Flying Squirrel

Second Design Report

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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 four team members listed above, those being John Avila-Capado, 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 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.

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1 BACKGROUND

In section 1.1 we will go over the project itself, what its main purpose is, and the various reasons for its existence while giving some reasons other options aren't adequate. Also, in this section we talk about our project's current budget and what we are looking at in terms of fundraising. In the next section, section 1.2, we go over several different deliverables that our client would like us to achieve by the end of our capstone. Lastly in section 1.3 we go over what success looks like for us and the Flying Squirrel using different success metrics to see if our end product is indeed successful.

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 a spiritual successor of the Hamster, a capstone project from the past year. 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; the current fundraising target is $300 which would put our budget over $4000 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 below $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 is capable of moving in the direction of X, Y and Z by the end of our 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 the actual 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 laid out 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. Also, in this section we will go over the engineering requirements associated best by meeting not only our clients' wants but the needs of the consumer 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)

Below is a list of customer requirements and the reasons why they're important for the customer of the flying squirrel robot.

1. **Affordability:** The main obstacle right now to physical therapy is either the patient doesn't have the time to travel to physical therapy or the means or money 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 the 3D the Flying Squirrel can access a whole host more exercises than the Hamster ever could.
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 home it has to be a relatively small and compact size so that it can be stored when not in use.
5. **Cosmetics:** If the robot is hideous people would be put off from buying it.
6. **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.

1. **Range of motion**: Moving the hand in 3D space up to 1ft above the surface of a table.
2. **Size**: Fit within a box of 8"x8"x8".
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**: Position sensing accuracy/control: <0.1mm. Force sensing accuracy/control: <0.1N.
6. **Production Cost**: The total "production" cost (bill of materials + manufacturing/labor cost) must

be <$1000. (Though this has changed to be more flexible as we have done more research, a 3-axis force sensor would cost more than half the initial design cost.)

2.3 *House of Quality (HoQ)*

		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

		Technical Requirements							Competitive Analysis								
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*				
Affordability	5	9			3	3			AB				C	**Relationships:**			
3rd Dimension Movement	4	3	1	1		1			C				AB	**9**	**3**	**1**	
Precision and Accuracy	3	3	9	9	9						C		AB	Strong	Moderate	Weak	None
Size	4	3	1			9			B		A		C	**Legend:**			
Cosmetics	1	1				1				C	B		A	A	Armeo SpringPro		
User Friendliness	5	3				9				A		B	C	B	ArmMotus M2 Pro		
Technical Requirement Units		Dollars ($)	Meters per Second (m/s)	Newtons (N)	Millimeters (mm)	Inches (in)								C	The Hamster		
Technical Requirement Targets		1000	1	10	0.1	8x8x8											
Absolute Technical Importance		31	42	35	93	100											
Relative Technical Importance		5	3	4	2	1											

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 from 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 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.**
  - $M = MP_{hm}g(L(1\text{-}0.5P_{hl}))+ MP_{fm}g(L(0.5P_{fl}+P_{al}))+ MP_{am}g(L(0.5P_{al}))$
- **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

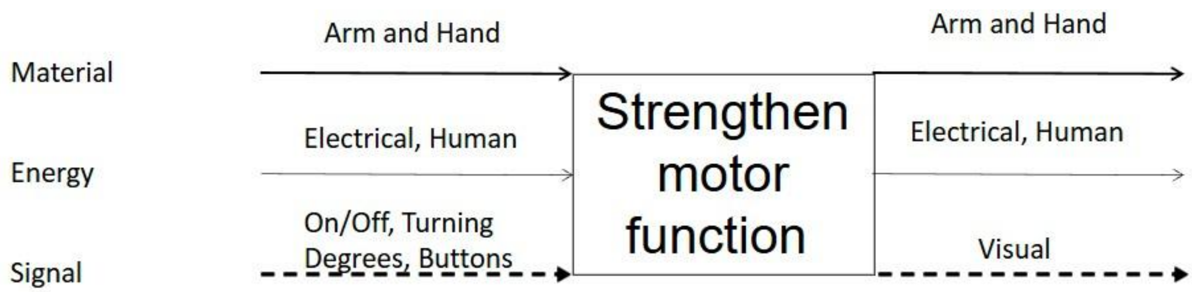


Figure 4: Black Box Diagram

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

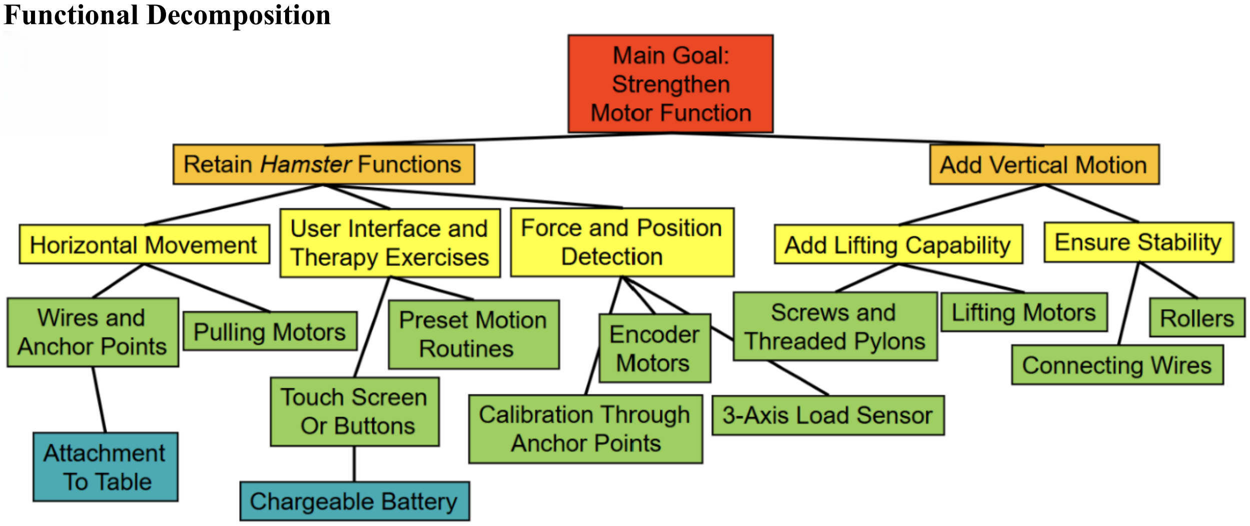


Figure 5: Functional Decomposition

The main function is expanded upon in figure 5 pictured above. 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 was important to identifying 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 generation 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

