GNG2101 Final Report

Tenaci Hand Grip

Submitted by

C2A

Chloé Richard, 8725971

Jimmy Deng, 8194330

Long Kit Sau, 8231852

Noah Fishman 300078707

William Choi 300079154

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University of Ottawa

Abstract

For those suffering from Thoracic Outlet Syndrome, or other conditions affecting an individual's ability to grip objects and overall dexterity, a product that is not only easy to use, but financially accessible, is paramount. As recommended by Tenaci's client, Adrienne, this project addresses the need for a product that is similar to a glove, light in weight and not covering the forearm, that can aid the user by increasing grip strength and dexterity in their fingers. The product had to follow a strict budget and be made of a breathable, thin fabric. Tenaci developed several prototypes, using flex sensors on the thumb, forefinger and pinky finger to enable the user to start and stop the gripping motion of the glove. In addition, fuzzy logic and encoders were developed to ensure that a fail safe is in place. The project also includes a description of a preliminary business model, feasibility study, primary learning outcomes and recommendations for future research and development in this technology.

the purpose, problem, methods, results, and conclusion of your work

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Acronym	Definition
PID	Proportional Integral Derivative control

1 Introduction

1.1 The Problem

Thoracic outlet syndrome is a condition that often results in the loss of muscle around the base of the thumb.[1] Our client Adrienne's thumb and index finger have deteriorated to a point where she does not possess the ability to flex these fingers. This inhibits her from accomplishing basic tasks such as handling small objects, typing, and lifting up large items. Ideally, the client would like a device similar to a glove that could increase the strength in her hand, helping her accomplish everyday tasks without difficulty.

1.2 User Requirements

The product designed was to improve our client's lost dexterity. It should be able to provide our client with a pinching motion suitable for most uses. It also required a portable power source to minimize discomfort using the device.

[1] "Thoracic Outlet Syndrome Information Page." *National Institute of Neurological Disorders and Stroke*, U.S. Department of Health and Human Services, 27 Mar. 2019, 16:20, www.ninds.nih.gov/Disorders/All-Disorders/Thoracic-Outlet-Syndrome-Information-Page.

1.3 Key Aspects

The key concept that separates the Tenaci Hand Grip from the other products is its level of automation. Using flex sensors, and force sensors, the grip is able to detect what position the fingers are at all times, and make use of that knowledge with fuzzy logic controllers. In addition, a unique double layer design was integrated to allow the use of a string based system without compromising comfortability or taking up unnecessary space.

2 Need Identification and Product Specification Process

Client Needs

Table 1. Client Needs

#	Need #	Importance
1	The Hand Grip can mimic pinching motion of thumb and forefinger	4
2	The Hand Grip has smooth texture across palm to avoiding catching on other objects	2
3	The Hand Grip allows user to pick up small or thin objects with thumb and forefinger, like knitting needle	4
4	The section holding thumb had enough motor strength to aid user in picking up heavy objects	4
5	The Hand Grip can accommodate for small change in finger and hand size resulting from swelling	2
6	The Hand Grip automatically triggers when gripping is desired	3
7	Hand Grip grasps delicate objects without breaking them	3
8	Hand Grip helps aids in typing	3
9	Hand Grip is water resistant	1
10	Hand grip allows a high degree of dexterity	3
11	Hand Grip is not uncomfortable to wear for long periods of time	3
12	Hand Grip has open fingertips	2
13	Device is producible at low cost	4
14	Hand Grip has a lightweight power supply	4

Very important	4
Important	3
Moderately important	2
Slightly important	1

Problem statement

The client, Adrienne, has compromised dexterity and strength in her thumb, index finger and mildly in her middle and ring finger. This is problematic for everyday tasks, including dishwashing, knitting, typing, and picking up objects. Ideally, Adrienne would like a device similar to a glove that could increase the strength in her hand, helping her accomplish everyday tasks without difficulty.

Benchmarking

Similar Product 1 - Bioservo Carbonhand

The Bioservo Carbonhand is a device that helps augment the grip strength of a user. The device consists of separated glove and control panel devices attached through cabling, this results in the control panel being worn on the hip, rather than attached to the glove. The carbonhand utilizes three motors to help emulate regular grip strength, or augment this strength in individuals losing their grip strength. The motors are actuated by sensors placed on the fingers, and different ‘grip profiles’ can be selected, offering different levels of strength in different areas of the hand.

Figure 1. Competition Product - Bioservo Carbonhand
https://www.bioservo.com/healthcare/carbonhand

Table 2. Bioservo Carbonhand Benchmarking

Client Need	Need Satisfied?
Returns Grip Strength	Yes
Device is lighter than cell phone	Yes
System is not bulky/intrusive	No
Device retains dexterity and freedom in hand	Yes
Solution is low-cost	No
Device avoids compression, adaptable for hand swelling	Yes
Allows accurate Gripping	Yes
Objects will not be caught in/on front of device	Yes
Fingers are not Separated	No
Device automatically senses when to grip	Yes
Device can be used to grab heavy objects	Yes
Fingers are uncovered	No

Similar Product 2 -Thumb Split

The thumb split is a device that helps stabilizing and supporting a weakened joint. This device provides extra support for the hand without actuation to help stabilize a weakened grip.

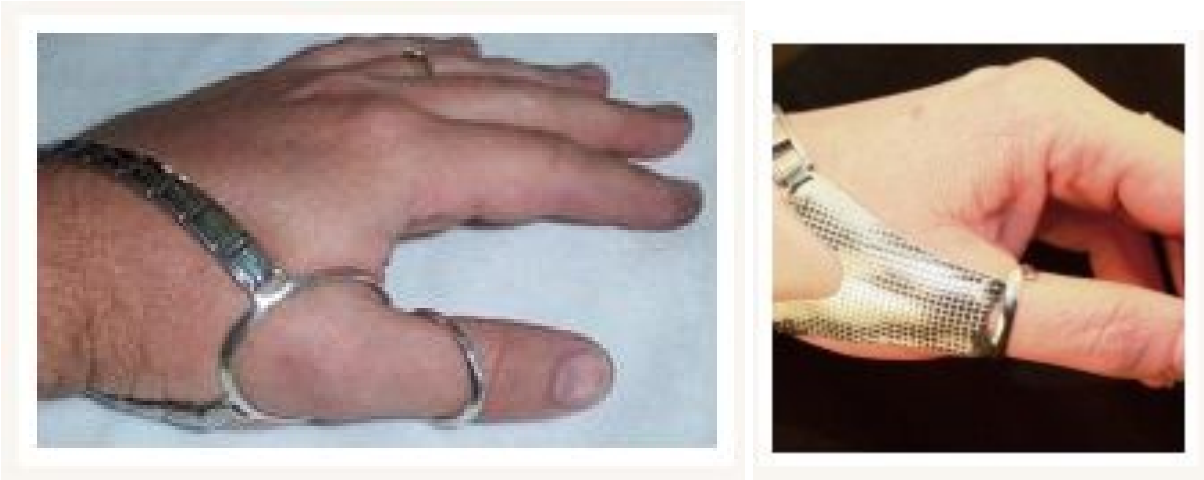


Figure 2. Competition Product - Thumb Splint
https://www.digisplint.ca/our-products/splint-types

Table 3. Thumb Splint Benchmarking

Client Need	Need Satisfied?
Returns Grip Strength	Yes
Device is lighter than cell phone	Yes
System is not bulky/intrusive	No
Device retains dexterity and freedom in hand	Yes
Solution is low-cost	Yes
Device avoids compression, adaptable for hand swelling	Yes
Allows accurate Gripping	Yes
Objects will not be caught in/on front of device	Yes
Fingers are not Separated	No
Device automatically senses when to grip	No
Device can be used to grab heavy objects	Yes
Fingers are uncovered	No

Similar Product 3 - Nasa and General Motors RoboGlove

The RoboGlove was created to amplify the grip of factory workers, allowing them to better grasp and lift objects, as well as to apply more pressure with limited effort. The RoboGlove utilizes sensors in the fingertips to understand when pressure needs to be applied, and cables to apply force on the object that needs to be grasped.

Figure 3. Competition Product: NASA RoboGlove
https://technology.nasa.gov/patent/MSC-TOPS-37

Table 4. NASA Roboglove Benchmarking

Client Need	Need Satisfied?
Returns Grip Strength	Yes
Device is lighter than cell phone	Yes
System is not bulky/intrusive	No
Device retains dexterity and freedom in hand	No
Solution is low-cost	No
Device avoids compression, adaptable for hand swelling	No
Allows accurate Gripping	No

Objects will not be caught in/on front of device	Yes
Fingers are not Separated	No
Device automatically senses when to grip	Yes
Device can be used to grab heavy objects	Yes
Fingers are uncovered	No

Metrics

Table 5. Metrics Decision Matrix

#	Need #	Metric	Important	Units
1	1,4,6	Return Grip Strength	4	gram
2	3,7,8,10	Grip Accuracy	3	mm
3	11	Weight (Light)	2	gram
4	11	Size (small)	2	mm
5	13	Cost (Low)	4	CA$
6	5,2,8,9,10,11,12	Comfort Level	2	hours

Very important	4
Important	3
Moderately important	2
Slightly important	1

Table 6. Target Specifications

Metrics #	Metric	Units	Marginal	Ideal
1	Return Grip Strength	pound	10	25
2	Grip Accuracy	mm	5	1
3	Weight (Light)	pound	5	1
4	Size (small)	list	glove	ring
5	Cost (Low)	$CAD	100	80
6	Comfort Level	hours	3	24

Justification:

Return Grip Strength - Ideal: hold a plate or a cup, Marginal: hold a phone
Grip Accuracy - ideal: grab a needle, Marginal: grab a grape
Weight - ideal: weight of a glove, Marginal: weight of a smartphone
Size - ideal: size of a thumb, Marginal: size of a glove
Cost - Ideal: Under $80, Marginal: Under $100
Comfort level - Ideal: Worn whole day without discomfort, Marginal: Worn 3 Hours without discomfort

Table 7. Benchmarking Metric

#	Metric	Imp	Units	Bioservo Carbonhand	Thumb Split	RoboGLove
1	Return Grip Strength	4	pound	45	10	25
2	Grip Accuracy	3	mm	5	10	5
3	Weight (Light)	2	pound	2	0.5	1
4	Size (small)	2	list	glove	ring	glove
5	Cost (Low)	4	CA$	200	20	100
6	Comfort Level	2	hours	12	24	12

Conceptual Designs

Functional Decomposition

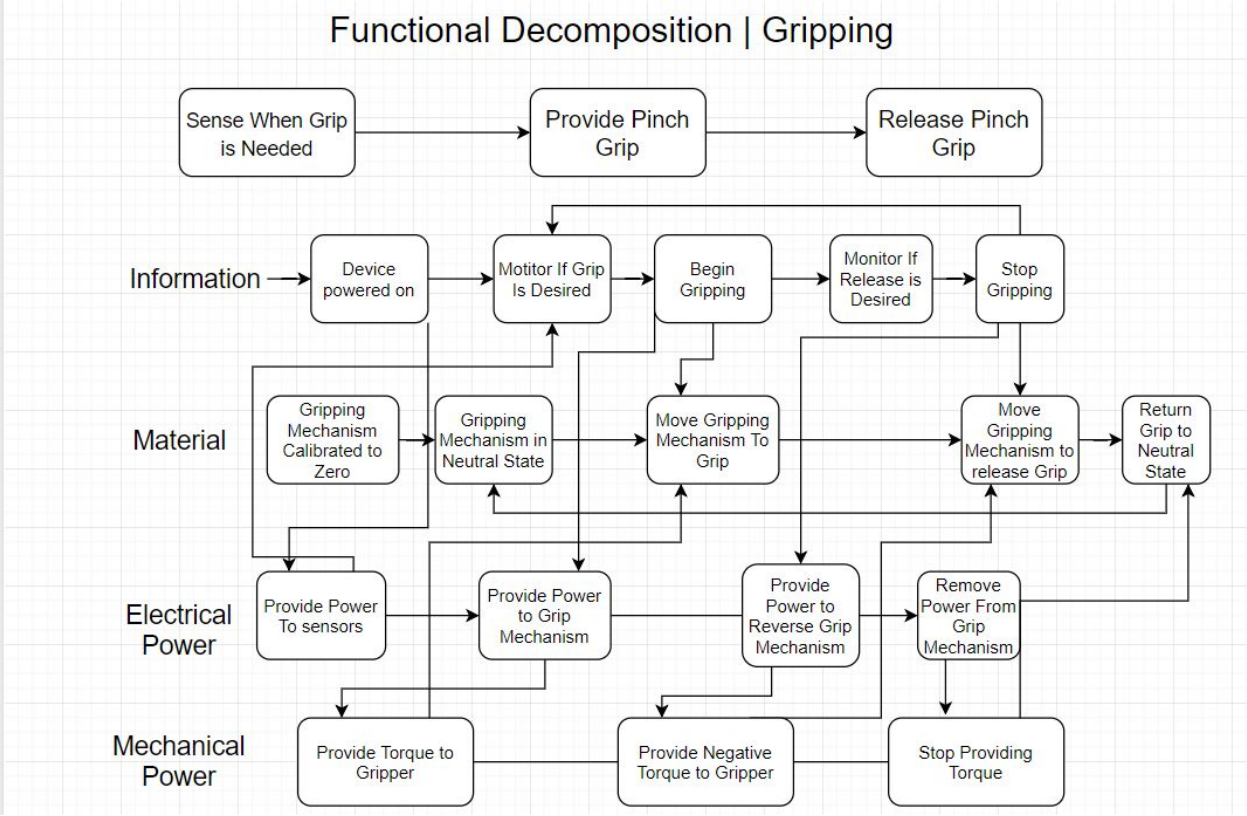


Figure 4. Functional Decomposition - Gripping

Subfunctions

Sensing:

- Glove receives sensor input when grip is desired
- Glove relays power to provide pinch grip
- Glove senses when to release the grip
- Glove removes power to providing grip
- Glove returns to sensing when to grip

Providing Pinch Grip:

- Glove receives power when pinching grip is desired
- Glove actuates, pinching inward, limiting dexterity in exchange for increased strength
- Glove maintains pinch, providing adequate grip

Releasing Pinch Grip:

- Glove stops receiving power
- Grip releases, allowing grip to be released
- Sensor returns for sensing when to grip inward
- Dexterity is returned, strength is limited

Dexterity:

- Thumb
    - Ability to move forward and backward (bend at metacarpophalangeal and base carpophalangeal joint, see figure below)
    - Picking up small objects (thin knitting needle for example)
    - Ability to bend at interphalangeal joint
- Forefinger
    - Most important mobility would be at carpometacarpal joint (base of index finger)
    - Ability to bend on other parts of forefinger

