Flying Squirrel

Final Report

John Avila Copado | Budget Liaison & Logistics Manager

Ryan Donnellan | Manufacturing Engineer

Justin Joy | CAD/CAM Engineer

Owen Kehl | Project Manager

Joseph Mathews | Test Engineer & Web Developer

Spring 2025-Fall 2025

NAU
NORTHERN ARIZONA UNIVERSITY

Project Sponsor: Dr. Reza Razavian

Instructor: Dr. Armin Eilaghi

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

Near the start of this semester, the five team members listed above, including John Avila Copado, Ryan Donnellan, Justin Joy, Owen Kehl, and Joseph Mathews, were assigned to execute the Flying Squirrel project. This project is sponsored by Dr. Razavian, who has outlined his engineering requirements, budget, and general expectations for the development of the Flying Squirrel. Since the start of the project, he has also met with the team on a weekly basis to receive updates and provide guidance. All concept generation was supervised by Dr. Razavian, and all suggested changes to the design were incorporated or rejected based on his advice.

The Flying Squirrel is a therapy rehabilitation robot designed to help restore, by training, arm function in stroke patients. This is to be accomplished through horizontal and vertical movement of the robot while the patient's hand is clasped or otherwise secured to it. In this way, the patient's arm undergoes movement most likely to increase its useability in daily life. In order to assess the problem of movement, members of the team generated several possible design ideas. Most of these were thrown out for being infeasible in one way or another or being incompatible with the design requirements. However, one design included the use of screws to lift the robot, a concept that was favored by both team members and the sponsor. The problem of horizontal motion was dispelled by Dr. Razavian, who recommended the use of tensile cables to pull the robot over a work surface. Both systems have remained part of the design throughout its alterations. The latter system of pulling cables requires anchor points, the attachment of which to the work surface being accomplished by c-clamps or suction cups for flexibility.

Since then, a few major additions and changes to the design have taken place. Dr. Razavian agreed to relax the design's 8-inch height requirement to allow the lead screws to protrude from the top of the robot. This allows the lifting system to be simplified greatly, while still achieving the 1-foot range of vertical motion. While the design of the anchor points was being deliberated, it was suggested that, rather than having cables emanate from the lifting section of the robot and fix to the points, the cables should run from the lifting section, thread through pulleys on the anchor points, and attach to the bottom half of the robot. Following this development, the team decided that the motors for pulling the cables should be on the bottom part of the robot, both to lower its center of gravity and decrease the amount of tension needed to move the robot.

TABLE OF CONTENTS

Contents

1 BACKGROUND

Section 1.1 will go over the project, its main purpose, and various reasons it is needed over other options that do not meet adequate needs. The section also discusses the current budget and efforts towards fundraising. Section 1.2 discusses deliverables to be met by the end of the 486C semester as set by Dr. Razavian. Section 1.3 covers the success metrics for the Flying Squirrel and briefly explains engineering and client requirements.

1.1 Project Description

The Flying Squirrel is meant to be a therapeutic rehabilitation robot focusing on restoring the motor functions in the arms of a stroke victim. The Flying Squirrel is the second iteration of the Hamster, a capstone project from previous semesters. While the Hamster and the Flying Squirrel share the same purpose and idea, that being a relatively cheap alterative robot to what's out on the current market, where these diverge is the scope while the Hamster is locked into the 2D plane the Flying Squirrels goal is to expand into the 3rd dimension. Our project development budget is $3750; but with current fundraising of $150 and various donated parts, it brings the budget up to $4050 in total budget for this project. One of the main reasons why this project is important, aside from rehabilitating stoke victims to give them use in their arms, is to make this robot cheap. As it stands, no similar device exists under $10,000. The end goal vision is that a person can buy this robot and set it up with relative ease and begin the road towards rehabilitation in their own home without breaking the bank.

1.2 Deliverables

The main deliverable for this project is to produce a robot that can move in the X, Y, and Z planes by the end of capstone. It also needs a system to track its position at all times and the amount of force it receives and produces, while also recording that information and sending it to a computer. Another deliverable that we need to carry out is an accurate and complete CAD model and drawings of the final design of the Flying Squirrel. All this will be accomplished while keeping up with other Capstone course deliverables such as presentations, reports and staff meetings.

1.3 Success Metrics

Our success with this project will be measured by whether we are able to produce the robot, and to what extent it fulfills the requirements set by our sponsor. These include the customer requirements, or the performance requisites expected by the user; and the engineering requirements, which refer to technical parameters defined by our sponsor. Each set of requirements will be explained further in section 2. Some simple conditions, such as the size of the robot in its inactive state, will be fulfilled in the course of its design. Other performance-related requirements will be validated through testing. We will attempt to ensure capabilities like force detection and position accuracy are present in our initial programming, but physical trials will likely be necessary to confirm their function.

2 REQUIREMENTS

In this section we will go over the different requirements that will be needed for the flying squirrel robot. This will cover our customers' requirements ranging from affordability to ease of use for the customer. We will also go over the engineering requirements associated best by meeting not only our clients' requirements, but the needs of the consumers that will be using the robot. Finally, there will be a Quality function deployment graph combining all the customer requirements and the engineering requirements to see how each induvial item correlates with one another.

2.1 Customer Requirements (CRs)

The primary requirements specified by our client are detailed below. Along win a brief explanation of each requirement, details about why they are important to the client for the Flying Squirrel robot are included with each CR

1. Affordability: The main obstacle right now to physical therapy would either be that the patient doesn't have the time to travel to physical therapy or the means to pay for extensive physical therapy. By making it as affordable as possible we can at least try to eliminate one of these problems.
2. 3rd Dimensional Movement: A lot of physical therapy exercises for patients require 3D movements, like reaching for a glass of water and drinking it. By giving it access to 3D movement, the Flying Squirrel can access a whole directory of exercises that the Hamster couldn't perform.
3. Precision and Accuracy: It's important to have an accurate and precise robot so that any data that it produces is reliable and can be used to plan out the next steps of the patient's recovery.
4. Size: If the main goal is to have the Flying Squirrel in people's homes, it must be relatively small and compact so that it can be stored when not in use.
5. Lifespan: The robot must be able to operate for extended periods of time while in use.
6. Cosmetics: The design of the Flying Squirrel must appear user-friendly and pleasant to look at, to a degree. If the robot is hideous, people would be put off from buying it.
7. User Friendliness: when the Flying Squirrel is in people's homes, it's imperative that it has a fast set up time and that it is easy to use so that people don't get discouraged from doing their therapy just because it's a hassle to set up.

2.2 Engineering Requirements (ERs)

The engineering requirements established by the team and our client are listed below. We have decided that these are the most important requirements we need to focus on over the course of this project and have defined the goal for each requirement that the Flying Squirrel needs to meet.

1. Range of motion: The robot needs to move the user's hand in a 3D space of 2 feet wide, 1 foot long, and up to 1 foot above the surface of a table.
2. Size: Fit within a box of 8"x8". The height was initially restricted to 8" as well, but due to the lifting mechanism that our client requested, the height requirement was lifted to the height the lead screw needed to be.
3. Speed: The device must be able to "catch up" with users at a hand speed of up to 1 m/s in any direction.
4. Force: The device must be able to produce forces of up to 10 N to the hand in any direction.
5. Sensing and Control accuracy: The robot must have accurate position sensing control within 0.1mm of its desired movement, and accurate force sensing control to output a steady force within 0.1N of the 10N force.

6. Battery Life: The Flying Squirrel needs to be able to run for about 30 minutes on battery life before needing to be recharged.
7. Production Cost: The total "production" cost (bill of materials + manufacturing/labor cost) must be <$1000. However, this changed to be more flexible as the project developed, since the 3-axis force sensor and motor sets cost more than entire original budget
8. Set-up Speed: The robot must be set up and ready to operate within 1 minute.

2.3 House of Quality (HoQ)

System QFD

Project:	Flying Squirrel
Date:	11/23/2025

TR Correlations					
Production Cost	9				
Speed	1	9			
Force	1	3	9		
Control and Detection	3	3	3	9	
Device Size	1	3	1	1	9

Customer Needs	Customer Weights (1-5)	Production Cost	Speed	Force	Control and Detection*	Device Size*	N/A	N/A	1 Poor	2	3 Acceptable	4	5 Excellent
		Technical Requirements							**Competitive Analysis**				
Affordability	5	9			3	3			AB				C
3rd Dimension Movement	4	3	1	1		1			C				AB
Precision and Accuracy	3	3	9	9	9						C		AB
Size	4	3	1			9			B		A		C
Cosmetics	1	1				1				C	B		A
User Friendliness	5	3				9				A		B	C
Technical Requirement Units		Dollars ($)	Meters per Second (m/s)	Newtons (N)	Millimeters (mm)	Inches (in)							
Technical Requirement Targets		1000	1	10	0.1	8x8x19							
Absolute Technical Importance		31	42	35	93	100							
Relative Technical Importance		5	3	4	2	1							

Relationships:			
9	3	1	
Strong	Moderate	Weak	None
Legend:			
A	Armeo SpringPro		
B	ArmMotus M2 Pro		
C	The Hamster		

Table 1: Quality Function Deployment (QFD)

3 Research Within Your Design Space

3.1 Benchmarking

- *Armeo SpringPro*

Figure 1: Armeo SpringPro

This device is an advanced motion rehabilitation machine designed to target the patient's arm. It provides a significant array of motion in three dimensions, and while in use fully supports the targeted limb according to the maker's website [1]. However, due to its technical complexity, the product is both cumbersome and not realistically affordable to individual consumers.

- *ArmMotus M2 Pro*

Figure 2: ArmMotus M2 Pro

This system also aims to restore arm movement in patients, specifically those suffering from neurological and musculoskeletal disorders as stated in the product's pamphlet [2]. In addition to providing simple 3D motion, the system comes with a variety of game programs to exercise the patient's arm. While an impressive product, it suffers largely the same drawbacks as the bulky and costly Armeo.

- *The Hamster*

Figure 3: The Hamster

Being the basis of our own project, this design addresses some of the issues present in the other two rehabilitation devices. Namely, it supplies arm movement in a more compact and affordable package. The description on the project website [3] states that it will eventually be programmed with exercise routines to facilitate the motor control of stroke victims. Its main drawback is that, while the omnidirectional wheels allow it to take any horizontal path on a surface, the Hamster lacks vertical movement.

3.2 Literature Review

- **3.2.1 Jonathan Avila**
    - *Rehabilitation Robotics: Technology and Application.* [4]
        - Rehabilitation Robotics gives an introduction and overview of different areas of rehabilitation robotics while also summarizing the different robot technologies and application of them. Seeing what kind of technology is already out there on the market gives us inspiration as to what alternative designs we can turn to during the concept generation portion of the project.
    - *Atlas of Orthoses and Assistive Devices.* [5]
        - The source detail various robots and more specifically medical devices in the medical field. This gives some examples of the do's and don'ts of what to do when creating a robot that has a better chance of succeeding.
    - *Wrench feasibility workspace analysis and adaptive rotation algorithm of cable-driven upper limb rehabilitation robot.* [6]
        - This source was useful in just seeing how it was possible to move a person around using cables though the main problem with this robot was that it was way

too expensive and bulky to be really practical.

- *Control of a large redundantly actuated cable-suspended parallel robot.* [7]
  - In this paper they go over how they control a large cable-suspended parallel robot that is able to do basic tasks such as in picking things up and dropping them off in a certain work area. But the most relevant part of this paper for us would be their proposition of a computationally efficient tension distribution algorithm allowing the robot to move not only very precisely but also accurately.
- *String-man: A new wire robot for gait rehabilitation.* [8]
  - In this source it describes a robot with a very similar style, essence, and function but just built for different aspects and a different stage of patient recovery. So, for us this paper shows how specifically patients interact with a cable driven robot assisting them, and what we might be able to do to improve the experience over different methods.
- *Garrett Brown's skycam history.* [9]
  - This source specifically talks about the history of the process of the making of cable driven robot before they knew what they were actually end up making. Which is very useful when making a cable driven robot yourself to see what kind of struggles other people had along the way so that we can avoid some of those pit falls.
- *How skycam works.* [10]
  - This explains some of the more in-depth mechanics as to how the sky cam works and being able to see how a cable driven robot can effort move in the XYZ plane effortlessly. Which helps us so that we aren't starting from scratch.
- *Rehabilitation Robot - an overview.* [11]
  - This specific source is an overview of a wide variety of robots, more specifically the rehabilitation aspect of patient care. Which just gives us a frame of reference for what other robots did and what worked and became successful and what didn't.
- Shigley's Mechanical Engineering Design, 11th Edition [12]
  - This textbook was just very helpful all around when we were designing all the different aspects of our robots like how to chose the bearings for our wheels and what are all the specific properties our lead screw needs to move up and down at 1m/s.
- Review on Comparative Analysis of Ball Screw & Lead Screw [13]
  - When we where looking at all the different lifting mechanics that we could use we eventually landed on lead screws and this paper offered us a good overview on the pros and cons as to why we should use lead screws or not.