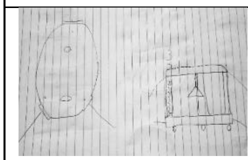
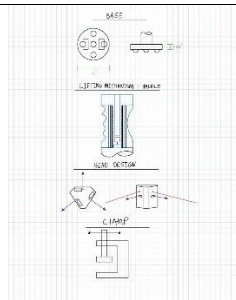
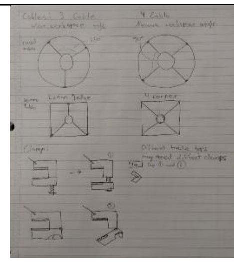
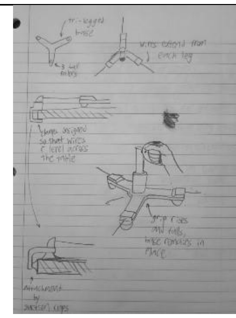
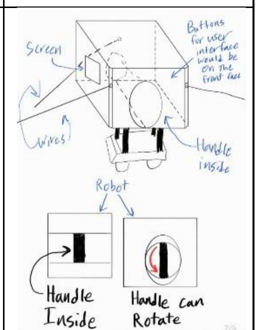
Design 1-Jonathan	**Design 2-Ryan**	**Design 3-Justin**	**Design 4-Owen**	**Design 5-Joey**
				
Pros: Robust lifting system, flexible handle, stable design	**Pros:** Ergonomic, stable clamp design	**Pros:** Different wire/anchor configurations, adaptable clamps	**Pros:** Adjustable handle, different 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

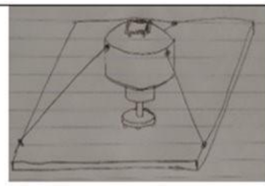
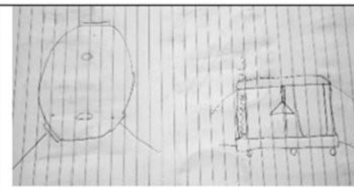
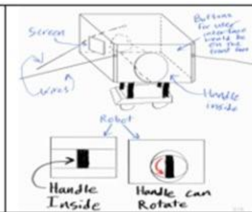
Criteria			
Design	1	2	3
Production cost	+ Smaller device	S	Datum
Speed of the Robot	-It has a smaller base to work with	+The base and double wire allow for fast accurate movement	Datum
Device Size	+ It has a small frame	+ it is more compact than the Datum	Datum
Position Tracking	S	S	Datum
Force	-Smaller 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 is the current CAD model we have, figure 6. This model is based on design 2 from the Pugh Chart. Dr. Razavian had 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.

