DESIGN OF AN ASSISTIVE UPPER LIMB

Final Report - June 2018

Abstract

The remit of the project in question was to integrate electronic assistance into an existing e-Nable mechanical prosthesis. The purpose of this additional assistance was to remove the strain required by e-Nable users when holding objects. The main vision of the project was to was to make partial hand prostheses easily accessible to all those in need and to create a device that improves the quality of life of users. A force resistive sensor was used to detect muscle contractions in the forearm, sending an electrical signal to an ARDUINO micro-processor which in turn initiated contraction of the prosthesis with the aid of a linear actuator. A prototype was created, however rework from other designers is encouraged to optimise the design and create a fully functioning solution.

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I. Introduction

The field of prosthetics has existed for centuries, evolving and changing its purpose over the years. The user must decide on a balance between aesthetics and functionality and are only limited by price and availability of such products. As prosthetics technology becomes more widespread, the possibilities of creation and development of prostheses by enthusiasts and experts increases. This is supported by the ease of sharing information on the internet, the advent of additive manufacturing and the increasingly powerful processors and circuit boards.

The rise of 3D printing in the prosthetics industry has allowed for an easier way to customise parts and quickly print using affordable materials. There are a number of mechanical devices available for people with residual partial palms, that can be 3D printed from models on the internet. E-Nable is an organisation of volunteers who have answered the need for a partial hand prosthetic with innovative 3D printed, mechanical solutions. Conversely, there are limited options for an electronically aided prosthesis for this purpose on the market. Furthermore, manufacturers of electronic prostheses tend to use high-cost materials creating very expensive solutions. The need for customised designs involving several tests and calibrations for each specific user is also a time consuming process.

There is a partnership between e-Nable and the GI-NOVA laboratory, part of the school of Génie Industriel of Grenoble INP. As a result of that association, adapting a robotic assistive technology in a mechanical prosthesis became the project for the course of Responsible Design in the second semester of 2017-2018. The present report aims to explain the development and final result of the project.

Throughout the project, modifications were made to an existing mechanical hand design. The adaptations included integrating electrical components and revising aspects of the original design in order to meet the needs from an electronic device of a person with below the wrist amputation.

With the aim of making the final prosthesis available for the broad public, it was determined that the whole process should be documented and the results made open-source, which also allows for future analysis and improvement by third parties. In addition, all of the mechanical were printed, with the exception of specific components such as Velcro, fishing line and others that can be easily purchased off the shelf.

II. Theory

A. Prosthetics - Upper Limb Prosthetics

Upper-extremity (e.g. fingers, arm, forearm, bicep or triceps) prosthetics is the broad classification that encompasses all devices that are fitted to patients as replacements for upper limbs. These can be anything from shoulder replacements joint to partial finger devices. There are three main categories of these types of prosthetics:

- Passive devices, which solely serve a cosmetic purpose and have no practical functionality;
- Body powered mechanical prosthetics which are mechanically operated by the individual to perform simple tasks;
- Electronic or electrically driven prosthetics that use sensors and actuators to perform functional tasks and can even incorporate haptic feedback to inform the user of the properties or form of objects.

B. Computer Aided Design (CAD)

CAD is a software that can be used to design products and documents in order to conceptualise the dimensions, tolerances, materials and processes of the product in question. This is often used to create two-dimensions and three-dimensional detail technical drawings, models and plans but can also be used to design and program electronic circuit boards. Many CAD software packages allow simulation prototyping such as kinematic modelling, which indicates how various parts dynamically interact with each other, and circuit modelling which shows how an input will translate through connections to an output.

C. 3D Printing - FDM

3D printing is a technique associated to various types of technologies which allow for the production of 3D objects. The products are fabricated through the creation of layers of material, based on a 3D CAD model. Some of the most notable characteristics of 3D printing are:

- **Freedom of conception:** With the help of supports and changing the inner density of parts, the final product can have complex geometries and lightweight designs. This is especially useful in a project of this type where parts have freeform surfaces and small splined tubes that would be impossible to machine using standard machining techniques.
- **Rapid prototyping:** Because of its freedom of conception, 3D printing is a very useful tool for creating personalised objects. It is not necessary to create a complete productive process for each design.
- **Environmentally friendly:** The process avoids waste of material because the supports and unused parts can be melted back into prime matter and reused in future prints.
- **Single tool:** Using only the 3D printer as a tool, it is possible to create various shapes and sizes, with different levels of precision. There is no need for specific tools for each desired result.

- **Software:** The specific software packages can specify the fastest and most precise way of printing, facilitating the process.

For 3D printing with plastics, Fused Deposition Modelling (FDM) is the most common method [b]. It consists in heating a thermoplastic filament, depositing it in sequential layers when it goes through the printer's extruder. A thermoplastic material is characterised by its soft and mouldable state when heated and solid state when the temperature lowers. The layer of material cools down and hardens after being placed on the desired position, adhering to the previous layer and creating continuity on the surface.

D. ARDUINO

ARDUINO is an Italian company which has developed several multifunctional processing boards with a simple user interface. Each ARDUINO board has different capabilities due to the microprocessors, and varying shapes and sizes according to the number of pins, the types of powering and other features.