- **3.2.2 Ryan Donnellan**
    - *Arduino Robotic Projects: Build Awesome and Complex Robots with the Power of Arduino*. [14]
        - ♣ This book covers the basics of Arduino, what is on an Arduino board, and how to use it. It gives examples of projects using Arduino to broaden the understanding of Arduino to the reader. It will be relevant to the project in the manner that the Flying Squirrel will be using Arduinos to control motors that control the movement of the robot.
    - *Raspberry Pi 3 Cookbook for Python Programmers: Unleash the Potential of Raspberry Pi 3 with over 100 Recipes.* [15]
        - ♣ This book gives an in-depth overview of how to use Raspberry Pis. It covers topics ranging from automating computer tasks to how to build a small robot. The content covered in this book will be used to set up the Raspberry Pi that is controlling the robot.
    - *Modeling cable-driven robot with hysteresis and cable–pulley network friction.* [16]
        - ♣ This article contains information on how to model the behavior of the cables that control a cable driven robot. It contains equations to calculate how much the cables will stretch while in use by the robot. This article could be applied to the project by helping to calculate the position in the event of the cables stretching.
    - *Permanent magnet DC motor control by using Arduino and Motor Drive Module BTS7960.* [17]
        - ♣ This article proposes a control system using pulse width modulation to control the output of a permanent magnet DC motor. This will be relevant to the project as the robot will be using pulse width modulation to control the motors that move the robot.
    - *Design and evaluation of a Bowden-cable-based remote actuation system for wearable robotics.* [18]
        - ♣ This article gives an example of a cable driven wearable robot that assists the motor function of the patient. It can help the team decide on what motors to use to drive the robot. It will help because the robot in the article has to support the weight of the arm, and the Flying Squirrel will not.
    - Automatic speed controller of a DC motor using Arduino and Variable Frequency Drive techniques. [19]
        - ♣ This article gives examples and explanations of how to control the speed of various kinds of DC motors using an Arduino and variable recurrence drive. It will be useful to the team because no matter the motor type we choose to drive the robot we will have a basis on how to program it.
    - Speed Control of BLDC Motor using PWM and Arduino Uno. [20]
        - ♣ This article gives an example of powering a brushless DC motor using an Arduino, pulse width modulation, and a LiPo battery pack. This will be useful to

the team because it is an extremely similar setup to how our robot will be set up. Using an Arduino to control a brushless DC motor and a LiPo battery pack to power everything.

- *Robot-assisted therapy in stroke rehabilitation.* [21]
    - This journal gives evidence as to what kind of robot works best and does not show evidence of working as a therapy device. It will help inform the design of the robot by improving upon what works and getting rid of what does not.
- *A novel cable-driven robotic training improves locomotor function in individuals post-stroke.* [22]
    - This article gives evidence on the success of cable-driven robots to improve the motor function of stroke victims. This article can help inform the design of the Flying Squirrel to incorporate what works best based on experiments that have already been done. It can also help by getting rid of what does not work based on the evidence presented in the article.
- *How to use Raspberry Pi and Arduino together.* [23]
    - This website gives an overview of how Raspberry Pi and Arduino work together. It tells you what hardware, software, and code you need to make the two work together. It will be relevant to the project because the Flying Squirrel will use a Raspberry Pi to change the input to the Arduino to control the motors.

- **3.2.3 Justin Joy**
    - *Encyclopedia of Smart Materials* [24]
        - This book covers materials that have one or more properties that can be significantly changed in a controlled manner. It provides information on fundamental and recent developments for design and applications. The applications include robotics which is relevant to the Flying Squirrel.
    - *Chapter 5 - Robotics and Rehabilitation: The Role of Robot-mediated Therapy Post Stroke* [25]
        - The chapter discusses the importance of exercise-based intervention for stroke patients. It then justifies how robotics can play a role in the therapy of stroke victims. The chapter reviews research of work done to implement robotics in stroke therapy
    - *Upper Limb Robot Mediated Stroke Therapy—GENTLE/s Approach* [26]
        - The article discusses how early therapy can enhance stroke recovery. Robots and VR-based systems encourage patients to exercise for longer periods of time. It is also quickly available at home. This can help develop strategies for our project for quick setup at home
    - *Multi-sensor Fusion for Body Sensor Network in Medical Human–robot Interaction Scenario* [27]
        - The article discusses how multi-sensor integration is important for data collection in real time. It is also important to collect data from the user for medical purposes. Multi-sensor fusion methods can improve the communication of data.

- *Development of an Integrated Haptic Sensor System for Multimodal Human–Computer Interaction Using Ultrasonic Array and Cable Robot* [28]
  - The article connects human interaction with cable drive robotic sensors and motors. The subsystems and sensors invoke realistic stimulation. The device uses a novel haptic sensor system. This is relevant for our project on how potential users can connect with the device.
- *Adaptive Robot-Assisted Feeding: An Online Learning Framework for Acquiring Previously Unseen Food Items* [29]
  - A feeding robot is programmed to adapt to different food preferences under uncertain conditions. Different manipulation strategies are used for successful bite acquisitions. These methods can be used to manipulate different user inputs.
- *Adaptive Assistive Robotics: A Framework for Triadic Collaboration Between Humans and Robots* [30]
  - Framework is given to provide a combination of biomechanical modeling and weighted multi-objective optimization. This allows for fine tuning of robot behaviors. The framework is illustrated in the article showing the benefits of the triadic approach.
- *A State-of-the-Art Review on Robots and Medical Devices Using Smart Fluids and Shape Memory Alloys* [31]
  - Various robots in this article use smart materials to activate functions. These smart materials include electro-rheological fluids, magneto-rheological fluids, and shape memory alloys. Specific types of mechanism in robots are investigated in medical devices and rehabilitation systems. This can be potentially useful for our device with size constraints for adding in sensors or actuators.
- *Robotic Arm Force Sensing Interaction Control* [32]
  - This paper presents a force control system for industrial robotic manipulator and an active force and torque sensing technique to send out the corresponding instruction when effected by the external power. The proposed sensor is implemented on the top of manipulator. This sensor can be the transducer measuring and outputting forces and torques from all three Cartesian coordinates. This will provide techniques for incorporating a force sensor in the Flying Squirrel.
- *Multi-Axis Force Sensor for Human–Robot Interaction Sensing in a Rehabilitation Robotic Device* [33]
  - Rehabilitation and assistive robotics are fields where interaction forces are required for both safety and increased control performance of the device with a more comfortable experience for the user. To provide efficient interaction feedback between the user and rehabilitation device, high performance sensing units are needed.

- **3.2.4 Owen Kehl**
  - *Chapter 6 - Robotics in Rehabilitation Medicine: Prosthetics, Exoskeletons, All Else in Rehabilitation Medicine*. [34]
    - This chapter talks about similar robotic rehabilitation equipment, as well as how

it is used in the physical therapy sphere. Given the nature of this project, material related to rehabilitation and robotics helps with benchmarking.

- *Chapter 3 – Sensors and Transducers*. [35]
    - In this chapter, the author discusses the different types of sensors used in bio mechatronics and writes a little about how the technology works. This information is good for deciding what sensors will work in our own design.
- *Forces and Moments Generated by the Human Arm: Variability and Control.* [36]
    - This study examines arm movements in response to forces exerted on the hand. Such data helps us to understand how people will respond to a moving handle, which our project may be crudely defined as.
- *Force Control and Degree of Motor Impairments in Chronic Stroke.* [37]
    - The focus of this study is to compare force application control in the fingers and wrists of stroke victims versus control subjects of a similar age. This helps us to get an idea of how users will interact with the Flying Squirrel.
- *A Low-Dimensional Representation of Arm Movements and Hand Grip Forces in Post-Stroke Individuals.* [38]
    - This investigation aims to observe how motor control is affected by a stroke, studying data from both stroke victims and a control group. Like the previous source, the data helps us to understand the arm motions of patients.
- *Human Body Mass Distribution.* [39]
    - Taken from a larger study, this table provides an idea of mass represented by different parts of the human body. This includes the arm and hand, which helps to understand the weight and moment applied by a person's extended arm.
- *Understanding Force Sensors: How They Work and Measure Force.* [40]
    - This page explains the mechanisms behind force sensors and the different types available. It is important that we understand how this technology works and what type of sensor should be used for our purposes.
- *Accurate Tracking: A Look at Position and Distance Sensors.* [41]
    - Similarly, this page discusses the different types of force sensors and their uses. Our final product needs to detect forces and its own position, so an understanding of position tracking is necessary.
- *Motor encoders: What is a motor encoder? How do motor encoders work?* [42]
    - This article discusses the different types of encoder motors and how each one works, which gives us another idea of how to track position.
- *Lead Screws 101* [43]
    - Since lead screws are the system with which our robot will be raised and lowered, the equations relating to them on this website will be invaluable to us.

- **3.2.5 Joey Mathews**
    - *Raspberry Pi Robotic Projects* [44]
        - This book starts with an overview and tutorial on how to use a Raspberry Pi. Each chapter after that focuses on applying a Raspberry Pi for different robots that each perform different tasks, and several sections within the chapters explain how to set up and use various components, such as servo motors and cameras. This book will be useful for us because it will help us understand how to integrate electronic components with a Raspberry Pi that we will be using.

- *Hands-on robotics programming with C++ : leverage raspberry pi 3 and C++ libraries to build intelligent robotics applications.* [45]
  - This book is similar to the previous source, as it introduces and explores how a Raspberry Pi works and what functions it is capable of. A larger portion of the book is dedicated to this than the previous source. It then explores different applications for the Raspberry Pi in robotics and has tutorials on how to build and program different types of robots. This source is beneficial for our group because it goes into further detail about how to set up and program different electronic components and how to use them for robotics applications.
- *ToF 3D Vision Algorithms in C++ for Robotic Applications* [46]
  - This article primarily focuses on different algorithms that can be used with a Raspberry Pi, and what kinds of algorithms the author used for their thesis work, and how these algorithms were applied. Again, this article will be beneficial for us because it goes further in depth on programming with Raspberry Pis for robotics applications.
- *Gesture Control Robot with Arduino* [47]
  - This article focuses on the creation of a robot that can be controlled by gestures. We've been tasked with adding a load cell into the Flying Squirrel, so when the user applies force, the robot will respond to it. While the connection is weak, I think it may still be useful in integrating these types of controls with the load cell.
- *Path Following System for Cooperative Mobile Robots* [48]
  - This paper describes the path following system utilized by the robots described in the paper. It explains the equations utilized by the robots' programming to track its movements. This source will be useful for us as it will help us understand and develop our own path following system along the cables.
- *Wire Robots Part I: Kinematics, Analysis & Design* [49]
  - This paper focuses on robots controlled by cables and wires. The details it provides on how those robots are controlled will be useful in the development of our cable system.
- *Robot dynamics and control* [50]
  - This book focuses on the physics and dynamics of robots, control systems, and how the two are related. There are many different aspects within the control system sections that will help us with the development of our programming. The sections regarding force control, trajectory and path planning, and velocity kinematics will likely be the most useful sections for us.
- *Controlling Tensegrity Robots through Evolution* [51]
  - This source is very similar to 41, and the reasoning is also similar. It focuses on how cable driven robots work, and the information it provides may be useful to the development of the Flying Squirrel.
- *Arduino meets Raspberry Pi in automation: an implementation of state-based distributed control with round-robin scheduling* [52]
  - This study explores a distributed control system where Arduino and Raspberry Pi collaborate using a round-robin scheduling approach, highlighting their roles in automation tasks.
- Raspberry Pi Arduino Serial Communication - Everything You Need [53]
  - A comprehensive guide detailing serial communication between Raspberry Pi and Arduino, including wiring, code examples, and troubleshooting tips.

3.3 Mathematical Modeling

Equations pulled from prior classes, so no citations are needed.

3.3.1 Attachment Cable and Motor System

- **Wire Tension- Jonathan A. and Justin J.**
  - $\sum MA = 0$
- **Maximum Motor Torque Estimates-Joey M. and Justin J.**
  - $\tau = F*r$
- **Wire Max Stress-Jonathan A.**
  - $S = (F*nf) / A = (T*nf)/ A$
- **Pulling Force for Four Wires-Owen K.**
  - F_c=√((0.5(dA-0.1437m))^2+(dr+0.0298m)^2)/((dr+0.0298m))∗5N

3.3.2 Battery

- **Total Battery Capacity Required- Ryan D.**
  - $Ah = I * h$

3.3.3 Lifting System

- **Necessary Lifting Strength- Owen K.**
  - $M = MP_{hm}g(L(1-0.5P_{hl}))+ MP_{fm}g(L(0.5P_{fl}+P_{al}))+ MP_{am}g(L(0.5P_{al}))$
- **Downward Force from Wires- Owen K.**
  - $F_y= F_t*\cos(\theta)$

3.3.4 Position and Motion Tracking

- **Vector Analysis for Motion and Angle Tracking- Joey M. and Ryan D.**
  - $\theta = \arctan(y / x)$
- **Engineering Tools**
  - Matlab/Python/C++

4 Design Concepts

4.1 Functional Decomposition

Black Box

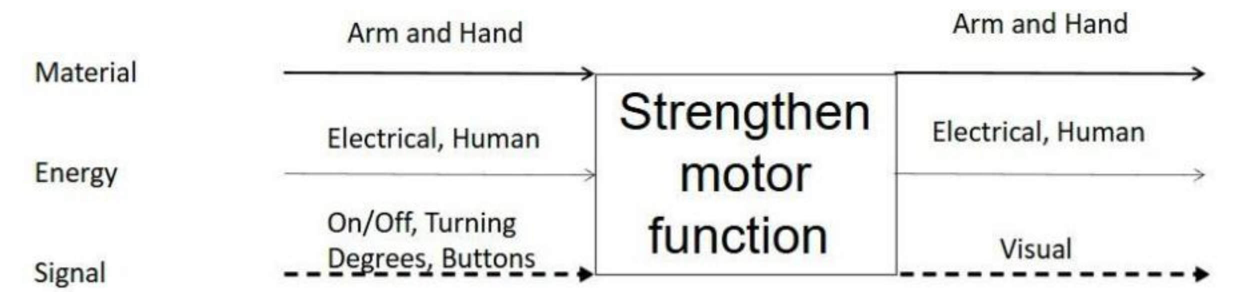


Figure 4: Black Box Diagram

Figure 4 pictured above shows our black box model and the different inputs and outputs of our system, in addition to its main function.

