Catheter Roller Robot

Initial Design Report

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DISCLAIMER

EXECUTIVE SUMMARY

The purpose of our project is to design, build, and test a robotics system that can translate and rotate a catheter into a benchtop blood vessel model through use of a remote control. Our clients for this project work on treatment of brain aneurysms in the circle of Willis and they work at the Bioengineering Devices Lab here on Northern Arizona University campus. The importance of this project is it will allow testing of catheters in an environment with high powered x-rays. To achieve this the system must be able to complete the tasks through use of a remote control. Our sponsor for this project is Dr. Becker, for this project we are given $5,000 with $500 dollars to be raised by the end of the year. As it currently stands seventy-five dollars have been raised.

Currently the project has a functional decomposition with inputs of catheter mounting, energy/power, rotational motor, transitional motor going into the catheter motion and outputs of a real-time display, translational force, and rotational forces. The system can be broken up into subsystems of translation, rotation, microcontroller, sensors, power supply, and controller. The focus on this report will be on the translation and rotation subsystems as well as the sensor subsystems. Through mathematical modeling and knowledge gained from a literature review the preliminary designs of each subsystem mentioned has been finalized for a first prototype. Starting with the translation subsystem the design uses rollers to push the catheter forward. The design has four rollers in total, two at the bottom and two at the top. The catheter will run in between the top and bottom roller pairs. One roller will be attached to a stepper motor and will drive the catheter while the other three will be idle rollers. The subsystem must be capable of running a catheter two feet long. Stepper motors are chosen for their precise motion.

For the rotation subsystem, there are two options. One design, which is currently in the lead, uses two plates which sandwich the catheter, the stop plate is made of a high friction material and can move left and right perpendicular to the axis of the catheter. The resulting force from this motion will rotate the catheter 360 degrees. This ‘friction plate design’ shines for its uniform forces applied to the catheter and directly mimics the real-life hand motion of a person manually rotating the catheter. The second design being considered is two rollers with their axis arranged horizontally. The catheter is squeezed between the rollers along their axis. One of the rollers will be driven by a stepper motor with the other being idle. There are some concerns for this design such as issues with the catheter on the rollers. To find which of these rotation subsystem designs are best suited for the final design both will be prototyped and tested.

Finally, the subsystem of sensors, unfortunately both designs for the sensors have been rejected by the clients. We continue to work as a team closely with our clients to come up with a design for the sensors that work best for their image. In the report we touch on the two designs we proposed to our clients. One is a load cell design where force feedback from the catheter will be read by the device and data recorded. This was rejected due to complexity. The second design was an rpm sensor which would read the motor speed and use math to calculate the change in forces. This was also deemed too complex by our clients. We are actively working with our clients to find a sensor system which will work best for what we need.

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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]

Our project's clients, from BDL, have asked us 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 our project's design. An additional $500 will be fundraised through GoFundMe and robotic part donations.

1.2 *Deliverables*

Our first major course deliverables for this project are three different presentations, a website, and two reports, including this one, to update the course instructor on our progress. Additionally, we must provide an analytical analysis memo, four prototypes shown in two prototype demonstrations, a final computer-aided design, and a bill of materials.

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 our final design. These include the ability to translate and rotate the catheter and measure forces, torques, and distance to a precision specified by our client and engineering requirements. This requires distance calculations from our motors, rollers, and other components in our robot. The design must not damage the catheters or blood vessel models used with our 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

Within this section of the report, we will go over requirements, these include the customers' requirements, the engineering requirements, and the house of quality. First, the customer requirements, these are requirements pulled straight from our customers project description as well as from initial talks with the client. Second, the engineering requirements are generated quantifiable requirements which must be reached by the design for it to be considered ideal. These have been based off what the customer has directly asked except will have numeric goals to reach in terms of forces, distances, and times. Finally, the house of quality will be showing the graded importance of each engineering requirement versus the corresponding customer requirements.

2.1 *Customer Requirements (CRs)*

- Translation and rotation of catheter
    - We must be able to move a catheter with the same functionality a person using the catheter would have. This includes moving the catheter in and out of the model and rotating the catheter to allow it to move properly through any bends in the model.
- Pre-programmed or controlled remotely
    - The current device our clients are using uses a step-by-step programing block system which they would like us to mimic. The clients also want our device to be controlled from a distance that way they can run lab equipment which would be harmful for them to be nearby.
- Measure data instantaneously
    - Data acquisition is very important, the clients need us to be able to measure torques, speeds, and forces which are acting on the catheter. It needs to be instantaneous since data gathered will be time critical. This is because 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.
- 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.
- 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 have given us the requirement that the system must be able to be leveled in some way.

- Force measurement equipment easy to replace
  - The device is expected to have a long lifetime and will certainly be designed as such so the need 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.
- Mechanism to prevent load cell damage
- 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.
- Force and distance calibrations and testing
  - For the data to be accurate during real testing the device will need to have the ability to save a zero state for the sensors. This is similar to what a scale does where you can zero it before use to make sure any false readings the sensor is recording are set to zero.

