard coded string parser. The first character would tell the Arduino if the system should be on or off, this was done with an 'A' for on and an 'a' for off. The next character will denote which motor system the user would like to move, "T" for the translation motor and "R" for the rotation motor. The motor selection character would be followed by any sized number (No limits were added yet) followed by an "S" to mean this is the designated speed the motor should run. Finally, the speed will be followed by any size number followed by a "D" to mean the degrees the motor should rotate till. An example command string would look like this "AT100S100D," this would mean system is on, move translation motor 100 degrees at 100 degrees per second. It is worth noting that this prototype testing had no motors attached and was just meant as a proof of concept that Arduino can take in commands from an external source. The second part of this prototype was sending data back. This was done by having the Arduino generate random 'sensor' values and send them through the serial monitor. Both of these tests were a success.

6.3 Other Engineering Calculations

6.3.1 Power Supply Calculations Arduino Code

Power supply calculations are based on a max load situation where all motors would run at the same time. Motors will also take the most power to run and therefore will be the focus.
NEMA 17 specs: 2.8 V 1.68 A
NEMA 11 specs: 6.2 V 0.68 A NEMA 17 power:

$$P_{17} = 2.8\ (V) \cdot 1.68\ (A) = 4.7\ (W)$$

NEMA 11 power:

$$P_{11} = 6.2\ (V) \cdot 0.68\ (A) = 4.2\ (W)$$

The voltage chosen was a 12 V power supply due to accessibility and ability to run all the electronics.
Convert power to amps based on a 12 V power supply. This is done with a simple power to current equation however it is multiplied by two since the motors are two phases.

$$A_{17} = \frac{4.7\ (W)}{12\ (V)} \cdot 2 = 0.78\ (A)$$

$$A_{11} = \frac{4.2\ (W)}{12\ (V)} \cdot 2 = 0.70\ (A)$$

A microcontroller with other sensors will be able to run off 12 V and will at most take 0.5 A.
Total current needed will be the sum of all currents (all electronics will be in parallel).

$$A_{total} = A_{11} + A_{17} + A_{ms} = 0.78 + 0.7 + 0.\ \ 5 = 1.98\ A$$

For the final expected current there is a safety factor of 2 multiplied into the total current to get the final current required.

$$A_{final} = 1.98 \cdot \quad = 3.96\ (A)$$

The final power supply will be a 48-Watt power supply capable of delivering 12 V and 3.96 Amps.

6.3.2 Catheter Forces

The catheter roller robot is required to handle catheters of sizes 2-15 French, or 0.67-5 mm. To avoid damaging a 2 F catheter, we must calculate the maximum force before the catheter yields. Catheters are often made of Pebax, a material with a yield stress of 12 MPa.

$$F = \sigma A_c$$

$$A_c = \frac{\pi d^2}{4}$$

Based on these equations, the maximum normal force exerted on a 2 F catheter before yielding is 4.19 N. For a 15 F catheter, the maximum normal force is 235.62 N.

In the worst-case scenario, the surface of the rollers for translation or rotation would be wet, with an arbitrary coefficient of friction of 0.1. Using the friction force equation, we can find the maximum force read by the robot's load cells before the catheter is damaged.

$$F_f = \mu F_N$$

Under these conditions, a 2 F catheter would have a force reading of 0.42 N, and a 15 F catheter would have a reading of 23.56 N. One of our engineering requirements is to read forces between 0.1-10 N, where 10 N would break any catheter smaller than 10 F. Thus, our emergency stop system must account for catheter size and trigger at forces under 10 N for catheters under 10 F.

6.3.3 Motor Calculations

Both the translation and rotation systems will need to move the catheter at a certain distance per step to meet our movement resolution. This is based on the built-in degrees per step of the stepper motors and the diameter of the roller used to move the catheter.

For the translation the resolution needed was 0.1 mm/step. The motor chosen for this task was a NEMA 17 5:1 gear ratio stepper motor paired with a 25 mm drive roller.

$$S = \frac{d_{roller}}{2} * \frac{\pi}{180} * 1.8 = \frac{25mm}{2} * \frac{\pi}{180} * 1.8 \left(\frac{deg}{step}\right) = 0.39 \frac{mm}{step}$$

For a direct drive system based on just the degree per step and the size of the roller the calculation shows the catheter will be moved more than 0.1. Comparing 0.39 to 0.1 gives a ratio of about 4:1. This would mean the motor would need to take a fourth of a step to meet the criteria. On the market we found a motor with a 5:1 gear ratio.

$$S_{new} = \frac{0.39 \left(\frac{mm}{step}\right)}{5} = 0.078 \frac{mm}{step}$$

This is below 0.1, thus meeting the criteria.

The rotation system has no criteria given by the client for resolution. Due to this fact a goal of 0.5 degrees per step was set. The smallest catheter to be used in the system will be 0.7 mm in diameter. The NEMA 11 used in the rotation system is paired with a 30 mm driver roller. The stepper motor has a base degree per step of 1.8 degrees.

$$\frac{30\ (mm)}{0.7\ (mm)} = 1{:}43\ ratio$$

This ratio between the driver roller and catheter diameter shows that a rotation of any degrees by the stepper motor will result in a much greater rotation by the catheter. The stepper motor will be controlled by a stepper motor driver. The stepper motor driver has the capability of doing a sub step.

$$\frac{0.5 \left(\frac{deg}{step}\right)}{43} = 0.012 \left(\frac{deg}{step}\right)$$

Using the ratio of the catheter rotation from before and dividing the desired degree per step will give what the stepper motor itself will need to move.

$$\frac{1.8\ (\frac{deg}{step})}{0.012\ (\frac{deg}{step})} = 150\ step$$

Dividing the native degrees per step by the newfound needed degrees per step the sub step level is found. However, no stepper motor driver goes to 150 sub steps so using the closest to this calculated value is needed. 128 sub steps are used, and much be checked.

$$\frac{1.8\ (\frac{deg}{step})}{128} = 0.014\ \left(\frac{deg}{step}\right) \cdot 43 = 0.6\ \left(\frac{deg}{step}\right)$$

This value of 0.6 degrees per step was deemed close enough to the desired value of 0.5 degrees per step.

6.3.4 Sensor Calculations

Calculations are necessary to determine the type of load cell used in our translation and rotation systems, as well as the length of the lever arm used to transfer motor torque into a readable force for the load cell. Since the engineering requirements have a maximum force of 10 N, and the translation system driving roller has a diameter of 25 mm, we can calculate the maximum torque on the system.

$$\tau = F \times r$$

For the translation system and using the values above, the maximum torque is 1.25 Nm. Reusing the torque equation with adjusted lever arm lengths, a new load cell force reading can be determined. Since load cells are often measured in kg, we converted force values using the gravitational force equation. After calculating several arm lengths in Excel, the following lengths were selected based on common masses available for commercial load cells:

Table 4: Lever arm length for different types of load cells to read forces between 0.1-10 N

Arm length (mm)	Arm length (in)	Force (N)	Mass (kg)	Weight (lbs)
25.5	1.00	49.02	5.00	11.02
51	2.01	24.51	2.50	5.51
63.5	2.50	19.69	2.01	4.43
127.5	5.02	9.80	1.00	2.20

A longer arm length requires a higher precision load cell, but it also ensures that there are smaller local non-perpendicular forces acting on the load cell, which increases the accuracy of the load cell readings.