Functional Decomposition

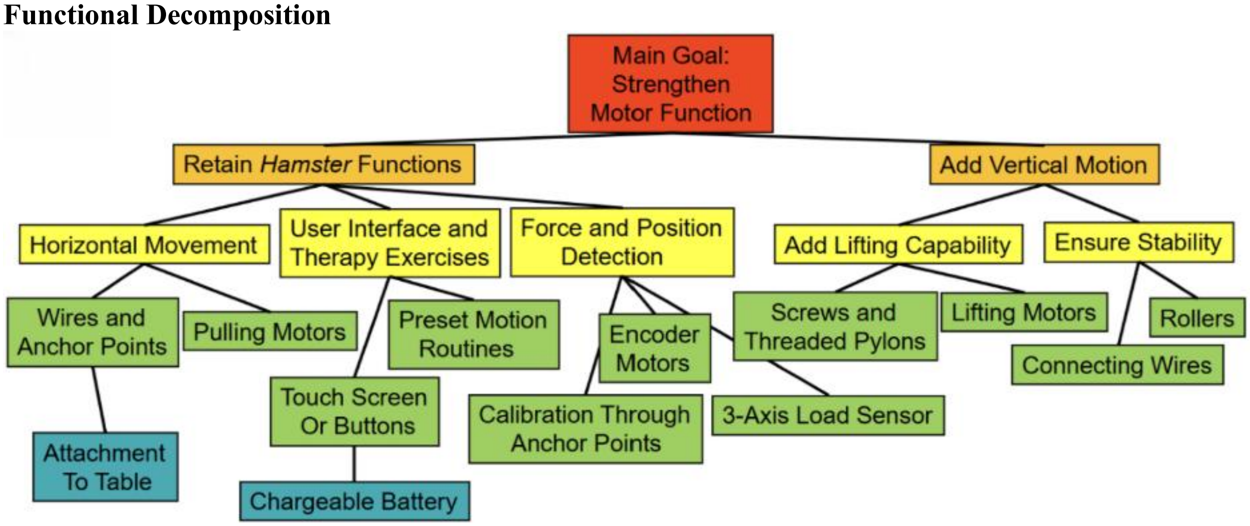


Figure 5: Functional Decomposition

The main function is expanded in Figure 5. It is divided into two major functions in orange, those being to capture the capabilities of the Hamster design and add vertical motion. Each major function is split into several yellow sub-functions. Green boxes indicate the components or systems necessary to realize the functions. Some of these include teal sub-components that are crucial for their design. This breakdown of functions is important to identify the necessary hardware that our robot would have to host. Additionally, knowing the required functions and components helped to focus our efforts during concept generation phases.

4.2 Concept Generation

After our first round of concept generation, Dr. Razavian broached the idea of a cable-driven robot. It was decided that this concept would be the basis for all future ideas going forward. From there, another round of concept generations based on the cable-anchor idea took place. Larger images of this phase's designs can be found in Appendix B. Designs from the initial concept generation can be found in Appendix A

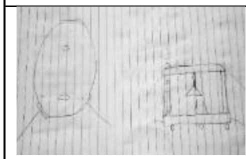
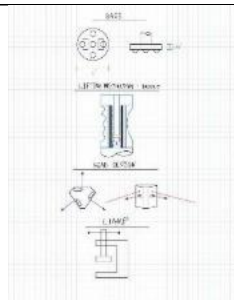
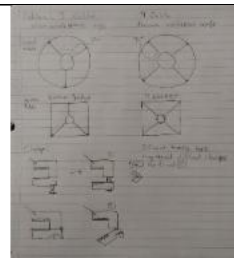
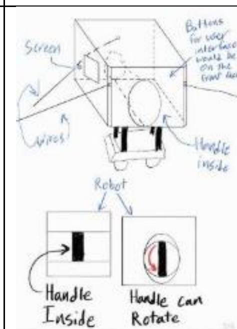
Design 1-Jonathan	**Design 2-Ryan**	**Design 3-Justin**	**Design 4-Owen**	**Design 5-Joey**
				
Pros: Robust lifting system, flexible handle, stable design	**Pros:** Ergonomic, stable clamp design	**Pros:** Different wire/anchor configurations, adaptable clamps	**Pros:** Adjustable handle, different clamp options	**Pros:** Arm support, stable lifting system
Cons:	**Cons:** Rigid handle	**Cons:**	**Cons:** Prone to tipping	**Cons:** Potentially bulky

Table 3: Concept Generation

4.3 Selection Criteria

The way we went about establishing our selection criteria was different from a normal concept generation and selection process. Dr. Razavian had already come up with the idea for the wire driven robot, so when we got to the stage to select what concepts to use, we ended up selecting pieces from each of the concepts we had generated that Dr. Razavian had liked, and incorporated those concepts into our next design until we had generated a design that was satisfactory and we moved forward from there. Most early designs were phased out because they did not meet Dr. Razavian's standards for cost-effectiveness and relative simplicity. These requirements applied to most of our ideas for the cable-driven robot, so further concepts were selected by feasibility and lifting capacity.

4.4 Concept Selection

Pugh Chart

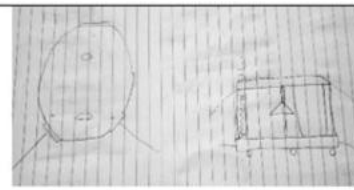
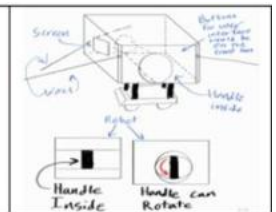
Criteria			
Design	1	2	3
Production cost	+ Smaller device	S	Datum
Speed of the Robot	-It has a smaller base to work with	+The base and double wire allow for fast accurate movement	Datum
Device Size	+ It has a small frame	+ it is more compact than the Datum	Datum
Position Tracking	S	S	Datum
Force	-Smaller base to account from moment	S	Datum
User Friendliness	-Setup difficulties from base size and user touchscreen.	+It has a fast and easy set up with a screen	Datum
Total +	2	3	
Total S	1	3	
Total -	3	0	

Table 4: Pugh Chart

The Pugh chart pictured above was used to narrow down the designs from the concept generation to choose a design which will be iterated on to eventually become the final design. Design 3 was chosen as the datum because it was the closest to what Dr. Razavian had proposed to the team.

CAD Model

Pictured below in figure 6 is the rough draft CAD model that was initially made at the end of the concept generation phase. This model is based on design 2 from the Pugh Chart. Dr. Razavian requested a rough draft CAD model as a next step to the concept design process. The purpose of this was to create a rough design that he could review and provide feedback on. The CAD model was reconfigured several more times throughout the two semesters to the final designs shown in figures 7 and 8. The first iteration of the final design consisted of three subassemblies; the top section, bottom section, and handle. The top section held the screen and housed the force sensor that is connected to the handle assembly. The handle assembly consists of the handle, strap, and mounting bracket to the force sensor. The lower section contains the rest of the parts for the robot to function such as the motors, Arduino, Raspberry Pi, motor drivers, and battery. It also held two lead screws driven by a belt connected to one motor and a support bar. The final design is a refined design of the first iteration. The battery and Raspberry pi were moved to the top sections while the motor controllers remained in the lower section but moved to the back wall that was added to the design. The design changed from using two lead screws to a single lead screw mounted at the back of the lower section and two support bars are used instead of one.