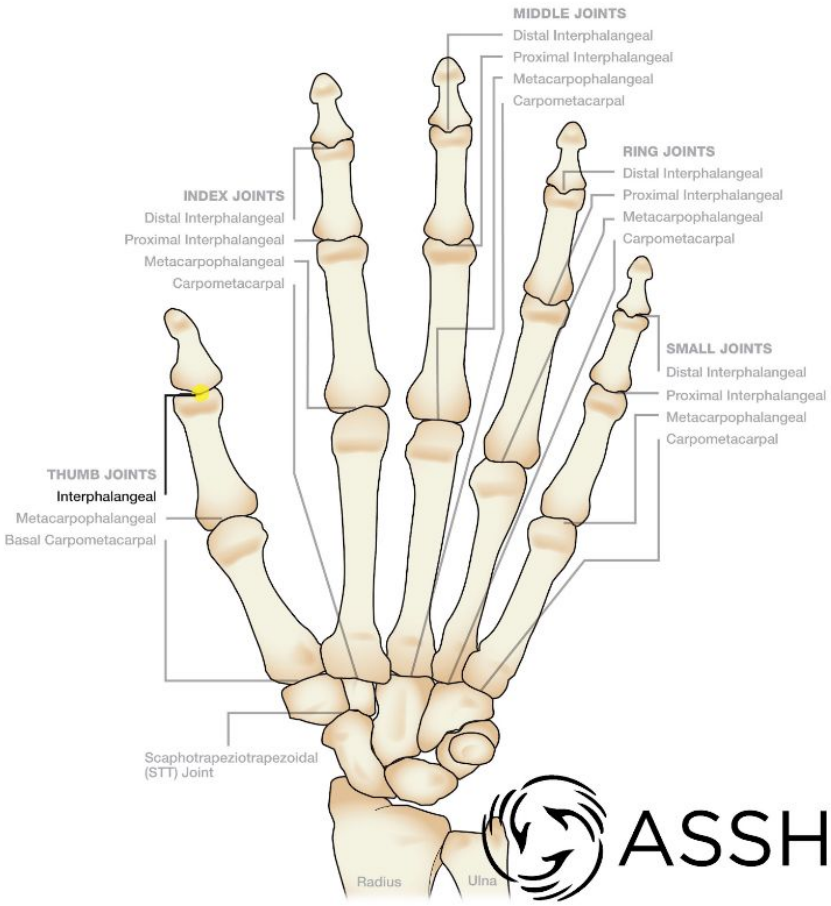


Figure 5. Structural of Hand
http://blog.handcare.org/blog/2017/10/26/anatomy-101-finger-joints/

Supporting the hand

- Keeping fingers firm:
  - Glove should cover up to first joint,
  - Firm material (e.g. rubber) to support fingers
  - Thumb, Index, and Middle finger should be bound together
- Aiding lifting larger objects:
  - Palm should have a material with high friction to be able to catch objects with it, without risking the object slipping off
- Comfortability:
  - Soft pads inside the gloves, all materials must be able to stretch to accommodate the hands swelling
  - Glove should be well fitting, no additional tension on the hand created by the glove

Team brainstorming and sketches

Table 8. Design Generation Matrix

			Option					
		Weight	Finger-Thumb Linkage		Glove with Tension Cable		Ring with Free Thumb	
Criteria	Return Grip Strength	0.3	4	1.2	4	1.2	3	0.9
	Grip Accuracy	0.15	3	0.45	2	0.3	4	0.6
	Weight (Light)	0.05	3	0.15	1	0.05	4	0.2
	Size (small)	0.05	3	0.15	2	0.1	4	0.2
	Cost (Low)	0.4	4	1.6	2	0.8	3	1.2
	Comfort Level	0.05	2	0.1	3	0.2	3	0.15
Score				3.65		2.6		3.25
Rank				3		1		2

Greatly Fulfils Need	4
Fulfils Need	3
Somewhat Fulfils Need	2
Barely Fulfils Need	1

Approach to Determining Group Concept (APPENDIX II for brainstorming design sketches):

In order to determine our final group concept, we initially analyzed each of our individual concepts according to the metrics established in deliverable B, by utilizing a weighted decision

matrix. Following this, one ‘best’ concept was determined for each team member. During a team meeting, everyone discussed their top idea, as well as key concepts from each of their other ideas. Additionally, we compared the metrics of each idea, and reviewed some external ideas found by team members, pointing out vital ideas and aspects of them that would be valuable in our design. After the discussion we created a prioritized list of needs, and synthesized ideas from each of the top concepts, discussing how well each aspect from different concepts fulfilled these needs. During this discussion, rudimentary sketches were created, demonstrating the ideas that were determined to be optimal. After the initial sketches were created, they were refined into our final concept sketches.

Final Design

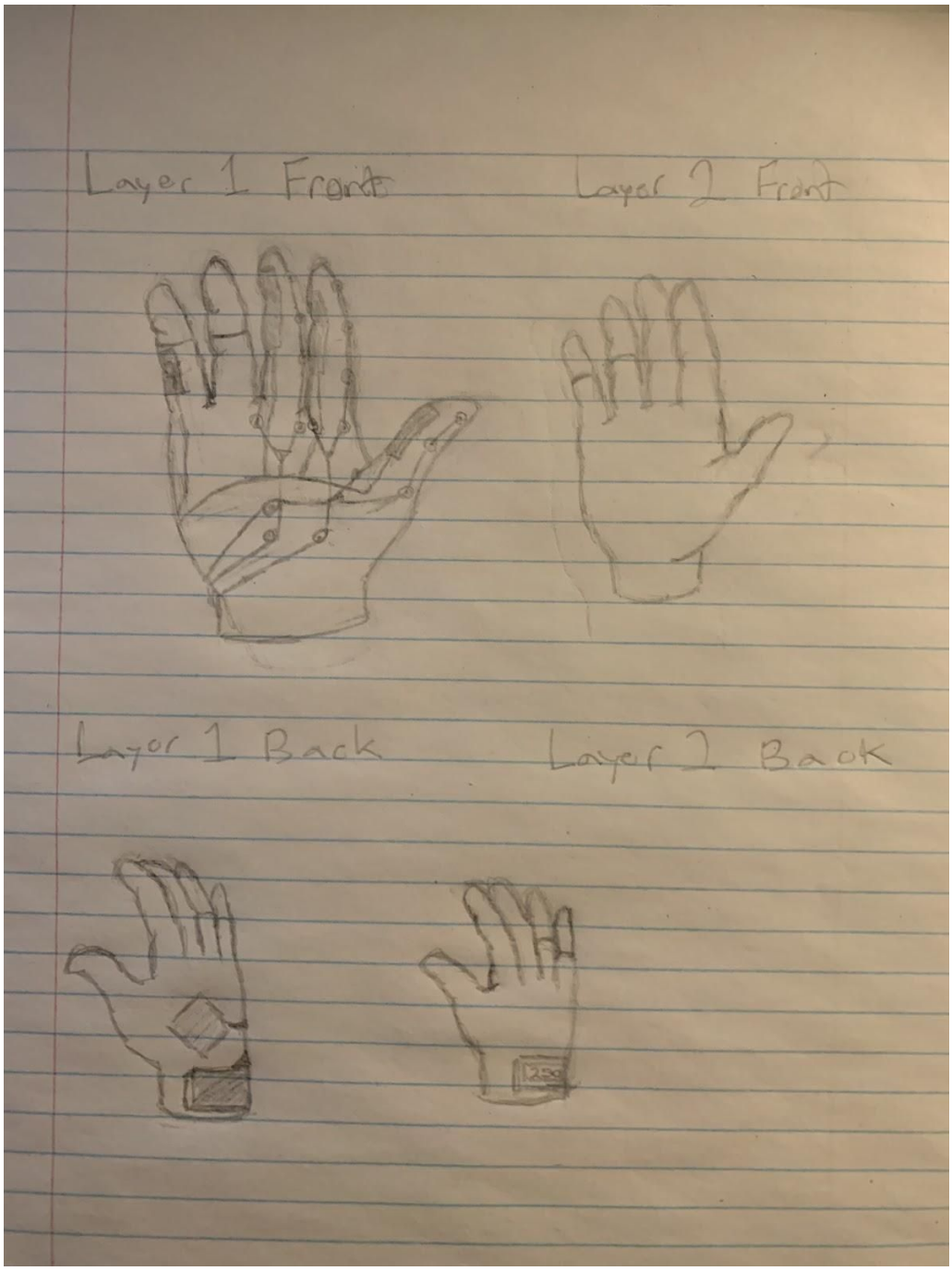


Figure 6. Final Design Sketch

Layer 1 Front:

Flex sensors line the inside of the pinky, index, middle finger & thumb. These sensors' cables are fed to electronics on the back of the hand. The later of the three sensors trigger a motor that pulls in cables, closing the user's fingers. While the pinky sensor triggers the release on the motor, allowing the user to open their hand. These cables are attached to the three appendages running along their sides attached at the joints & an anchor in the fingertips. These cables run into the back of the hand where they are fed into pulleys that orients them towards the back of the wrist.

Layer 1 Back:

The wires wrapped around from the sensors on the front join the electronics mounted on the back of the hand. The cables similarly wrap around & feed into the motor on the wrist.

Layer 2 Front:

Glove is stretchy & lined with a thin gripping rubber. Glover only runs half way up the pinky & ring fingers.

Layer 2 Back:

Motor/electronics case on wrist is styled to look & function as a watch.

Justification of chosen solution:

Throughout the course of the meeting, many designs were considered. The idea that a string-based mechanism would be used was decided early on. However, the client has pointed out she did not have the mechanism in the open, so it was decided the string will he hidden under a layer of a glove, where the motors will be hidden on the back of the hand. The electronics

controlling the mechanism would be hidden in the wrist, under a digital watch. Due to the nature of how fingers bend, the string would have to tug the fingertips, which presents an issue as the client wants open fingertips. The consensus made was the material for the fingertips will be very thin. Pressure and flex sensors on the thumb and index finger will be used in conjunction for the grip to detect when the user wants their fingers closed. Upon discussion, the fact that it would be very difficult for the same sensors to detect when the user wants the grip to be loosened, so an additional flex sensor on the pinky will accomplish the task instead. A pad with a high friction material was suggested to aid in her method of gripping large objects, which was to support it with her palm. The material of the grip must be flexible as the client's hands are known to swell.

Solution benefits/drawbacks and implementation concerns:

Our design targets the main goal of the client, which is providing strength and mobility to her index finger & thumb. While providing support, the glove is lightweight, fitting and durable. A functional case conceals all bulky moving parts, which is an idea the client loved. Unfortunately, the clients want of open fingertips on the glove limits the room for sensors and would make the cable system almost impossible. Therefore, only the pinky & index fingers remain open.

Table 9. Bill of Materials

Item #	Part	Description	Quantity	Unit Cost ($CAD)	Extended Cost ($CAD)
1	Pressure sensor	0.5" radius resistive pressure pad	2	9.11	18.22
2	Flex sensor	3" resistive flex sensor	3	10.42	31.26
3	Glove		1	14.99	14.99
4	PLA filament		0.05	40	2
5	Battery	9V	1	8	8
6	Battery clip		1	0.68	0.68
7	Arduino Nano		1	5.6	5.6
8	Fishing line	20lbs	0.05	14	0.7
9	Hookup wire		0.1	29.01	2.9

10	Various resistors		1	1	1
11	Various capacitors		1	1	1
12	PTFE tubing	1/4" OD, 1/8" ID	0.2	11.22	2.24
13	Rocker switch		1	0.89	0.89
14	Linear slide potentiometer	10KΩ	1	1.76	1.76
15	Continuous servo	1.51 kg-cm torque	1	6.12	6.12
		Total			97.36

Project Planning and Feasibility Study

Project Planning

APPENDIX II for Gantt Chart

Critical path (42 days) is shown on the Gantt Chart.

Decomposition of Work Milestones

Client meet #2
Formal brainstorming
Decide on final solution (Prototype 1) based on customer needs and metrics
Sketch/model of solution for prototype 1

Protype 1
List of materials + cost
Purchase materials
Build prototype
Test prototype - evaluate using metrics and specifications

Make list of improvements/things to troubleshoot

Prototype 2
Troubleshoot issues from prototype 1
Brainstorm solutions using existing ideas and new ones
sketch /model solution for prototype 2
Build prototype 2

Client meet #3
Make plan - write out simplified list of pros and cons of prototype 1 and 2
Understand limitations and benefits of prototype 2 to be able to relay them to the client

Prototype 3
Must have tangible improvements from Prototype 2, addressing client needs
Reassessment of budget - make sure we're still within budget

Feasibility Study

Technical: Does your team have enough expertise and technical resources?

The Hand Grip is a challenging project, requiring knowledge in software, electronics, hardware, and some concepts in mechanical engineering. However, our team is open to learning whatever expertise needed to ensure success of the project. On our team, we have two team members in first year Electrical Engineering, who will be able to broaden their hands-on knowledge in the field. In addition, we have another team member who is very well versed in all things Makerspace and is in Software Engineering. Finally, we have two team members in Chemical Engineering, and one in Civil Engineering. Combining our knowledge and points of view in respective fields will be crucial to completing the project.

Economic: Can the cost of your project be reasonable?

As long as we're resourceful when building the prototypes, the cost of our project is reasonable. We will be using moving gloves as well as fishing line in our initial prototype, and will try to use simple, cheap materials (like cardboard) to minimize the cost. The biggest expense will be the battery, the motor, and some electronic components of the Hand Grip.

Legal: Are there any legal issues with releasing your solution to the public?

We must ensure that we are not copying anyone's patented technology when designing the glove. Also, if our Hand Grip is a success, we may need to patent our own design.

Operational: Are there any organizational constraints that will prevent your success?

As our team is composed of six people, our greatest challenge will be working around everyone's schedule, particularly for meetings. However, everyone has been very flexible and communicating well, so it should not prevent us from succeeding. In addition, we noticed that we sometimes forgot to identify who the note taker would be, which was problematic. We have now assigned a specific note taker to solve this problem.

Scheduling: What are the deadlines and are they reasonable for your solution?