2.2 *Engineering Requirements (ERs)*

- Translation of catheter at least 2 ft
  - The catheters we will be using will be two feet long. Thus, our device must be able to work with catheters of this length effectively and translate the catheter its whole length.
- Rotation of catheter at least 360 degrees
  - With many twists and turns in the model the catheter must be able to do a complete rotation allowing it to move wherever is necessary.
- Remote controlled from at least 10 ft away
  - To prevent harm to lab personnel the device must be controlled from ten feet away.
- 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.
- 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.' The conversion between French and millimeter is three French equals one millimeter.
- Measure push resistance force between 0.1-10 N
  - The catheter will experience resistive forces which must be measured. These forces will be between point-one to ten newtons.

- 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 point-one millimeter.
- System noise/tolerance: ± 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.
- Total size under 1 cubic foot
    - The total volume of the device must be under one cubic foot when not in use. The size of the device when deployed is not given. This simply covers the size it must be when taken apart and not in use.

2.3 *House of Quality (HoQ) [2]*

	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/tolerance
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/tolerance			1	9		3	3	
Limited volume	1		1			1	1	

Project title:	Catheter Roller
Project team:	F24toSp25_02
Date:	9/11/2024

Customer Needs	Customer Weights	Technical Requirements: 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/tolerance	Limited volume	Customer Opinion Survey: 1 Poor	2	3 Acceptable	4	5 Excellent
Translation and rotation of catheter	1	9	9	1	3	3		9	3				A		B C
Pre-programmed or controlled remotely	1	3	3	9			1		3			A			B C
Measure data instantaneously	3	1	1		9	1	3	3	9						A C
Emergency stop system	2			3					1				C		A
Level introducer and system to prevent kinking	3						9								A
Force measurement equipment easy to replace	4						3			1			A		
Mechanism to prevent load cell damage	3				3		3		1					A	
Easy to disassemble/reassemble, transport case	5			1						9	A		C		B
Force and distance calibrations and testing	3	3	3		1	3	3	3					C		A
Technical Requirement Units		ft	degrees	ft	Samples/sec	F	lbf	in	lbf	ft^3	Legend	System name			
Technical Requirement Targets		2	360	10	5 to 30	2 to 15	0.0225-2.25	0.0034	0.0112	<1	A	MSI interventional device testing equipment 3000			
Absolute Technical Importance		24	24	21	42	15	67	27	38	49	B	Microbot Medical: Liberty Robot			
Relative Technical Importance		1	2	3	7	4	6	5	8	9	C	Catheter Navigation Using Haptic			

3 Research Within Your Design Space

3.1 *Benchmarking*

3.1.1 Josh P:

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 or translation. It also contains systems for motion and torque feedback. According to our QFD, this design fits our engineering and customer requirements. However, it is not perfect for our project as it does not fit the volume or remote-controlled aspect of our criteria. [3]

3.1.2 Josh H:

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 we are working on making it a very 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 Gray:

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 our 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 our project. Its ability to work with off-the-shelf catheters additionally demonstrates the design's flexibility, which is important to consider for our 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 us if we decide to use LabVIEW for our program. Our clients recommend LabView for our software side and to read the data we collect. This guidebook provides the information we need 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 section we will be focusing on is tooling and manufacturing. It goes

into the tools needed for different manufacturing details. This will be useful for our project as we will be working on a smaller scare and need 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 to our project if we want to use pneumatics in our translation system. We 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 we are using a stepper motor over a servo, this is still helpful to us as a guide on how to set up our motor interface. Additionally, we can used their methods 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 our project in that we are investigating ways to control and monitor our motor as it runs. It also provides an alternative to LabView which is talked about above. With two program options, we 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 to us because we are making a device that is able to perform these tests. Our project must be able to 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 us organize the layout of our design. We can take inspiration from how they perform each test to build our components. We can also see the tools they use so we can research similar ones.

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 us in finding a sensor for our project. We will need some way to measure the force put onto the catheter as well as the force of the catheter on the vein system. By reading this article and looking through the catalog, we can find a force sensor that is applicable in our design.

3.2.2 Josh H.

Handbook to electric motors, 2nd ed. Chapter 2: types of motors and their characteristics [14]

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 [15]

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 [16]

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 [17]

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, 2^{nd} ed. Chapter 3: Motor Selection [18]

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 [19]

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 [20]

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 goes over power supplies in a more application specific way.

A design of the automatic anti-collision system [21]

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.

3.2.3 Gray

Theory and Design for Mechanical Measurements 7th Edition [22]

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 [23]

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 [24]

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 [25]

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 [26]

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 [27]

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 [28]

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 [29]

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.