6.3.5 Data Acquisition Resolution

Load cell specs:
Max measurement: 1 kg or 9.81 N
Output: 1 mV/V
Excitation: 5 V

Use these specs to calculate the max output voltage by multiplying the output by the excitation.
Max output voltage: 5 mV

The data is recorded through the 24-bit analog to digital converter, HX711. There are two gain modes on the chip, gain 64 and gain 128. All calculations will be done using the gain 128 due to improve accuracy. Setting the gain to 128 will cause the voltage range detectable by the chip to be ±20 mV. The sensors max output is well within the range.

The ADC can record 24-bits worth of data, however it can be assumed some bits will be lost to noise. A safety factor of 8-bits lost is shown in calculations based on the information from the HX711's data sheet.

$$LSB_{128} = \frac{40\ (mV)}{2^{16}} = 0.61\ \mu V$$

LSB is the smallest voltage needed to change the least significant bit of the 16 data bits. 40 mV is the total range between the –20 mV and 20 mV given by the gain of 128.

$$Force\ per\ mV\ = \frac{\text{max measurment}}{\text{max output}}$$

Equation to find the force per mV based on the highest measurement and the max voltage of the sensor.

$$Force\ per\ mV = \frac{9.81\ (N)}{5\ (mV)} = 0.962 \frac{N}{mV}$$

The final resolution is based on the LSB voltage and the force per mV.

$$F_{res=}\ 0.61\ (\mu V) \cdot 1.962 \left(\frac{N}{mV}\right) = 1.2\ (mV)$$

This fits the project's requirement of a resolution to the nearest 0.01 N.

6.4 Future Testing Potential

6.4.1 Translation

From our prototype testing, the translation model passed initial analysis. Despite this, the system is far from being complete. One error from testing is the small amount of slipping the catheter would experience. Future testing for this would include increasing the weight applied to the catheter to increase its friction against the bearings.

Additionally, the system has yet to be used with the motor driving the rollers. Once the motor, driver, and code are complete, the above experiment will be repeated. The motor will apply motion in small steps instead of the constant rotation used in the test.

6.4.2 Arduino and Motor systems

Prototype two plans to test the motors. The motors will be wired to the power supply, drivers, and Arduino. Using Arduino code and possibly the command string tested in the last prototype the movement of the motors will be tested. Additionally, more functionalities can be added with every step of testing, even going as far as adding the rollers from the translation and rotation systems to the device. The stepper motor drivers will need heat sinks due to the running voltage being above the threshold for no heat sink.

6.4.3 Rotation

The rotation will be tested to see if our current design will be able to rotate a catheter. The idea of vertical rollers comes from a simplistic and cheap way to make the component. There needs to be testing to make sure this method works. Possibly this can tell us if we need side plates to hold the catheter in place. We also need to run the system with the motors attached, which will be in the future.

6.4.4 Sensors

Prototypes for the sensor systems will be developed in the spring semester as an extension of modified initial translation and rotation prototypes. Testing will involve calibrating the force sensors with known masses, then moving the motors one step at a time and picking up force readings from the moment arm system. The resulting values will determine if the project design meets the clients' requested measurement resolution.

7 Final Hardware

7.1 Final Physical Design

Taking the research and testing above, the final system, as shown in figure 21 and detailed in Appendix , was assembled. The device includes translation and rotation components modified from the prototypes as well as a sensor mechanism implementing the load cell system. Each part is fixed to a framing rail to keep is secured and prevent unwanted movement.

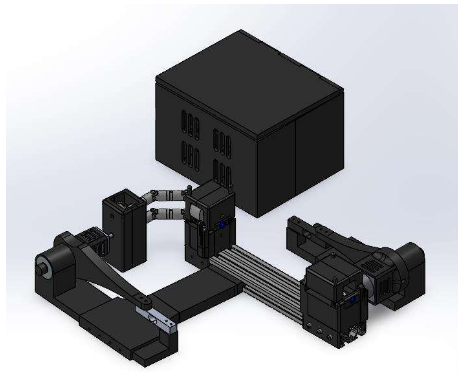


Figure 21: Full Project CAD

The translation component, in figure 22, was kept similar to the design made in the prototype. To update and professionalize the design, more parts were purchased. The shafts that support the roller bearings got exchanged for stainless steel for reduced friction. Due to the small forces that the housing experiences, the housing remained 3D printed the main of which was made of PLA. Other components were made of Vero and Agilus on the Bioengineering Devices Laboratory. These materials are softer and do not damage the catheter like PLA does. Therefore, the inlet and outlet holes for the catheter were manufactured with this material. To move the top piece up and down, the team bought micro lead screws. These screws contain a small stepper motor, so the height of the screw is always known. Two screws are arranged in opposite corners of the housing with shafts on the other sides for support. The motor connected to the driver wheel is not connected to the housing and is contained by the sensor system described below.

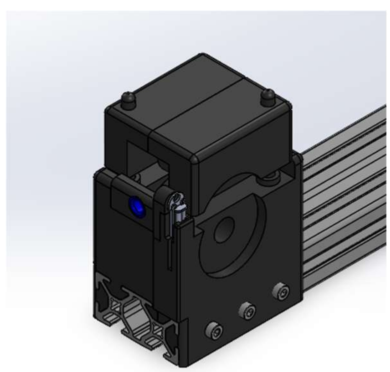


Figure 22: Translation system CAD

The rotation component, in figure 23, was modified significantly from the initial design and prototyping. The changes include linking the motor to both rollers so the catheter can be twisted without kinking or slipping. The motor is connected to a gear box that induced rotation in both rollers. The housing is made of PLA and Vero and

Agilus like the translation. Because the catheter moves along the axis of the motor shaft, this assembly would prevent it from moving in a straight path. To correct this, U-joints set at a roughly 90° angle turn the motor and the gearbox away from the catheter. The same lead screw set up as seen in the translation system is used.

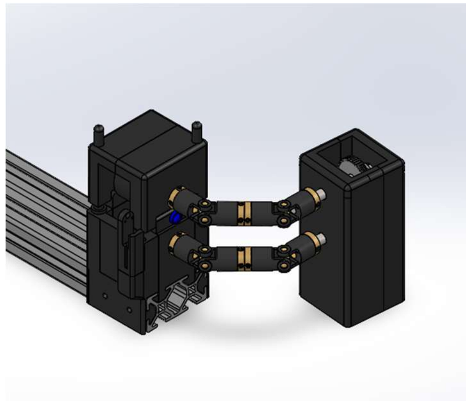


Figure 23: Rotation CAD

To sensor system measures reaction forces though a torque arm arrangement. The motors are fixed in a cage restricting all degrees of freedom except rotation. The cage is attached to a housing block that connects to the framing rail. A shaft on the back of the cage is supported with bearings to allow the rotation. A load cell device connects to a long arm coming off the cage and fastened to the housing on the other side. This means that as the motor turns the rollers, the reactionary forces push on the load cell. The load cell uses a whetstone bridge and strain gauges to measure the force applied by the motor.