As a group, the team looked at the class deadlines and made some projected deadlines of our own. The team believe they are reasonable for our solution, because of the consideration of holidays like reading week, as well as the busiest times of the semester. For a couple deadlines, the team will have to meet up twice in a week, but the team have agreed that this is okay with everyone. The team must take potentials setbacks or additional time to troubleshoot mechanical or software issues

3 Analysis:

Figure 7: Client's hand with labels indicating dimensions

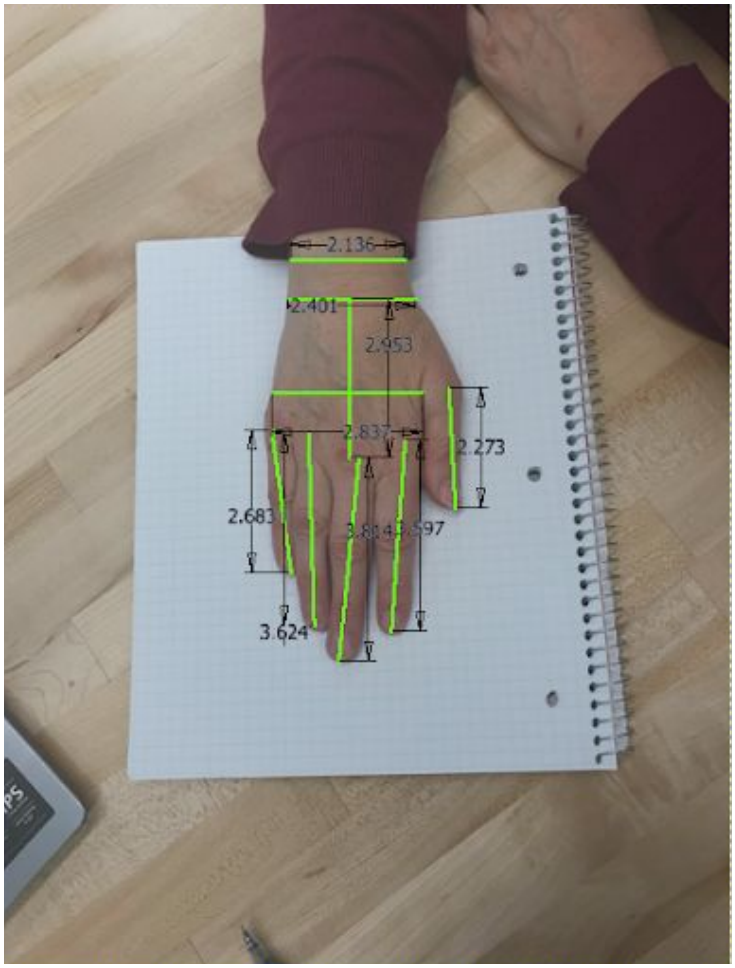


Figure 8: client's hand with labels indicating digit width

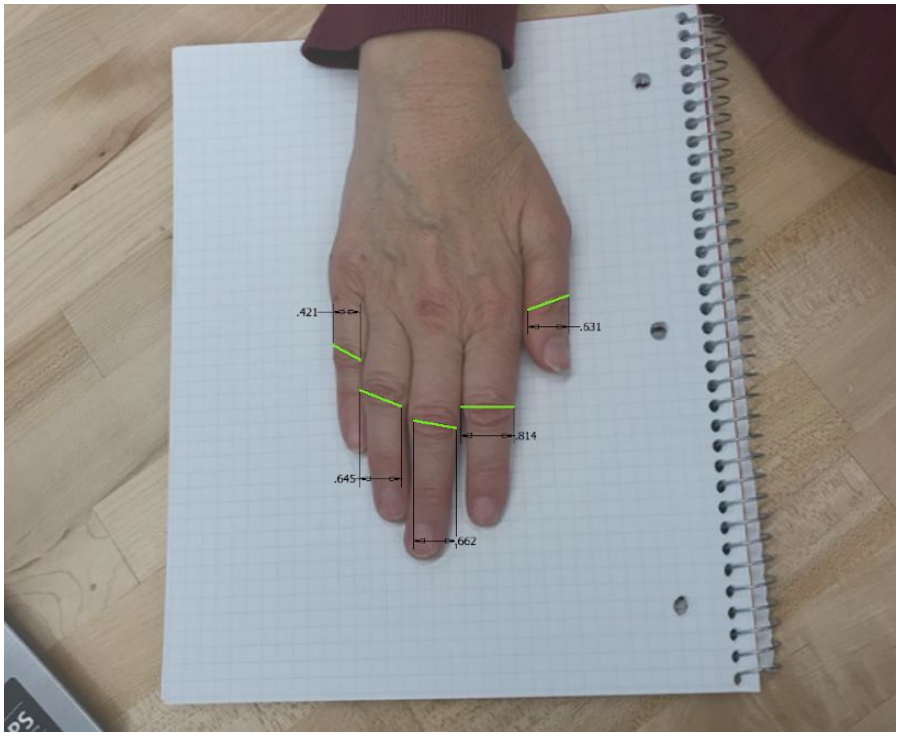


Figure 9: component placement on the client's hand

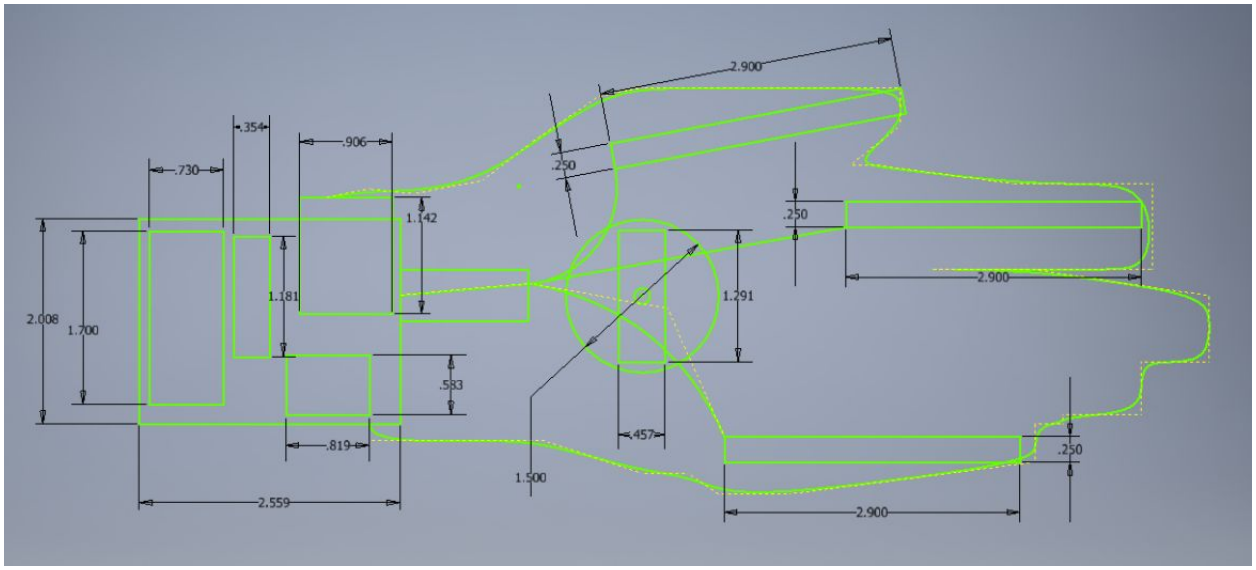


Figure 10: Grip force calculations

$$F = \frac{T}{r \cdot sin(\theta)}$$
$$= \frac{1.51kg \cdot cm}{0.5cm \cdot sin(90)}$$
$$= 3.02kg$$
$$= 29.6N$$

Figure 11: Battery runtime calculations

$$t_{avg} = \frac{Q}{A_{avg}}$$
$$= \frac{2Ah}{0.3A}$$
$$= 6.67h$$

4 Prototyping, Testing and Validation.

Prototype I

Our initial prototype was a very low fidelity proof of concept to verify whether implementing our desired grip mechanism would be feasible. Strings were attached to a human hand, as shown in figure 12, and were manually tensioned to grip a half-full water bottle. This test was successful and indicates that the mechanics involving dual-interlinked cords can be progressed to future prototypes. An alternate low fidelity prototype was created, as shown in figure 14. This is a more visual demonstration of how cord routing was performed.

Figure 12: Demonstration of hand gripping mechanics on a human hand

Figure 13: Angle of palm for prototype I

Figure 14: Prototype I mounted to a 3D printed hand

Prototype II

At this point, a single entity to label as a prototype has not yet been created. However, significant progress on separate submodules had been made. The software architecture had been defined, the software skeleton had been implemented, the fuzzy logic membership functions were being defined, the sensors had been tested and calibrated, and key elements within the mechanical system, including a custom polyester-lycra glove and motor couplers, were being designed and fabricated.

The main test performed at this stage was testing whether the torque output from the motor will reproduce the calculated force values which were obtained during analysis. This was tested by attaching the structure shown in figure 16 to a human hand. The testing from prototype I was performed and a water bottle was successfully gripped and lifted, as well as higher weight objects as shown in figure 15.

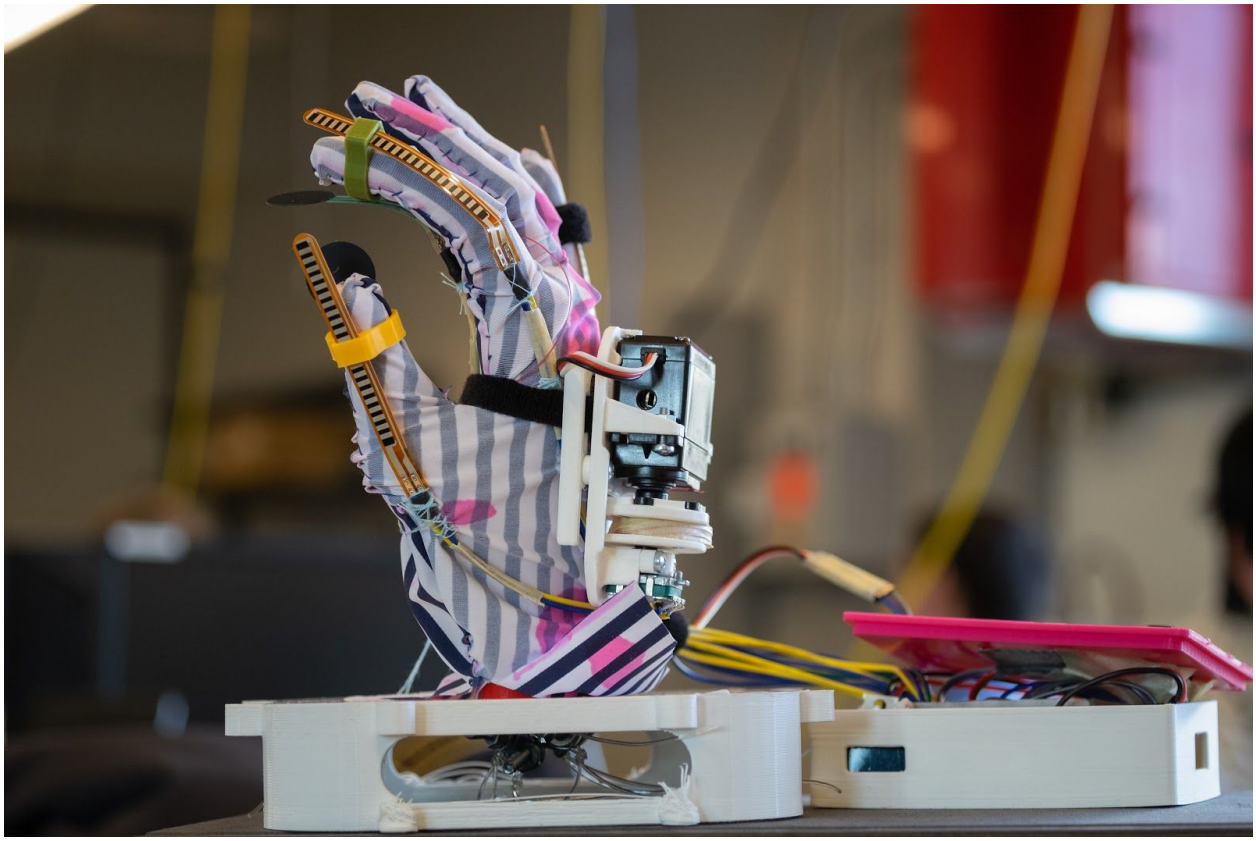
Figure 15: High-weight servo testing

Figure 16: Demonstration of motor mechanics

5 Final Solution

Due to the complexity of our final solution, this explanation will be separated into the following sections: overall functionality, mechanical subsystem, electrical subsystem, and software subsystem.

Figure 17: Overall glove and control box



Overall functionality

Due to complications involving the mechanical subsystem, our final solution was not fully functional. However, essentially all of the individual submodules had been completed and all that is required for a

fully functional final solution is the integration of the separate mechanical, electrical, and software modules.

From a top down view, the following functionality was achieved:

- Accurate digit position measurement
- Accurate grip force measurement
- Motor control in an open-loop system
- The ability to determine a target digit flex angle from measured values

Mechanical subsystem

The mechanical subsystem is required to allow the various mechanical components to interact with each other and to allow the electrical subsystem to be mounted to the glove. The following are the mounting mechanisms that had to be designed and fabricated:

- Spool with integrated servo-encoder coupler
- Finger mounting rings for flex sensors with integrated attachment points for fishing line
- Mounting plate to attach the servo-encoder assembly to the back of the hand
- Enclosure for control board