The ARDUINO boards are low priced and can be found in very small dimensions, which makes it simple for hobbyists to make creations using the devices. This phenomenon has given place to several online tutorials and forums where creators from around the world can solve problems and gain inspiration from each other. This web of information confers to the boards the advantage of easier comprehension of use and versatility.

In order to facilitate the programming of the ARDUINO board, the developers created a specific programming language, based on *processing*, which is very similar to C. The ARDUINO programming language can be compiled and uploaded to the board through a platform called ARDUINO IDE (Integrated Development Environment), which is available for free download on their website, but can also be used online though the *ARDUINO Web Editor*, with data saved on the cloud.

E. Sensors

Sensors are means of measuring variables and collecting data and information. They are used only in closed control loops. They convert physical variables in a convenient form of lecture (electrical signals). Sensors can be passive or active - working with or without the need of an external source of power to operate, respectively.

In the field of prosthetics, it is observable that certain types of sensors are more widespread. Those sensors are the electromyography sensor (EMG), the force sensing resistor (FSR) and the flex sensor, explained below:

1) Myoelectric EMG Sensor

EMG sensors are based on electrodes placed on the surface of the skin, used to measure the electrical activity resultant of nerve stimulation on muscles. The data is then amplified and converted into voltage that can be read by the processor associated to the sensor. The output voltage can go from 0V up to the voltage of the power source, proportionally to the sensed activity. The electrode placement for the EMG sensor is of great importance because it affects the intensity of the read signals. Below is an example of an advanced EMG sensor.

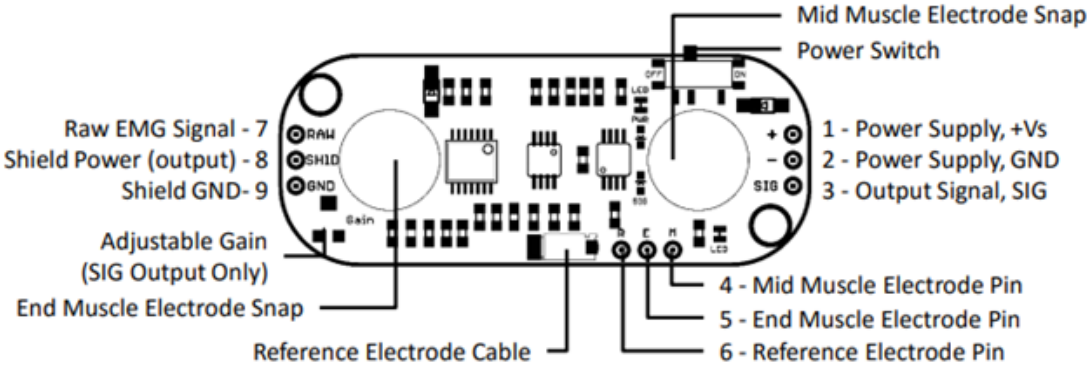


Figure 1 - EMG Sensor Layout [k]

2) Force Sensing Resistors

FSRs (shown in *Figure 2*) register applied pressure through the variation of resistance in an inversely proportional relation. This type of sensor is made for use in human touch and is characterized by the sensing area and by sensing range. The sensing area defines the precision of the applied force, and the sensing range specifies the upper and lower limits of interpretable pressure. The reduction of the resistance level occurs when the interdigitating electrodes touch the semiconductor area across the spacer adhesive. The more the electrodes touch the semiconductor, the lower the resistance. It is important to mention that, despite the similar properties, FSRs are different from a load cell or a strain gauge.

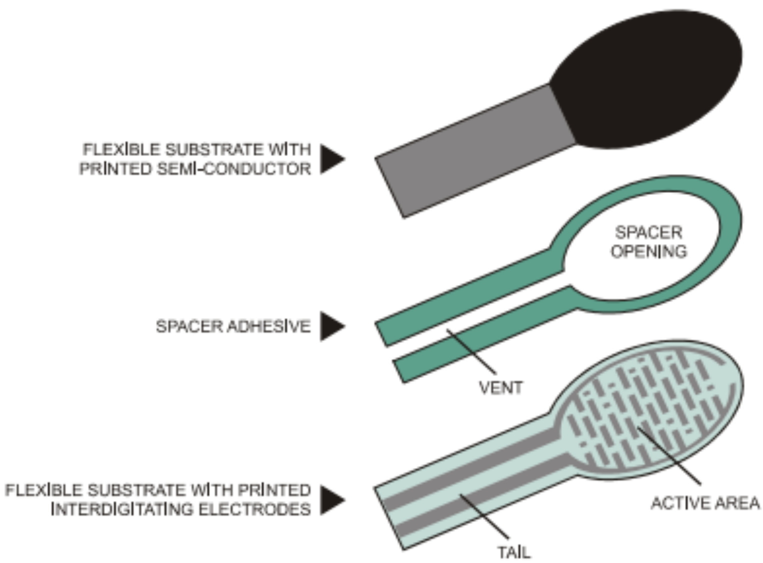


Figure 2 – Composition of a Force Sensing Resistor [j]

3) Flex Sensors

Flex sensors are carbon based resistors in form of stems that measure the amount of deflection through the directly proportional variation of resistance. The principle is that in one of the sensor's surfaces there is a polymer ink with conductive particles. The distance between the particles defines the resistance of the sensor, so if the stem is bent in a way that expands the distance between the particles, the resistance rises. A schematic is presented below:

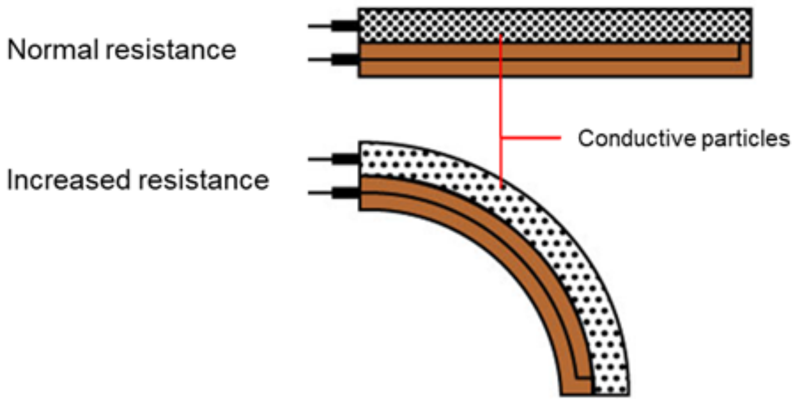


Figure 3 - Explanatory Diagram of a Flex Sensor [i]

F. Actuators

An actuator is a mechanical or electromechanical device which moves or controls a mechanism, it translates a control signal into mechanical action. Actuators can be powered by hydraulic, pneumatic, electric, thermal or mechanical means, and their movement can be characterised as linear, rotary or chain. Some of the key specifications are the motor type, rotation or expansion limits, force capacities, mounting configuration and number of positions, as well as other characteristics. Types of actuators include: electric linear, electric rotary, fluid power linear, fluid power rotary, linear chain, manual linear, manual rotary.

G. Open Source

Open source is a term that refers to any technology where the design and/or code is made freely available to others to view, copy, learn from, alter and share. The most important aspect of this trend is that it is used to promote cooperation by allowing contributors to share their knowledge and experience, and have their ideas critiqued on a public platform. As with proprietary data, users must accept the term of the license before they can utilise the open source technology.

Source technology/code distributors abide by a number of rules, including, but not limited to, [c]:

- Free Redistribution

> **"Source Code**
>
> The program must include source code, and must allow distribution in source code as well as compiled form. There must be a well-publicised means of obtaining the source

code for no more than a reasonable reproduction cost, preferably downloading via the Internet without charge."

"Derived Works

The license must allow modifications and derived works, and must allow them to be distributed under the same terms as the license of the original software."

- Allow the code to be easily modified and peer-reviewed

"Integrity of The Author's Source Code

The license may restrict source-code from being distributed in modified form only if the license allows the distribution of "patch files" with the source code for the purpose of modifying the program at build time. The license may require derived works to carry a different name or version number from the original software."

- Ensure the author is known and their reputation is protected, unofficial versions can be identified

"No Discrimination Against Persons or Groups
[...] the maximum diversity of persons and groups should be equally eligible to contribute to open sources."

H. Additional Relevant Electronics Information

1) Boost Converter

Regular source voltages often do not satisfy the levels required by the chosen components. Boost converters, also known as step-up converters, are circuits that convert a standard input voltage into a chosen output voltage fit for use. This process depends on several components, such as semiconductors and energy storage elements, using current reduction [I]. The converters use magnetic fields created by inductors as a switch to alternately store energy and release it at a higher voltage, also reducing its ripple. The schematic can be found in *Figure 4.*

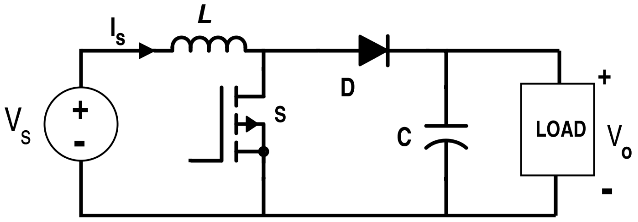


Figure 4 - Boost Converter Schematic

The principle is that the inductor (represented by L), charged with a certain amount of energy, then acts as a source of power when releasing the stored energy. The transistor behaves as a switch controlled by voltage. When the switch is closed, the power coming from the battery loads the inductor, increasing the current value. Once the switch is opened, the current flows through the rest of the circuit and induces an elevation in the voltage. The voltage provided to the load depends on the amount of time the switch stays open and closed. The regulation of the desired output voltage can be made through either voltage or current feedback.

2) PWM - Pulse Width Modulation

This is a type of digital signal that creates several pulses with varied widths, often used to simulate an analogue behaviour. The widths of the pulses are measured according to the percentage of time the signal is kept as high, which is called a duty cycle. A visual demonstration of PWM can be seen below in *Figure 5:*

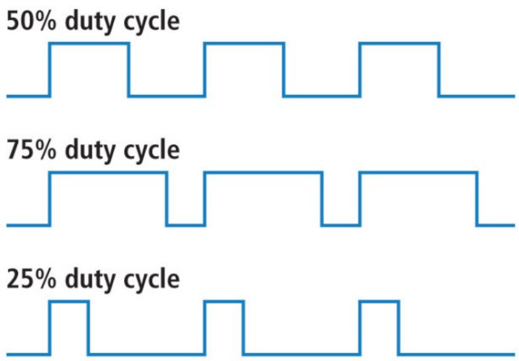


Figure 5 - Pulse Width Modulation Graphs [g]

3) Switches

Switches are devices that have the basic function of opening or closing the connecting paths for the current to flow through the circuit. It could be used to turn a circuit on or off. Switches can be classified according to the number of poles and throws. Poles define the amount of separate circuits the switch can control. The number of throws represents how many positions each pole can be connected to. Therefore, the classifications are: SPST (Single Pole Single Throw), SPDT (Single Pole Double Throw) or DPDT (Double Pole Double Throw) [e]. These types of switches are shown in order in *Figure 6*.