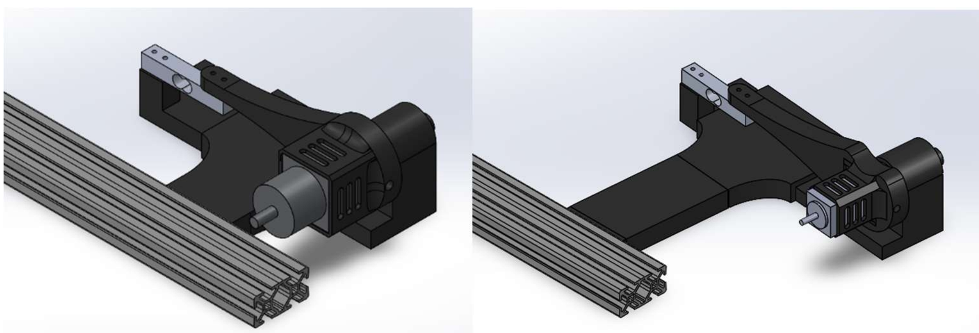


Figure 24: Sensor CAD for Translation and Rotation

8 Final Testing

8.1 Top level testing summary table

With the full system built, the team tests its ability to meet all customer and engineering requirements detailed in sections 2.1 and 2.2. Table 4 shows each experiment and what it tests for. Most of the tests rely on measuring data while code runs part of the system. Below is a more in-depth breakdown of each experiment and how it was performed.

Table 4: Catheter Roller Robot Experiments

Experiment	Relevant DRs	Testing Equipment	Other Resources
EXP1 - Motion Test	CR1, ER1, ER2	Arduino code Measuring tape Protractor	Catheter
EXP 2 - Remote Control Test	CR2, CR4, ER3	Arduino code Computer Measuring tape Stopwatch	Catheter
EXP 3 - Calibration Test	CR9, ER8	Arduino code Computer Weights	Load cells (partially removed from system)
EXP 4 - Data Collection Test	CR3, ER4, ER6, ER7	Arduino code Computer	Catheter
EXP 5 - Level/Bending Test	CR5	Level Protractor	Catheter
EXP 6 - Assembly Test	CR6, CR8, ER9	Measuring tape Stopwatch	Lab space
EXP 7 - Water Resistance Test	CR7	Voltmeter	Water
EXP 8 - Lead Screws Test	ER5	Arduino code Calipers	Multiple catheters
EXP 9 - Heat Test	ER10	Arduino code Temperature gun	Room-temperature environment

8.2 Detailed Testing Plan

8.2.1 Test 1: Motion Test

8.2.1.1 Summary

This test will determine whether the catheter roller robot can translate and rotate a catheter (CR1). The catheter must translate at least 2 feet (ER1) and rotate at least 360 degrees (ER2). Arduino code will be necessary to activate the motors and perform this test. Length and angle will be directly measured, and calculations will determine the runtime of the code.

8.2.1.2 Procedure

The Arduino code will cause the translation motor to activate continuously for several seconds, and the change in length of the catheter emerging from the translation system will be measured with measuring tape. Then, the code will stop translation and activate the rotation motor for several seconds while one person observes the rotation of the catheter tip.

8.2.1.3 Results

The results of this experiment should show a full range of motion of the catheter that allows it to make it through any given vein network. To translate the catheter 2 feet and rotate it 360 degrees, Equation 1 converts between linear and rotational distance. Success of this test means the system is able to operate in a vein model. Navigation in the model involves forward motion to pass though the straighter sections and the ability to twist to find the path around a curve. Failure in this test indicates an inability to move through the provided model. A redesign of the system would be needed to correct the points of failure.

$$\frac{L}{\theta * \frac{\pi}{180°}} = r$$

The translation system performed well, meeting the requirements and the approval of the client. The rotation system did not meet the requirements and was redesigned to fix the failure points. The new system does perform at the standards of the client.

8.2.2 Test 2: Remote Control Test

8.2.2.1 Summary

This test will determine whether the catheter roller robot can be operated remotely (CR2) and be stopped immediately in case of emergency (CR4). The operator must be at least 10 feet away from the robot (ER3). A computer will be needed to activate the Arduino code's emergency stop, and a stopwatch will determine how long the system takes to completely shut off, while a measuring tape will determine the operator's distance from the robot.

8.2.2.2 Procedure

The computer will be attached to the electronics box by a cord longer than 10 feet. Arduino code will run initially to determine whether the system can operate remotely, then the emergency stop will be activated on the computer while a person starts a stopwatch until the catheter ceases movement.

8.2.2.3 Results

Measurements include distance and time, and no calculations will be necessary for this test. The results will show the system running with the controls far away and no associated error. The operation of the system will not be impacted by the distance of the cables. Since the system has a 20-foot cable attached to it, we can expect the operating distance to be around 16 ± 4 ft, which will meet our requirements. Meeting these test requirements means the laptop that records the data and stores the code can be stationed and operated at a safe distance. Not meeting the predicted results means a new cable would need to be bought or a wireless data transfer technique will be researched.

The cable was able to connect the electric box to a laptop ten feet away and can stretch up to twenty feet. The emergency stop in the code took 4 seconds to activate due to the operations in the code. This is over the customer requirements and will be worked on to shorten.

8.2.3 Test 3: Calibration Test

8.2.3.1 Summary

This test will determine the calibration (CR9) of the load cell bridges in the sensor systems. According to engineering requirement eight (ER8), the sensors must accurately record data with an accuracy of 0.05 N. Arduino code and a computer will be required to record data, and weights of known values will aid in calibrating the load cells. Measurements include voltage, and a calibration curve will be used to calculate force and torque.

8.2.3.2 Procedure

To test this, the load cells will be detached from the robot and arranged in a beam deflection system. One end of the cell will be fixed with the other set up with known weights pulling down. The strain gauges will be connected to the Arduino program on a computer so the outputs can be read.

8.2.3.3 Results

The load cell has a zero output of -0.15 ± 0.05 mV/V, a rated output of 1.0 ± 0.1 mV/V, and a capacity of 1 kg. Performing the test correctly leads to the load cell collecting the torque data accurately. Performing the test incorrectly means a recalibration will be performed to remove the error.

When the calibration was done, the max weight applied was 800 grams. This was done to avoid reaching the limit of the load cell and preventing damage. The resolution of the force measurements came to be 0.01 N.

8.2.4 Test 4: Data Collection Test

8.2.4.1 Summary

This test will determine if data can be collected from the robot instantaneously (CR3) and record force and distance measurements (CR9). Data must have a sampling frequency of 5-30 Hz (ER4), read forces between 0.1-10 N (ER6), read displacement with an accuracy of 0.1 mm (ER7), and have perturbations smaller than 0.05 N (ER8). Arduino code and a computer are necessary to record measurements and change frequency. Voltage, distance, and sampling rate are the measured variables.