Figure 18: Motor-encoder assembly mounted to back of hand

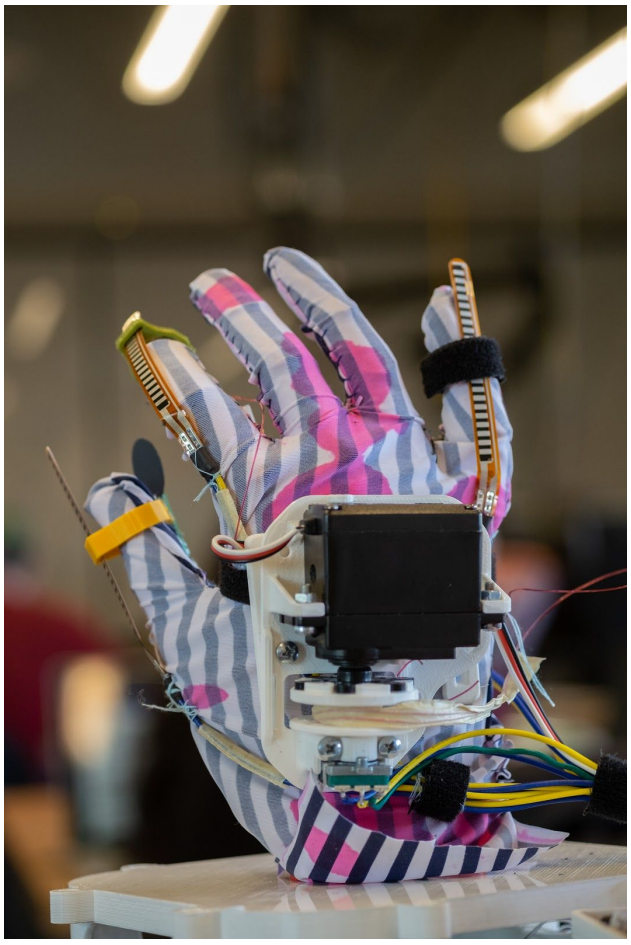


Figure 19: Close-up image of spool with integrated servo-encoder coupler

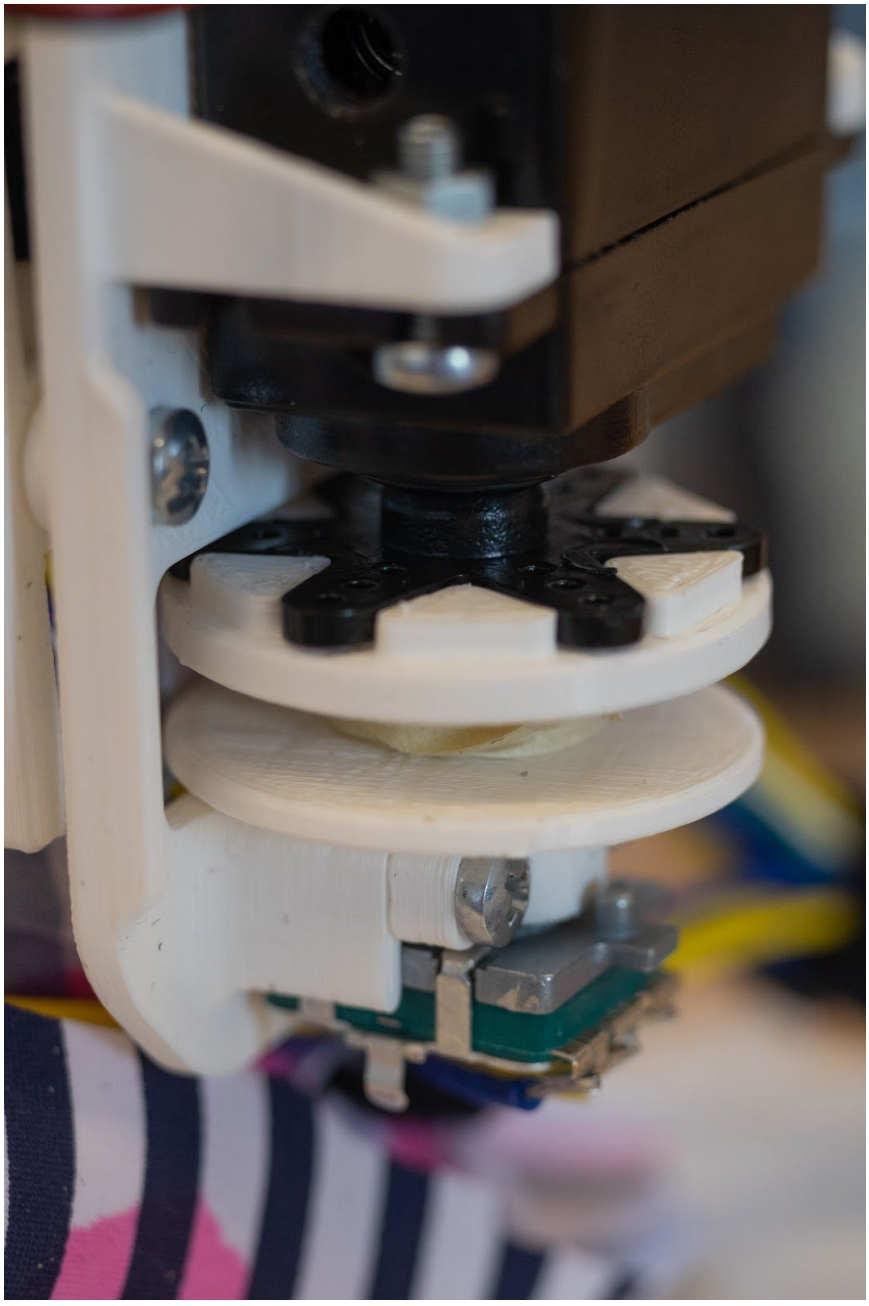


Figure 20: CAD assembly of motor-encoder mounting plate

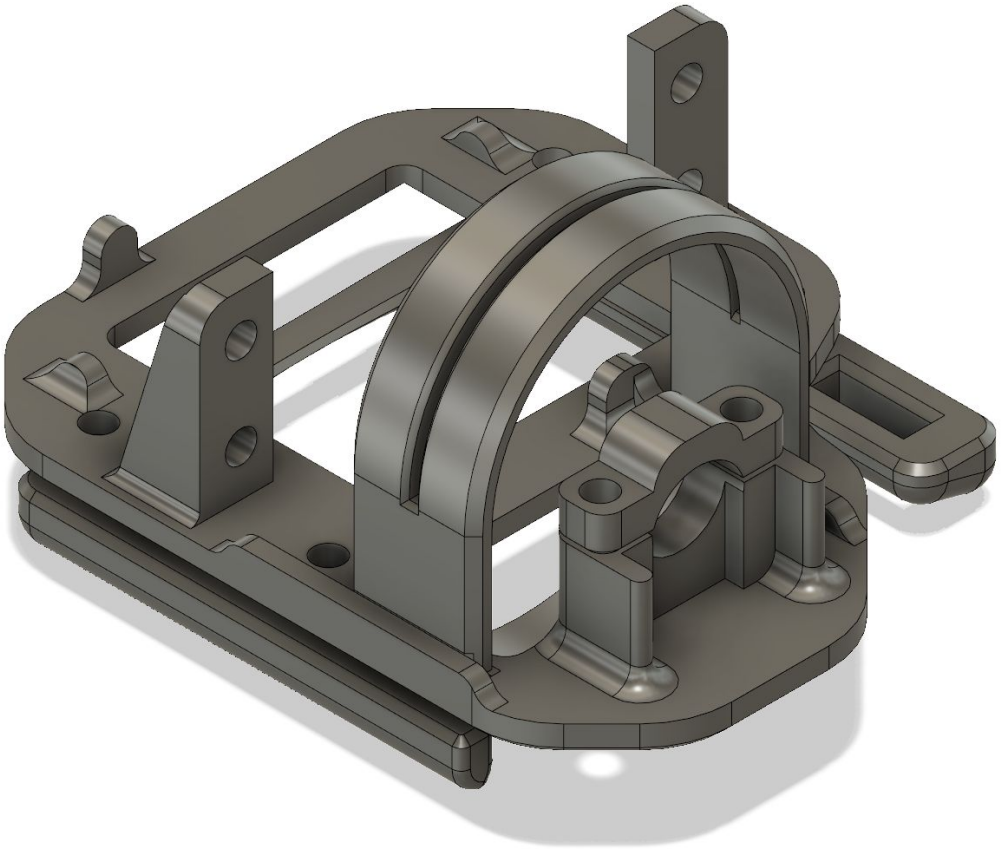
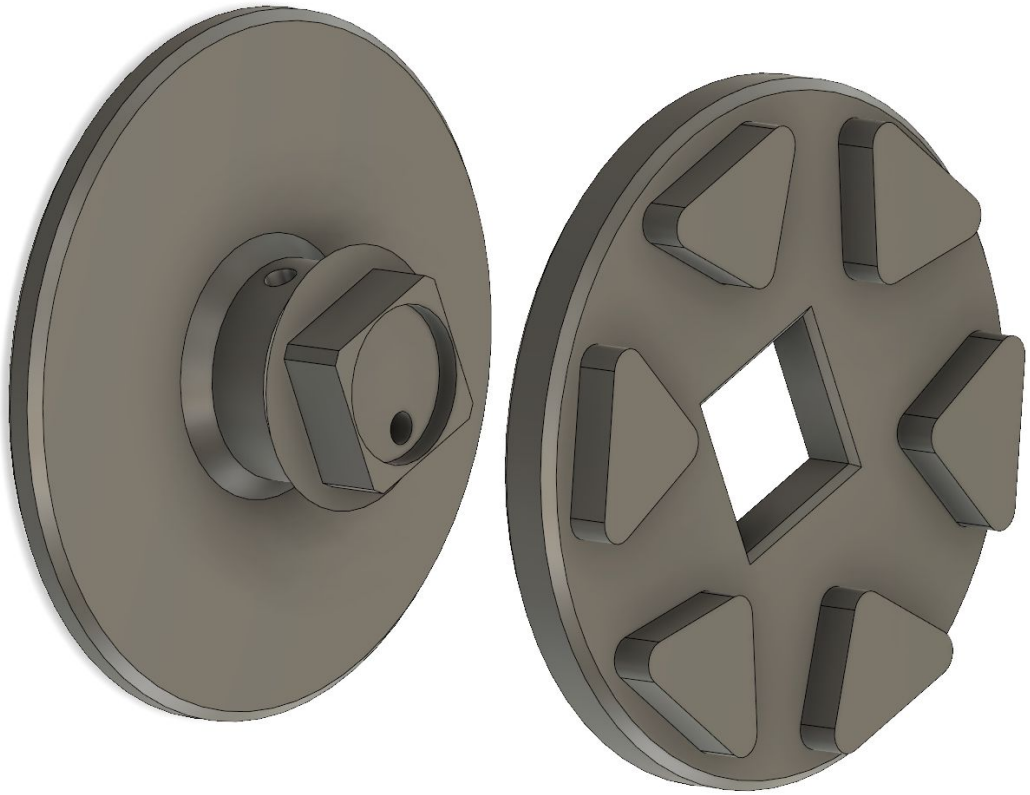


Figure 21: CAD assembly of spool with integrated servo-encoder coupler



Electrical subsystem

The electrical system revolves around the Atmel ATmega328p microcontroller on the Arduino Nano development platform. We decided to use this platform due to its performance, its simplicity, and due to our electrical team's existing experience with this platform.

The two main sensors for the Tenaci Hand Grip are resistive flex sensors and resistive force sensors. These two sensors operate by varying its resistance based on its state of flex/compression. This is measured using voltage dividers and the analog to digital converters on the Arduino Nano development board.

The system is powered using a 1-cell LiPo battery with a 2Ah capacity which will allow for approximately 6.7 hours of operation according to figure S. This is connected to a battery charge circuit which boosts the 3.7V output to 5V, which is required by the rest of the electronics. The battery charge circuit also allows for easy charging through a micro-USB interface and prevents overcharging and overdischarge which can cause damage to the battery.

The motor is simply a continuous servo which can be controlled using a pulse-width modulated (PWM) signal. Using the servo by itself will result in an open-loop control system which will result in a large amount of inaccuracy and drift. This is fixed by coupling the output shaft of the servo with a rotary encoder, resulting in a closed-loop system. An additional PID controller can be added in software to precisely control the motor shaft angle according to a target angle.