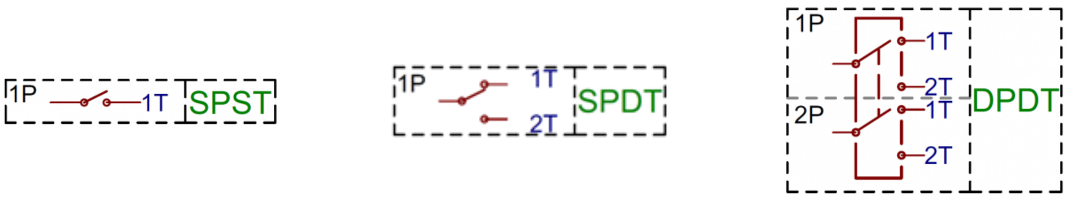
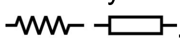


Figure 6 - Examples of Different Switches

Resistors are basic components that convert electrical energy into thermal energy. This feature creates the capacity of limiting the passage of current through the circuit. They are characterised by resistance, which is measured in ohms (Ω) on the International System of Units (S.I.). Resistors are represented by the following symbols in a circuit: . Resistors can be combined in parallel or in series, which result in different resistances.

4) Soldering

This is a technique used to join parts, such as wires and other electrical components, through melting a filler metal in the joint. The rule for choosing the filler metal is that it must have a lower melting point than the metal in the parts to be joined. Soldering is considered a permanent form of connection, and it is done with the use of a soldering iron. The soldering iron is a heating device with a handle for easier manipulation and a pointy end for better precision.

5) Solder board

Used to organise the wiring of a circuit, this type of device is a board with several holes for soldering. Once the components are soldered into the solder board, it becomes difficult to modify the circuit, so it is a component used mostly for final products. Prototyping is commonly made in breadboards, which are easily modifiable and do not demand soldering.

III. State of the Arts

A. Summary of Findings

In order to understand the current state of the field of prosthetics, a study was carried out to determine the state of the arts solutions in the various aspects of the project. In this section, some relevant aspects approached in the State of the Arts Report are summarised.

A number of electronic hand solutions were identified and analysed, which had similar specifications and capabilities to those required by this project. These hands were the i-digits Range, Brunel, HACKberry, Taska, Bebionic, Michelangelo, Toronto Bloorview Macmillan (TBM), Southampton, Iowa and Claws from Carter.

Most of these had common elements, including a rotary or linear actuator for each individual finger and thumb. The independent motion of the fingers allows for various grip patterns. This was mainly a feature of full hand prostheses where there was enough space inside the palm to house the additional components. However, in the proposed partial prosthesis there would not be enough room in the palm to allow for this. One or two rotary or linear actuators that could pull all fingers would be preferred for that matter.

The actuators considered were as follows:

- **Stepper motors:** Rotate in discrete increments, allowing for position measurement but with inferior load bearing capacity;
- **Servo motors:** Light and inexpensive, with position feedback that is not limited to discrete steps;
- **Linear motors:** Transmit motion in a straight line and can be affordable and compact.

Types include pneumatic, hydraulic, with electro-mechanical as a common choice in prosthetics.

Myoelectric sensors were also found in the HACKberry, Taska, Bebionics, Michelangelo and Claws from Carter hands. The use of those allowed for intuitive user input in controlling the grip position.

The sensors considered were as follows:

- Myoelectric sensors: Detects EMG signals emitted from the muscle. Although this method requires less physical effort, it also requires the accurate positioning of the electrodes and precise calibration.
- Force sensors: This works along the same line as a myoelectric sensor although rather than detecting the EMG signal, it detects the resultant muscle contraction.

Those with sensors are also equipped with an embedded microprocessor, such as ARDUINO boards, for control between the sensor and the actuation. This was required to use the input sensor signal to generate an output that would drive the actuator. ARDUINO codes are open source, allowing for developers to modify, evolve and reproduce them. The use of ARDUINO boards in prosthetic devices can be owed to its simple interface, ease of operation and affordability. The ARDUINO Company is an advocate of open source creations, leading creators who use ARDUINO boards to share their experiences and ideas.

Some of the analysed prostheses, like the Brunel and HACKberry hand, rely on open source development, a model that has allowed for rapid innovation. The designed prosthesis must be made open source with easily accessed file formats and technical information. Uniquely, the HACKberry hand is a 3D printed solution to aid in open source availability.

The Bebionic hand is the strongest of the electronic upper limb prosthetics with a load capability of 45kg. It integrates soft finger pads and anti-slip sensors to create a more efficient grip interface. Other existing solutions also use silicone finger tips for additional grip.