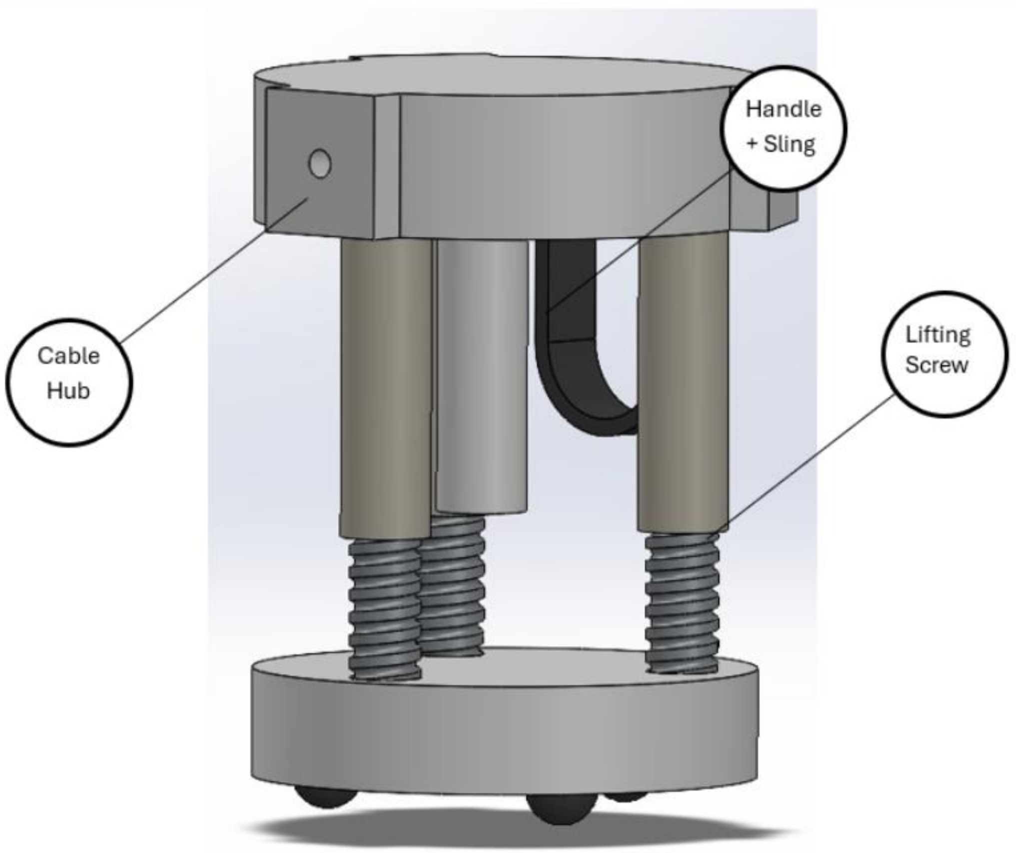


Figure 6: CAD Model

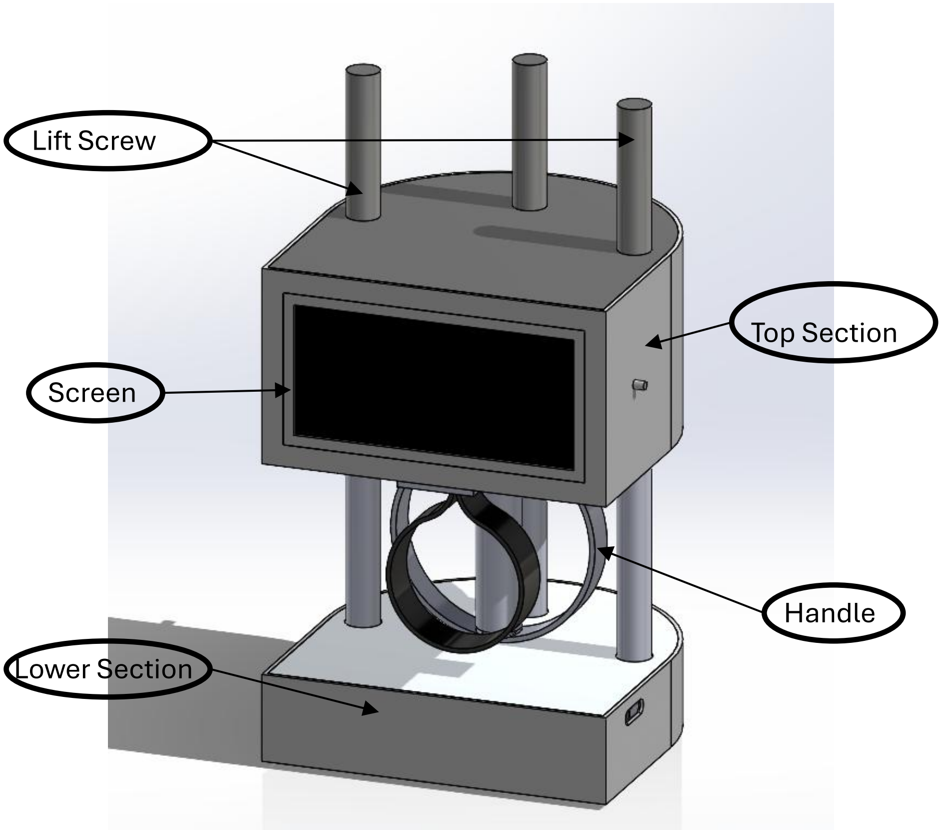


Figure 7. First Iteration of Final Design

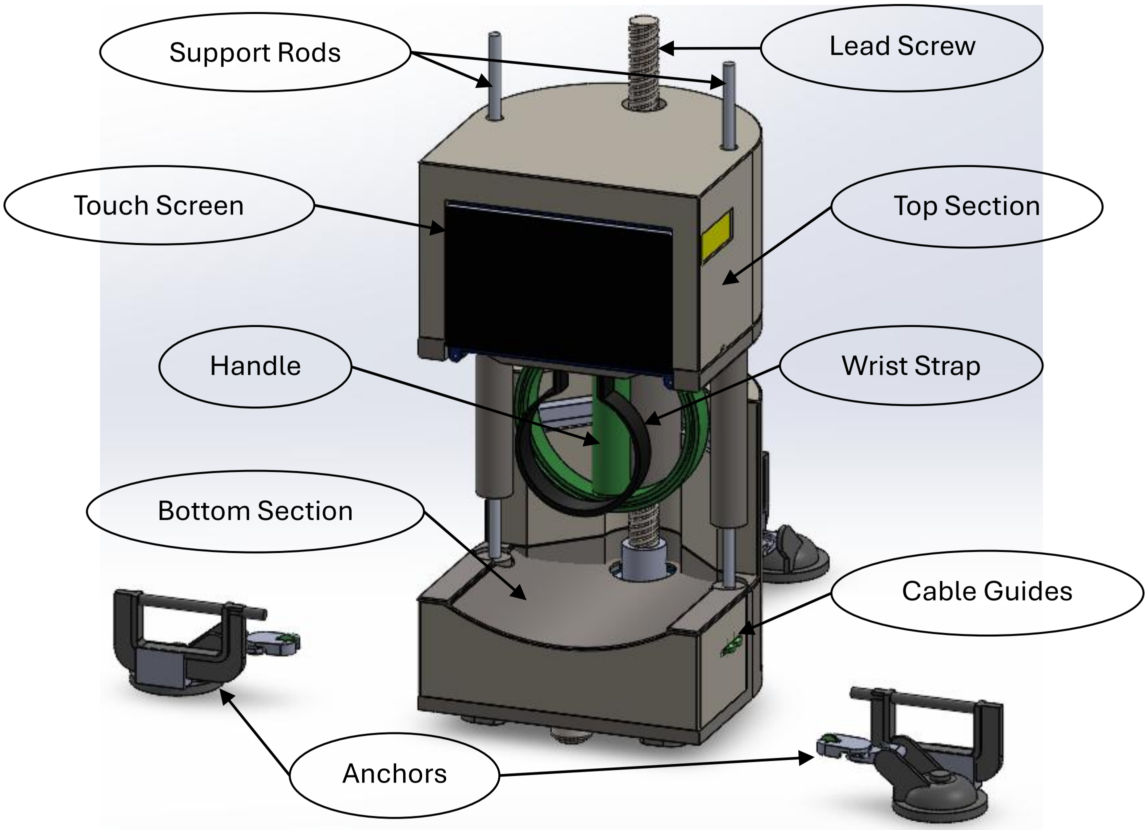


Figure 8. Final Design

Hybrid Clamp Design

The hybrid clamp concept, shown in Figure 9, represents our efforts to make a more versatile robot that works on different surfaces. In situations where the table being used is too thick, or the anchors cannot be attached to the edge, the anchor points can be secured by suction cup. In other situations, the c-clamps can be used to fix the anchor points. Figure 10 shows the final cad design of the hybrid clamp assembly, and figure 11 shows the assembled hybrid clamp.

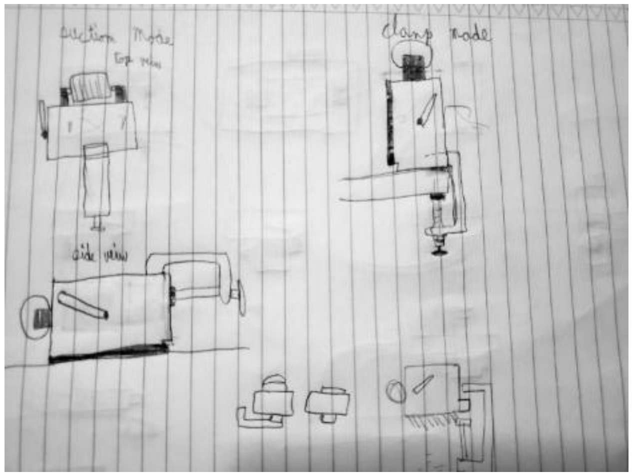


Figure 9: Hybrid Clamp Concept

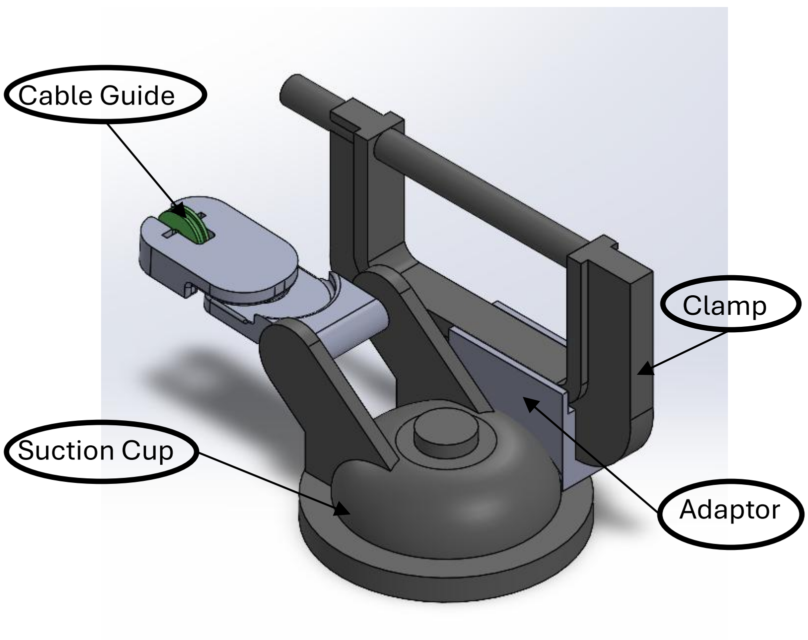


Figure 10. Hybrid Clamp CAD Model

5 Project Management

5.1 Schedule

[Show your detailed Gantt chart for the first semester and a draft of the second semester. Show your work-breakdown-schedule and describe each task.]

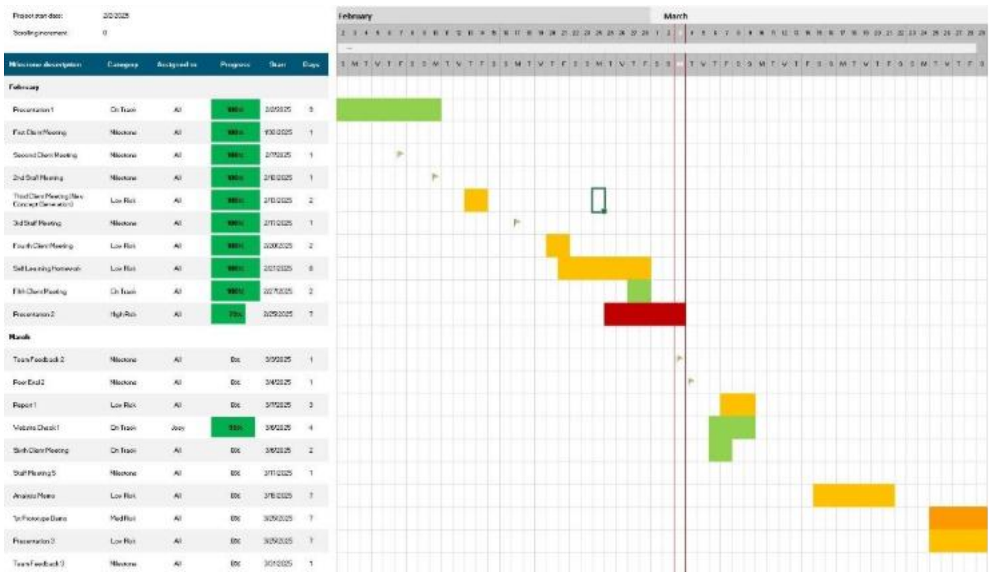


Figure 11: First Half of the Spring 2025 Semester Gantt Chart

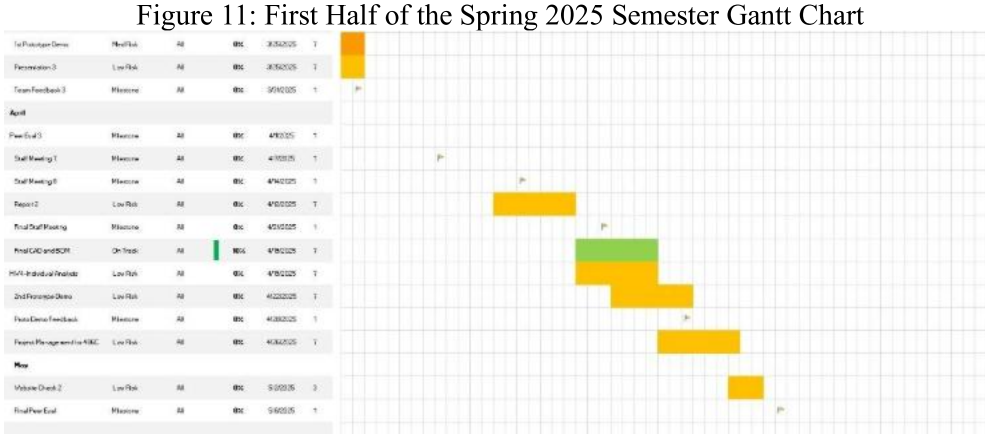


Figure 12: Second Half of the Spring 2025 Semester Gantt Chart

Our first capstone schedule mostly consisted of class deliverables such as presentations and demonstrations. These helped us to stay on track with our concept generation phases and performing engineering calculations. During our meetings with Dr. Razavian, we will discuss our progress on the project and next steps. Our sponsor would usually give us some tasks to prepare for the next meeting, though these did not have a strict due date. These are usually related to updating the design and CAD model, performing necessary calculations, or procuring parts for the assembly.

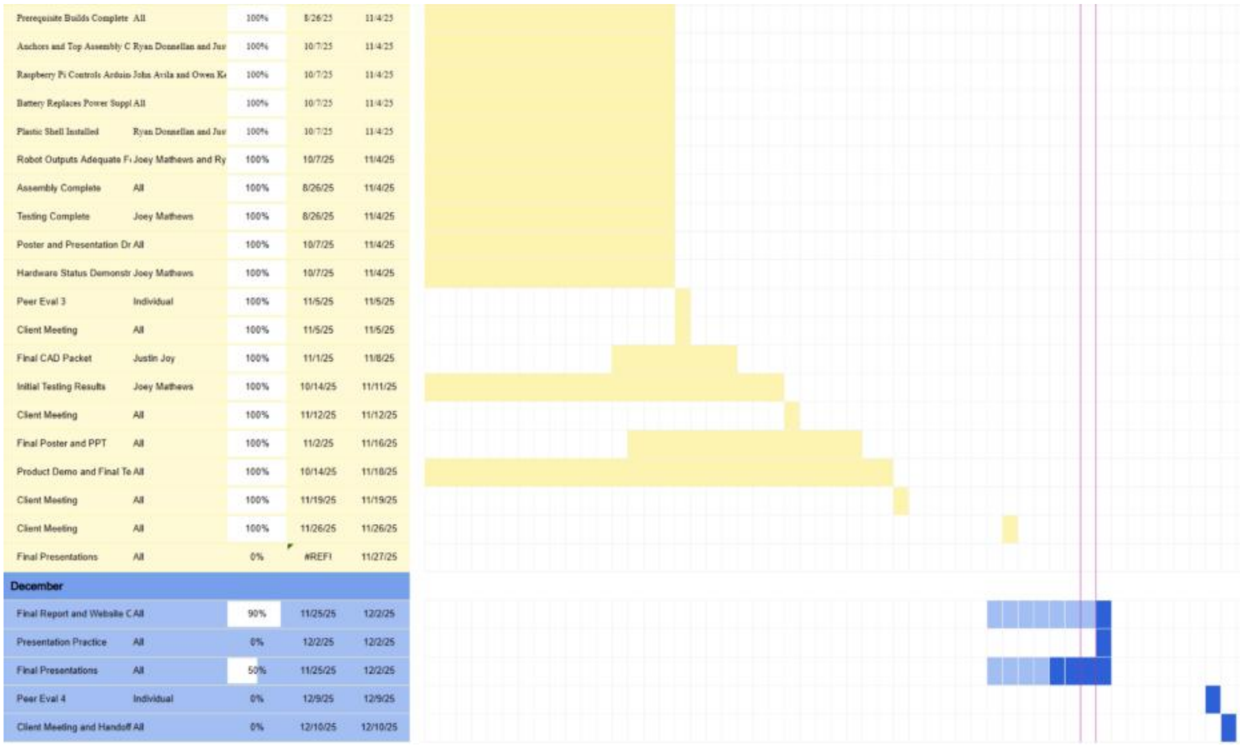


Figure 13: Fall 2025 Gantt Chart

This semester, our tasks mainly consisted of meeting build checks and performing testing. We continued to have weekly meetings with our client, where we discussed progress and possible obstacles to the project. With this version of the chart, we were able to delegate specialized tasks to individual members of the team, rather than just marking them for everybody. Assignments like reports and presentations were the exception to this. The figure above shows the end-of-semester tasks, most of which have been completed by now.

5.2 Budget

Anticipated expenses	$0
Actual expenses to date	$2353.09
Project's budget including income	$3750
Fundraising	$120
Resulting balance	$1396.91

Table 5: Budget

As things currently stand, we came in under budget after completing the final version of the flying squirrel prototype with almost $1400 dollars left over from the budget, at the writing of this report. And with half of our fundraising being fulfilled by the Canes fundraiser last semester, the rest was done by donated parts and $30 from a Go Fund Me.