Figure 22: Electrical system schematic

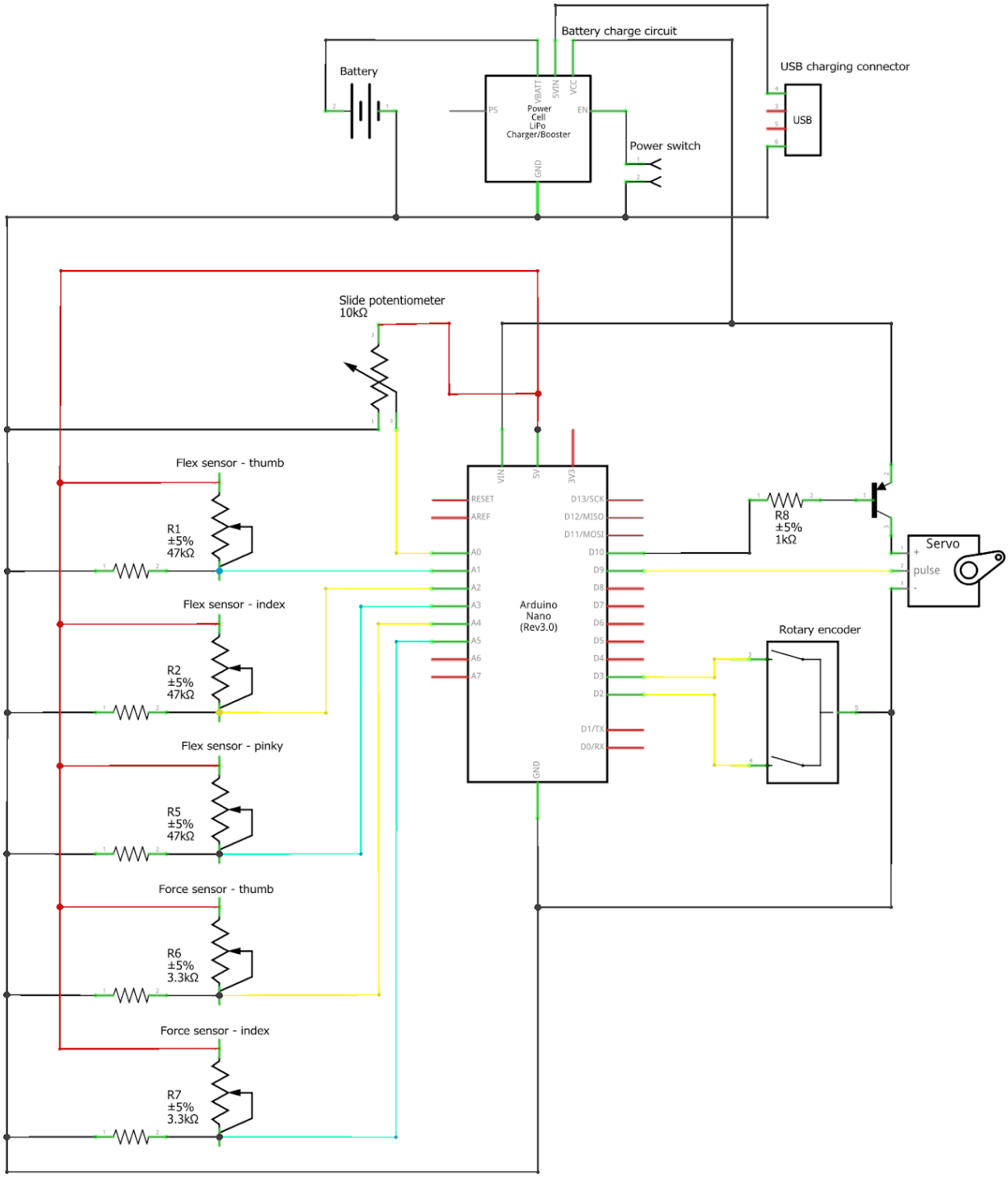


Figure 23: Assembled control board in a 3D printed enclosure

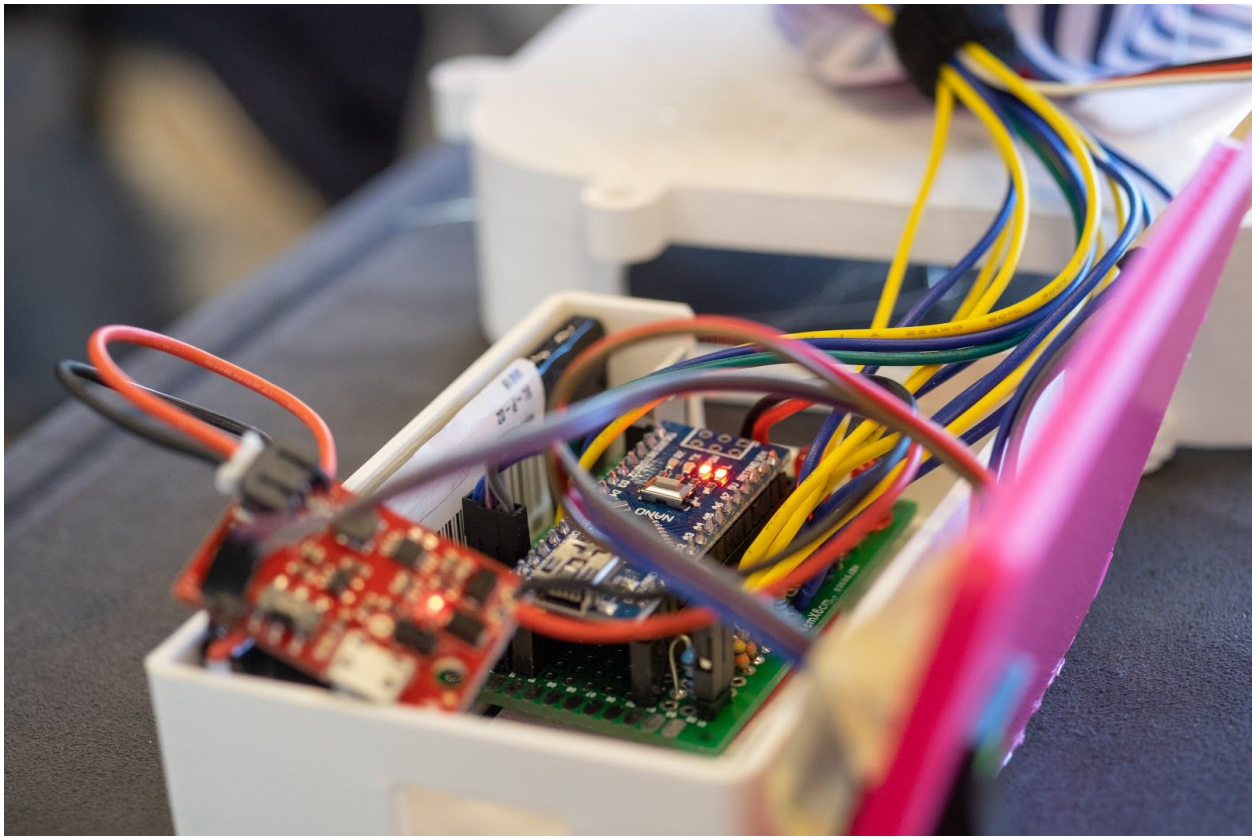
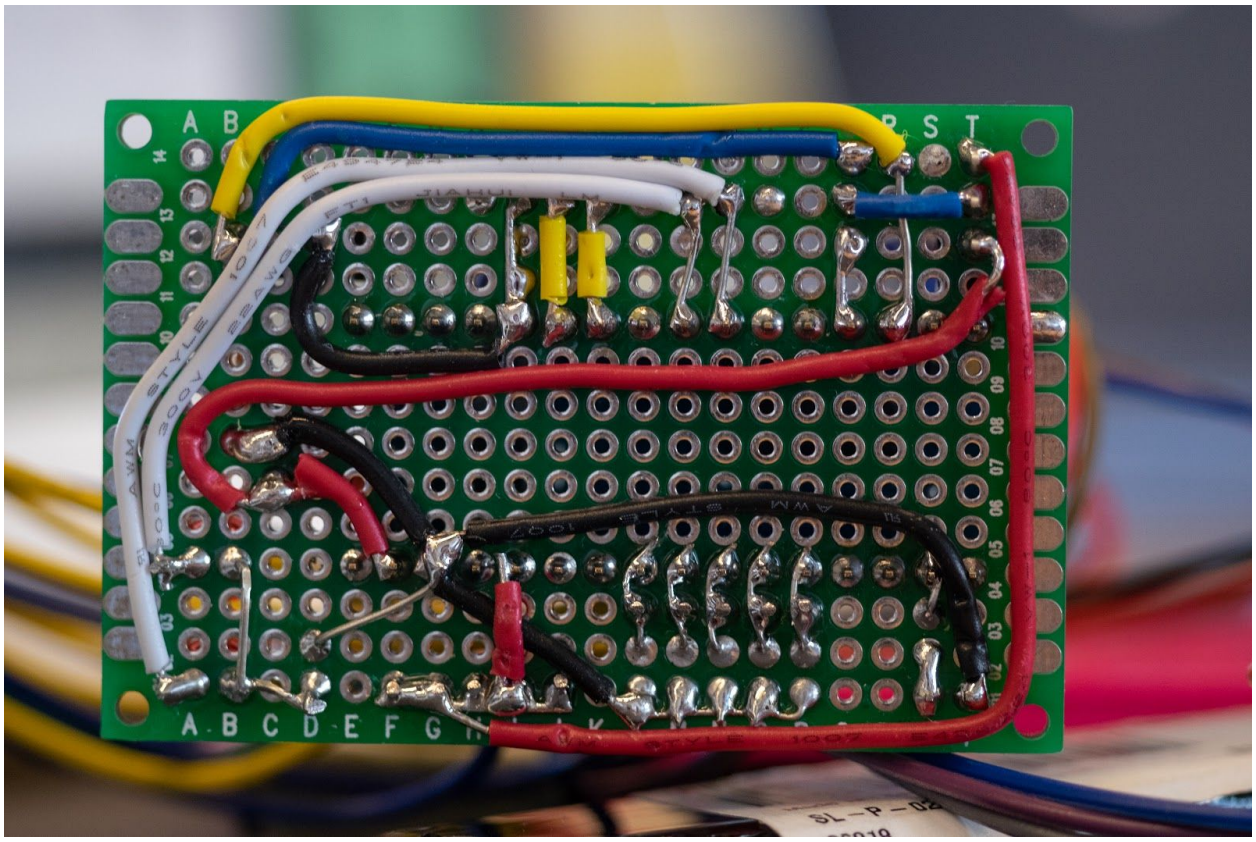


Figure 24: Bottom of assembled control board



Software subsystem

The control system is based on a fuzzy logic controller and a PID controller. We decided to use fuzzy logic because the states in this system cannot be properly represented by traditional boolean logic. The use of fuzzy logic allows for degrees of truth within the continuous set of input values and the library we had chosen to use allows for trivial integration of linguistically defined system states like partially flexed or medium force. A PID controller is necessary to allow precise control of the motor. As stated earlier, the Tenaci Hand Grip uses a continuous servo with no feedback, resulting in an open-loop system. Continuous servos are not accurate in this configuration and require additional sensors, a rotary encoder in this case, for feedback to create a closed-loop system where the motor shaft position is always known. The PID controller is used to control the motor to accurately move to a specified position. A PID controller also has the advantage of allowing us to precisely tune its acceleration and feedback curve to drastically change its behaviour.

Figure 25: surface plot approximating grip behaviour based on flex and force inputs

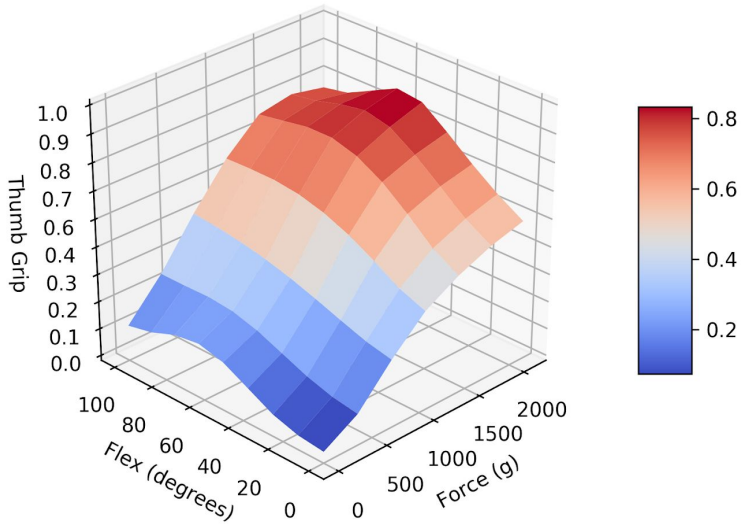


Figure 26: Membership functions for flex inputs

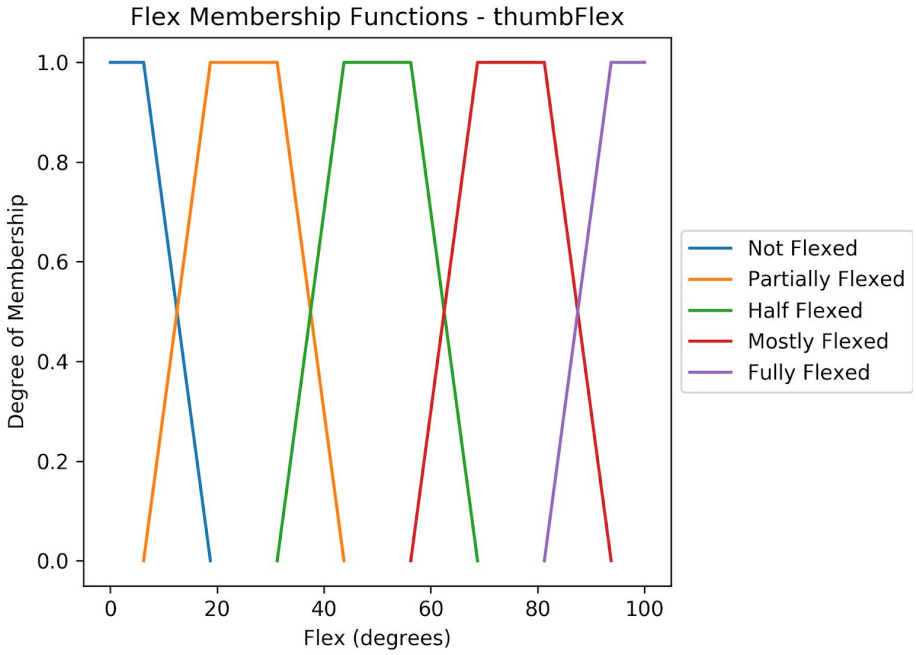
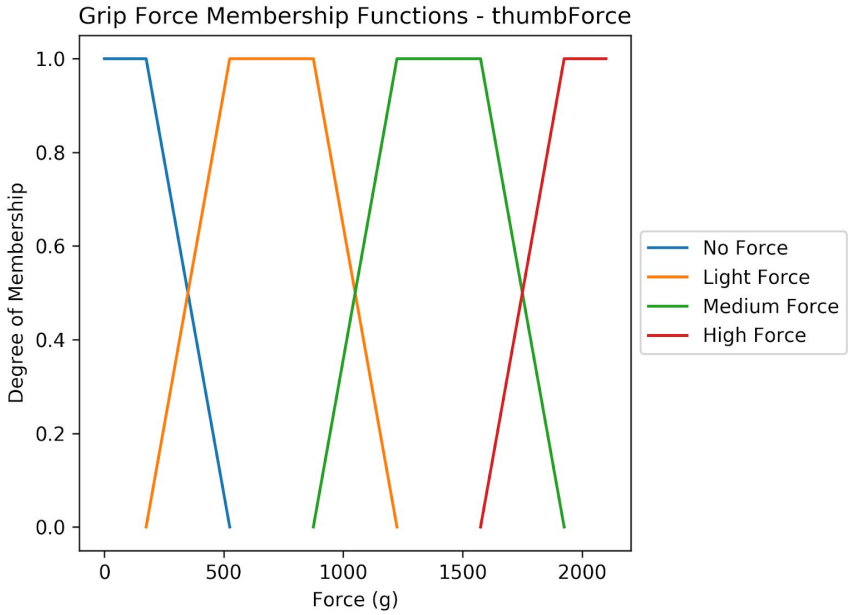
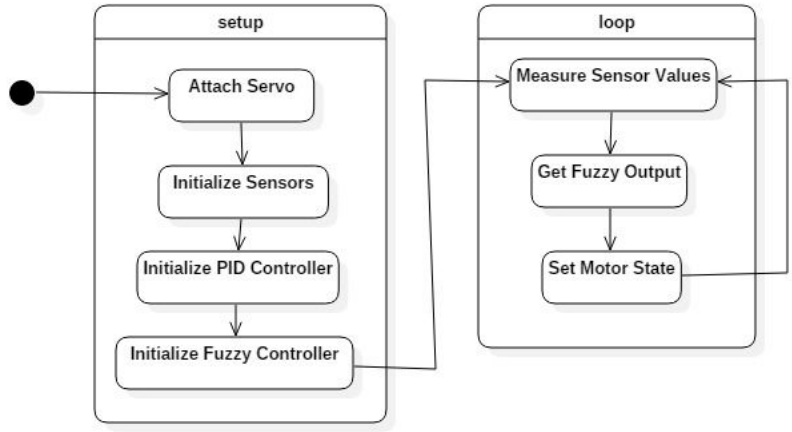


Figure 27: Membership functions for force inputs



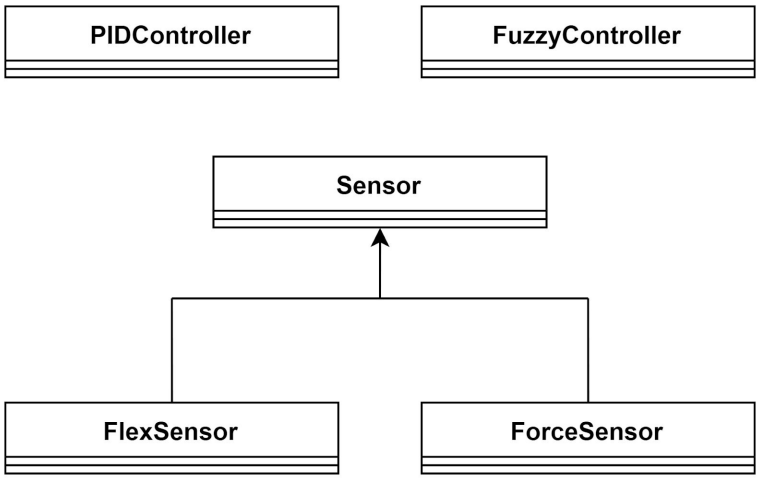
As with a traditional Arduino sketch, two high level states exist: setup and loop, as shown in figure 27. The setup state is reached only once and as implied by its name, is used for the setup steps, which consists of connecting the motor, initializing the flex and force sensors, initializing an instance of the PIDController class, and initializing an instance of the FuzzyController class. The loop state is reached indefinitely after and setup state and never exits. It is used to measure the sensor inputs (flex, force, encoder), calculate a target value using its fuzzy logic controller, and control the motor position using its PID controller.