Regarding the modelling of the prosthesis, in the State of the Art report, the online CAD package Onshape was compared with other CAD software packages, including Fusion 360, Solidworks, FreeCAD and Autodesk AutoCAD. Onshape allows collaboration and sharing using a cloud-based data storage system. Multiple users can edit a document simultaneously, with a historical record enabling the restoration of previous versions. Parametric Multi-Part Modelling and Kinematic Animation are two of many features available. The software uses the *.stl* format, which is compatible with most 3D printers and with most other CAD software packages, allowing the import and export of documents. Additionally, Onshape is open source and can be continually improved by its users through the FeatureScript programming language. It was deemed to be the most appropriate for the open sourced design of a prosthetic hand. (The core geometric 3D modeler and the data base management system are not open source, but every high level operator is developped with the FeatureScript language and can be accessed and freely reused.)

B. Analysis of Existing Solutions

The e-Nable hands are driven using the wrist motion: when the wrist is bent, cables that pass through the fingers are tensioned thereby closing the hand; when the wrist is relaxed, the fingers remain open. The fingers each have one degree of freedom and are separated into two parts. The cables pass from the fingers and thumb, through the palm portion and into a gauntlet which holds the cables in place using a gripper box. e-Nable has a number of wrist powered solutions, including, but not limited to, the: Cyborg Beast, Raptor Reloaded, Phoenix and Nathalie’s hand.

The Raptor Reloaded is a development of the original Raptor Hand, offering 3D printed snap pins at the joints rather than screws. Elastic bands on each finger, rather than elastic wire, also made for easier assembly. No supports were required to print this hand. This too had a non-adaptive grip, meaning that the fingers cannot vary their grip depending on the shape of the object.

The Phoenix introduces a whippletree mechanism, creating an adaptive grip. The whippletree is contained within a gripper box together with a single tensioning pin. The whippletree secures four fingers while the thumb is attached to the tensioning pin. Additionally, a thermoformed gauntlet is used which is lighter, stronger, uses less filament, is quicker to print and can be adjusted to better fit the forearm [m].

Nathalie's hand is a modified version of the Kwawu Hand, which is equipped with a gear wheel, stop and lever that form part of a wrist locking mechanism. Its neutral position is slightly closed, unlike the Raptor Reloaded, and it has a thumb that is always in opposition to the fingers. The joints are printed in flexible filament and dispense the need for elastics in the assembly. The fingers and the thumb coming together allows the grip of small objects. It also has a more anthropomorphic design with the aesthetic addition of nails. It is equipped with a whippletree, similar to that of the Phoenix, allowing a compliant grip.

Each design requires wrist strain to close the hand.

Nathalie's hand was used as the base design for the palm and fingers as this was the most advanced of the mechanical solutions. Due to the need for placing actuators in line with the whippletree and finger cables, the Phoenix hand gauntlet will be used as the base for this design.

C. Standard Parts

1) Gripper Box

Contains whippletree and tensioning pin where the cables from the fingers connect. Slides along the gauntlet along a linear guide.

2) Whippletree

A mechanism that allows equal distribution of a load across the fingers of the hand. The index and middle finger are connected across a pulley with the ring and pinky finger connected across another. When any of the fingers are stopped, the whippletree will pivot about its centre allowing the other fingers to continue.

3) Gauntlet

Attaches around the user's forearm and wrist enabling contact and relative movement between the wrist and palm. Contains gripper box, slider and whippletree. Secured to the forearm using integrated Velcro straps.

4) Palm

Made to fit around residual palm of the user, either custom printed or filled with foam padding. Base attachment for all of the fingers and pivoting connection point for the gauntlet. Cable pathways are integrated into the back of the palm. Uses curves and meshes to create a more anthropomorphic appearance and suitable grip surface.

5) Fingers

Four fingers are separated into three sections namely the distal, intermediate and proximal phalanges. The thumb is sectioned into the distal and proximal phalanges. This imitates the human hand. The intermediate and proximal phalanges are further separated into two halves and printed from the same material as the palm, gauntlet and other 3D printed components. The distal phalanges are printed using a material with a higher friction coefficient. Closes to create a grip around an object using tensioned cables running through them that are pulled back.

IV. Project Scope

A. Needs Analysis

The team initiated the project with a user-centred design, work was done to determine the needs, goals and aspirations of the users. The user mainly under consideration was Nathalie, for whom the base hand was designed for. Nathalie is an e-Nable hand user who has been in contact with Philippe Marin at GI-Nova to continuously develop her prosthetic hand design. During the early stages of the project the team was able to meet with Nathalie to determine her requirements, her use of other prosthetics devices was also discussed to establish what she liked and disliked about the various designs.

In the past, Nathalie tested both a mechanical e-Nable prosthesis and an electronically powered partial hand prosthesis. Her assessment of both devices is shown below:

1) Mechanical device

Positives

Lightweight:	Around 250g
Affordable:	Produced for less than €100 and donated to her
Waterproof	No electrical components

Negatives

Tiring to use:	Requires physical effort from user
Lower grip strength:	Limited by strength of residual limb

Limited functionality	Only ‘open’ or ‘closed’, no grip patterns

2) Electronic device

Positives

Intuitive:	Myoelectric Sensors
Multiple grip patterns:	Microprocessors and Individually Actuated Fingers
High grip strength:	Individual finger actuation

Negatives

Heavy:	Approximately 1.5kg
Expensive:	€ 48,000
Sensitive to vibrations:	Myoelectric sensors
Not waterproof	Electronic presence

One of the main objectives of the project is to develop a solution that combines the positive aspects of the two options described above, without the negative aspects.