5.3 Bill of Materials (BoM)

	Raw Materials, Parts or Components	($) Unit Cost	make/buy	Primary vendor	Manufacturer	lead time	Part Status	QTY	($) Total cost
1	3 Axis force sensor	320.57	buy	zhimin	zhimin	Arrived	on hand	1	320.57
2	ODrive S1	148.00	buy	Odriverrobotics	Odriverrobotics	2 week	on hand	4	592
3	16384 CPR Absolute RS485 Encoder with Cable for ODrive Pro or S1	59	buy	Odriverrobotics	Odriverrobotics	2 week	on hand	4	236
4	Heat Spreader Plate	12	buy	Odriverrobotics	Odriverrobotics	3 week	on hand	3	36
5	Harness Build Kit	9	buy	Odriverrobotics	Odriverrobotics	4 week	on hand	4	36
6	Dual Shaft Motor - D5312s 330KV	59.00	buy	Odriverrobotics	Odriverrobotics	2 week	on hand	4	236
7	PLA (3Kg)	49.71	buy	Amazon	creality	2 days	on hand	1	49.71
8	drylin® lead screw, dryspin® high helix thread, right-hand thread, 1.4301 (304) stainless steel	64.8	buy	Roton	Roton	1.5 weeks	on hand	1	64.8
9	dryspin® lead screw nut, high helix thread, RSF	48.02	buy	Roton	Roton	2months	on hand	1	48.02
10	2x OVONIC 3S Lipo Battery 15000 mAh 130C 11.1V LIPO battery with EC5 plug for 1/8 RC truck	138.38	buy	ovonic	ovonic	1 week	on hand	1	138.38
11	Raspberry Pi 5 8GB	80	buy	electromaker	raspberrypi	Arrived	on hand	1	80
12	Arduino UNO R4	27.5	buy	Amazon	ELEGOO	Arrived	on hand	1	27.5
13	Strap	8.99	buy	industrialsafety	industrialsafety	1 week	on hand	1	8.99
14	6.5x3 touch LED screen	0	buy	waveshare	waveshare	2 weeks	on hand	1	0
15	Ball bearings	8.99	buy	harborfreight	harborfreight	3 days	on hand	1	8.99
16	DC power supply	33.94	buy	Amazon	Nice-Power	3days	on hand	1	33.94
17	Suction cup	12	buy	Amazon	Airhead	3 days	on hand	3	36
18	Fishing line	10.98	buy	Amazon	eyond Braid Braide	3 days	on hand	1	10.98
19	C-Clamp	5	buy	Home depot	Amerella	3 days	on hand	3	15
20	screws	18.98	buy	Home depot	Amerella	3 days	on hand	1	18.98
21	linear ball bearings	5.83	buy	misumi	misumi	1 week	on hand	1	5.83
22	Amplifier Load cell	6.99	buy	Amazon	amazon	3 days	on hand	1	6.99
23	Uxcell 10mm OD 8mm Inner Dia 400mm Length 6063 Aluminum Tube	6.22	buy	harfington	harfington	1 week	on hand	2	12.44
24	Dc power steper	6.99	buy	Amazon	Amazon	2 week	on hand	1	6.99
25	terminal block distribution	12.99	buy	Amazon	OOMO	3 days	on hand	1	12.99
26	Breadboard	9.99	buy	Amazon	amazon	Arrived	on hand	1	9.99
								Total=	2353.09

Table 6: Bill of Materials

This final bill of materials for our first prototype and will set the framework for our final design will most likely cost. All of the parts for this robot were purchased instead of building them in house, because we have determined that it would not only be more cost effective, but we would save a bit of time in assembling the parts into a function system, than having to make it all from parts and then building the robot's core system. Most of the items on the bills of materials did have a short lead ranging from around a couple of days to a week at most, depending on when the purchase request was received and processed. The only item with a longer lead time than a month was the force sensor, but considering the alternative is almost $400 price differential for the next best available option, it was chosen. Though most things that had an exceptionally longer lead time were ordered over summer break so that we could hit the ground running. With the only one exception being that of the lead screw nut ran longer than any of estimates given to the team, due to the manufacture having problems in fulfilling that order.

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Flying Squirrel		Development Team: Jonathan Avila, Ryan Donnellan, Justin Joy, Owen Kehl, Joey Mathews				Page No. 1 of 3			
Bottom Plate						FMEA Number: N/A			
ALL						Date: 3/31/2025			
ALL									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 Roller Bearing	Surface Fatigue	Increased force to move robot	5	Assembly error	1	Pull with force sensor	1	5	Purchase high quality parts
2 Base Shell	Brittle Fracture	Appearance	3	Impact loading	3	Visual inspection	2	18	Use high in-fill for plastic
3 Battery	High-cycle Fatigue	Gradual decrease of run time	2	Overdischarging	2	Test with voltmeter	2	8	Revised higher stress test plan
4 Microcontroller (Teensy)	Electrical Shorting	Causes robot to become inoperable	9	Assembly error	1	Run test program	1	9	None
5 Motor Controller	Electrical Shorting	Reduction in performance of all axis movement	7	Over voltage/current	2	Run test program	1	14	Purchase High Quality
6 Lifting Motor	High-cycle Fatigue	Loss of z-axis movement	8	Over voltage/current	2	Test with RPM, force, and voltmeter	1	14	None
7 Drive Motor	High-cycle Fatigue	Loss of xy-axis movement	8	Over voltage/current	2	Test with RPM, force, and voltmeter	1	32	None

Figure 13: Bottom Plate FMEA

Flying Squirrel		Development Team: Jonathan Avila, Ryan Donnellan, Justin Joy, Owen Kehl, Joey Mathews				Page No. 1 of 3			
Bottom Plate						FMEA Number: N/A			
ALL						Date: 3/31/2025			
ALL									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 Roller Bearing	Surface Fatigue	Increased force to move robot	5	Assembly error	1	Pull with force sensor	1	5	Purchase high quality parts
2 Base Shell	Brittle Fracture	Appearance	3	Impact loading	3	Visual inspection	2	18	Use high in-fill for plastic
3 Battery	High-cycle Fatigue	Gradual decrease of run time	2	Overdischarging	2	Test with voltmeter	2	8	Revised higher stress test plan
4 Microcontroller (Teensy)	Electrical Shorting	Causes robot to become inoperable	9	Assembly error	1	Run test program	1	9	None
5 Motor Controller	Electrical Shorting	Reduction in performance of all axis movement	7	Over voltage/current	2	Run test program	1	14	Purchase High Quality
6 Lifting Motor	High-cycle Fatigue	Loss of z-axis movement	8	Over voltage/current	2	Test with RPM, force, and voltmeter	1	14	None
7 Drive Motor	High-cycle Fatigue	Loss of xy-axis movement	8	Over voltage/current	2	Test with RPM, force, and voltmeter	1	32	None

Figure 14: Center Structure FMEA

Flying Squirrel		Development Team: Jonathan Avila, Ryan Donnellan, Justin Joy, Owen Kehl, Joey Mathews				Page No. 3 of 3			
Top Plate						FMEA Number: N/A			
ALL						Date: 3/31/2025			
ALL									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
12 Top Shell	Brittle Fracture	Appearance	3	Impact loading	3	Visual inspection	2	18	Use high in-fill for plastic
13 Drive Motor	High-cycle Fatigue	Reduction in performance of x,y-axis movement	7	Over voltage/current	2	Test with RPM, force, and voltmeter	1	14	None
14 Microcontroller (Raspberry Pi)	Electrical Shorting	Causes robot to become inoperable	10	Assembly Error	1	Run test program	1	10	None
15 Winch Housing	Abrasive Wear	Inaccuracy of x,y-axis movement	4	Overstressing	2	Visual inspection	2	16	Use high in-fill for plastic
16 Winch Line	Creep	Inaccuracy of x,y-axis movement	5	Overstressing	3	Visual inspection	7	105	Test line weight
17 Screen	Impact Wear	Unable to program movement of robot	6	Impact loading	4	Power on	1	24	Purchase high quality parts

Figure 15: Top Plate FMEA

Pictured above in figures 13-15 are the team's FMEA pages, with one for the bottom, center, and top structures of the robot. The part numbers list all the parts of the robot from the bottom up, starting with the roller bearings and ending with the screen. Some critical potential failures of the robot are the lifting screws failing, the Arduino/Raspberry Pi failing, and the cables snapping. Our design has mitigated these problems by using a lead screw with deep enough threads and a wide enough diameter so that any force experienced by the robot is nowhere near enough to cause damage. The design does not have much impact on the Arduino and Raspberry Pi, but the design will make sure they do not short and have adequate cooling, so they do not overheat. For cables snapping, our design incorporates fairleads to slow down the wear on the cables. The risk trade-off analysis that the team performed focused mainly on the lifting mechanism. Originally the team wanted to do a double screw mechanism to achieve the target of moving the hand one foot above its starting position. After conferring with the client, we were informed that this approach is possible but extremely difficult and the client changed the max height so that we can use longer lead screws for lifting as this saves time and money for the team and reduces the cost of the robot.

6.2 Initial Prototyping

Sub-prototype 1:

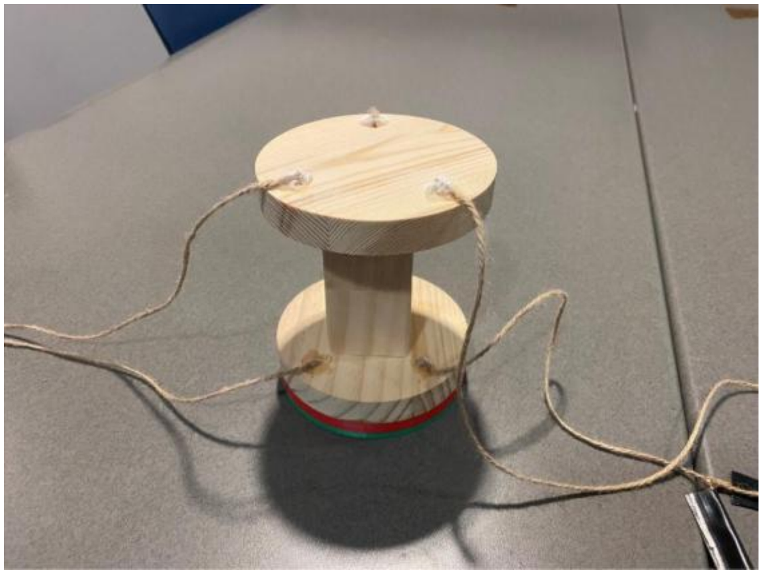


Figure 16: Sub-prototype 1

1. The questions we were trying to answer with this prototype were, what is the best mounting solution to ensure the moment created by the user's hand is at a minimum? Is four inches enough for the average hand to fit comfortably? How well do ball bearings roll against 3D printed surfaces.

2. The answer to the first question was, having the cables mounted to both the top and bottom of the robot resulted in the smallest moment by the user's hand. The answer to the second question is yes, four inches is enough space for the average hand to fit comfortably. The answer to the final question is, they roll relatively well but the layers of the 3D printed surface must be sanded down so there are no hard edges for the ball bearings to roll against.

3. We plan to use the information gained from this prototype by having the cables of the robot be mounted to the top and bottom of the robot. As well as to have the ball bearings roll against the aluminum subframe that the motors will be mounted to as this will be CNC machined so it will be smooth and ensure that there is as little friction between the ball bearings and the robot as possible.

Sub-prototype 2:

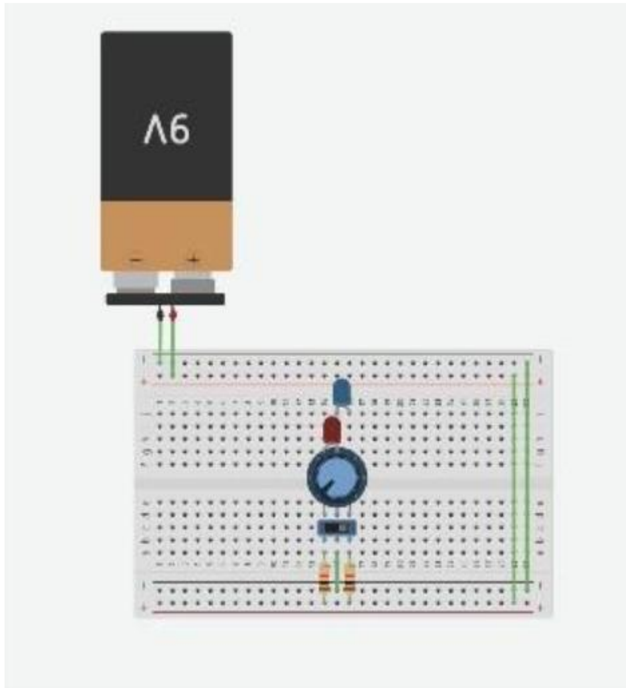


Figure 17: Sub-prototype 2

1. The main question we were trying to answer with this prototype was, what is the simplest circuit we can design to flip the direction the motors are spinning.

2. The answer was, not including the power source or motors, only 4 pieces of equipment were needed. However, on the actual robot, one of the pieces of hardware will be replaced with just software so only 3 pieces of equipment would be needed.

3. This informed the design of our robot by helping to eliminate as many unnecessary parts as possible, making the robot as simple and as reliable as possible as there are less parts to fail.

Virtual Prototype:

Figure 18: Virtual Prototype

1. The question we were trying to answer with this virtual prototype was, with the 2 lifting pillars being right next to the wrist, is there enough clearance when the robot moves left or right so that the pillars do not contact the wrist.

2. The answer to the question was, no, there is not enough clearance, and the wrist contacts the lifting pillars.

3. We plan to use this information to iterate on the previous design by changing from three lifting pillars to two located next to the handle and one static pillar behind the handle to increase the structural rigidity of the robot.