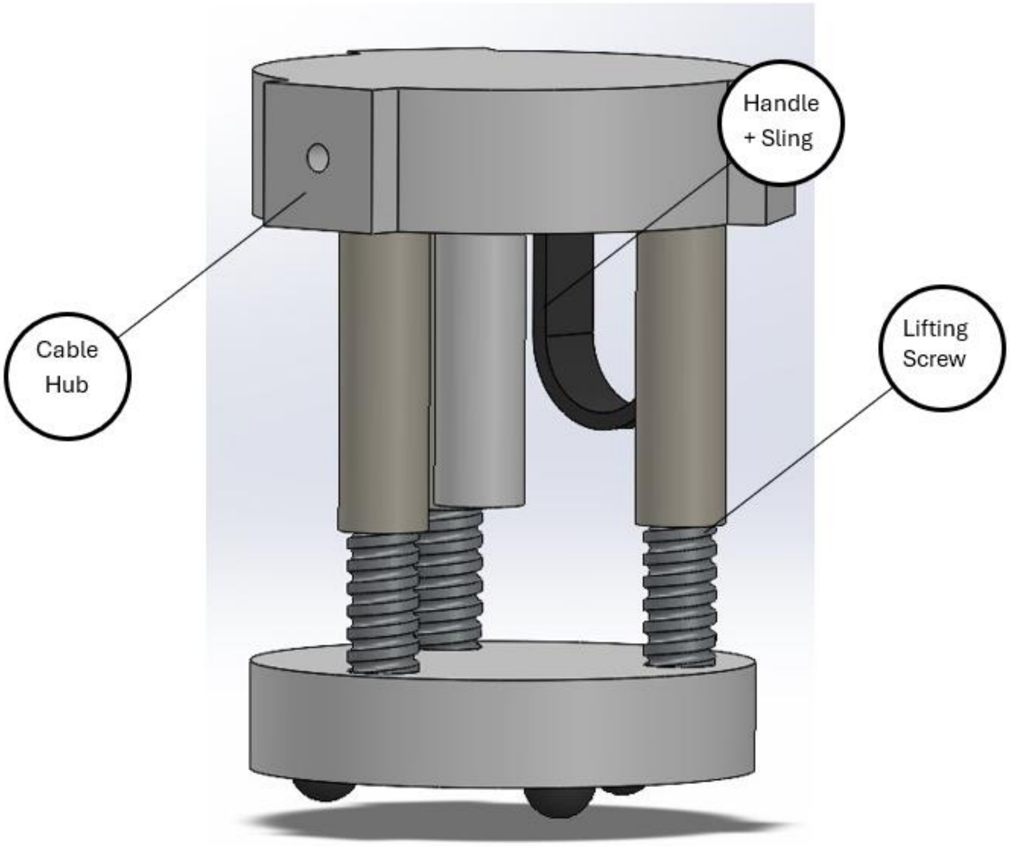


Figure 6: CAD Model

Hybrid Clamp Design

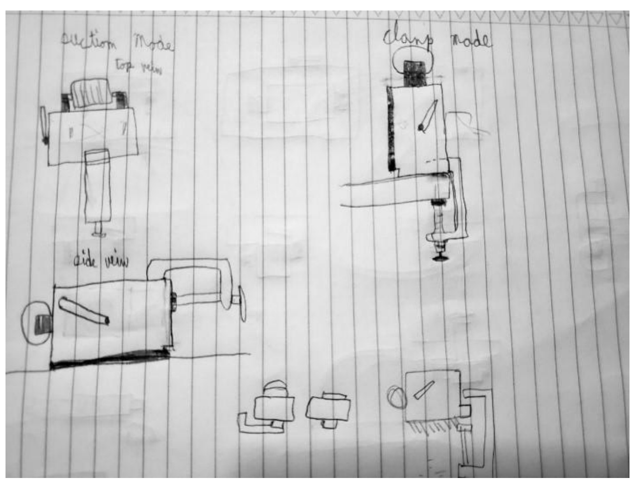
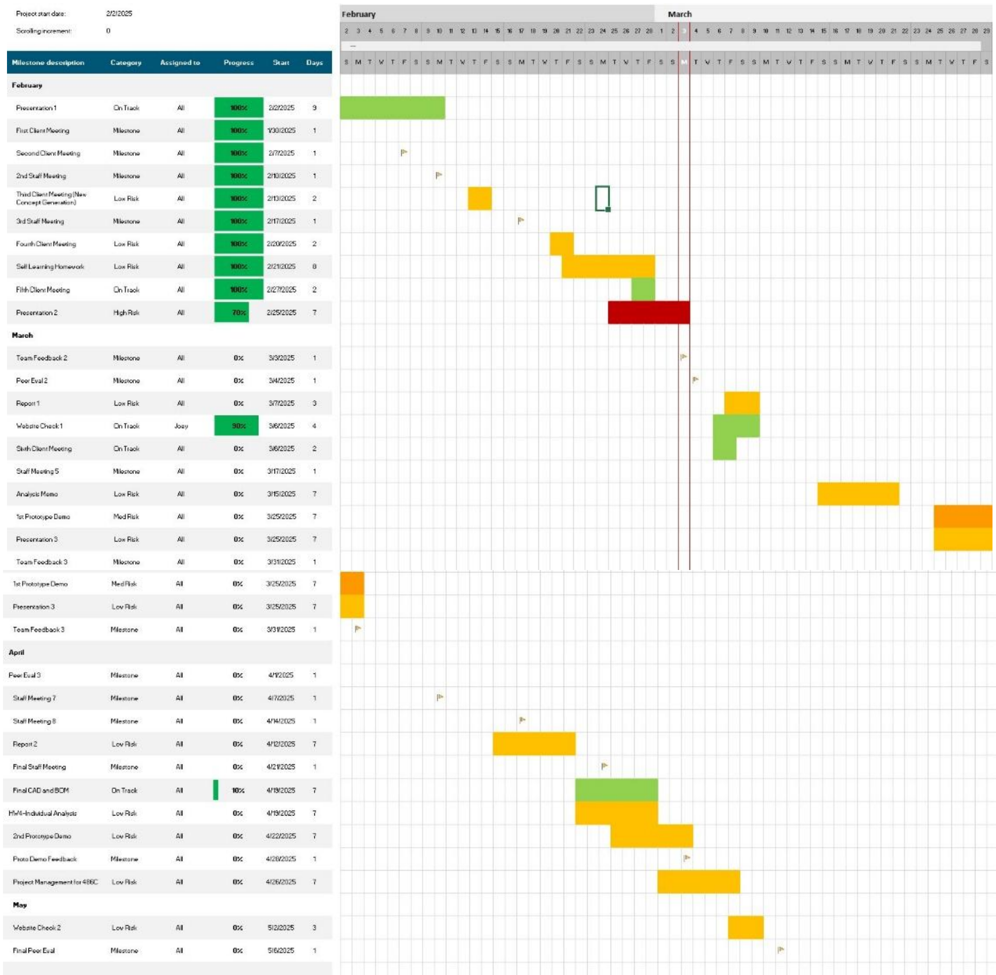


Figure 7: Hybrid Clamp

The clamp, shown in Figure 7, 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.