Nathalie also stated a preference for the more natural look, in terms of the shape and colour, of the latest e-Nable mechanical solution.

The low level user requirements were translated to technical design requirements of the final product.

B. Assumptions, Limits and Exclusions

For the development of the project, it was deemed necessary to define its assumptions, limits and exclusions.

1) Assumptions

Assumptions are situations that are expected to be true, but are uncertain and uncontrollable. Risks exist because of the possibility of presuppositions being false. As an auxiliary measure for the risk assessment, the listing of assumptions is relevant on the early stages of project planning.

- The prosthetic hand, to be used as basis for the design, functions as expected
- Required parts are available and can be ordered in
- Parts can be ordered in and printed according to the lead time
- Parts ordered in will function as specified by the supplier
- 3D printers are all functioning according to their specifications when required

- 3D CAD model of design can be printed
- Accuracy of the project schedule dates with some float
- There will be sufficient materials to print the hand as designed.

Post delivery:

- Builders will have internet to access Onshape
- Builders will be able to order parts
- Builders will have access to technical documentation
- Builders will have access to the ARDUINO software
- Potential users are in favour of an electronic solution of this type

2) Limits

Constraints are imposed by the stakeholders and the listing of those related to the design allows for a better establishment of a scope for the project.

- Hand must include electronics to assist in carrying or gripping objects
- Hand must be prototyped and available for open-source sharing by the 15th of June 2018
- The prosthetic hand must cost less than €500
- Design, testing and prototyping must be done for under €
- The CAD model of the hand must be made public on Onshape
- Prototyping limited to plastics available at GI-Nova
- Fused deposition modelling (FDM) machines available are to be used
- scope, quality, schedule, budget, resource, and risk

3) Exclusions

In order to use the available time in a more efficient way, some tasks were excluded from the scope of the work in developing the project. Those are listed below:

- Lifecycle of hand will not be calculated: Estimations regarding the battery life can be made, but the lifecycle of the full hand will vary gravely in time depending on the frequency of use, purposes of usage and maintenance;
- Accurate theoretical strength calculations will not be made: Considering that different printing resolutions and materials used provoke various values for friction and abrasion of the parts, whether the printed parts or others, the calculations regarding strength could not be accurate at a global level. Rough calculations were made through measurement with a digital electronic dynamometer;
- Haptic feedback will not be provided to the user in the prosthetic hand: The inclusion of haptic feedback would increase the circuitry with complexity and cost for a feature that was not explicitly requested in the project proposal. The presence of haptic feedback on prosthesis has polarized users, with mixed positive and negative reviews;
- Base hand will not be redesigned: Although modifications were made for the insertion of the finger releasing mechanism, the main design and mechanics of the fingers and the palm remained untouched.

C. Risks

Table 1 – Project Risks

Risk	Likelihood	Serverity	Total Risk Rating (likelihood x serverity)	Control Measures
Scope creep leading to an inability to deliver on time	4	8	**32**	Clearly defined requirement specifications. Began design process considering only demands then adding wishes in order of their priority with additional time.
Preferred hardware not being available	6	5	**30**	Had alternative hardware options.
Builders not being able to order parts	4	6	**24**	Ensured hardware had not been discontinued and ordered from French suppliers.
Parts ordered not functioning as specified by the supplier	3	7	**21**	Had alternative hardware options and allowed float for discrepencies.
Ordered parts and printing not abiding by their lead times	4	4	**16**	Ordered with float. Had alternate hardware options that were available at GI-Nova.
Final design costing over €800	5	3	**15**	Completed comprehensive cost estimations, discussing price creep with e-NABLE representative.
3D CAD model of design cannot be printed	2	7	**14**	Printed and tested prototype. Allowed time for adjust and reprinting.
Project dependencies creating inefficiencies and delays	2	7	**14**	Held weekly meetings to update team on progress and check against schedule. Adapted quickly to eliminate delays before a cumulative delay occurred. Completed independent tasks simultaneously.
3D printer not functioning when needed	3	4	**12**	Printed main large parts first. There are five 3D printers available in GI-Nova which can be used to print the required parts. Additionally there had been some float allocated for delays in 3D printing.
Builders not having access technical documentation	2	6	**12**	Ensure adequated open-source sharing on e-NABLE website, Facebook, Instructables, Thingiverse etc.
CAD software is not the platform of choice for other builders	4	2	**8**	Used a OnShape CAD software which allows imports/exports from most file formats including the widely compatible .stl format.
Design not well received by end users	2	3	**6**	Involved users in the design process.
The original hand used as a basis for our design not functioning as expected	1	5	**5**	Completed simulations using CAD software and prototype to confirm functionality. Adjusted CAD model as required.
Insufficient materials to print the hand as designed.	1	3	**3**	Confirmed availability of materials and ordered in new spool where necessary.