Figure 28: simplified state diagram indicating the Tenaci Hand Grip state transitions



Multiple custom C++ classes, as shown in figure 28, had been written to abstract and encapsulate the functionality of certain modules within the system. The PIDController class is used to accept a target value and control the motor using said target angle as an input into a PID controller. The FuzzyLogic class is used to calculate a target angle for digit flex based on input pointers to the flex and force sensors. The Sensor, FlexSensor, and ForceSensor classes are used to abstract the functionality of the sensors, which includes initialization, calibration, and measurement.

Figure 29: Simplified class diagram indicating custom Tenaci Hand Grip classes



6 Business model

Figure 30: Business Model Canvas[2]

For the team's business model, Tenaci opted to work with existing medical distributors, rather than finding customers directly. As such, in addition to suppliers, Tenaci's key partners are those involved in the medical field. Tenaci relies on medical professionals in order to find customers. By establishing direct relationships with the healthcare field, and ensuring they understand the power of our product, Tenaci is able to rely on doctor recommendations of the

[2] Adapted From: Osterwalder, A. (2004) The Business Model Ontology—A Proposition in a Design Science Approach. PhD Thesis, University of Lausanne, Switzerland.

hand grip to individuals with conditions who would benefit from an assistive grip device. Additionally, Tenaci will also work with medical suppliers, pharmacies, and hospitals, to ensure their product is easily available and accessible to individuals who need it. The key activities of Tenaci outside of producing the hand grip device are to maintain a company website in order to look appealing to both customers and medical professionals, as well as to network with and market directly to medical professionals. As Tenaci does not need to perform mass consumer marketing, they are able to have a more refined cost structure, allowing the product to be offered at a lower price. Without mass marketing, the company's two largest costs are our continued product development, as Tenaci works to refine and improve our product, and the materials required to produce products. By working with medical distributors and facilities such as hospitals, most of Tenaci's revenue will come from large bulk orders that are fulfilled by these distributors, rather than by us directly. By working with medical distributors and professionals, this business model allows us to easily provide our customers with our key value propositions of restoring grip strength and serving as an alternative to prosthetic devices.

7 Economic Analysis

Table 10: Related costs to project

Cost	Classification
Production Materials	Direct, Variable, Material cost
Production/Warehouse Facilities	Indirect, Fixed, Expenses cost
Electricity	Indirect, Semi-Variable, Expenses cost
Marketing	Direct, Semi-Variable, Expenses cost
Income taxes	Indirect, Semi-Variable, Expenses cost
Employee Payment	Indirect, Fixed, Labour cost
Overhead	Indirect, Fixed, Expenses cost
Travel to meet w/ clients / attend conferences	Direct, Semi-Variable, Expenses cost
Production Machinery	Direct, Fixed, Expenses cost
Initial Prototype Cost	Direct, Fixed, Material cost

Interest Payments	Indirect, Fixed, Expenses cost
Research & Development	Indirect, Fixed, Expenses+Labour cost

Tenaci Hand Grip

Income Statement

End of Fiscal Period

Sales Revenue:	$2, 220, 000.00
Cost of Goods Sold:	$1, 054, 600.00
Gross Profit on Sales:	$1, 165, 400.00
Operating Expenses:	
Marketing:	$25,000.00
Salaries:	$500,000.00
Research & Development	$75,000.00
Facilities:	$100,000.00
General & Admin Expenses	$40,000.00
Total Operating Expenses:	$740,000.00
Total Operating Income:	$425,400.00

Break Even + Return on Investment Analysis

The following calculations assume that operating income evenly distributed across the first three years.

The operating income per year for this analysis is $262,083.33 following the first year's investment.

The total Investment is $2,000,000 which included land, machines, equipment research, and development of the initial prototype.

Return on investment in the first year = $262083.33/$2,000,000 = 13.104%

Simple payback period = $2,000,000/$262083.33 = 7.63 years

Net Present Value Based Break Even Point, using operating income from above:

Year	cash flow	discounted value
1	$ 262,083.33	$ 254,449.84
2	$ 262,083.33	$ 247,038.68
3	$ 262,083.33	$ 239,843.38
3	$ 262,083.33	$ 239,843.38
4	$ 262,083.33	$ 232,857.65
5	$ 262,083.33	$ 226,075.39
6	$ 262,083.33	$ 219,490.67
7	$ 262,083.33	$ 213,097.73
8	$ 262,083.33	$ 206,891.00
Total (8 yrs)	262083.3333	2079587.705
NPV (eight years)		79587.70456

Table 11: Net Cash Flow Analysis

It would take eight years following the initial development time to break even according to a yearly NPV analysis

4. Describe and justify all assumptions that you have made in developing your economics report.

1) Cost of Production of actual units will be much lower than prototype production, streamlining processes, developing specific microcontrollers, and purchasing materials in bulk will all contribute to this. Therefore, we estimate our cost of production of each unit to be $95.
2) Assuming a sales price of $200 CAD, this is a reasonable price due to the components and development put into creating the product, as well as the fact all components will need to be medical-grade and because the client's insurance could potentially assist in payment for the device.

3) The population of Canada is approximately 37,000,000 people, and seeing as thoracic outlet syndrome occurs in 1-2% of the population, we estimate 555,000 individuals suffer from it. If we assume 2% of these individuals purchased our product within the first 3 years of production, 11,100 units would be sold within the first three years.
4) Our marketing costs remain relatively low, as most marketing is not nationwide, public campaigns, but rather, marketing our device to medical professionals and relying on doctor recommendations as outlined in out business plan.
5) The initial investment for the break-even analysis was $2,000,000.

8 Conclusions and Recommendations for Future Work

As future engineers, some of the most crucial lessons of this project revolved around project management and the application of learned skills in a team setting. When the Gantt chart was initially created and the critical path planned out, the team did not take potential setbacks into consideration, which added additional stress when dealing with mechanical complications. Due to the complexity of this project, it is very difficult to integrate all electrical components of the glove. On the other hand, as most team members were from different fields of Engineering, it was crucial that everyone practiced good communication skills to transfer knowledge in respective fields efficiently to ensure everyone was on the same page, saving time. Furthermore, it was equally important to be able to communicate our plans to Tenaci's first client, Adrienne; a product will never be interesting or appealing to potential customers if they do not have a straightforward explanation of how it works.

When completing concept generation and designing prototypes, it was discovered that the most important factor was designing for the *client*, not the designer or engineer. It is often easy to believe that the technical experts can create the best solutions and "know their stuff" the most. However, as the client will be the user of the product, it is paramount that their advice and recommendations are made a priority. Moreover, when prototyping, it was discovered that failure, whether it is in the functionality of the prototype, or the materials used, is of great

value. Failure allows teams to identify what should not be done or what needs to change, enabling good prototyping iterations and an improved final product.

For Tenaci, the next steps are the integration of software. This step is particularly difficult, as there are many components that must work together, including the fail safe, the flex sensors and the "stop" mechanism in the pinky finger. Afterwards, the electrical components will need to be scaled down to be more user friendly. In addition, the polyester and lycra blend will need to be tested as the material used for both layers of the glove, as it may not be breathable enough for long term wear. Finally, when Tenaci succeeds in creating a final product, it will have to be expanded to a larger market than a single client. As mentioned in the business model canvas, the best course of action is to reach out to medical distributors, as they would allow Tenaci to reach a greater part of their clientele.

9 Bibliography

1. "Thoracic Outlet Syndrome Information Page." *National Institute of Neurological Disorders and Stroke*, U.S. Department of Health and Human Services, 27 Mar. 2019,16:20,www.ninds.nih.gov/Disorders/All-Disorders/Thoracic-Outlet-Syndrome-Information-Page.
2. Osterwalder, A. (2004) The Business Model Ontology—A Proposition in a Design Science Approach. PhD Thesis, University of Lausanne, Switzerland.

APPENDICES

APPENDIX I: User Manual

Product Features:

- Automatic fail-safe grip stopping
- Pressure & finger attitude based grip triggering
- Pinky-triggered Finger Attitude based release
- Synchronized index-finger and thumb gripping
- Fuzzy-logic based control system
- Integrated rechargeable battery

Product Functions and Capabilities:

The Tenaci Hand Grip's primary function is the provide a pinch grip between the index finger and thumb of the user. Currently, this pinch grip is the only grip profile the device can provide and allows users to grasp several different objects effectively. In order to trigger the tension-based gripping motion, the user only needs to begin to grasp an object. When pressure and finger flex have been detected by the device, the assistive grip will be initiated, providing the user with extra grip strength by tensioning cabling attached to rings within the glove's inner layer. While gripping, the hand grip system continues to monitor the strength of the grip by use of the pressure sensors, as well as the finger's angle, and tracks how far the spool has wound.

This allows the device to be safe, by automatically stopping the grip once a threshold for flex or pressure have been exceeded, and reduces potential damage to the device by ensuring the spool does not wind too far. Whether or not the failsafe has been triggered, the user can stop the grip when desired, by simply straightening their pinky, triggering the flex sensor mounted to it, and releasing the grip. Once the grip has been released, the spool will begin to unwind, un-tensioning the strings attached to the finger and thumb rings and allowing the user to freely open their hand. While releasing, the encoder mounted to the spool will monitor the amount the spool has unwound, restoring it to the same neutral position each time.

Installation Instructions:

The Tenaci Hand Grip will arrive as two separated parts, the control box and the glove. In order to begin using the Hand Grip, these devices must simply be connected together, using the following process.

1. Place the included charging cable into slot on left side of control box to initiate device charging
2. Plug color-coded quick-disconnect wires from the top-face of the control box to the corresponding coloured wires on the bottom-half of the glove
3. Remove the top layer by separating the hook-and-loop tape connecting the two glove layers along the bottom seam of the glove. Ensure the cable is securely connected to each of the finger rings and that the flex sensors are correctly seated. Re-attach the two layers.

4. Once the battery has been fully charged, flip the switch on the top of the control box. This will power on the device.
5. Adjust the hook-and-loop strip attached to the control box to comfortably fit onto your wrist.

The device has now been properly set up and is ready to use.

Safety Guidelines, Precautions, and Health Issues

- When using the device for the first time, although the failsafe is present, be prepared to turn off the device if the finger tension exceeds a comfortable level.
- There may be small delay between lifting the pinky to release grip and the device releasing the tension. If the grip does not release instantly, continue to hold your finger straight until the glove begins to release the grip.
- The device takes time to unwind the spool and release the grip. Do not try to force the hand open during this time at risk of injuring yourself and damaging the device. Instead, wait for the tension to be released from your hand before trying to open your hand.
- The device is not waterproof despite the two layer design. Either ensure the glove is covered in a waterproof layer before exposing it to water, or keep the glove away from water

Troubleshooting

- Device not sensing grip triggered

    - Ensure all wires are properly plugged in from the glove to the control box, and that all colours properly match. Ensure all sensors on the outside of the inner layer are properly mounted, and the pressure sensors make contact with the object to be gripped. Ensure device is properly charged.
- Grip is not triggering
    - Ensure device is properly charged and that all wires from the glove are properly plugged into corresponding wires from the control box.
- Motor can be heard triggering, but grip is not being augmented
    - Ensure fishing line on the inner layer of the glove is properly attached to both thumb and forefinger, as well as to the spool itself
- Straightening Pinky does not release at a comfortable point
    - Slide pinky flex sensor upwards in its housing so that straightening the pinky has a greater effect on the flex sensor readings
- Device is not automatically shutting off at a comfortable point
    - Slide thumb and forefinger flex sensor upward such that they trigger with less flex. Additionally, ensure the encoder is properly seated into the spool, and that all wires are properly connected.