8.2.4.2 Procedure

To prove the system can record data at these specifications, the motors will run at a variety of speeds while the load cell system takes in measurements. Additionally, the motor will be coded to switch between different speeds to measure the reaction time of the load cell. As the motor moves, the code will also keep track of distance. Sampling frequency will be modified in the code to test its capabilities to reach 5-30 Hz.

8.2.4.3 Results

No new calculations will be used for this test, as Experiment 1 provides the equation for distance, and Experiment 3 gives the conversion to force. Meeting the values defined in the engineering requirements means the system can collect data in real time. Collecting data at too high of a frequency means the code will need adjustments to change the speed of input and output variables to record data faster.

Counting the speed of data readings and the details of the code, the frequency was found in readings per second and converted to Hertz. The value came out to be 30 Hz which is within range for the requirements.

8.2.5 Test 5: Level/Bending Test

8.2.5.1 Summary

This test will determine if the robot is leveled and how much bending the catheter undergoes (CR5). The catheter should not bend more than 60 degrees.

8.2.5.2 Procedure

A level will be used to determine if the system is leveled, and a protractor will determine the angle that the catheter must bend to feed through the rotation system.

8.2.5.3 Results

Angle will be directly measured, and no calculations are required for this test. Success for this test means that the catheter does not experience extreme deformation and will not kink in regular use. Failure of this test means the inlet and outlet for the catheter must be redesigned.

Measuring with a level, the system did not deviate significantly from the level of the table or itself. The translation system caused no excess bending on the catheter staying around the natural angle of the catheter. The rotation system did bend the catheter up to 15 degrees which contributed to the choice for a system redesign.

8.2.6 Test 6: Assembly Test

8.2.6.1 Summary

This test will determine if the force measurement components are easy to replace (CR6) and if the system is easy to assemble, disassemble, and transport (CR8). The total size of the robot must be under 1 cubic foot (ER9).

8.2.6.2 Procedure

Measuring tape is needed to obtain dimensions, and a stopwatch will record time for assembly. Measured variables are length and time.

8.2.6.3 Results

Volume will be calculated by multiplying the lengths of the components. Completing the test to the specifications of the ERs means the system can fit in the designated space of the BDL. Not meeting these values means the team will need to meet with the client about the allowable space for the project and how much more is needed.

A tape measure showed the surface area of the system was $240\ in^2$. This led to a total volume of $1.34\ ft^3$. This value is over the engineering requirement for volume but was allowed by the client, so no adjustment was made. Assembly for the system takes a couple minutes while quick changes take a few seconds.

8.2.7 Test 7: Water Resistance Test

8.2.7.1 Summary

This test will determine whether the system effectively protects its components to prevent load cell damage (CR7). The wires must be functional after exposure to water.

8.2.7.2 Procedure

A continuity test from a voltmeter will determine functionality.

8.2.7.3 Results

No quantitative measurements or calculations are involved in this test. Water not having an effect on the equipment means the system is safe to use in the wet lab environment. If the system does get damaged by the water, the damaged parts will be replaced and the new parts will be made more resistant to water damage.

Splashing a small amount of water on the system caused no effects to the performance of the equipment. The code and components were watched carefully for any changes during the test. The electric box was not tested because the circuits are exposed to the open environment, and it will be placed away from the lab equipment.

8.2.8 Test 8: Lead Screws Test

8.2.8.1 Summary

This test will determine if the robot can handle catheters of varying sizes. The range for this test is 2-15 French

(0.67-5mm) (ER5).

8.2.8.2 Procedure

Arduino code will activate the lead screws, and calipers will measure the distance between rollers.

8.2.8.3 Results

Measurements include determining the size of each catheter and the distance between the rollers of the translation and rotation systems. Calculations include the conversion from millimeters to French. If the lead screws can move to any distance between 0 and 5mm the system is ready to move any catheter. If the lead screws fail move or cannot move far enough, the method of clamping the catheter will be changed.

When powered, the lead screw did move its full range of 8 mm.

8.2.9 Test 9: Heat Test

8.2.9.1 Summary

This test will determine whether device components remain at a temperature under 60°C (ER10).

8.2.9.2 Procedure

Arduino code will run the system, while a temperature gun will be used for measuring temperature on an ABS slab

8.2.9.3 Results

The only measurement for this test is temperature, and no calculations are required. If the temperature does not damage the part, the components of the system that get exposed to high temperatures will be made from this stronger material. If the part does get damaged, a better material would be researched.

The heat gun brought the surface of the part to 60 degrees to mimic the effect of the hot motor. The other side of the slab was measured and found to be 35 degrees proving ABS is temperature resistant enough to work in the system

9 Future work

If this project were to continue by the lab researchers or another capstone team, some of the things that would be done would be standardized medical device testing, a move to clinical settings, and remote operation on patients. Standardized medical device testing would entail creating tests for the system that corresponds to the standards talked about above. These tests would investigate the devices' ability to perform in a professional lab environment and around real patients. With the development of these tests, use on patients in clinical trials and lab work could begin. The system could be revised upon to better work in these environments.

10 CONCLUSIONS

The goal of this project is to create a preprogrammed and data collecting device for catheter testing. The applications of this project are for the BDL lab to test their catheters and vein networks. To achieve these objectives, our clients gave us a list of engineering and customer requirements.

By comparing these to each other and our State-of-the-Art references, some of the most important criteria for our system to account for are measuring push resistance, being controlled from a distance, fully rotating a catheter and having an emergency stop. Measuring the forces is important so the motors do not break the catheter or the vessel model. To include this deliverable in our design, we added feedback collection in the sensor subsystem. A very important piece of the project proposal is for our final design to operate without the user near it. This is accomplished through a list of premade executables in a laptop that can tell system what to do. It will also have a connection to a remote board that is placed outside of the x-ray zone for a user to pilot in real time. On the remote and inside the sensor program will be an emergency stop. Similar to the feedback component, this is necessary to avoid forces the system is unable to handle.

With these and the other requirements to consider we broke the project into three parts: translation, rotation, and sensors. The catheter will be fed through the rotation part and then the translation component. Both parts have a feeder before and after to keep the catheter along its path. When a command is given to one of the subsystems, that one will clamp down on the catheter while the other is released. As the motors turn the desired amount, the sensors will record the real data and watch for any unwanted effects.

From the above definitions, each subsystem can be modeled. The translation system was based off our SOTA research which all included similar feeding mechanisms. After comparing multiple configurations of the rollers through brainstorming and mathematical calculations, we found the best layout for the rollers is a square design where the top and bottom cases both contain two rollers. To provide the motion discussed above, one of the rollers on the bottom will be attached to a motor. And the top and bottom plates will be connected by a threaded column that adjusts the height. The height adjustment will be set manually before the motor is turned on.