3.3 *Mathematical Modeling*

3.3.1 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 3mm as it is the average size of system will need to test. The distance between the catheter and the vein is 1mm. 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 260MPa. With these values the deformation can be found. The critical load is the maximum force before the column bends. The calculation for this is:

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

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

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

Where P was made to be 0.1N(left) and 0.5N(right) that produces the graphs:

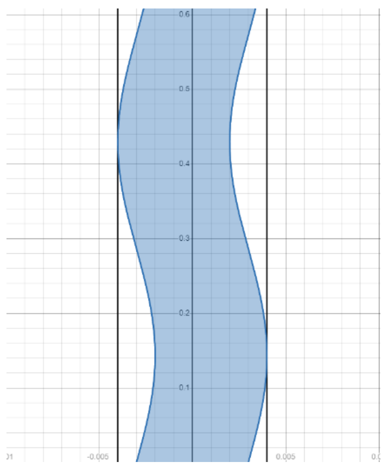


Figure 1. Deformation when P = 0.1N

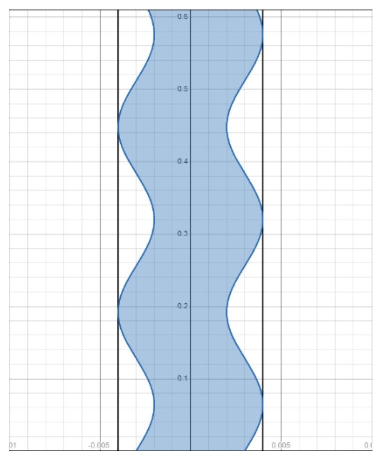


Figure 2. Deformation when P = 0.5 N [31]

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 Josh H.

The mathematical modeling done here was focused on the electronics and the motor calculations. In this project there is a subsystem breakdown of a power supply, stepper motor drivers, stepper motors, controller, microcontroller, and sensors. Here is a visual breakdown of these subsystems plus an additional component being shown in a power tree branching from the power supply.

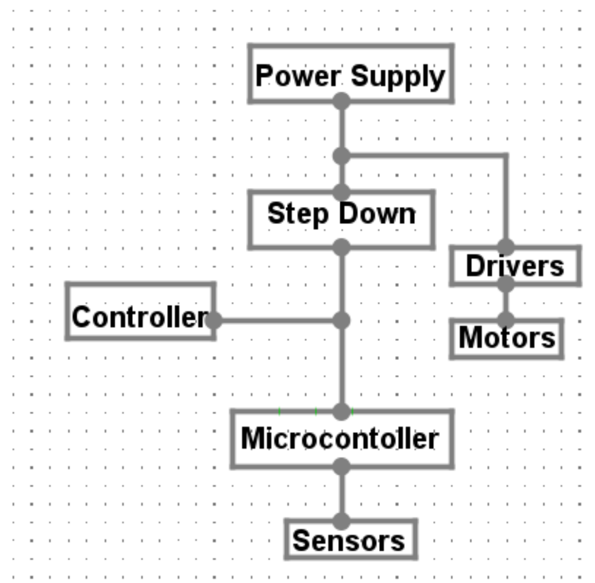


Figure 3. Power

The step down is a component which will be needed to convert the higher DC voltage coming from the power supply into a lower DC voltage for the microcontroller and sensors. Stepper motors were chosen as the motor of focus early on as they can perform very small and precise movements, the angle which is most common for these types of motors to 'step' is one point eight degrees. First on the list for calculations is about stepper motors, looking at the engineering requirements we have one pertaining to movement resolution being one tenth of a millimeter. With a step angle of point-eight we must find the size of the roller to which the catheter will sit on. This is because of the relation between linear distance and rotational distance. Using the equation below:

$$\frac{L}{\emptyset * \frac{\pi}{180}} = r$$

Knowing the degree of the step is point-eight, and the distance resolution needed being point-one millimeters the max radius the roller pushing the catheter can be is three-point-two millimeters. Now knowing this the required torque of the stepper motor can be found. Another engineering requirement talks about a range of forces needed by the device. The requirement states a force range between point-one to ten newtons, to simplify this let's choose the max force, which is required, ten newtons. Knowing that torque is a force applied at a distance we use the equation below to calculate the torque needed.

$$T = r * F * 0.142$$

Using ten newtons as the force (F) and three-point-two millimeters as the radius (r) we get a max torque of four-point-five ounce-force-inches. The reason we have the 0.142 in our torque equation is it converts the newton-millimeters to ounce-force-inches, the reason we need the latter dimensions is because this is the unit stepper motors have their torques. Using the calculated torque, we can now look at stepper motors which are on the market and see what power they require to calculate an estimate for the power supply. Going over some common sense the stepper motors needed will be on the smaller size. This would be stepper motors such as the 'NEMA 8', 'NEMA 15', and 'NEMA 17'. All are very small motors with the biggest, the 'NEMA 17,' being one-point-seven by one-point-seven inches in height and width. Relating these sizes to the needed torque we can find an average required voltage of twenty-four volts and two amps. It is worth noting these values don't belong to a specific motor instead the values are an average of what was seen by on the market motors meaning this is a huge estimation but should result in a good ballpark estimate for power supply requirements. A preliminary estimation of motors comes out to two motors (it is worth mentioning this estimation is semi-inaccurate as later in the design stages secondary motors are needed to move other things, but two primary motors is still accurate), both motors requiring two amps each running at the same time will need four amps in total. Using the equation below we can calculate the power based on the current (I) needed and the voltage (V) needed.