APPENDIX II: Design Files

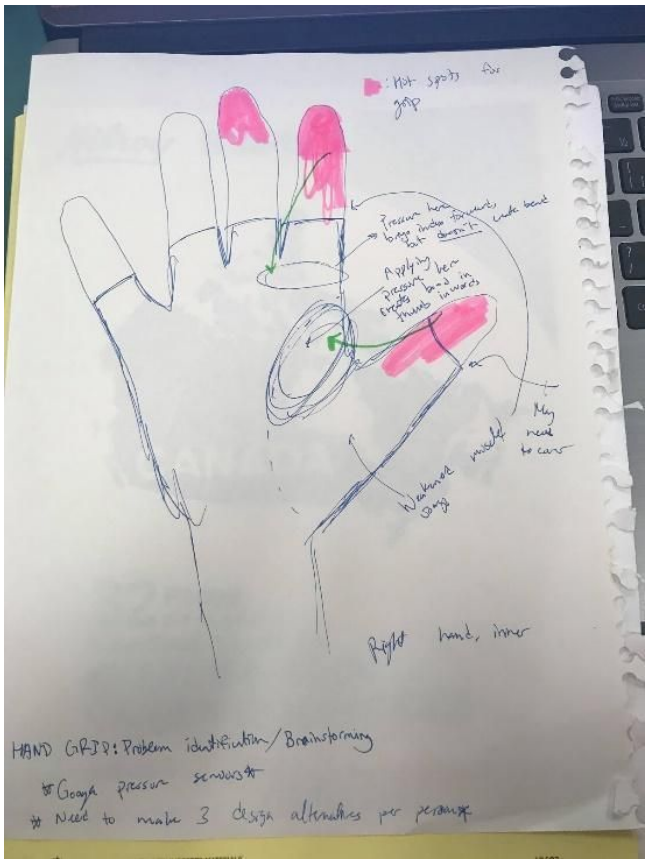


Figure 31. Brainstorming Design Sketch 1

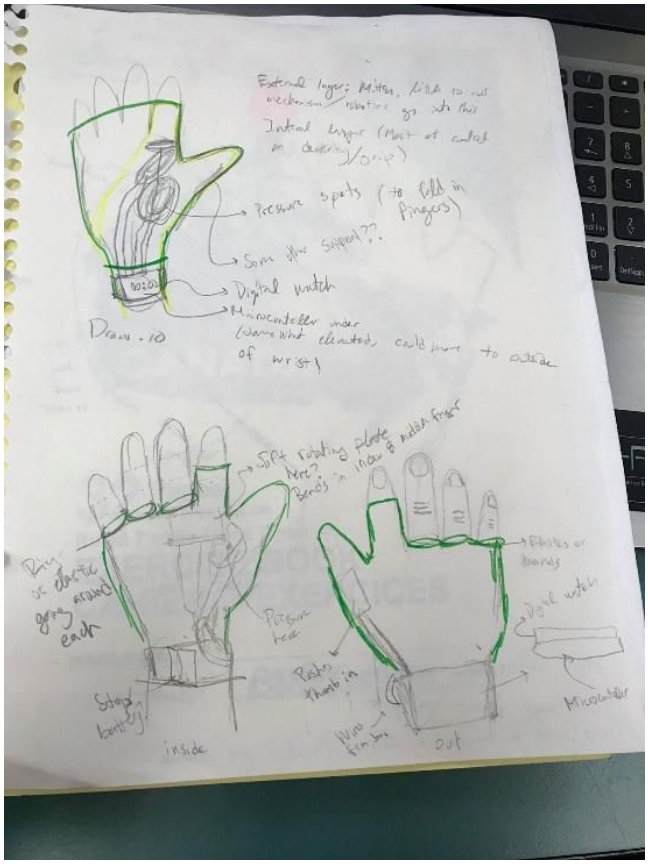


Figure 32. Brainstorming Design Sketch 2

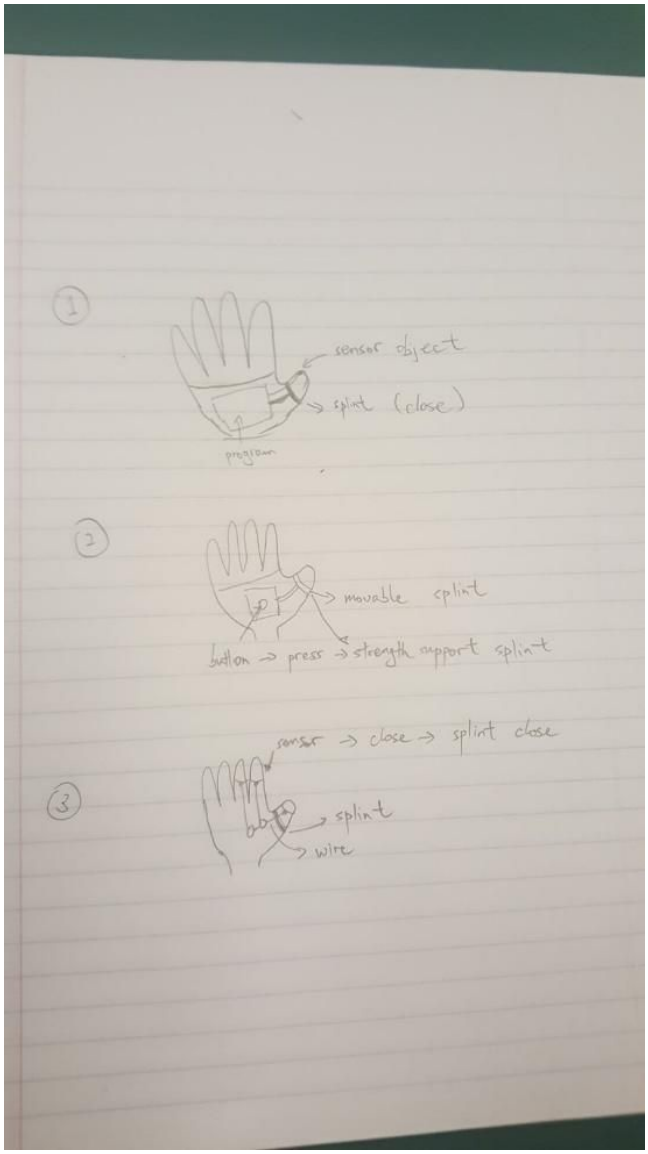


Figure 33. Brainstorming Design Sketch 3

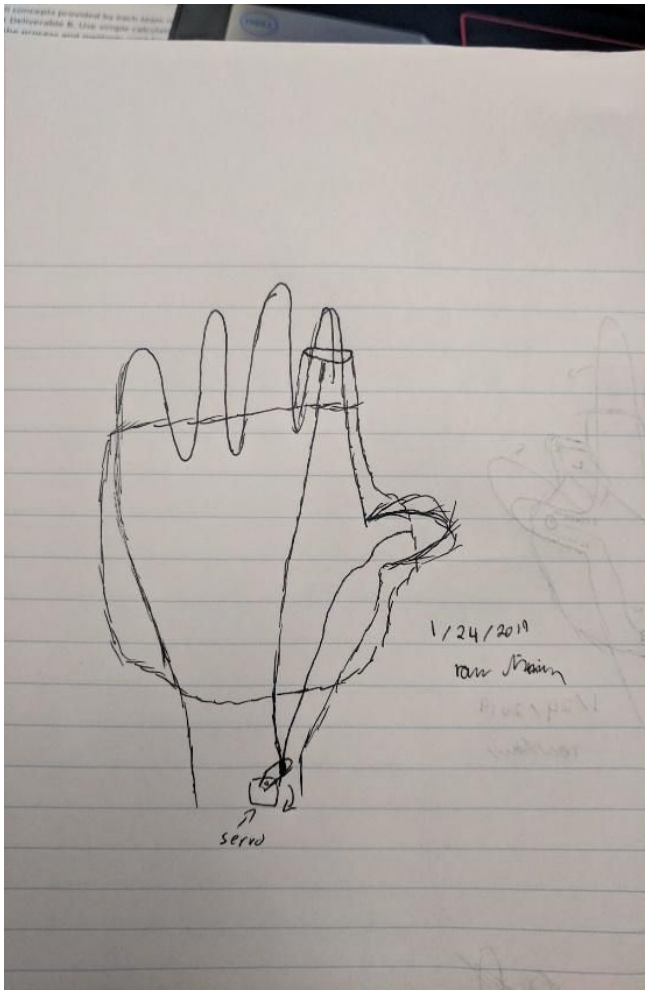


Figure 34. Brainstorming Design Sketch 4

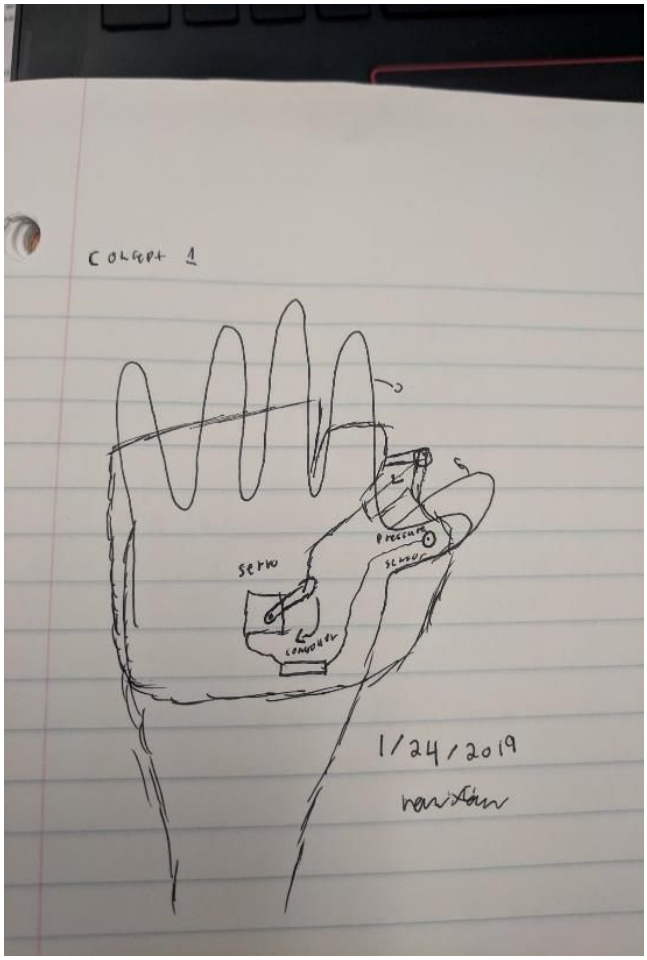


Figure 35. Brainstorming Design Sketch 5

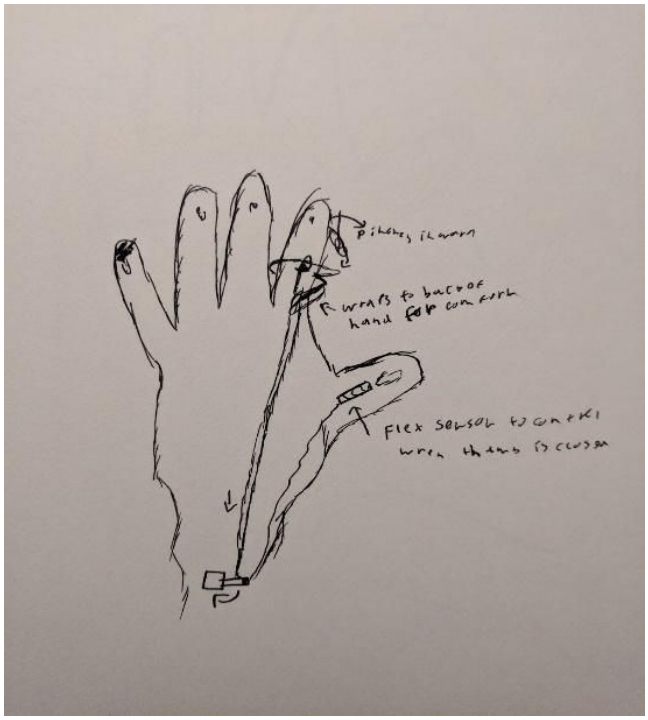


Figure 36. Brainstorming Design Sketch 6

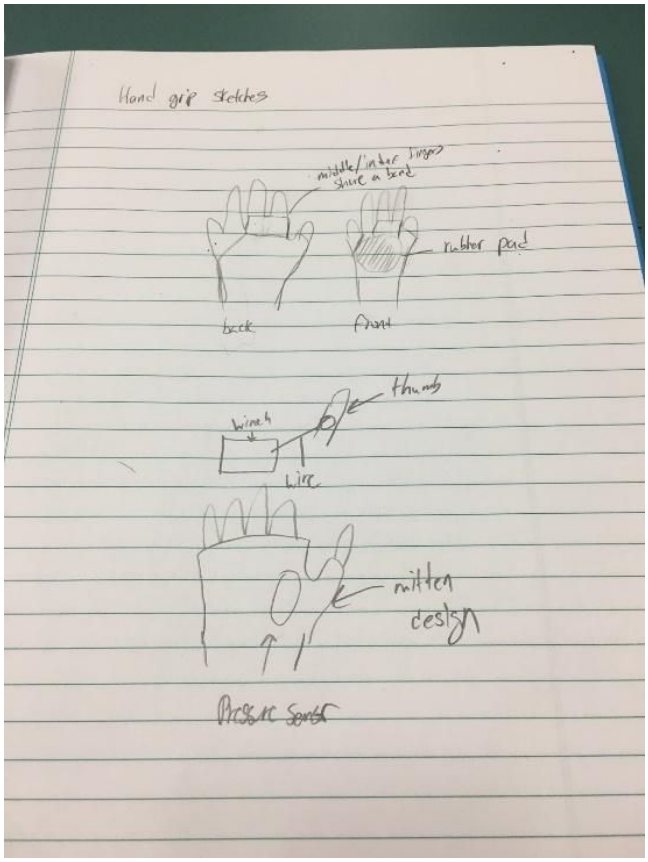


Figure 37. Brainstorming Design Sketch 7

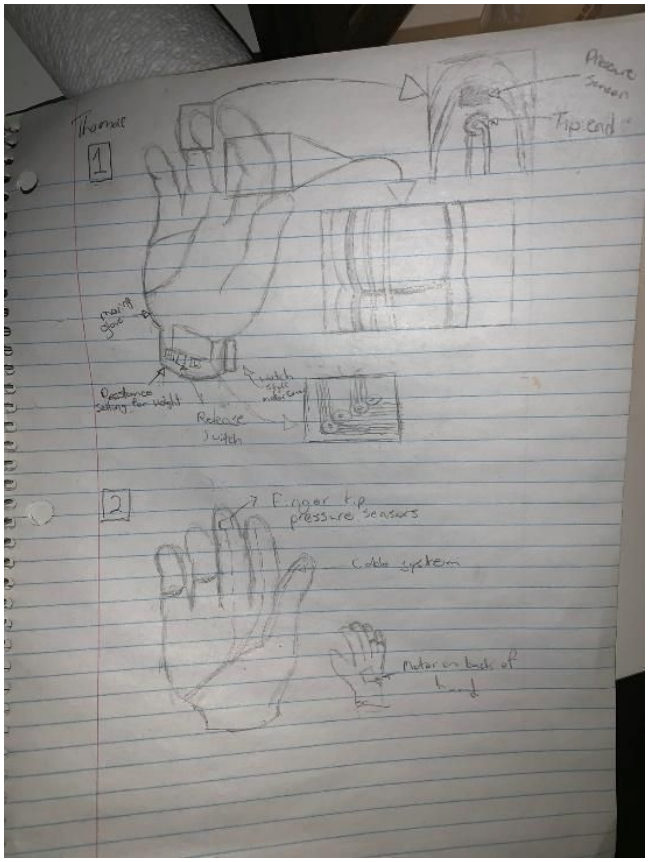


Figure 38. Brainstorming Design Sketch 8

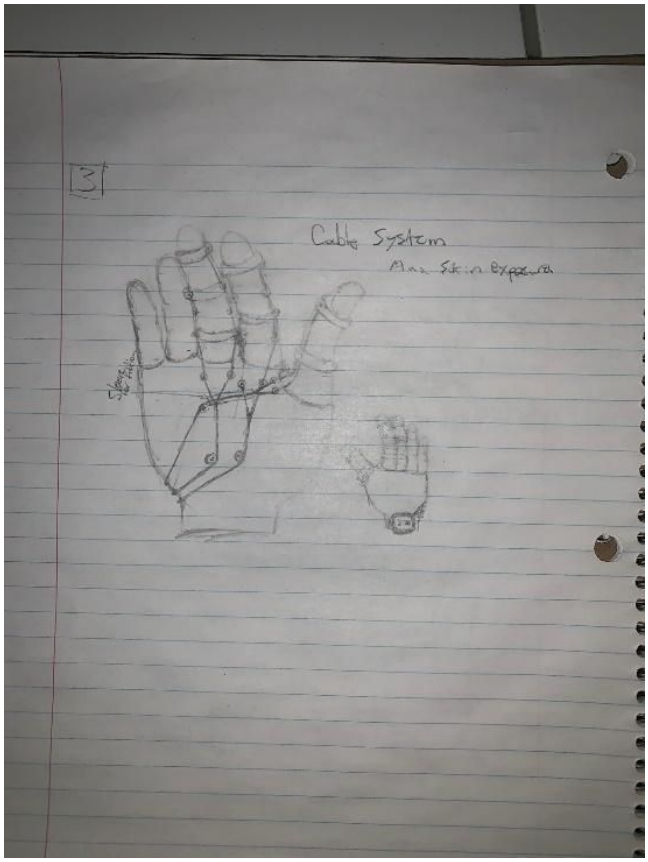
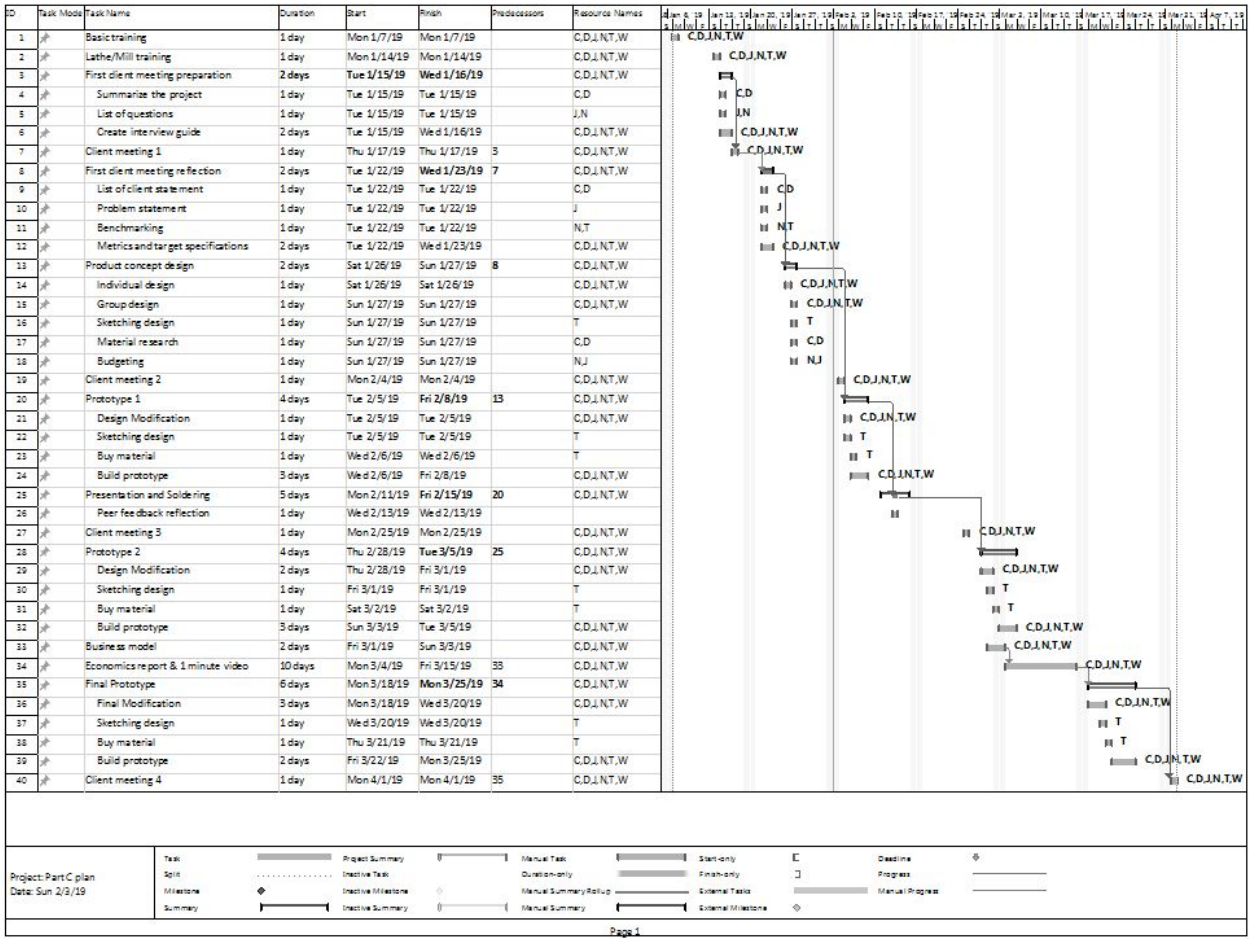


Figure 39. Brainstorming Design Sketch 9



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1		Basic training	1 day	Mon 1/7/19	Mon 1/7/19		C,D,J,N,T,W
2		Lathe/Mill training	1 day	Mon 1/14/19	Mon 1/14/19		C,D,J,N,T,W
3		First client meeting preparation	2 days	**Tue 1/15/19**	**Wed 1/16/19**		C,D,J,N,T,W
4		Summarize the project	1 day	Tue 1/15/19	Tue 1/15/19		C,D
5		List of questions	1 day	Tue 1/15/19	Tue 1/15/19		J,N
6		Create interview guide	2 days	Tue 1/15/19	Wed 1/16/19		C,D,J,N,T,W
7		Client meeting 1	1 day	Thu 1/17/19	Thu 1/17/19	3	C,D,J,N,T,W
8		First client meeting reflection	2 days	Tue 1/22/19	**Wed 1/23/19**	7	C,D,J,N,T,W
9		List of client statement	1 day	Tue 1/22/19	Tue 1/22/19		C,D
10		Problem statement	1 day	Tue 1/22/19	Tue 1/22/19		J
11		Benchmarking	1 day	Tue 1/22/19	Tue 1/22/19		N,T
12		Metrics and target specifications	2 days	Tue 1/22/19	Wed 1/23/19		C,D,J,N,T,W
13		Product concept design	2 days	Sat 1/26/19	Sun 1/27/19	8	C,D,J,N,T,W
14		Individual design	1 day	Sat 1/26/19	Sat 1/26/19		C,D,J,N,T,W