With no reference for the rotation that fits with our criteria we had to come up with a concept from scratch. Our final idea uses the concept of two moving driver rollers to control the rotation. We used a similar clamping idea to the translation component that is manually set. Once the catheter is fixed between the rollers, it is twisted and allowed to travel along the catheter until it reaches the tip where it can follow the next bend in the vein.

After many ideas for the feedback sensors, none could meet all the needed requirements. The two we initially considered above were rejected by the client. After more research, the system that was chosen was a reaction torque strain gauge. The strain gauge is locked to the base and to a arm coming off the motor. As the motor turns the reaction rotation is pressed on and recorded by the load cell.

After our designs were finalized, we moved to preparing for prototyping. Complete models were made of each system and materials were sourced. Some parts were printed, and others were purchased. Our first prototype was a test of the translational system of if it was able to meet the engineering requirement of translating over a distance of over 2ft. Switching out the motor for a hand-turned shaft, the system moved the catheter proving the model was successful. In addition to this model, we tested if the Arduino could communicate with the computer and an external system. The code written for this model was able to answer the question however, we struggled to get the communication between the systems to happen at the same time.

With the knowledge gained from our first tests and some more calculations we completed; we prepared for the next round of testing and prototyping. We came up with more question that need to be answered and wrote them into our second prototype. For the next prototype, we tested the twisting ability of our rotational model and further the communication capability of the Arduino and motor system. With the results from these experiments, we hope to end this semester with most of our subsystems passing initial testing. This would allow us to focus on the other systems with only minor iterations needed for the current designs.

After all prototyping and research had been done, the final system was assembled. Some changes were made from the prototypes for many reasons such as compatibility with the rest of the device and errors in its performance. All components of the assembly was connected to a framing rail for stability. The system was then tested in its ability to meet the customer and engineering requirements from our client. A total of 9 tests were set up and performed while data was collected. Once testing was done, the data was compared to the target values and changes were made to correct any values that were too far off. These results were handed to the client and signed off on meaning the project is successful.

The final deliverables for the project include presenting the teams work at the undergraduate symposium and writing an operation manual on how to work the system.

11 REFERENCES

[1] T. Becker, “Bioengineering Devices Laboratory Remote Catheter Advancement System,” unpublished.

[2] Copyright © 2005 Kevin Otto, www.robuststrategy.com, kevin_n_otto@yahoo.com,http://www.kevinotto.com/RSS/templates/QFD Template.xls, Modified from a template from Design4X Inc.

[3] M. Equipment, “Catheter and medical device testing equipment with water tank,” MSI, https://msi.equipment/product/idte_3000/ (accessed Sep. 12, 2024).

[4] G. Fagogenis et al., “Autonomous robotic intracardiac catheter navigation using Haptic Vision,” Science robotics, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6693882/ (accessed Sep. 16, 2024).

[5] C. Hale, “JPM: Microbot Medical unveils disposable device for remote catheter procedures.” Fierce Biotech. https://www.fiercebiotech.com/medtech/jpm-microbot-medical-unveils-disposable-device-for-remote-catheter-procedures (accessed Sept. 14, 2024).

[6] *LabVIEW Fundamentals*. National Instruments Corporation (accessed Sept. 13, 2024).

[7] E. OBERG, El al, “TOOLING AND TOOLMAKING,” in *Machinery's Handbook*, 29th ed, INDUSTRIAL PRESS, INC., 2012, pp. 754–1003

[8] J. F. Carneiro and F. G. de Almeida, “Friction characteristics and servo control of a linear peristaltic actuator,” The International Journal of Advanced Manufacturing Technology, vol. 96, no. 5–8, pp. 2117–2126, Feb. 2018. doi:10.1007/s00170-018-1678-6

[9] P. Larsson, “Prevention of Servo-Induced Vibrations in Robotics,” thesis, 2011

[10] A. Haidar, C. Benachaiba, and M. Zahir, “Software interfacing of servo motor with microcontroller,” Journal of Electrical Systems, vol. 9, pp. 84–99. [Online]. Available: https://ro.uow.edu.au/eispapers/468/

[11] Cardiovascular implants — Endovascular devices, ISO 25539-1, 2017

[12] “Catheter testing and delivery system testing,” ViVitro Labs, https://vivitrolabs.com/services/catheters-and-delivery-systems/.

[13] J. Lyon, “The six factors you need to consider when picking a force sensor,” Interlink Electronics, https://www.interlinkelectronics.com/blog/the-factors-you-need-to-consider-when-choosing-a-force-sensing-solution (accessed Sep. 12, 2024).

[14] Standard Test Method for Rubber Property—Durometer Hardness, ASTM D2240, 2015

[15] Engine Oil Viscosity Classification, **SAE J300**, 2015

[16] H. A. Toliyat and G. B. Kliman, *Handbook of Electric Motors*, 2nd ed. New York: Marcel Dekker, 2004, ch 2.

[17] NEMA ICS 16-2001.

[18] “Nema stepper motors - NEMA steppers: Electromate inc,” Electromate Inc., https://www.electromate.com/mechatronic-automation/mechatronic-automation-components/stepper-motors/nema-stepper-motors/ (accessed Sep. 14, 2024).

[19] V. Vladinovskis, "Selection of microcontroller board and stepper motor driver for FDM 3D printing to reduce power consumption," 2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 2023, pp. 1-6, doi: 10.1109/RTUCON60080.2023.10413037.

[20] H. A. Toliyat and G. B. Kliman, *Handbook of Electric Motors*, 2nd ed. New York: Marcel Dekker, 2004, ch 3.

[21] “Tech tip: How to choose and use Stepper Motor Power supplies from AutomationDirect,” AutomationDirect, https://www.automationdirect.com/videos/video?videoToPlay=lTtYkofw-Jg#:~:text=We%20recommend%20two%20different%20ways,phase%20current%20of%206.3%20amps. (accessed Sep. 14, 2024).

[22] “Selecting the best power supply for your stepper or Servo Motor Application,” Teknic, Inc., https://teknic.com/selecting-power-supply/ (accessed Sep. 14, 2024).

[23] H. Zhu, M. Zhou and S. Zhu, "A Design of the Automatic Anti-Collision System," 2009 International Workshop on Intelligent Systems and Applications, Wuhan, China, 2009, pp. 1-4, doi: 10.1109/IWISA.2009.5072613.

[24] “Arduino tutorial: Serial inputs,” Norwegian Creations, https://www.norwegiancreations.com/2017/12/arduino-tutorial-serial-inputs/ (accessed Oct. 4, 2024).

[25] Ed, “Arduino interrupts tutorial - the robotics back,” End, https://roboticsbackend.com/arduino-interrupts/ (accessed Oct. 4, 2024).

[26] R. S. Figliola and D. E. Beasley, *Theory and Design for Mechanical Instruments*, 7th Edition. Hoboken, NJ: Wiley, 2019. [Online]. Available: https://www.wiley.com/en-us/Theory+and+Design+for+Mechanical+Measurements%2C+7th+Edition-p-9781119475651. Accessed: Sep. 13, 2024.