$$P = V * I$$

With our voltage of twenty-four volts and current of four amps the power supply required will be around ninety-six watts. As a last note for the power supply calculations the device will need microcontrollers and sensors, these components will run on five volts and a max current of point-five amps. The voltage supplied will always be more than enough meaning there is a need for a voltage step down. The current draw is so small that we could ultimately ignore it at this stage. In conclusion, using the engineering requirements of the project the radius of the roller to push the catheter must be three-point-two millimeters, the stepper motor must have a max torque of four-point-five ounce-force-inches, and finally a power supply capable of ninety-six watts, twenty-four volts, and four amps.

3.3.3 Gray

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.

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 4. 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.

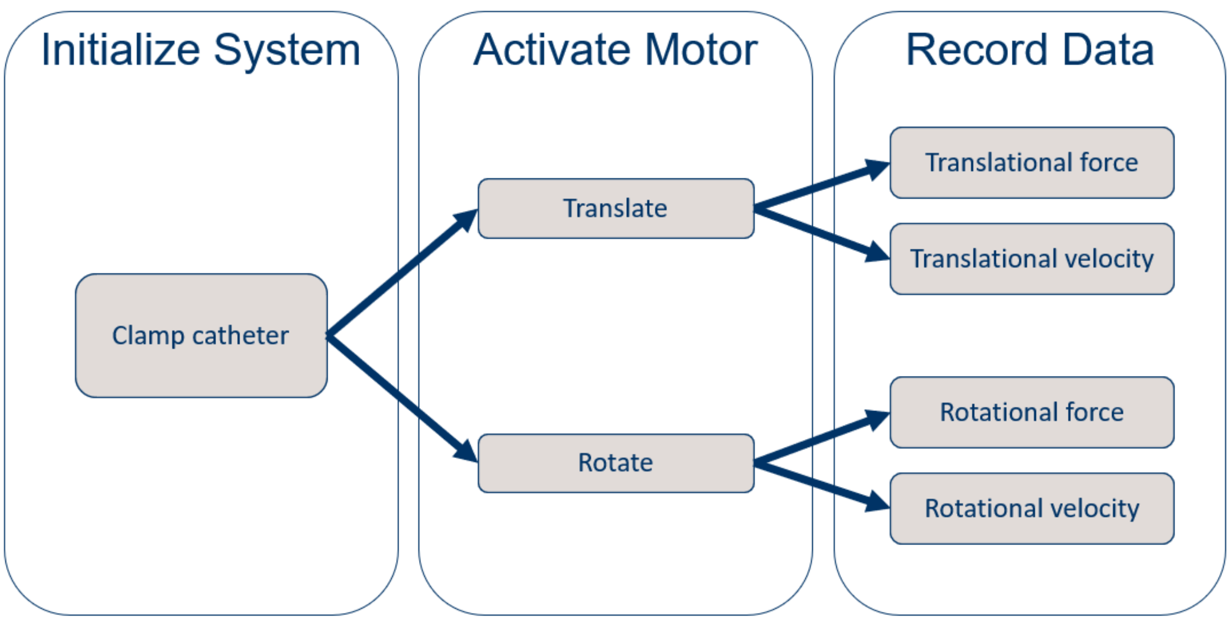


Figure 4. Functional Flow Model

4.2 *Concept Generation*

This section aims to go over the subsystems we have focused on in hopes to prototype. This includes subsystems for translation, rotation, and sensors.

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 (Fig 1). This is the most similar to 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.

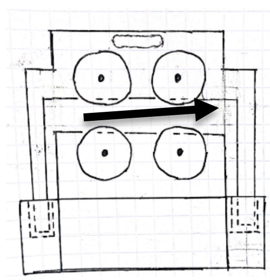


Figure 5. Square Design

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 similar to the above design (Fig 2). 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.

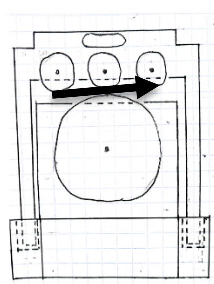
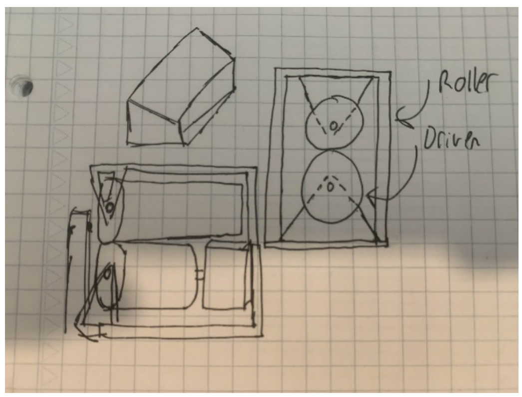


Figure 6. Triangle Design

4.2.2 Rotation

Like the translation component, the rotation part of our design does not have much variety. This is because none of our comparative research includes a rotation system. Almost all the systems we could find were still hand rotated or used a torque load cell. Neither of these ideas are applicable in our design because of our engineering and project definition requirements. Instead, we had to come up with ideas with no existing reference which led to many ideas that were not practical enough to consider. Finally, we ended up with two ideas that could be used and would not be difficult to make. They both exploit the concept of how something rolls when places between two oppositely moving objects.