15		Group design	1 day	Sun 1/27/19	Sun 1/27/19		C,D,J,N,T,W
16		Sketching design	1 day	Sun 1/27/19	Sun 1/27/19		T
17		Material research	1 day	Sun 1/27/19	Sun 1/27/19		C,D
18		Budgeting	1 day	Sun 1/27/19	Sun 1/27/19		N,J
19		Client meeting 2	1 day	Mon 2/4/19	Mon 2/4/19		C,D,J,N,T,W
20		Prototype 1	4 days	Tue 2/5/19	**Fri 2/8/19**	13	C,D,J,N,T,W
21		Design Modification	1 day	Tue 2/5/19	Tue 2/5/19		C,D,J,N,T,W
22		Sketching design	1 day	Tue 2/5/19	Tue 2/5/19		T
23		Buy material	1 day	Wed 2/6/19	Wed 2/6/19		T
24		Build prototype	3 days	Wed 2/6/19	Fri 2/8/19		C,D,J,N,T,W
25		Presentation and Soldering	5 days	Mon 2/11/19	**Fri 2/15/19**	20	C,D,J,N,T,W
26		Peer feedback reflection	1 day	Wed 2/13/19	Wed 2/13/19		
27		Client meeting 3	1 day	Mon 2/25/19	Mon 2/25/19		C,D,J,N,T,W
28		Prototype 2	4 days	Thu 2/28/19	**Tue 3/5/19**	25	C,D,J,N,T,W
29		Design Modification	2 days	Thu 2/28/19	Fri 3/1/19		C,D,J,N,T,W
30		Sketching design	1 day	Fri 3/1/19	Fri 3/1/19		T
31		Buy material	1 day	Sat 3/2/19	Sat 3/2/19		T
32		Build prototype	3 days	Sun 3/3/19	Tue 3/5/19		C,D,J,N,T,W
33		Business model	2 days	Fri 3/1/19	Sun 3/3/19		C,D,J,N,T,W
34		Economics report & 1 minute video	10 days	Mon 3/4/19	Fri 3/15/19	33	C,D,J,N,T,W
35		Final Prototype	6 days	Mon 3/18/19	**Mon 3/25/19**	34	C,D,J,N,T,W
36		Final Modification	3 days	Mon 3/18/19	Wed 3/20/19		C,D,J,N,T,W
37		Sketching design	1 day	Wed 3/20/19	Wed 3/20/19		T
38		Buy material	1 day	Thu 3/21/19	Thu 3/21/19		T
39		Build prototype	2 days	Fri 3/22/19	Mon 3/25/19		C,D,J,N,T,W
40		Client meeting 4	1 day	Mon 4/1/19	Mon 4/1/19	35	C,D,J,N,T,W

Figure 40: Gantt Chart

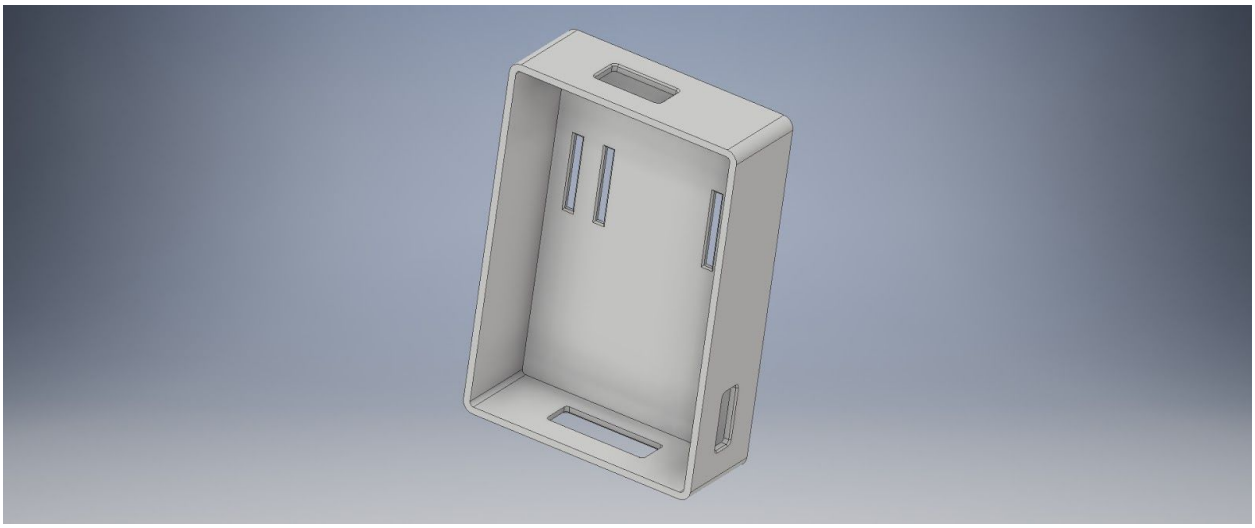

Figure 41: Control Box

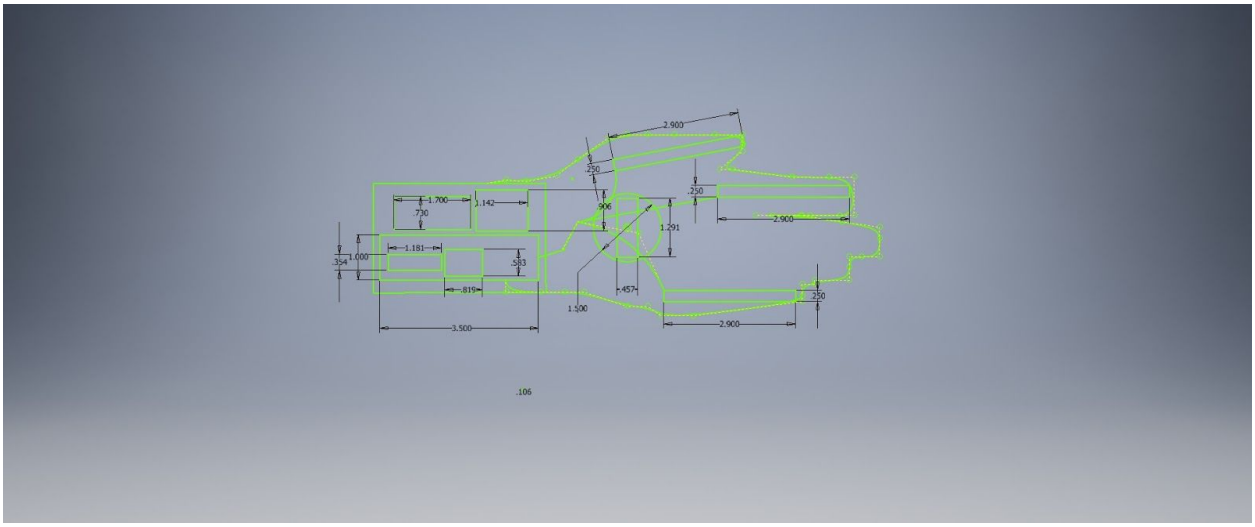

Figure 42: Plan for Component Placement

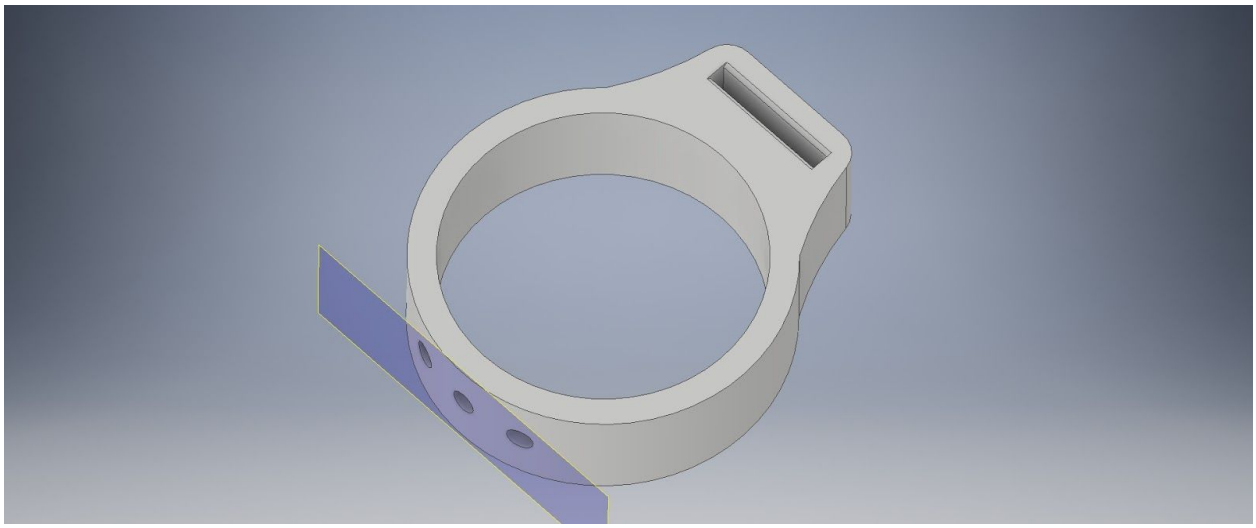

Figure 43: Ring used for flex sensor and fishing line mounting