5 Schedule and Budget

5.1 *Schedule*



Project start date: 2/2/2025

Scrolling increment: 0

Milestone description	Category	Assigned to	Progress	Start	Days
February					
Presentation 1	On Track	All	100%	2/2/2025	9
First Client Meeting	Milestone	All	100%	1/30/2025	1
Second Client Meeting	Milestone	All	100%	2/7/2025	1
2nd Staff Meeting	Milestone	All	100%	2/10/2025	1
Third Client Meeting (New Concept Generation)	Low Risk	All	100%	2/13/2025	2
3rd Staff Meeting	Milestone	All	100%	2/17/2025	1
Fourth Client Meeting	Low Risk	All	100%	2/20/2025	2
Self Learning Homework	Low Risk	All	100%	2/21/2025	8
Fifth Client Meeting	On Track	All	100%	2/27/2025	2
Presentation 2	High Risk	All	70%	2/25/2025	7
March					
Team Feedback 2	Milestone	All	0%	3/3/2025	1
Peer Eval 2	Milestone	All	0%	3/4/2025	1
Report 1	Low Risk	All	0%	3/7/2025	3
Website Check 1	On Track	Joey	90%	3/6/2025	4
Sixth Client Meeting	On Track	All	0%	3/6/2025	2
Staff Meeting 5	Milestone	All	0%	3/17/2025	1
Analysis Memo	Low Risk	All	0%	3/15/2025	7
1st Prototype Demo	Med Risk	All	0%	3/25/2025	7
Presentation 3	Low Risk	All	0%	3/25/2025	7
Team Feedback 3	Milestone	All	0%	3/31/2025	1
1st Prototype Demo	Med Risk	All	0%	3/25/2025	7
Presentation 3	Low Risk	All	0%	3/25/2025	7
Team Feedback 3	Milestone	All	0%	3/31/2025	1
April					
Peer Eval 3	Milestone	All	0%	4/1/2025	1
Staff Meeting 7	Milestone	All	0%	4/7/2025	1
Staff Meeting 8	Milestone	All	0%	4/14/2025	1
Report 2	Low Risk	All	0%	4/12/2025	7
Final Staff Meeting	Milestone	All	0%	4/21/2025	1
Final CAD and BOM	On Track	All	10%	4/19/2025	7
HW4-Individual Analysis	Low Risk	All	0%	4/19/2025	7
2nd Prototype Demo	Low Risk	All	0%	4/22/2025	7
Proto Demo Feedback	Milestone	All	0%	4/28/2025	1
Project Management for 486C	Low Risk	All	0%	4/26/2025	7
May					
Website Check 2	Low Risk	All	0%	5/2/2025	3
Final Peer Eval	Milestone	All	0%	5/6/2025	1

Figure 8: Gantt chart of the current semester

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 would 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.

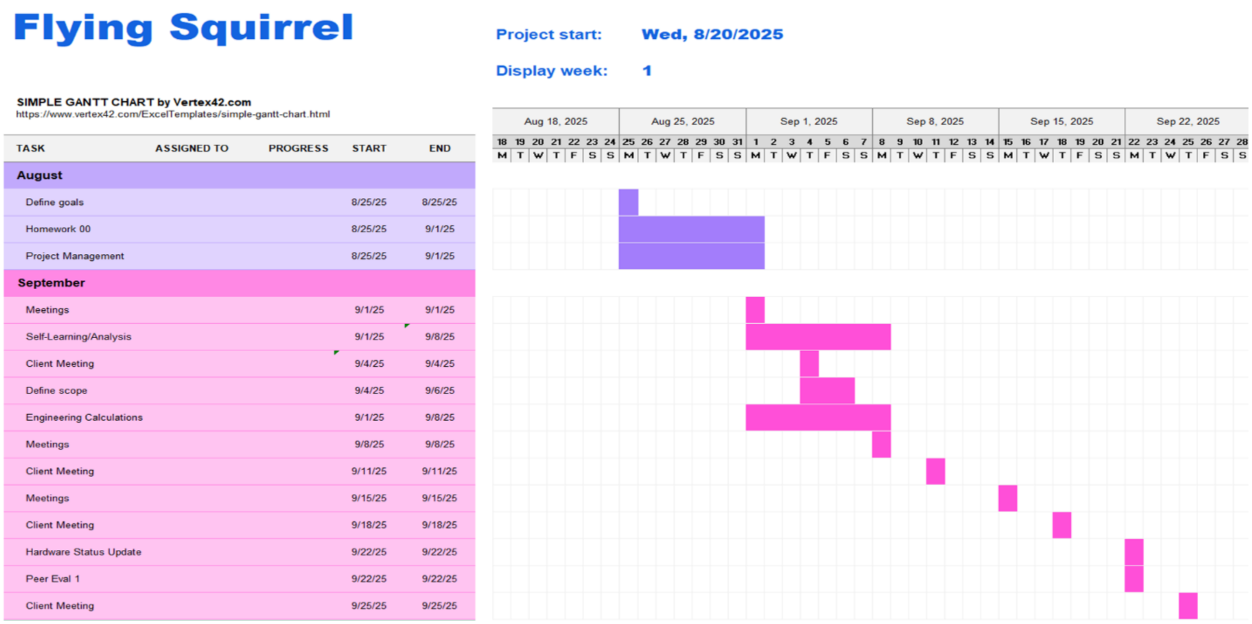


Figure 9: Gantt chart of the next semester

The next semester will also have class deliverables and individual homework assignments, but the bulk of our time will probably be spent in assembling our complete prototype and testing its capabilities. All the while we will be updating Dr. Razavian on the system's performance and incorporating his feedback.

5.2 Budget

anticipated expenses	\$531
actual expenses to date	\$370
project's budget including income	\$3750
fundraising	\$120
resulting balance	\$2969

Table 5: Budget

As things currently stand, we will come in under budget after we complete our first prototype allowing us to have a bit of wiggle room if we need to build a second prototype we can before we need to build a final design. And with half our fundraising done we look to have the last half complete near the beginning of next semester.