One of these ideas was to use a similar system to the translation component and roll the catheter between two wheels. The axis of the wheels would be parallel to the cross-sectional axis of the catheter. One of the wheels will be driven by a motor while the other spins freely causing a rotational effect onto the catheter placed between them (Fig 4). The advantages of this system are its simplicity and torque calculations. The downside is that it requires fine adjustments to keep the catheter between the wheels as slipping is very easy.



gure 7. Roller Rotator

Another idea is creating a friction plane that clamps the catheter between to plates. The bottom plate is stationary while the top plate will move back and forth to rotate the catheter in either direction. The motion of the top plate is controlled by a motor and a lead screw with a frictional plate placed on it (Fig 4). The benefits of this design are it has better grip on the catheter over the rollers and allows for more uniform rotation along the catheter. The disadvantages however are that it requires a more complicated assembly and would be harder to manufacture.

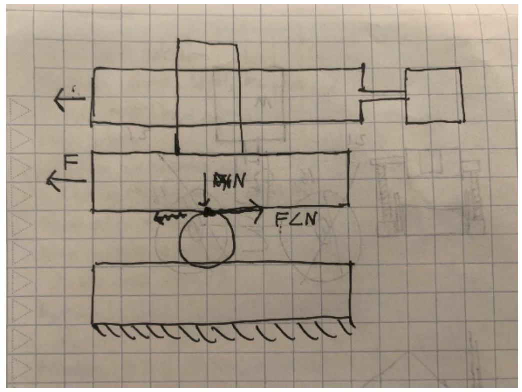


Figure 8. Friction plane rotator

4.2.3 Sensors

One of our customer requirements is to collect and record how the system is reacting 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.

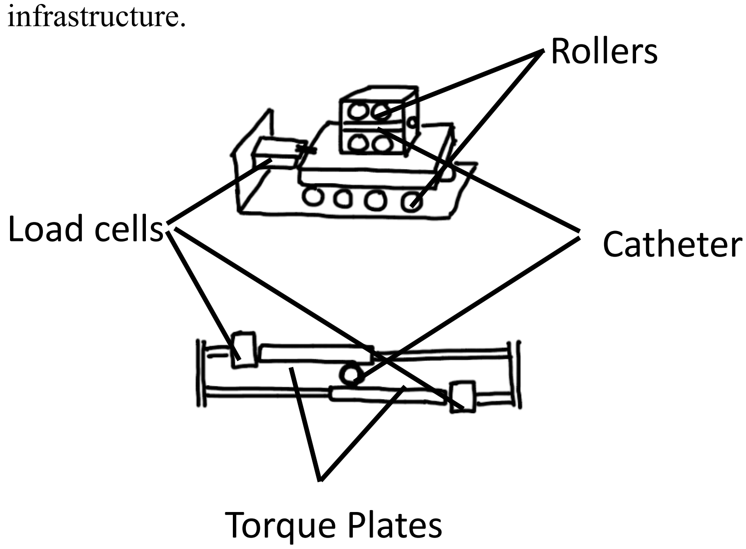


Figure 9. Load Cells for Translation and Rotation

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.

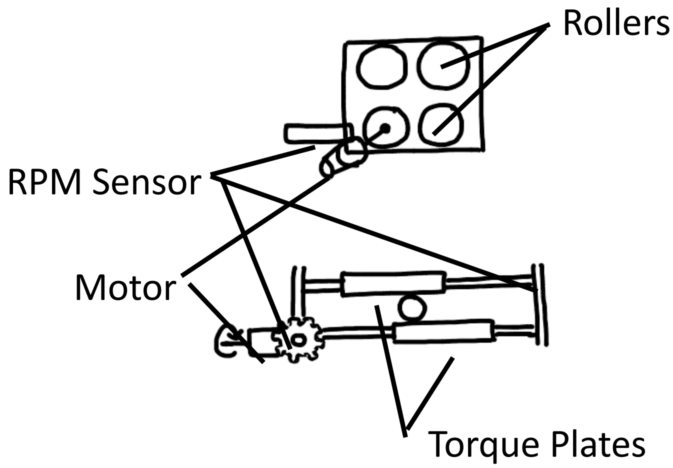
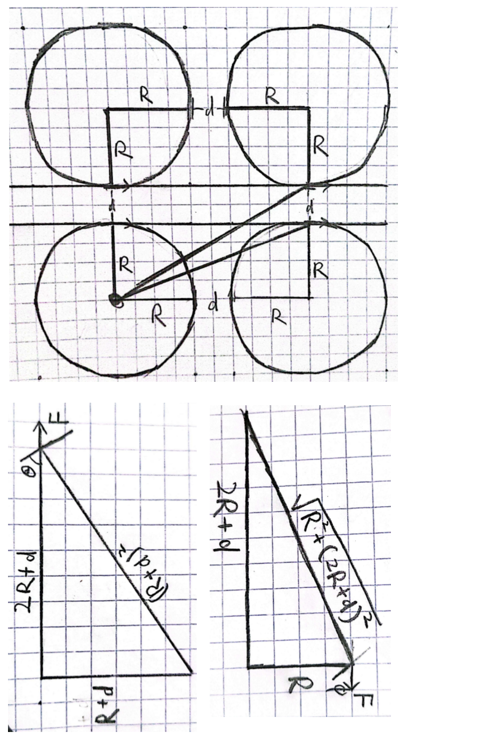