[27] R. G. Budynas and J. K. Nisbett, “Finite-Element Analysis,” in *Shigley’s Mechanical Engineering Design*, 11th Edition. New York, NY: McGraw-Hill Education, 2020, ch. 19, pp. 955-974. [Online] Available: https://www.mheducation.com/highered/product/shigley-s-mechanical-engineering-design-budynas-nisbett/M9780073398211.html. Accessed: Sep. 13, 2024.

[28] M. Khoshnam, A. C. Skanes, and R. V. Patel, “Modeling and estimation of tip contact force for steerable ablation catheters,” *IEEE Trans Biomed Eng.*, 2015. doi: 10.1109/TBME.2015.2389615.

[29] N. K. Sankaran, P. Chembrammel, and T. Kesavadas, “Force calibration for an endovascular robotic system with proximal force measurement,” *International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 16, no. 2, Apr. 2020, https://doi.org/10.1002/rcs.2045.

[30] A. Hooshiar, A. Sayadi, M. Jolaei, and J. Dargahi, ”Accurate Estimation of Tip Force on Tendon-driven Catheters using Inverse Cosserat Rod Model,” *2020 International Conference on Biomedical Innovations and Applications (BIA)*, Varna, Bulgaria, 2020, pp. 37-40, doi: 10.1109/BIA50171.2020.9244512.

[31] *Intravascular Catheters – Sterile and single-use catheters*, ISO 10555-1, 2023.

[32] “Horizontal Testing of Catheter Systems.” ZwickRoell. https://www.zwickroell.com/industries/medicalpharmaceutical/catheters-and-stents/horizontal-testing-of-catheter-systems/ (accessed Sep. 13, 2024).

[33] Nanoflex. https://nanoflexrobotics.com (accessed Sep. 13, 2024).

[34] L. W. McKeen, *Fatigue and Tribological Properties of Plastics and Elastomers*, 3rd ed., 2016. [Online]. Available: https://www.sciencedirect.com/book/9780323442015/fatigue-and-tribological-properties-of-plastics-and-elastomers#book-info. Accessed: Oct. 6, 2024.

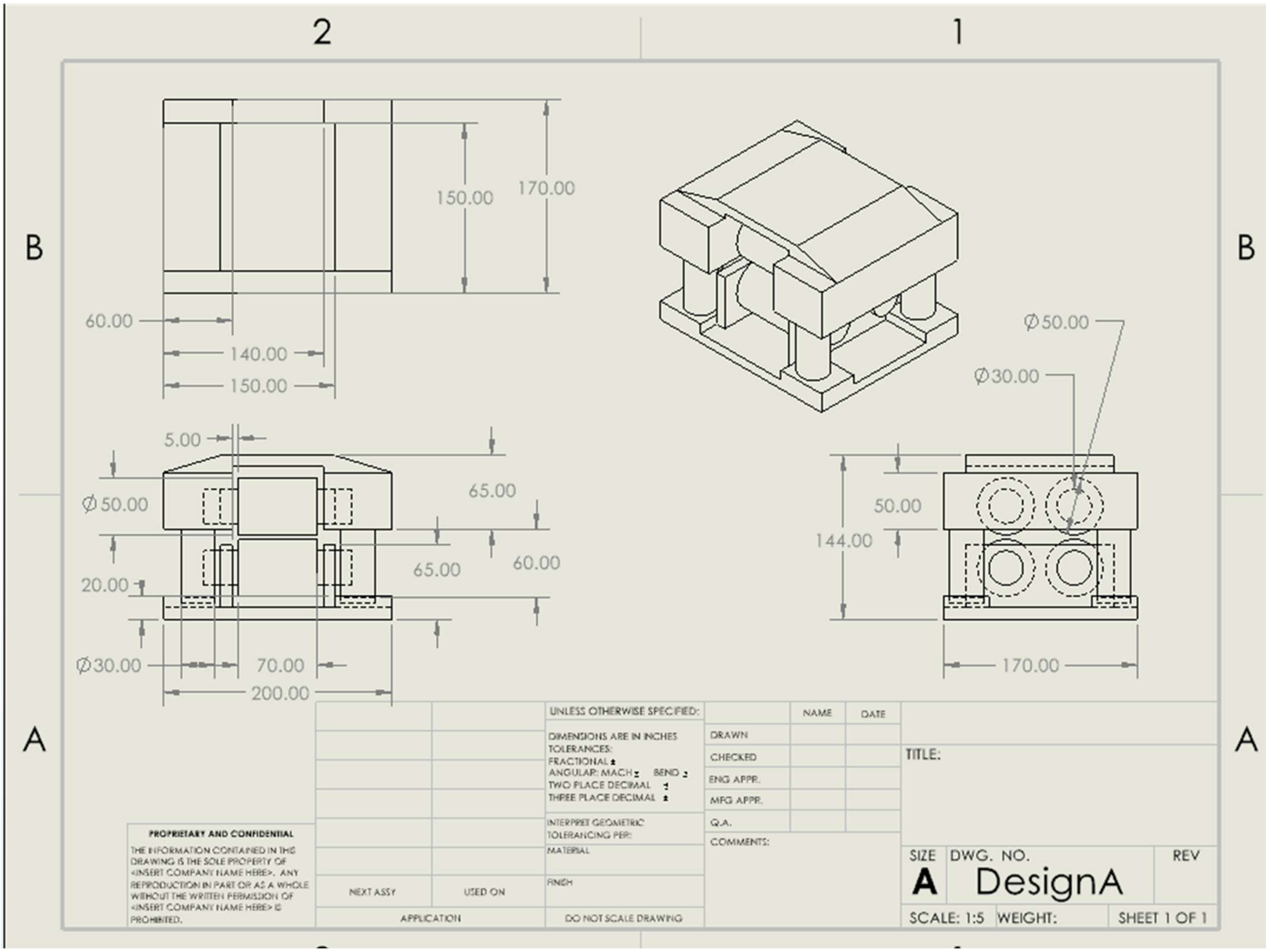
[35] National Instruments. “LabVIEW Programming Reference Manual.” https://www.ni.com/docs/en-

US/bundle/labview-api-ref/page/intro.html (accessed Nov. 27, 2024).