6.3 Other Engineering Calculations

6.3.1 Velocity and RPM

- **Motor RPM- Justin J.**
  - o (V/C) x 60

6.3.2 Cable Angles

- **Maximum Cable Angle for RPM- Justin J.**
  - o θ = arccos((Min RPM for Max V) / (Max Motor RPM))

6.3.3 Cable Length

- **Minimum Cable Length- Justin J.**
  - Law of Sines: sin(A)/a = sin(B)/b

6.3.4 Ball bearings life cycle

- **Basic Rating Life (L_{10})- Jonathan A.**
  - $L_{10} = (C/P)^p$ *10^6
    - C = dynamic load rating
    - P = equivalent dynamic bearing load
    - p = exponent
- **Basic Rating Life in hours (L_{10h})- Jonathan A.**
  - $L_{10h} = L_{10}$ /(60*N)
- **Bearing RPM (N)- Jonathan A.**
  - N = (v*60)/(pi*D)
    - D = Diameter of bearing
    - v = velocity of bearing

6.3.5 Driving Motor Forces and Torque

- **Applied Forces (N)- Joey M**
  - F_x=cos(θ)*F
  - F_y=sin(θ)*F
  - [Desired Forces] = [F_x, F_y, 0] (Used as MATLAB matrix for the user-applied forces onto the robot to find the torque required for each motor's cable to output the necessary forces for movement)
- **Torque on the Winches (Nm)- Joey M**
  - T=F*r (Recorded in the x, y, and z directions, then each motor's total torques were summed into $T_{motor\#}$)
  - $T_{total}=T_{motor1}+T_{motor2}+T_{motor3}$

7 Final Hardware

7.1 Final Physical Design

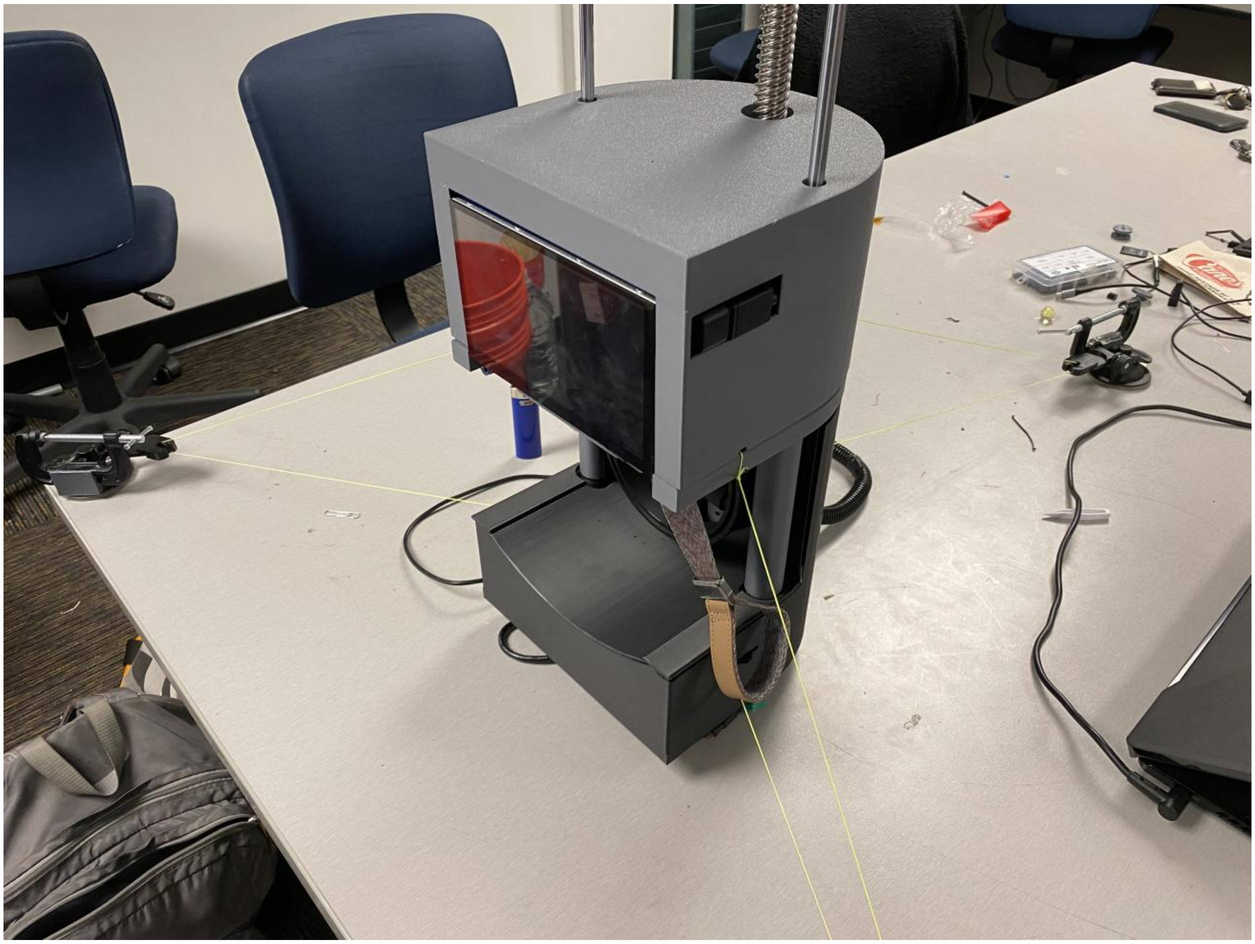


Figure 19: Flying Squirrel Physical Model

7.1.1 Top Assembly

The top assembly contains aspects of the user interface, including the touch screen and Raspberry Pi to control it. In addition, it contains the battery which powers all the Flying Squirrel's components. One other important part is the lead nut, with which the lead screw interacts and causes the assembly to lift when it rotates.

7.1.2 Bottom Assembly

This section contains the necessary movement systems for the robot. Four motor sets, including the motor itself, the encoder, and the driver, reside here. The pulleys are mounted to the three horizontal movement motors, with one end of each fishing line tied to them. These motors and other components of the design are monitored and controlled by the Teensy within this sub-assembly. It is also the attachment point for the lead screw and the two support pillars. Finally, to assist with the pulling motion of the fishing lines, the bottom assembly sits atop five roller bearings.

7.1.3 Handle

While this sub-assembly is simpler than the previous two, it does feature one of the robots' most complex and costly parts. The force sensor is the only connection between the handle and the rest of the robot, ensuring that all of the forces applied by the patient are detected and accounted for. The handle itself can rotate in the frontal plane to allow different hand placements while using the device. Also attached to the force sensor is a strap to support the patient's wrist.

7.1.4 Anchors

To allow the anchors to be secured on a variety of work surfaces, they include both a clamp and a suction cup. Changing from one attachment method to another is a simple matter of rotating the anchor. Additionally, each one features a pulley to reduce wear on the fishing line. These pulleys are set in rotating fixtures that can change angle as the robot's position changes.

Figure 20: Hybrid Anchors

8 Final Testing

8.1 Top level testing summary table

The tests that need to be performed with the Flying Squirrel are detailed below. These tests will determine whether the engineering and customer requirements are being met, and what would need to be changed moving forward.

Table 7: Top Level Testing Summary Table

Experiment	Relevant DRs	Testing Equipment Needed	Other Resources
EXP1 – Force Output Test	**ER4** – Force	-Luggage Scale (for XY motors) -Food Scale -Weights (for Z motor)	-3+ People
EXP2 – Movement Test	**CR2** – 3D Movement **CR3** – Precise and Accurate Movement **ER1** – Range of Motion **ER3** – Speed **ER5** – Sensing and Control Accuracy	-Motion capture cameras located in Raz labs along with associated software -Tape measure -Marking Stickers	-Raz Labs
EXP3 – Endurance Test	**CR5** – Long Battery Life **ER6** – 30 Minutes of use	-Completed Robot -Camera with long enough battery life to video entire run time	-Table at least 4ft x 4ft in size -Weights
EXP4 – Setup Test	**CR7** – User Friendly **ER8** – Setup Time	-Completed robot -Stopwatch	-Table at least 4ft x 4ft in size
EXP5 – Size Test	**ER2** – Size **CR4** – Relatively Compact for Storage	-Assembled bottom half of robot -Tape Measure	
EXP6 – Budget Test	**CR1** – Affordability **ER7** - Production Cost (<$1000, later removed)	-BOM	
EXP7 – Aesthetic Test	**CR6**- Aesthetically Pleasing	-Client -Completed Flying Squirrel Prototype	

8.2 Detailed Testing Plan

8.2.1 Force Output Test

8.2.1.1 Summary

- Will test force produced by the robot (ER4)
- Utilizes: luggage scale, food scale, weights
- Isolated Variables: Force and Mass
- Calculated Variables: Force = mass * acceleration

8.2.1.2 Procedure

- For xy motors, one team member must pull on the cable with the luggage scale while another holds the robot in place (with the motor pulling towards the robot), until the motor stalls
- Mass value is read from the scale and multiplied by gravitational acceleration to obtain force value
- For the z motor, weights are stacked on the stripped-down top plate to simulate the weight of the top components plus ten Newtons

- Motor is run to see if vertical motion occurs

8.2.1.3 Results

- The minimum stalling force for one of the horizontal motors is approximately 29 Newtons
- The vertical motor can lift the fully assembled top plate with an extra 10N of force applied, which is approximately 54N in total

8.2.2 Movement Test

8.2.2.1 Summary

- Tested the velocity at which the robot moves as well as how accurate and repeatable the movements are (CR2, CR3, ER1, ER3, ER5)
- Utilizers: Motion capture cameras and tracking dots
- Isolated Variables: Position and time
- Calculated Variables: Revolutions to millimeters (In code), velocity from change in position divided by change in time

8.2.2.2 Procedure

- Place tracking dots on robot so cameras can track its movement
- Place motion capture cameras surrounding the test area of the robot
- Setup robot
- Run robot and motion capture software then analyze the movements to see if the velocity and position are within specification.

8.2.2.3 Results

- The robot, when tested, was able to move about 1 m/s vertically and 2 m/s horizontally
- Velocity measured using motion capture cameras with an accuracy of less than 1mm/s

8.2.3 Endurance Test

8.2.3.1 Summary

- The robot's battery life while in use will be determined by this test (CR5, ER6)
- Utilizes: complete Flying Squirrel, video camera
- Isolated Variables: Battery Life
- Calculated Variable: None

8.2.3.2 Procedure

- We plan to run a procedure that will involve all four motors and simulate extended use by a patient
- While the robot is continuously running, it will be monitored by either team members or the video camera
- We will monitor the time to see if it can run for 30 minutes

8.2.3.3 Results

- After force testing which required the motors to exert more work than the robot will see during actual use the battery depleted less than 1%, giving us a run time of significantly greater than 30 minutes
- Following the actual test, examining battery revealed that it had depleted about 15%
- From full charge, the Flying Squirrel should be useable for around 2 hours 10 minutes before it reaches half charge
- The battery will not reach dangerous state of charge due to depletion below 20%

8.2.4 Setup Test

8.2.4.1 Summary

- This test will evaluate how long it takes to set up the robot from its most inactive state (CR7, ER8)
- Utilizes: compete Flying Squirrel, stopwatch
- Isolated Variables: Setup Time
- Calculated Variables: None

8.2.4.2 Procedure

- The robot will be reduced to its stowed position, with power off, cables retracted, and anchors detached from any work surface
- One team member must carry the Flying Squirrel to a proper work surface, pull out and attach the anchors, then power it on while another team member monitors the time elapsed

8.2.4.3 Results

- Setting the Flying Squirrel up from its stowed configuration took approximately 43 seconds

8.2.5 Size Test

8.2.5.1 Summary

- This test will evaluate the size of the robot (CR4, ER2)
- Utilizes: tape measure
- Isolated Variables: Length, Width, Height
- Calculated Variables: None

8.2.5.2 Procedure

- One team member will simply measure the length and width of the Flying Squirrel's base, then measure the height from the work surface to the tallest point (The support rods)

8.2.5.3 Results

- The length and width of the robot are both within the 8-inch limit
- The lead screw and the support rods exceed 8 inches at 19 inches, but our client has long since

retired the height limit

8.2.6 Budget Test

8.2.6.1 Summary

- This test will evaluate the cost of robot (CR1, ER7)
- Utilizes: BOM
- Isolated Variables: Price
- Calculated Variables: None

8.2.6.2 Procedure

- Total cost of BOM

8.2.6.3 Results

- Total budget spent: $2357.09
- Total budget remaining: $1392.91

8.2.7 Aesthetic Test

8.2.7.1 Summary

- This test will evaluate the size of the robot (CR6)
- Utilizers: Client
- Isolated Variables: Client Approval
- Calculated Variables: None

8.2.7.2 Procedure

- Observed by client

8.2.7.3 Results

- Client approved

9 Looking Forward

While we are pleased with the result of this project, there are always improvements that can be made. The biggest would likely be to replace the simple movement routines with an actual algorithm for complex 3d movement and position detection. Additionally, while the device can detect forces with fair accuracy, its programming would need to be updated to generate specific forces. These would both need to be tested to ensure that they meet the precision requirements of the project. Some smaller updates include the UI, which can be tuned to be more user-friendly. The plastic shell might be modified to be easier to assemble/disassemble; ventilation for the electronics could be improved, and wiring in the top assembly can also be simplified. If possible, further testing should be done with actual stroke patients to receive feedback on the design and programmed behavior.