Figure 10. RPM Sensors for Translation and Rotation

4.3 *Selection Criteria*

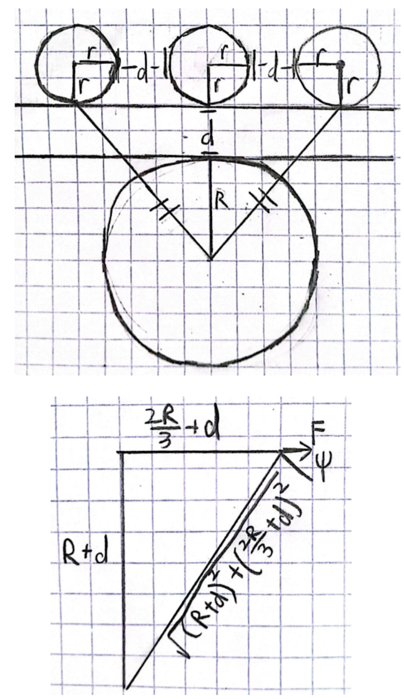
4.3.1 Translation

To determine the best layout for the rollers, I looked at which design requires more torque from the motor. By choosing the axle of the motor as the center of mass, I can evaluate the sum of moments and find 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. With this information, I derived and plugged the equations into MATLAB and 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.



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

Figure 11. Square Design - Moment Diagram



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

Figure 12. Triangle Design - Moment Diagram

This led me 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. 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.

4.3.2 Rotation

The rotation of the catheter is paramount to the project's success; however, how to obtain this motion needs some discussion. The two designs of rotation serve the same function but perform the action of rotating in different ways. The roller design simply rotates the driven roller to transmit the rotation to the catheter and the friction plate method uses a translating friction plate to squeeze and cause rotation on the catheter. Rotation of the catheter depends on the friction between itself and the components trying to move it. To calculate which method is better we first look at how much torque would be needed to rotate the catheter and how long the friction plate would have to be to give one full rotation of the catheter. To do this we use the equation:

$$l = d * \pi$$

This will turn our diameter into linear distance traveled. Using our engineering requirement of a catheter size between two to fifteen French, or rather point-seven to five millimeter in diameter we can calculate the largest plate size but taking the max of our diameter range for d, ultimately getting a plate size of fifteen-point-seven millimeters. This is the minimum plate size for one full rotation so for the max sized catheter to make one full rotation the plate would have to use its full length starting from corner to corner. To make this easier the plate size is doubled to thirty-one-point-four millimeters that way the catheter can start its rotation in the middle of the plate and have some 'le-way' distance to make a full rotation. Analysis of the plate size is these sizes are small regardless so ultimately the bigger size has no negative effect on the design. The next step is calculating the moment of inertia for the catheter. This calculation assumes that the catheter is a straight cylinder however should be good enough in ultimately determining the force needed to rotate. Using the moment of inertia equation of:

$$I = \frac{1}{2} * M * r^2$$

Then converting this equation to:

$$I = \frac{1}{2} * p * \pi * r^4 * L$$

This is so the moment of inertia can be calculated in terms of density (p), radius (r), and length (L) of the catheter. Density (p) is very hard to narrow down a value for as each catheter is different and manufacturers are very secretive so, we will be setting density as a constant. The radius range to be used is point-thirty-five to two-point-five millimeters. The length of the catheter is given by the engineering requirement of a max catheter size of two feet. Plugging in these numbers we get a minimum moment of inertia of $7.18 * 10^{-15}\ kgm^2$ and a maximum moment of inertia of $1.87 * 10^{-11}\ kgm^2$. Again, the inertia values are missing the density values as that is set to a constant, keep in mind the real values would be multiplied by the density. Using this we can now find the torque needed using the equation below:

$$T = a * I$$

Where a is angular acceleration and I is the moment of inertia we have. The friction plate version of catheter rotation will have the plate itself as well as any necessary components to make it work. Preliminary design shows this includes the plate, friction material, housing, and lead screw. All of these will have mass and resistance and will require a motor/torque capable of moving them. The materials and therefore the mass is unknown and will remain unknown until later in the design process however, a work around is deciding how long it should take the catheter to do a full rotation and from that finding the constant acceleration needed to make this happen. To do this we use an excel sheet to auto calculate angular acceleration and torque by iterating through how long in seconds the catheter should take to rotate. This is shown in the figure below:

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 13. Excl sheet calculations for torque

To explain the excel sheet we have all the values previously calculated. We then have a range of times it should take for a full catheter rotation to happen, ranging from one to nine seconds. Knowing the distance which needs to be traveled by the plate for one rotation and the time we can create values for constant acceleration. The reason for this is to essentially ‘ignore’ the mass and resistances we would normally need to overcome and calculate into our torque. Now using the equation for torque above and the newfound angular acceleration values we can calculate a range of torque which is needed to rotate the catheter. It is worth noting that these values are very small this is because the density of the catheter is still out of the equation, once the density is found it would be as simple as multiplying the density by the torques. It is worth clarifying that this torque value is for turning the catheter, not pushing the entire plate system. The stepper motor powering this component will need to be able to overcome resistances which aren’t accounted for here. These small torque values make more sense when thinking of them in terms of a requirement to rotate a catheter which are very light and small, making them easy to move. Using the catheter sizes, we can then find the linear force the plate will have to be acting on the catheter to cause the rotation. We know that when it comes to friction the normal force times the coefficient of friction will give the friction force. This can be considered the max force we are able to linearly apply. To increase the friction force we can increase the normal force acting on the catheter through adjustments however this runs the risk of squeezing and deforming the catheter. Using this logic, we can say that having a lower necessary linear force will allow for a lower friction force leading to less deformation on the catheter. This means the values gathered here are good.

In conclusion the plate design will be the focus going into prototyping. There seems to be no mathematically apparent advantage to either design leading to the decision that real world testing is in order. During the prototype phase as said before the plate design will be the focus however, creating the roller design will also be necessary to see which truly comes out on top. Reasons for choosing the plate design currently are due to the uniform and consistency of the movements, the mimicking of the real-world hand motion to rotate a catheter, and adjustability. The reasons to why not the roller design is there are concerns that the rollers will cause stress to the catheter, and there is also concern that with how slippery the catheter would be there is a chance it would slip out from its resting place between the two rollers. Overall, the mathematic modeling gives a good idea what to expect from the more complicated friction plate design but ultimately doesn’t hold any apparent advantage over the roller design leading to both needing to be prototyped and tested against one another to see which one is best.

4.3.3 Sensors

One of the project requirements is the ability to detect forces and torques from our robot. While a load cell provides a straightforward force measurement, the RPM sensor approach requires a calculation to implement. The power equation can be adapted to find force.

$$P = VI = Fv$$

$$v = r\omega$$

$$F = \frac{VI}{r\omega}$$

Torque sensors can be derived in a similar manner.

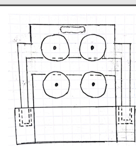
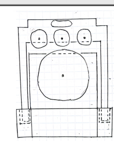
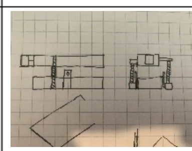
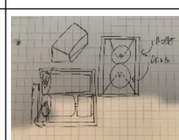
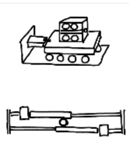
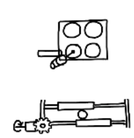
$$\tau = F \times r$$

$$\tau = \frac{VI}{\omega}$$

If a motor provides a voltage of 10 V and a current of 1 A, and our roller had a speed of 500 rpm and a radius of 20 mm, the resulting force would be 9.55 N.

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		
B. Rotation		
C. Sensors		

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.

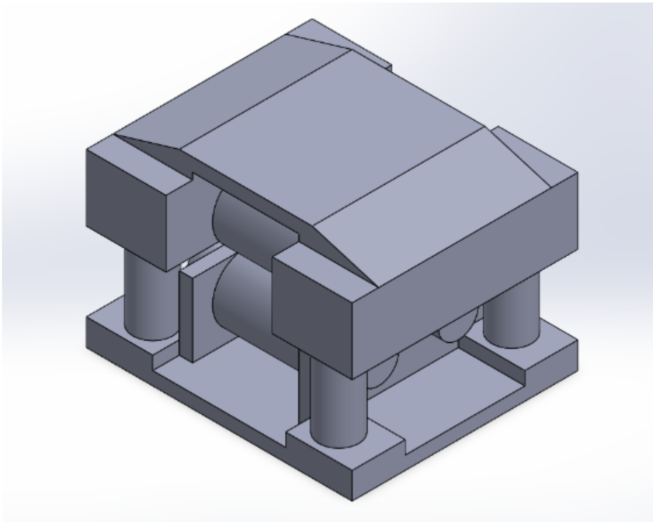


Figure 20. Square Design (SOLIDWORKS)

The better rotation component is 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.