5.3 Bill of Materials (BoM)

Item	***Quantity***	***Cost Per Unit (\$)***	***Final Amounts (\$)***
3-axis force sensor	***1***	*290*	*290*
Optical encoder motors	*4*	*75*	*300*

LiPo Battery Pack	*1*	*70*	*70*
Braided Fishing Line	*1*	*30*	*30*
Circuits and wires	*1 Sold as a set*	*45*	*45*
Misc. Electronics and Screws	*1*	*80*	*80*
Stainless Steel Ball Bearings	*1 sold in large set amounts*	*6*	*6*
Suction Mechanism	*3*	*15*	*45*
C clamps	*3*	*5*	*15*
PLA(1kg)	*1*	*20*	*20*
		Total=	*901*

Table 6: Bill of Materials

This bill of materials is going to be for our first prototype and will set the framework for our final design will most likely cost. Most of the parts for this robot we are purchasing 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 have a short lead ranging from around a couple days to a week at most. The only item with a lead time longer than a month would be the force sensor but considering the alternative is almost $400 price differential for the next best option.

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	Occurance (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 (Arduino)	Electrical Shorting	Causes robot to become inoperable	9	Assembly error	1	Run test program	1	9	None	
5 Microcomputer (Raspberry pi)	Electrical Shorting	Causes robot to become inoperable	10	Assembly error	1	Run test program	1	10	None	
6 Lifting Motor	High-cycle Fatigue	Reduction in performance of z-axis movement	7	Over voltage/current	2	Test with RPM, force, and voltmeter	1	14	None	
7 Drive Belt	Surface Fatigue Wear	Loss of z-axis movement	8	Poor maintenance	4	Visual inspection	1	32	Purchase high quality parts	

Figure 10: Bottom Plate FMEA

Flying Squirrel		Development Team: Jonathan Avila, Ryan Donnellan, Justin Joy, Owen Kehl, Joey Mathews				Page No. 2 of 3			
Center Structure						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	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
8 Lifting Strut	Surface Fatigue Wear	Loss of lifting performance	5	Overstressing	1	Ensure nut slides smoothly over lift screw	1	5	Purchase quality parts
9 Handle Rotation Mechanism	Surface Fatigue Wear	Increase handle rotation resistance	5	Overstressing	2	Rotate handle thorough many cycles to ensure smooth movement	1	10	Use high in-fill for plastic
10 Handle	Impact Fracture	Loss of handle	8	Impact loading	2	Visual Inspection	2	32	Use high in-fill for plastic
11 Capture Strut	Surface Fatigue Wear	Loss of lifting performance	5	Overstressing	3	Ensure nut slides smoothly over lift screw	1	15	Use high in-fill for plastic

Figure 11: 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	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
12 Top Shell	Brittle Fracture	Appearance	3	Impact loading	3	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 Motor Controller	Electrical Shorting	Reduction in performance of all axis movement	7	Over voltage/current	2	Run test program	1	14	Purchase high quality parts
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 12: Top Plate FMEA

Pictured above in figures 10-12 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:

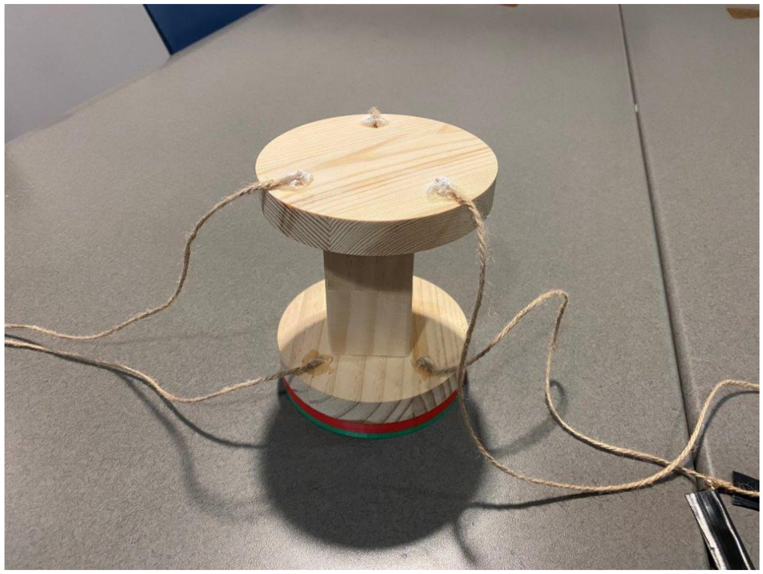


Figure 13: Sub-prototype 1

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:

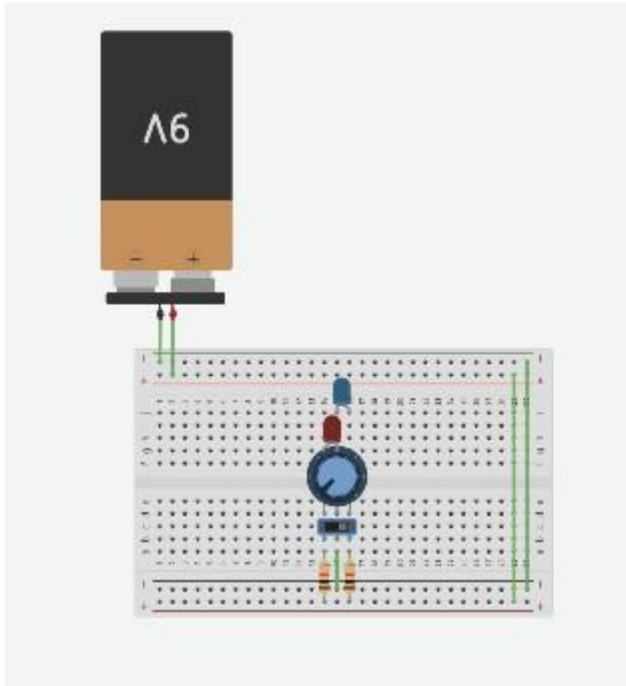


Figure 14: Sub-prototype 2

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 15: 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.**
    - o 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**
    - $F_x=\cos(\theta)*F$
    - $F_y=\sin(\theta)*F$
    - [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 $T_{motor\#}$)
    - $T_{total}=T_{motor1}+T_{motor2}+T_{motor3}$