10 CONCLUSIONS

As this report shows, we have largely accomplished the goals set by our client and the purpose of this project. With Dr. Razavian's guidance, we were able to generate possible designs, evaluate those designs based on the project parameters, settle on a feasible design, then modify and optimize our model based on new data. This allowed us to build a compact, affordable arm therapy device for recovering stroke patients. The Flying Squirrel can move in a 2'x1'x1' work envelope, achieve speeds up to 1m/s in any direction, and generate up to 10N of force. In fact, it meets all requirements except a few of the detection and output precision requirements. Unfortunately, these parameters required the robot to be fully programmed, which we were unable to do within the project's time constraints. However, since all the necessary components are present, in the future this device can quickly be programmed by someone with proper knowledge. With some testing and tweaks to the code, the Flying Squirrel will soon be able to fulfill its purpose and help patients more efficiently than any other device.

11 REFERENCES

[1] “Armeo®Spring Pro.” Hocoma. https://www.hocoma.com/us/solutions/armeo-spring-pro/ (accessed Mar. 9, 2025).

[2] “ArmMotus™ M2 Pro.” Fourier Rehab. Accessed online at https://www.fftai.com/uploads/upload/files/20240930/337b9b48d58a4f1a5ab114a212676ac1.pdf (accessed Mar. 9, 2025).

[3] “Project Description.” Hamster Capstone. https://www.ceias.nau.edu/capstone/projects/ME/2024/Sp24toF24_Hamster/index.html (accessed Mar. 9, 2025).

[4] R. Colombo and V. Sanguineti, Rehabilitation Robotics: Technology and Application. London: Academic Press, 2018.

[5] J. B. Webster and D. Murphy, Atlas of Orthoses and Assistive Devices. Philadelphia, PA: Elsevier, 2019.

[6] Y. Li, A. Song, J. Lai, H. Li, and K. Shi, “Wrench feasibility workspace analysis and adaptive rotation algorithm of cable-driven upper limb rehabilitation robot,” Proceedings of the 2023 9th International Conference on Robotics and Artificial Intelligence, pp. 32–37, Nov. 2023. doi:10.1145/3637843.3637844

[7] J. Lamaury and M. Gouttefarde, “Control of a large redundantly actuated cable-suspended parallel robot,” Login - CAS – central authentication service, https://doi-org.libproxy.nau.edu/10.1109/ICRA.2013.6631240 (accessed May 9, 2025)

.

[8] D. Surdilovic and R. Bernhardt, “String-man: A new wire robot for gait rehabilitation,” IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA ’04. 2004, Apr. 2004. doi:10.1109/robot.2004.1308122

[9] E. Wong, “Garrett Brown’s skycam history,” Futurism, https://vocal.media/futurism/garrett-brown-s-skycam-history (accessed Feb. 9, 2025).

[10] N. Chandler, “How skycam works,” HowStuffWorks, https://electronics.howstuffworks.com/cameras-photography/digital/skycam.htm (accessed Feb. 9, 2025).

[11] “Rehabilitation robot,” Rehabilitation Robot - an overview | ScienceDirect Topics,

https://www.sciencedirect.com/topics/nursing-and-health-professions/rehabilitation-robot (accessed Feb. 9, 2025).

[12] *BUDYNAS, Shigley's Mechanical Engineering Design, 11th Edition, SI Units. (NO US Rights). MCGRAW-HILL EDUCATION (AS, 2020.*

[13] W. Zhang, X. Zhang, J. Zhang, and W. Zhao, "Review on Comparative Analysis of Ball Screw & Lead Screw," *International Research Journal of Engineering and Technology (IRJET)*, vol. 6, no. 6, pp. 30–44, Jun. 2019. doi:10.1016/j.precisioneng.2019.03.003

[14] R. Grimmett, Arduino Robotic Projects: Build Awesome and Complex Robots with the Power of Arduino. Birmingham, England: Packt Publishing, 2014.

[15] T. Cox, Raspberry Pi 3 Cookbook for Python Programmers: Unleash the Potential of Raspberry Pi 3 with over 100 Recipes. Birmingham, UK: Packt Publishing, 2018.

[16] M. Miyasaka et al., "Modeling cable-driven robot with hysteresis and cable–pulley network friction," IEEE/ASME Transactions on Mechatronics, vol. 25, no. 2, pp. 1095–1104, Apr. 2020. doi:10.1109/tmech.2020.2973428

[17] S. Syukriyadin, S. Syahrizal, G. Mansur, and H. P. Ramadhan, "Permanent magnet DC motor control by using Arduino and Motor Drive Module BTS7960," IOP Conference Series: Materials Science and Engineering, vol. 352, p. 012023, May 2018. doi:10.1088/1757-899x/352/1/012023

[18] U. A. Hofmann, T. Butzer, O. Lambercy, and R. Gassert, "Design and evaluation of a Bowden-cable-based remote actuation system for wearable robotics," IEEE Robotics and Automation Letters, vol. 3, no. 3, pp. 2101–2108, Jul. 2018. doi:10.1109/lra.2018.2809625

[19] M. S. Ibrahim, A. S. Kaittan, A. N. Abdullah, and M. H. Ali, "Automatic Speed Controller of a DC motor using Arduino and variable frequency drive techniques," *E3S Web of Conferences*, vol. 542, p. 02003, 2024. doi:10.1051/e3sconf/202454202003

[20] M. Sai Prasad Reddy *et al.*, "Speed control of BLDC motor using PWM and Arduino Uno," *E3S Web of Conferences*, vol. 619, p. 02007, 2025. doi:10.1051/e3sconf/202561902007

[21] W. H. Chang and Y.-H. Kim, "Robot-assisted therapy in stroke rehabilitation," Journal of stroke, https://pmc.ncbi.nlm.nih.gov/articles/PMC3859002/ (accessed Feb. 8, 2025).

[22] M. Wu et al., “A novel cable-driven robotic training improves locomotor function in individuals post-stroke,” Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, https://pmc.ncbi.nlm.nih.gov/articles/PMC4006736/ (accessed Feb. 8, 2025).

[23] L. Pounder, “How to use Raspberry Pi and Arduino together,” Tom’s Hardware, https://www.tomshardware.com/how-to/use-raspberry-pi-with-arduino (accessed Feb. 8, 2025).

[24] A. G. Olabi, Encyclopedia of Smart Materials. Amsterdam: Elsevier, 2022.

[25] E. K. Stokes, “Chapter 5 - Robotics and rehabilitation: the role of robot-mediated therapy post stroke,” in Enabling Technologies: Body Image and Body Function, Birmingham, UK: Packt Publishing, pp. 77–96

[26] R. Loureiro, F. Amirabdollahian, M. Topping, B. Driessen, and W. Harwin, Autonomous Robots, vol. 15, no. 1, pp. 35–51, 2003, doi: https://doi.org/10.1023/a:1024436732030.

[27] K. Lin, Y. Li, J. Sun, D. Zhou, and Q. Zhang, “Multi-sensor fusion for body sensor network in medical human–robot interaction scenario,” Information Fusion, vol. 57, pp. 15–26, May 2020, doi: https://doi.org/10.1016/j.inffus.2019.11.001.

[28] L. Fan, A. Song, and H. Zhang, “Development of an Integrated Haptic Sensor System for Multimodal Human–Computer Interaction Using Ultrasonic Array and Cable Robot,” IEEE Sensors Journal, vol. 22, no. 5, pp. 4634–4643, Mar. 2022, doi: https://doi.org/10.1109/jsen.2022.3144888.

[29] E. Gordon, X. Meng, T. Bhattacharjee, M. Barnes, and S. Srinivasa, “Adaptive Robot-Assisted Feeding: An Online Learning Framework for Acquiring Previously Unseen Food Items.” Accessed: Feb. 06, 2025. [Online]. Available: https://personalrobotics.cs.washington.edu/publications/gordon2020adaptive.pdf

[30] D. F. N. Gordon, A. Christou, T. Stouraitis, M. Gienger, and S. Vijayakumar, “Adaptive assistive robotics: a framework for triadic collaboration between humans and robots,” Royal Society Open Science, vol. 10, no. 6, Jun. 2023, doi: https://doi.org/10.1098/rsos.221617.

[31] J. Sohn, G.-W. Kim, and S.-B. Choi, “A State-of-the-Art Review on Robots and Medical Devices Using Smart Fluids and Shape Memory Alloys,” Applied Sciences, vol. 8, no. 10, p. 1928, Oct. 2018, doi: https://doi.org/10.3390/app8101928.

[32] X. Han, L. Zhang, and C. Zhou, “Robotic arm force sensing interaction control,” pp. 481–485, Jul. 2012, doi: https://doi.org/10.1109/iciea.2012.6360776.

[33] V. Grosu, S. Grosu, B. Vanderborght, D. Lefeber, and C. Rodriguez-Guerrero, “Multi-Axis Force Sensor for Human–Robot Interaction Sensing in a Rehabilitation Robotic Device,” Sensors, vol. 17, no. 6, p. 1294, Jun. 2017, doi: https://doi.org/10.3390/s17061294.

[34] D. P. Murphy, "Robotics in Rehabilitation Medicine: Prosthetics, Exoskeletons, All Else in Rehabilitation Medicine," in Robotics in Physical Medicine and Rehabilitation, First edition. Philadelphia, PA: Elsevier, 2025.

[35] J. Segil, "Sensors and Transducers," in Handbook of biomechatronics. London, United Kingdom: Academic Press, an imprint of Elsevier, 2019.

[36] Y. Xu, A. V. Terekhov, M. L. Latash, and V. M. Zatsiorsky, “Forces and moments generated by the human arm: variability and control,” Experimental brain research, vol. 223, no. 2, pp. 159–175, 2012, doi: 10.1007/s00221-012-3235-0.

[37] N. Lodha, S. K. Naik, S. A. Coombes, and J. H. Cauraugh, “Force control and degree of motor impairments in chronic stroke,” Clinical neurophysiology, vol. 121, no. 11, pp. 1952–1961, 2010, doi: 10.1016/j.clinph.2010.04.005.

[38] C. M. Kanzler et al., “A low-dimensional representation of arm movements and hand grip forces in post-stroke individuals,” Scientific reports, vol. 12, no. 1, pp. 7601–7601, 2022, doi: 10.1038/s41598-022-11806-4.

[39] D. Matos. "Human Body Mass Distribution." ResearchGate. https://www.researchgate.net/figure/Human-body-mass-distribution_tbl2_303379664 (accessed February 9, 2025).

[40] I. Patsiaouras. "Understanding Force Sensors: How They Work and Measure Force." BOTA Systems. https://www.botasys.com/post/force-sensors (accessed February 9, 2025).

[41] A. Armenta. "Accurate Tracking: A Look at Position and Distance Sensors." Control.com. https://control.com/technical-articles/accurate-tracking-a-look-at-position-and-distance-sensors/ (accessed February 9, 2025).

[42] “Motor encoders: What is a motor encoder? How do motor encoders work?” Encoder Products Company. https://www.encoder.com/motor-encoders (Accessed 4/18/2025)

[43] “Lead Screws 101” Haydon Kerk Pittman. https://www.haydonkerkpittman.com/learningzone/whitepapers/lead-screws-101. (Accessed 4/18/2025).

[44] R. Grimmett, Raspberry Pi Robotic Projects. Packt Publishing Ltd, 2016.

[45] D. Tavasalkar, Hands-on robotics programming with C++ : leverage raspberry pi 3 and c++ libraries to build intelligent robotics applications. Birmingham, UK: Packt Publishing Ltd, 2019.

[46] “ToF 3D Vision Algorithms in C++ for Robotic Applications - ProQuest,” Proquest.com, 2022. https://www.proquest.com/docview/2696854523?pq-origsite=primo&sourcetype=Dissertations%20&%20Theses (accessed Feb. 07, 2025).

[47] C. P. Kumar and Salumari Madhu, “Gesture Control Robot with Arduino,” IOP Conference Series Materials Science and Engineering, vol. 455, pp. 012106–012106, Dec. 2018, doi: https://doi.org/10.1088/1757-899x/455/1/012106.

[48] I. Dinulescu, D. Popescu, M. Nitulescu, and A. Predescu, “Path Following System for Cooperative Mobile Robots,” Solid State Phenomena, vol. 166–167, pp. 161–166, Sep. 2010, doi: https://doi.org/10.4028/www.scientific.net/ssp.166-167.161.

[49] T. Bruckmann, L. Mikelsons, T. Brandt, M. Hiller, and D. Schramm, ‘Wire Robots Part I: Kinematics, Analysis & Design’, Parallel Manipulators, New Developments. I-Tech Education and Publishing, Apr. 01, 2008. doi: 10.5772/5365. https://www.intechopen.com/chapters/763

[50] M. W. Spong and M Vidyasagar, Robot dynamics and control. New York: Wiley, 2004.