D. Requirement Specification

Table 2 – Needs and Requirements of the Project

Ref.	Need	Associated Requirement	Demand (D)/ Wish (W)	Wish Priority	Potential Solutions
A	**Operational**				
A1	Picks up small dailylife objects eg. bottles, books	Sufficient grip strength	**D**	-	Different strengths of actuator
		Sufficient friction in the fingertips	**D**	-	Filaflex, rubber, silicone
		Feedback on grip force for variable grip strengths depending on object	W	Medium	Actuator output, force sensors
		Adaptive grip to conform to the shape of the object	W	High	Whippletree, continuum differential mechanism
		Uses information from user to control hand	**D**	-	Sensors (myoelectric, force, flex)
		Hand driven into open and close position	**D**	-	Actuator (linear, servo, rotary)
A2	Hold objects continuously	Maintain grip strength unless instructed otherwise	W	High	Controller to maintain actuator position
		Maintains grip position	**D**	-	Controller to maintain actuator position, manual positioning fingers/hand locked into place
A3	Does not require continued strain from the user	Maintain grip strength/position effortlesslyunless instructed otherwise	W	High	Actuator, finger/hand locking
A4	Prosthesis can be used with or without electronic assistance	Electronics independent of the mechanism in the hand	W	Medium	Switch to disable electronics, mechanism to realease actuator (slider/lever to give slack to line)
					Keep original e-Nable hand design
A5	Can be exposed to water	Water resistant	W	Low	Electronic components well sealed in waterproof housing
					Electronics removed from hand, i.e. in gauntlet with wires sealed
A6	Allows typing	Independent position of a single finger	W	High	Locking fingers eg. cam, button, tensioning mechanism
					Individual actuation of one or more fingers
A7	Can be used throughout a day	Sufficient number of cycles from battery	W	High	Research long life batteries that can be used, replace battery as needed
		Ability to recharge battery	W	Medium	Use rechargable battery
		Switch device on/off to prolong batterylife	W	High	Include a switch in the circuit
A8	Ability to move the wrist while the hand is closed	Movement of wrist independent from gripping mechanism	W	Low	Pass cables through the pivot point in the wrist
					Use inner and outer cables, independent from each other
					Position the actuators on the hand to avoid this issue altogether

Ref.	Need	Associated Requirement	Demand (D)/ Wish (W)	Wish Priority	Potential Solutions
B	**Technical**				
B1	Similar dimensions to the human hand	Dimensions must be close to those of a human hand	W	Medium	Design hand with humanlike dimensions
		Hardware and electronics must add minimal volume	**D**	-	Use as few and smallest components possible and arrange to ensure compactness
B2	Similar weight to human hand (400g)	Weight must be below 500g for an adult prosthesis	W	Medium	Use low weight components where possible
		Hardware and electronics must add minimal weight	**D**	-	Use low weight components where possible
B3	Design must be adjustable to different users	Palm cavity can fit a range of users	**D**	-	Large cavity with foam to fill space between palm and hand
		Prosthesis can be scaled up or down depending on the user	W	Medium	Use parametric or linear scaling for 3D printed parts, use different hardware depending on user
C	**Economic**				
C1	Hand must be affordable for builders and users	Total manufacturing cost must be less than €500	**D**	-	Low cost materials (3D printed plastics) and hardware
					Actuators will be the defining cost and must be limited if possible
D	**Environmental**				
D1	Prosthesis can be cleaned if necessary	All parts likely to become dirty must be easily accessed	W	Low	Create disassemblable design
		Parts must be waterproof when turned off	W	Low	Electronic components well sealed in waterproof housing
D2	Parts are environmentally friendly	Parts must be recyclable or reusable	W	Low	Use recyclable materials
					Design parts that are compatible with another hand solution
E	**Schedule**				
E1	Project to be completed by the 8th of June		**D**	-	Follow accurate schedule
F	**Marketability**				
F1	Resemble human hand		W	High	Four fingers, a thumb and a palm
					Skin tone colour plastics
F2	Reproducible	All data and designs must be available online for open source distribution	**D**	-	Use freely available CAD software
					Use hardware and electronics that can be ordered

E. Approach to Problem

Although several robotic hand solutions for below elbow amputees exist, those have a considerably larger space available within the prosthesis to embed all of the electronic components without a breach in the aesthetical standards of human-like appearance. Even considering the existing solutions for people with partial palm, all of their parts are all fully designed and fabricated with that purpose, having a more ergonomic result.

In the case of this project, the fact that all of the components should be found online for purchase and as little modified as possible posed as a challenge to be considered when designing the gauntlet and fitting all of the components in a non-bulky way.

V. Business considerations

A. Introduction to e-Nable

E-Nable started when Ivan Owen started designing a prosthesis out of his garage, in his spare time, for a man that had lost his fingers in an accident. The two communicated over the phone throughout the design process and successfully created a device that worked. This success ultimately led to a mother of a young boy contacting him in order to create a similar device for her son.

Ivan created a first prototype for the boy and with the ambition of continuing to build better and stronger prosthetics, contacted a 3D printing company that donated 2 printers to his cause. Rather than patent his design and try to make a profit from it, Ivan published all of the design information as open-source. He did this in the hope that, with the right materials, anyone who needed a hand could print one. He also wanted other engineers would take his design and make improvements.

A database was created to share the location of all the people that owned 3D printers and were willing to build prosthetics. The e-Nable community started with around 100 builders who were willing to print the CAD files designed by Ivan but then other designers got involved and started to innovate and make improvements to the devices. During the first year of e-Nable, the number of builders grew from 100 to 3,000 strong global community and over 750 hands were printed across the world.