6.4 Future Testing Potential

6.4.1 Planned Testing Procedures

Once the Flying Squirrel reaches the prototyping phase, multiple tests will be conducted to attempt to meet all the requirements. The first will be testing how long it takes to set up before use. We will conduct this test by finding volunteers who will be given instructions in place of an instruction manual that would come with the final product if it were to be produced, and then the volunteer will be timed as they set it up. Another test that will be conducted is an endurance test. For these tests, the robot will follow a continuous program that will have it be powered on and moving until the batteries die. More tests that will be conducted will also include anchor tests, which have already started. These tests will utilize potential anchor products that could be viable on several tabletop types, ensuring that the anchors will hold on virtually any surface. Accuracy tests will be conducted, using dots on a table, and run a program within the robot to test for accurate position tracking. Motor backlash will also be tested during these runs. Finally, the last tests that are planned will be speed and force tests. These tests will involve the team using the robot by running different movement programs, and will test the robot's speed, both with the cable movement and the lifting movement. The force aspect of those tests will include utilizing a handheld scale, such as a luggage scale, and will test if each cable and their motors can apply the required forces.

6.4.2 Success Criteria

The team plans on measuring the success of these tests by comparing the results with the defined customer and engineering requirements. For the setup tests, the goal is for the volunteers to be able to set up the robot for use in a minute or less, after receiving the necessary instructions. The endurance tests will be considered a success if the robot is able to run for a minimum of 30 consecutive minutes. The success criteria for the anchors include being able to attach to different table sizes with different textures and be able to hold up to about double the expected applied forces. The accuracy tests must be able to have the robot move within 0.1mm of the target position and the motor's backlash must also be 0.1mm or less while the motors are locked to be considered a success. Finally, the speed and force tests require the robot to be able to move up to 1m/s in all directions and each cable and the lift mechanism must be able to apply up to 10N of force in all directions and will only be a success if all those criteria are met.

7 CONCLUSIONS

So far, we have been able to examine the purpose of this project, take the customer and engineering requirements into account, and make good progress in developing a solution. In addition to the information provided by our sponsor, we have also compiled a good list of relevant sources to draw upon and equations to calculate necessary quantities. Through design generation and meetings with Dr. Razavian, we have been able to narrow down possible designs and converge upon our current wire-driven design. Further concept generation and selection has allowed us to select a final design and construct a tentative CAD model of it. With known subsystems, we have been able to complete two prototype demonstrations, testing electrical components and physical attributes of the device. If we continue at this rate, we are confident that our team will produce a capable design that is able to produce 10 Newtons in any direction, lift 1 foot off its work surface, detect force and position with great accuracy, fit within 83 cubic inches of space, and cost little more than $1000 to produce. Ultimately, our final product will improve upon the Hamster design and provide efficient and affordable rehabilitation assistance to stroke patients.

8 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

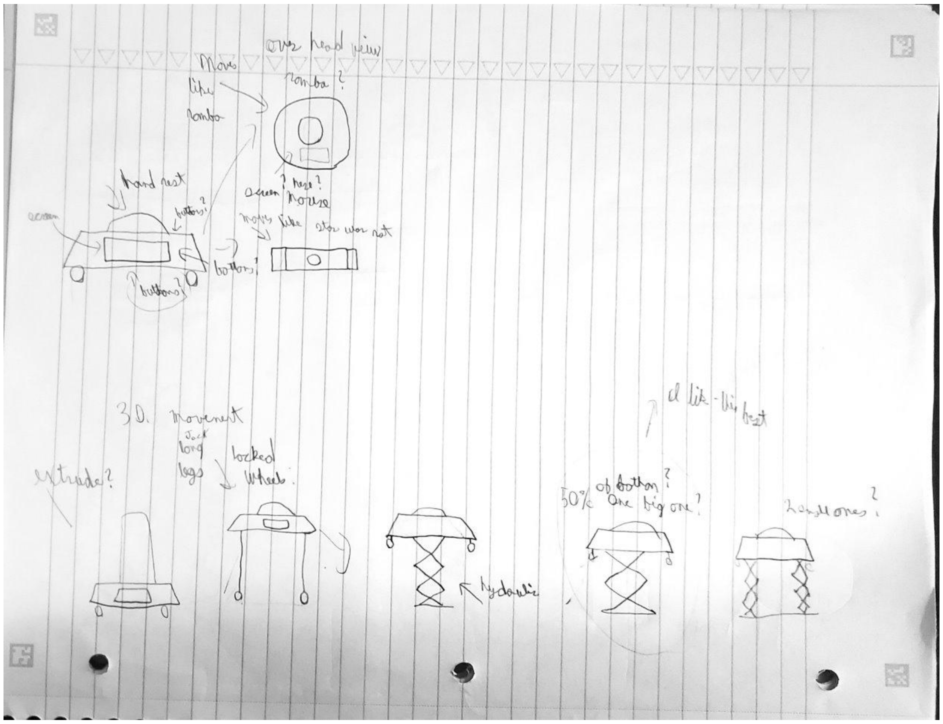
[52] S. M. Staroletov, “Arduino Meets Raspberry Pi in Automation: An Implementation of State-Based Distributed Control with Round-Robin Scheduling,” *2022 International Russian Automation Conference*