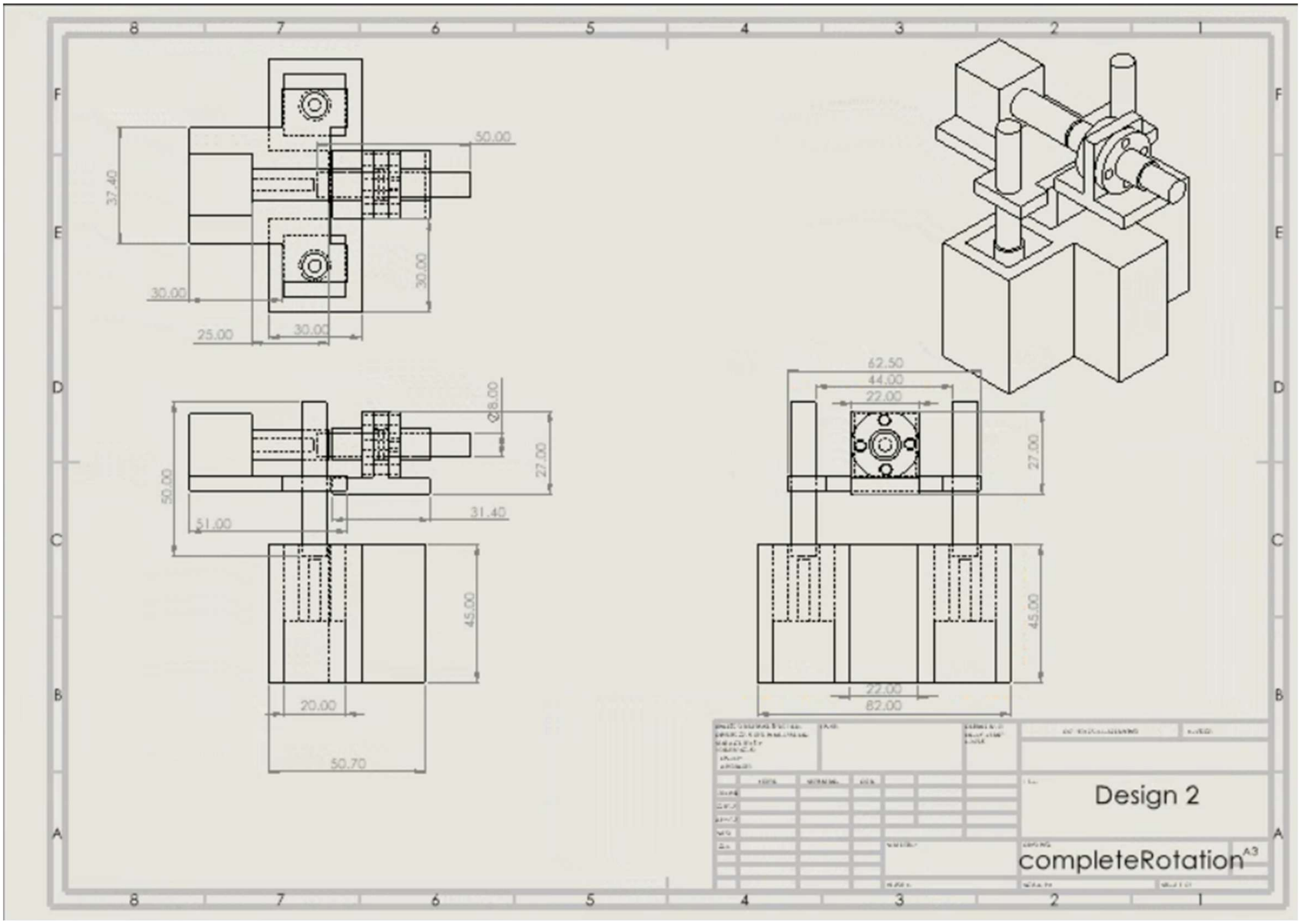
12 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report.]

12.1 Appendix A: SOLIDWORKS dimensioned drawing the square translational roller layout



12.2 Appendix B: SOLIDWORKS dimensioned drawing for the rotational plate layout



12.3 Appendix C: Arduino code used in prototypes

```
#define STEP_PIN 2
#define DIR_PIN 3

bool dirHigh;

void setup()
{
  dirHigh = true;
  digitalWrite(DIR_PIN, HIGH);
```

```
  digitalWrite(STEP_PIN, LOW);
  pinMode(DIR_PIN, OUTPUT);
  pinMode(STEP_PIN, OUTPUT);
}

void loop()
{
  // Toggle the DIR pin to change direction.
  if(dirHigh)
  {
    dirHigh = false;
    digitalWrite(DIR_PIN, LOW);
  }
  else
  {
    dirHigh = true;
    digitalWrite(DIR_PIN, HIGH);
  }

  // Step the motor 50000 times before changing direction again.
  for(int i = 0; i < 50000; i++)
  {
    // Trigger the motor to take one step.
    digitalWrite(STEP_PIN, HIGH);
    delay(100);
    digitalWrite(STEP_PIN, LOW);
    delay(100);
  }
}
```

Data code:

```
String inputString =""; // string for command
int degree = 0; // degree value
int speed = 0; // Speed value
```

```
bool systemOn = false; // system state
char motor = ' '; // motor selection
unsigned long previousMillis = 0; //time managment for data sending
const long interval = 200; // 200 for 5 Hz data transfer rate 33 for 30 Hz


const int buzzer = 9;

// Random number generator for sensor
void generateAndSendSensorData()
{
  int simulatedForce = random(20,30);
  int simulatedTorque = random(40,60);

  // Create message for sending
  String sensorData = "DATA:F" + String(simulatedForce) + "T" + String(simulatedTorque);
Serial.println(sensorData);
}

void setup()
{
  Serial.begin(9600);
  randomSeed(analogRead(0)); // random seed based on pin 0 reading
  tone(buzzer,1000);
  delay(1000);
  noTone(buzzer);
}

void loop()
{
  unsigned long currentMillis = millis();

  // Check if command is available
```

```
 if (Serial.available() > 0)
 {
  inputString = Serial.readStringUntil('\n'); // read till new line
  parseInput(inputString);

  // Execute motor contol
  if(systemOn)
  {
   if (motor == 'R')
   {
    runRotationMotor(degree,speed);
   }
   else if (motor == 'T')
   {
    runTranslationMotor(degree,speed);
   }
  }
   else
   {
    stopMotors();
   }
  }

  // Periodically send sensor data
 if (currentMillis - previousMillis >= interval)
  {
   previousMillis = currentMillis;
   generateAndSendSensorData();
 }
}
```

```
void parseInput(String input)
{
 // Check length for valid string
 if (input.length()<5)
 {
  Serial.println("Invalid Command");
  return;
 }

 // parse on/off command
 char systemState = input.charAt(0);
 systemOn = (systemState == 'A');

 // Motor selection command
 motor = input.charAt(1);

 // Find Degree and speed
 int degreeIndex = input.indexOf('D');
 int speedIndex = input.indexOf('S');

 if (degreeIndex != -1 && speedIndex != -1 && speedIndex > degreeIndex)
 {
  String degreeString = input.substring(2,degreeIndex);
  degree = degreeString.toInt();

  String speedString = input.substring(degreeIndex + 1, speedIndex);
  speed = speedString.toInt();
 }
 else
 {
```