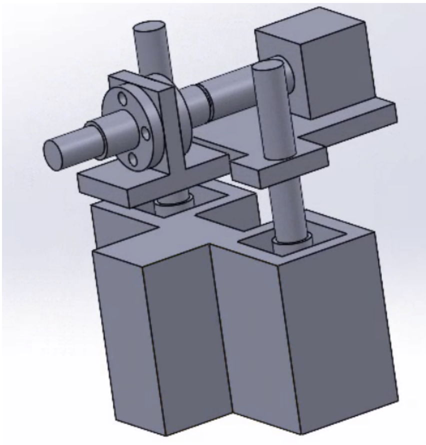


Figure 20. Rotational Design (SOLIDWORKS)

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 CONCLUSION

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 oppositely moving plates to drive the rotation. We used a similar clamping idea to the translation component that is manually set. Once the catheter is fixed between the plates, the top plate is moved by a motor forcing a twisting motion on the catheter. This motion is 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 considered above were rejected by the client and no others have been found since. This will force us to come up with new ways to measure the feedback while we move forward with the translation and rotation components. Once we find a working model for the sensors, the needed changes will be made to these systems to account for this function.

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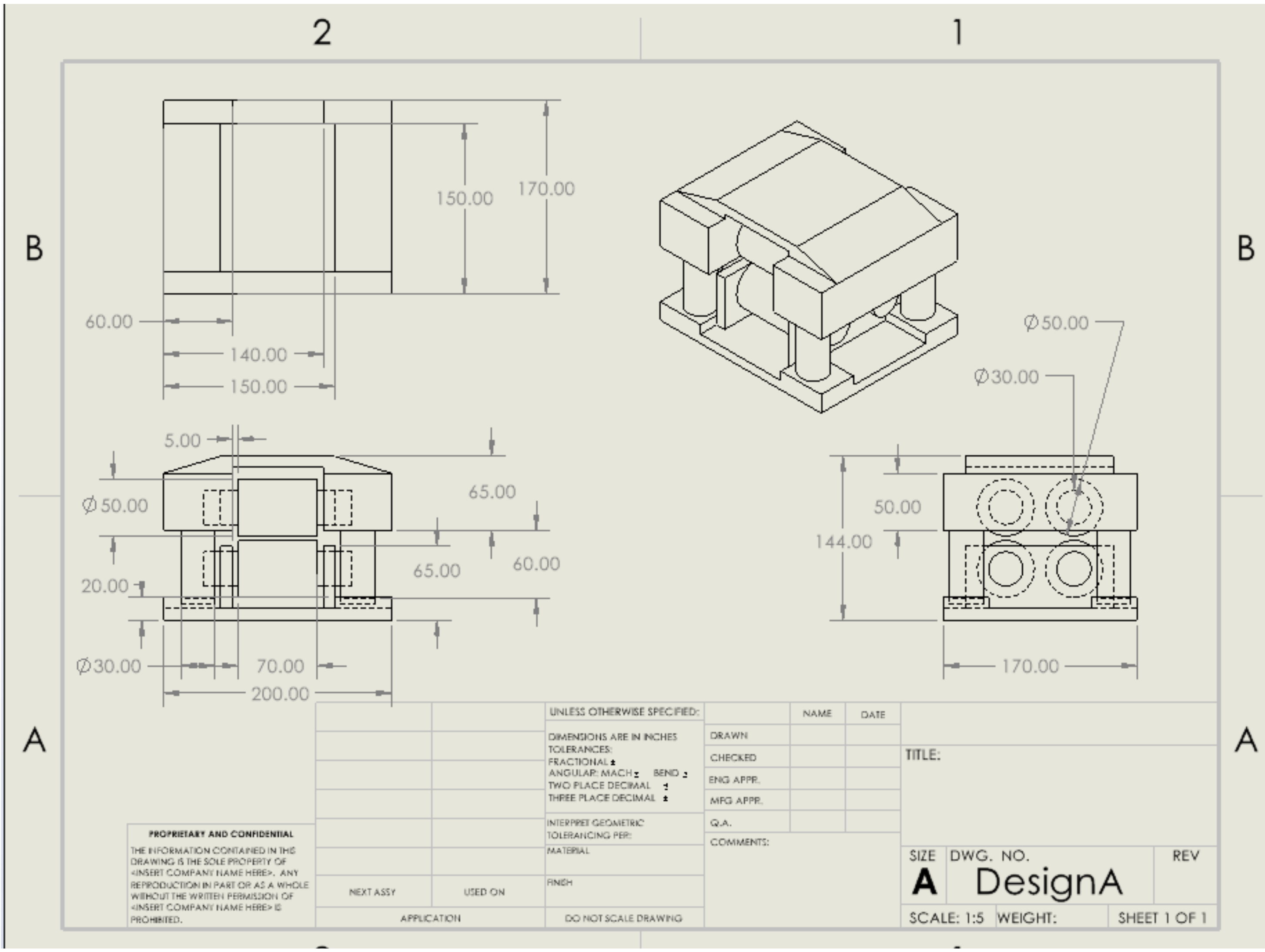
7 APPENDICES

7.1 *Appendix A: SOLIDWORKS dimensioned drawing the square translational roller layout*



7.2 *Appendix B: SOLIDWORKS dimensioned drawing for the rotational plate layout*