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

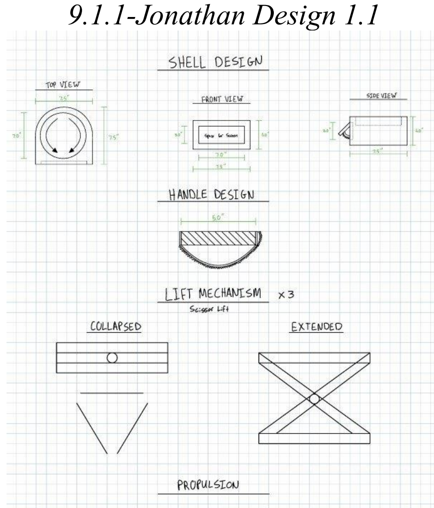
[53]"Raspberry Pi Arduino Serial Communication - Everything You Need To Know," *The Robotics Back-End*, Nov. 11, 2019. https://roboticsbackend.com/raspberry-pi-arduino-serial-communication/

9 APPENDICES

9.1 Appendix A: 1st Concept Generation



9.1.1-Jonathan Design 1.1



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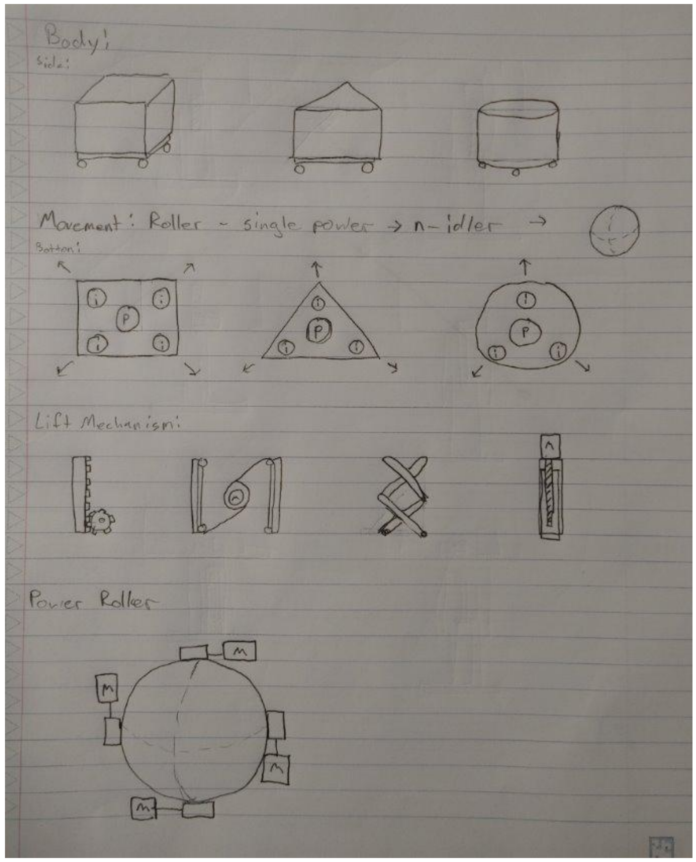

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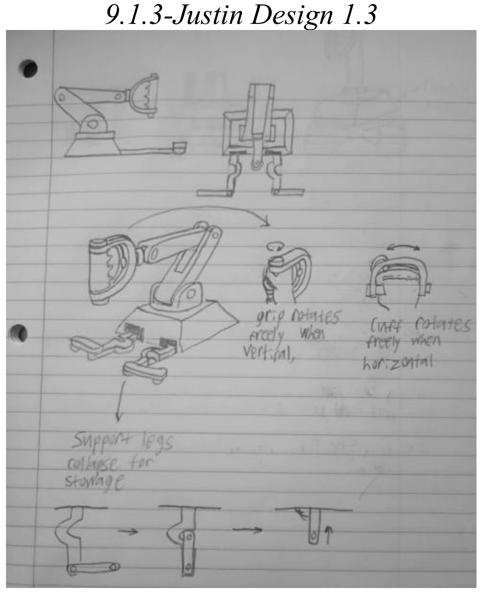

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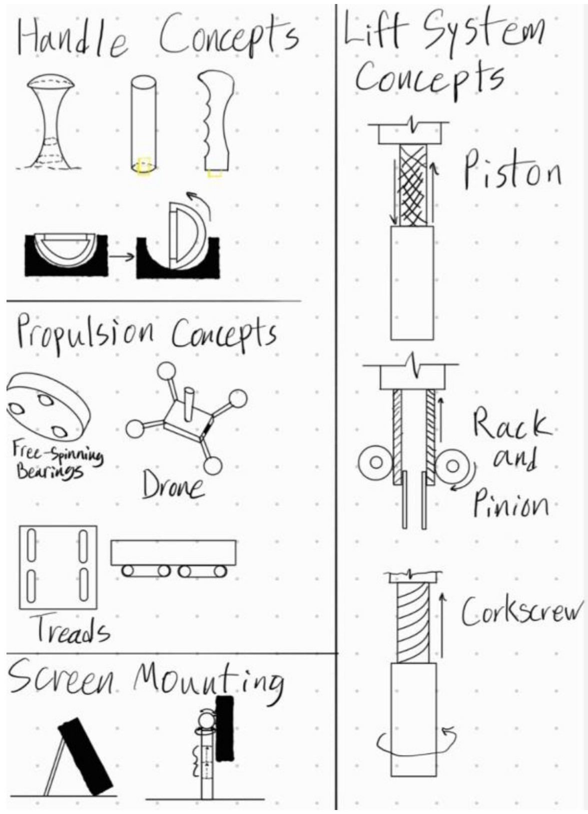
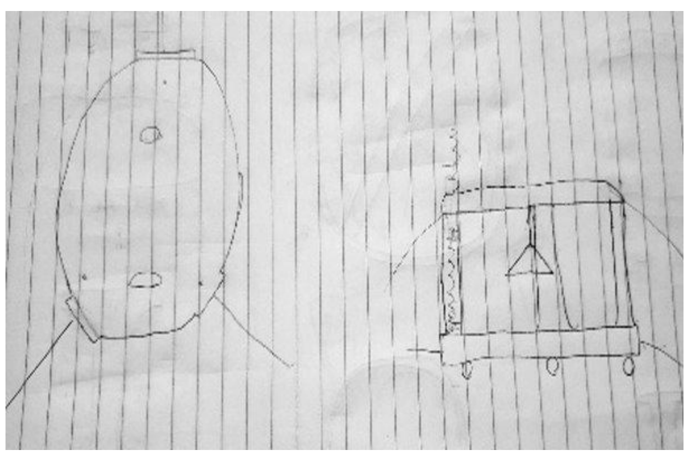