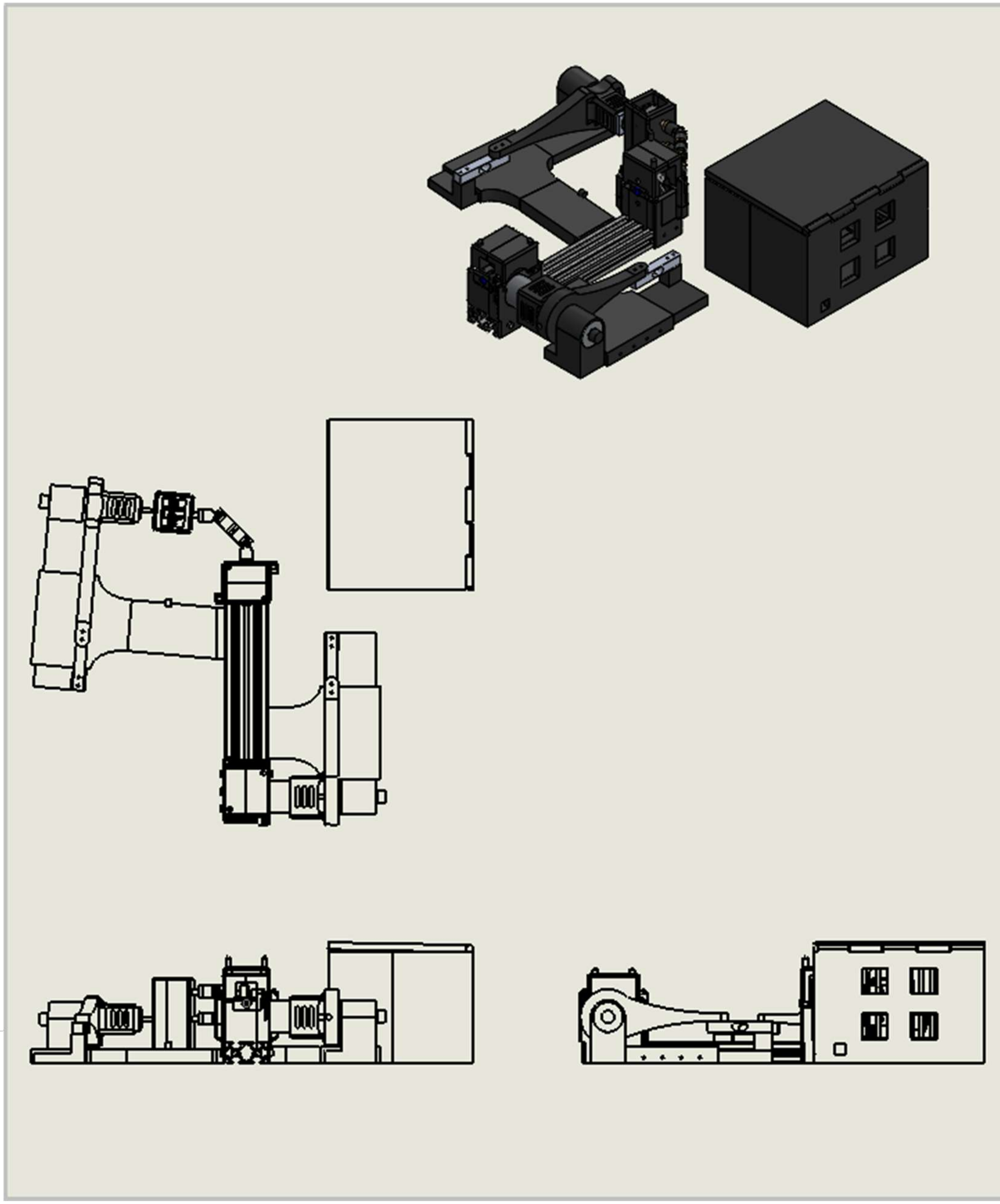
```
    Serial.println("Invalid Format");
  }
}

void runRotationMotor(int degree, int speed)
{
  Serial.print("CMD:Running Rotation Motor - Degree: ");
  Serial.print(degree);
  Serial.print(", Speed: ");
  Serial.print(speed);
  tone(buzzer,2000);
  delay(1000);
  noTone(buzzer);
}

void runTranslationMotor(int degree, int speed)
{
  Serial.print("CMD:Running Translation Motor - Degree: ");
  Serial.print(degree);
  Serial.print(", Speed: ");
  Serial.print(speed);
  tone(buzzer,3000);
  delay(1000);
  noTone(buzzer);
}

void stopMotors()
{
  Serial.println("CMD:System off, Stopping all motors.");
}
```

12.4 Appendix D: Final Assembly Drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	4633N22	T-SLOTTED FRAMING RAIL	1
2	TBOTTOM1		1
3	TBOTTOM2		1
4	TSHAFT		2
5	LEADSCREW		4
6	LEADSCREWSLIDER		4
7	TFASTEN1		1
8	DRIVERSHAFT		1
9	BEARINGSHAFT		5
10	2483K13	ABRASION-RESISTANT IDLER ROLLER	3
11	2481K922	TIGHT-TOLERANCE DRIVE ROLLER	1
12	TSLEAVE10		4
13	TOP1FINAL		1
14	TOP2FINAL		1
15	91290A144	ALLOY STEEL SOCKET HEAD SCREW	6
16	2481K924	TIGHT-TOLERANCE DRIVE ROLLER	1
17	CATHETERROLLER MOTOR HOLDER NEMA17		1
18	CATHETERROLLER MOTOR CASING NEMA17		1
19	SHANGHJLOADCELL		2
20	CATHETERROLLER MOTOR CASING BEARING SPACER		2
21	CATHETERROLLER MOTOR CASING BEARING		4
22	CATHETERROLLER MOTOR CASING SMALL SPACER		2
23	MOTORCASINGINSERT17		1
24	MOTOR		1
25	RSHAFT		2
26	R_BOTTOMINSERT		2
27	R_BOTTOMSIDE1		2
28	R_BOTTOMFRONT		1
29	R_BOTTOMBACK		1
30	R_DRIVERSHAFT		1
31	SOFTINSERT		1
32	RINSERT1		1
33	R_INSERT		1
34	R_TUBE		1
35	RTOP1		1
36	RTOP2		1
37	RBEARINGSHAFT		3
38	57155K375	STAINLESS STEEL BALL BEARING	6
39	UJOINT		2
40	CATHETERROLLER MOTOR HOLDER NEMA11		1
41	ROTATIONTEST		1
42	NEMA11STEPPERMOTOR		1
43	MOTORCASINGINSERT11 (2)		1
44	2473K72	PRESS-FIT LOW-PROFILE DRIVE ROLLER	1
45	S25CR_ELECTRICALBOXDOWEL		1
46	S25CR_ELECTRICALBOXLID		1
47	S25CR_ELECTRONICSBOXBASEPART1		1
48	S25CR_ELECTRONICSBOXBASEPART2		1
49	TINSERT1		1
50	TINSERT2		1
51	CATHETERROLLERMOTORHOLDERNEMA17		1
52	1327K95	ROTARY SHAFT	1
53	60355K851	BALL BEARING	2
54	6832K45	METAL GEAR - 20 DEGREE PRESSURE ANGLE	3
55	GEARBOX11		1
56	GEARBOX2		1
57	7880K17	METAL GEAR - 20 DEGREE PRESSURE ANGLE	1
58	GEARSLEAVE13		1
59	GEARSLEAVE5		1
60	CATHETERROLLERMOTORFASTENERNEMA11		1