[51] A. Iscen, A. Agogino, A. Agogino@nasa, V. Gov, Sunspiral, and K. Tumer, “Controlling Tensegrity Robots through Evolution,” 2013. Accessed: Feb. 10, 2025. [Online]. Available: https://ntrs.nasa.gov/api/citations/20160000329/downloads/20160000329.pdf

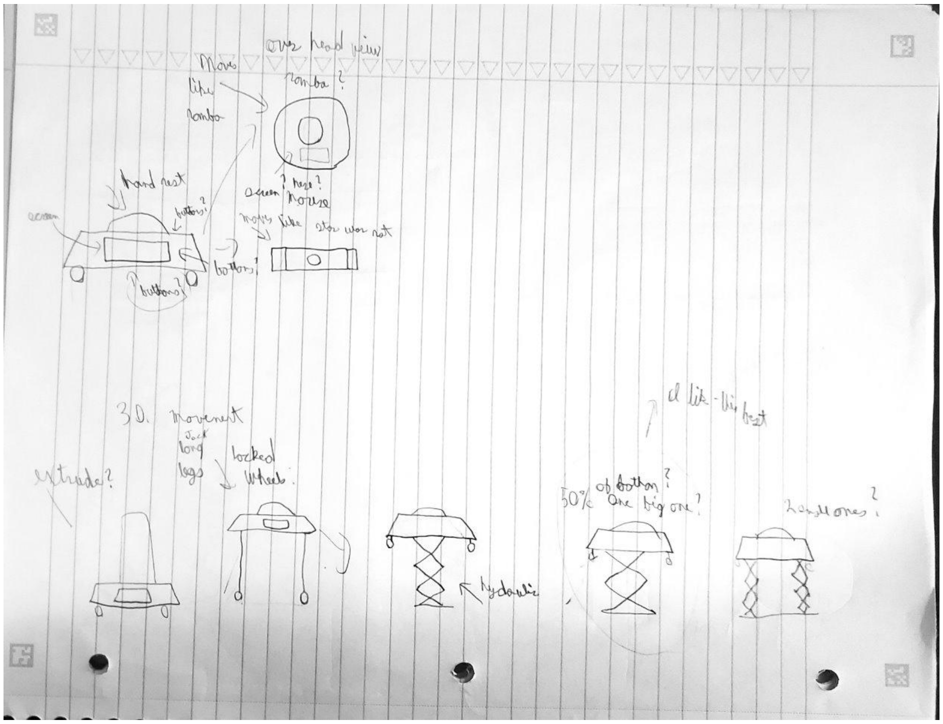
[52] S. M. Staroletov, “Arduino Meets Raspberry Pi in Automation: An Implementation of State-Based Distributed Control with Round-Robin Scheduling,” *2022 International Russian Automation Conference*

(RusAutoCon), pp. 109–114, Sep. 2024, doi: https://doi.org/10.1109/rusautocon61949.2024.10694294.

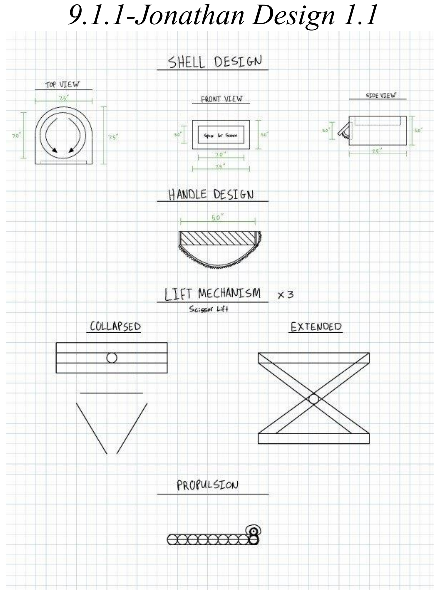
[53]"Raspberry Pi Arduino Serial Communication - Everything You Need To Know," *The Robotics Back-End*, Nov. 11, 2019. https://roboticsbackend.com/raspberry-pi-arduino-serial-communication/

12 APPENDICES

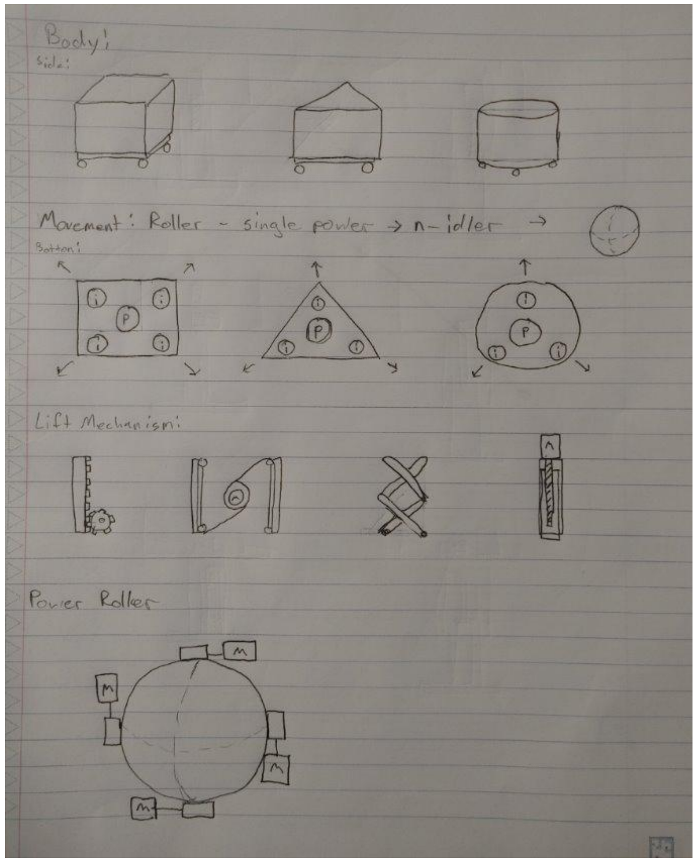
12.1 Appendix A: 1st Concept Generation



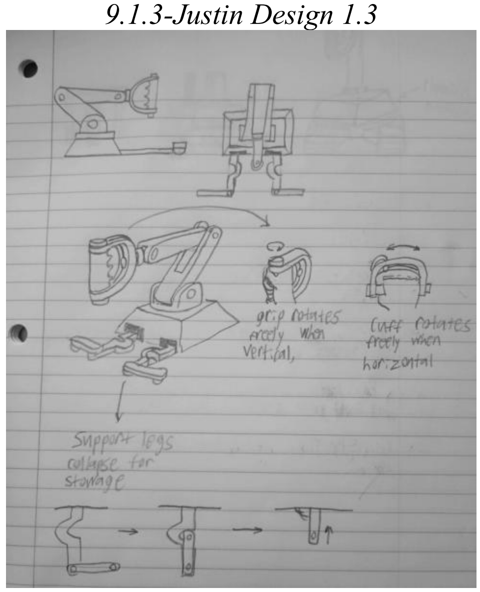
9.1.1-Jonathan Design 1.1



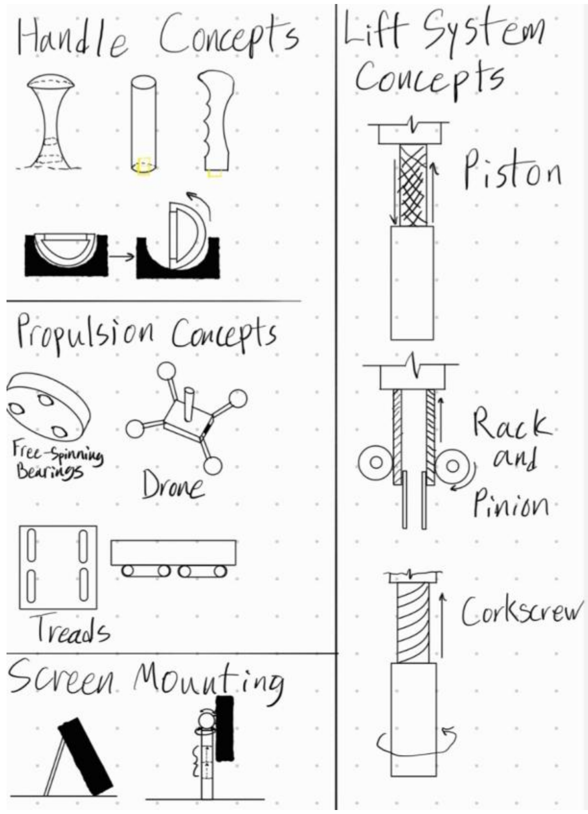
9.1.2-Ryan Design 1.2



9.1.3-Justin Design 1.3

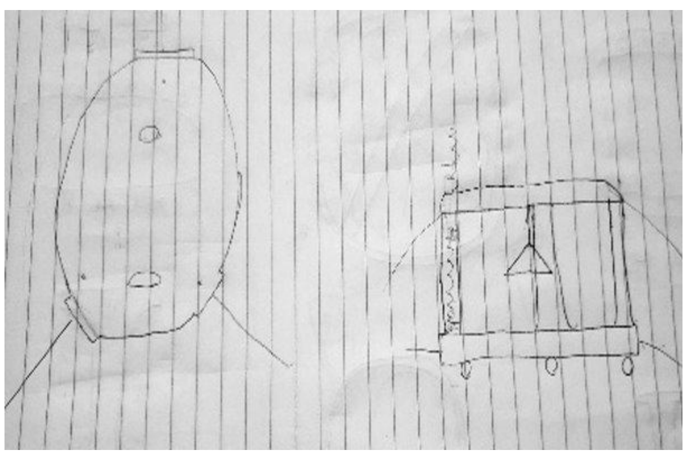


9.1.4-Owen Design 1.4

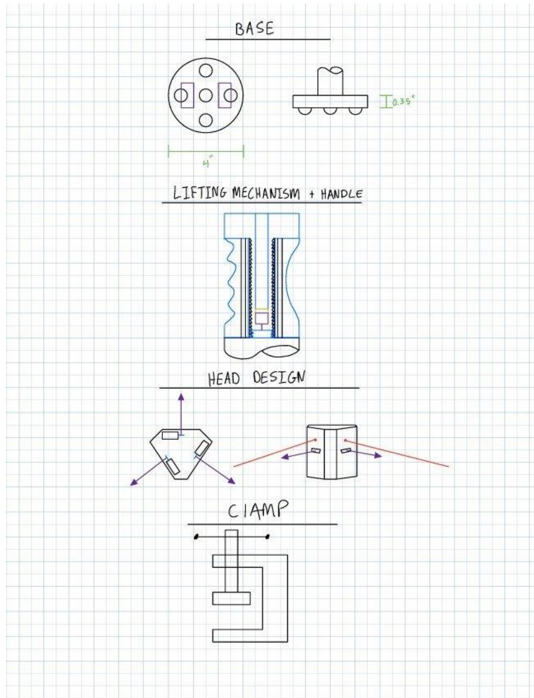


9.1.5-Joey Design 1.5

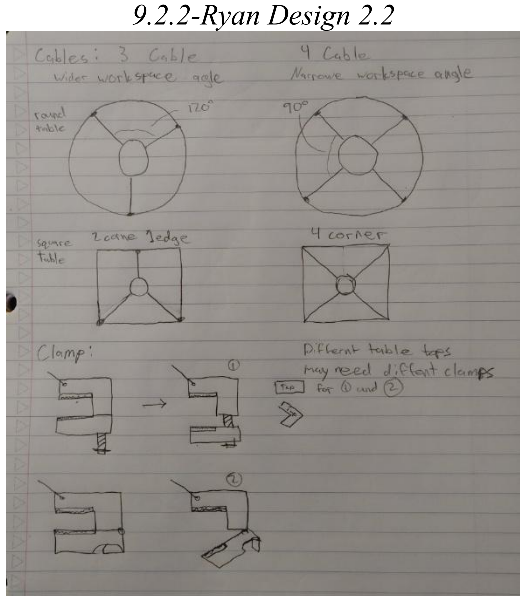
12.2 Appendix B: 2^{nd} Concept Generation



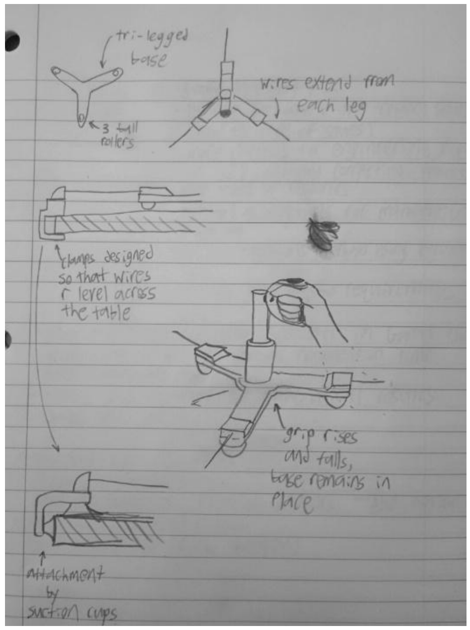
9.2.1 Jonathan Design 2.1



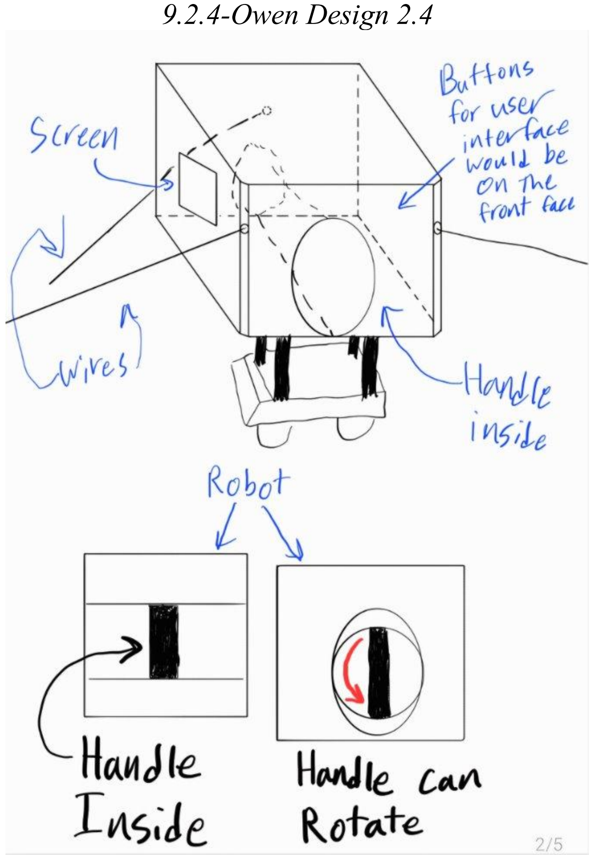
9.2.2-Ryan Design 2.2



9.2.3-Justin Design 2.3



9.2.4-Owen Design 2.4



9.2.5-Joey Design 2.5