9.1.5-Joey Design 1.5

9.2 Appendix B: 2nd Concept Generation



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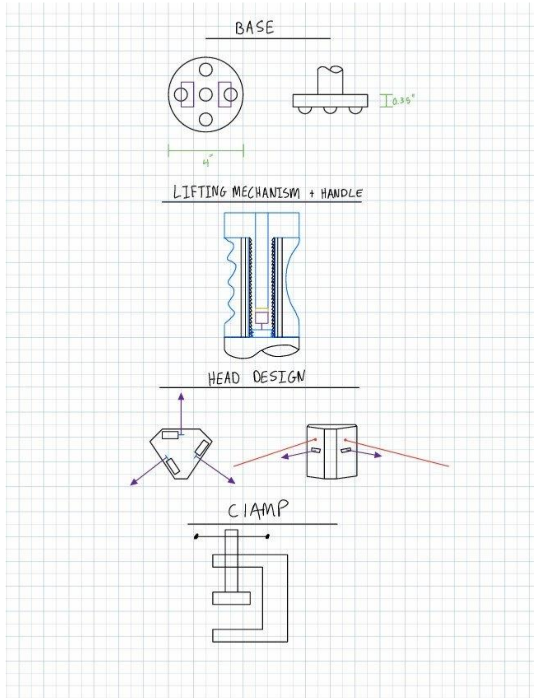

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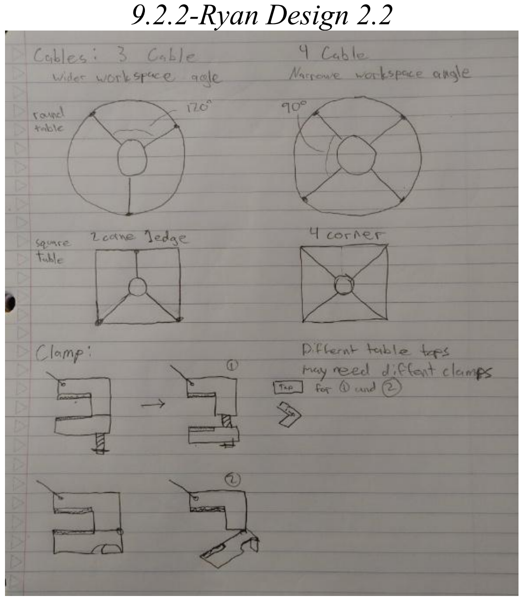

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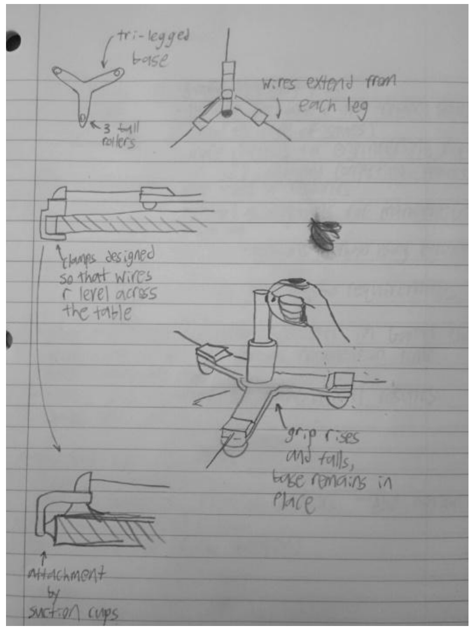

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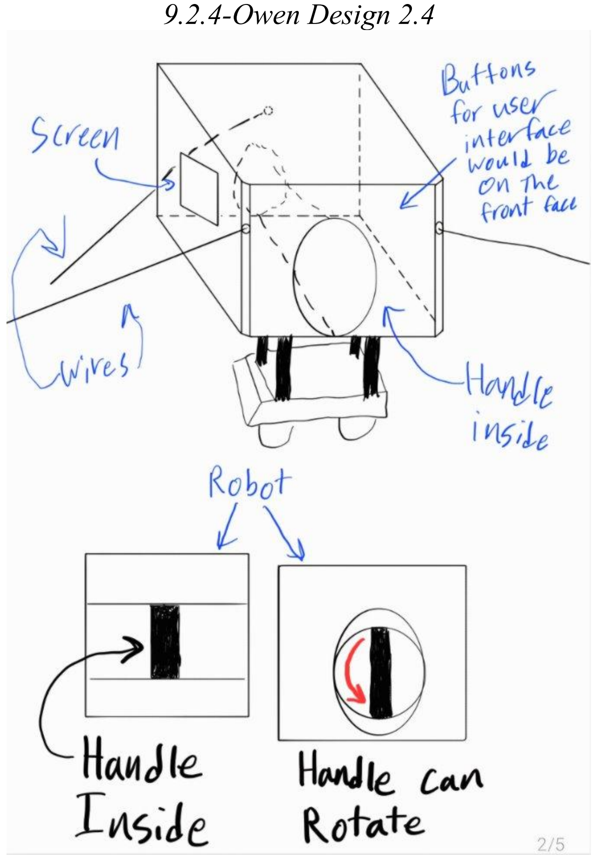

9.2.5-Joey Design 2.5