All of the prosthetics were gifted for free to children and adults in need of them thanks to the generosity of the volunteer builders.

A website was created and run by a volunteer, so that the members could communicate more easily and share their stories and designs with each other.

The entirety of the designs created by members of the e-Nable community are shared as open source designs online. This is to encourage continuous development in the goal of continuing to innovate and produce the best designs possible. None of the designs are patented and all are accessible for free online.

B. Context

E-Nable is a non-profit organisation, that donates prosthetic devices to people in need of them. There are also a large number of commercial organisations that also design, make and sell prosthetics. One of the most positive aspects of e-Nable's model is that as its community of builders continues to grow and the number of people that can access their devices also grows it creates competition in the market. This competition puts a great deal of pressure on the big companies selling commercial devices to lower their prices, which in turn benefits the users.

However, e-Nable does not protect its designs, so there is a risk that another company could start a business selling low cost prosthetics very similar to those made by e-Nable. As e-Nable is still growing and is far from reaching all of those in need of prosthetic devices. A competitor could sell to this market.

C. Mini Grant Program

E-Nable have a Mini-Grant program that gives funding to projects that are deemed worthy of it by the organisation. This scheme has a strict selection criteria based on the validity of the project and the experience of the builder. This allows e-Nable to continue to innovate and strive towards better designs that can be accessed by a larger number of people in need of assistive devices.

D. The Business Model - Donations

E-Nable relies mostly on the donations of benefactors and a number of sponsor companies who, over the lifetime of the organisation, have given them some kind of aid in the form of funds or a service. The company uses the same business model as a charity and asks for donations which are used to maintain the website and keep the open source information, stories, resources and helpful links created by the e-Nable Community, in an accessible location to all people involved. The help of generous patrons helps to ensure that the 3D printable hands, tool files, resources, stories, educational materials, tutorials and support to those reaching out to e-Nable for help. As well as monetary donations, supporters can gift builder kits that are essential for the assembly of the prosthetic hands. These kits include all of the non 3D printed parts such as screws, fishing line, and silicone grips for the fingertips.

The e-Nable website also has a sales page to sell different accessories, the proceeds of which go back into maintaining and growing the organisation.

Builders who have trouble being matched one-on-one with a potential user, can donate partially assembled prosthetics to be used as an educational tool. These are particularly beneficial for occupational therapists, prosthetists, hand specialists, nurses and clinicians who want to learn how to assemble such low cost assistive devices for the benefit of their patients. The unassembled kits are also distributed to schools and universities as an educational tool but can also be useful for inspiring the next generation of builders.

E. Sponsors

One of the main sponsors of e-Nable is 3D Universe who have distributed over 5,700 assembly kits for prosthetic devices, most of which were discounted to very near the cost of the raw materials. They show their support by speaking publicly about e-Nable in schools and libraries in the hope that this will encourage them to start their own e-Nable programs. Additionally, they provide help by creating video tutorials and developing the e-Nable Web Central application which facilitates matching the individuals in need of prostheses with the builders that are able to print them.

A number of other smaller sponsors provide services for the organisation such as sharing the CAD files of their prosthetic devices.

VI. Conceptual Design

A. Main Concepts

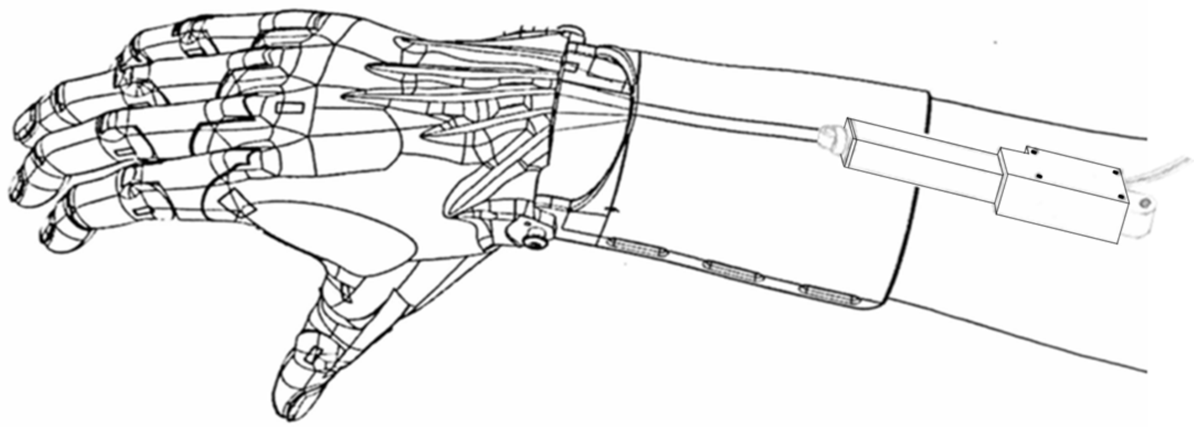


Figure 7 - Actuation Concept 1: Linear actuator

The simplest design wherein a single linear actuator pulls on the gripper box which slides along the gauntlet as shown in *Figure 7.* The gripper box contains the whippletree mechanism that connects the finger lines. Therefore, when the actuator retracts, it pulls all of the fingers closed and when it extends, it releases tension allowing all of the fingers to open.

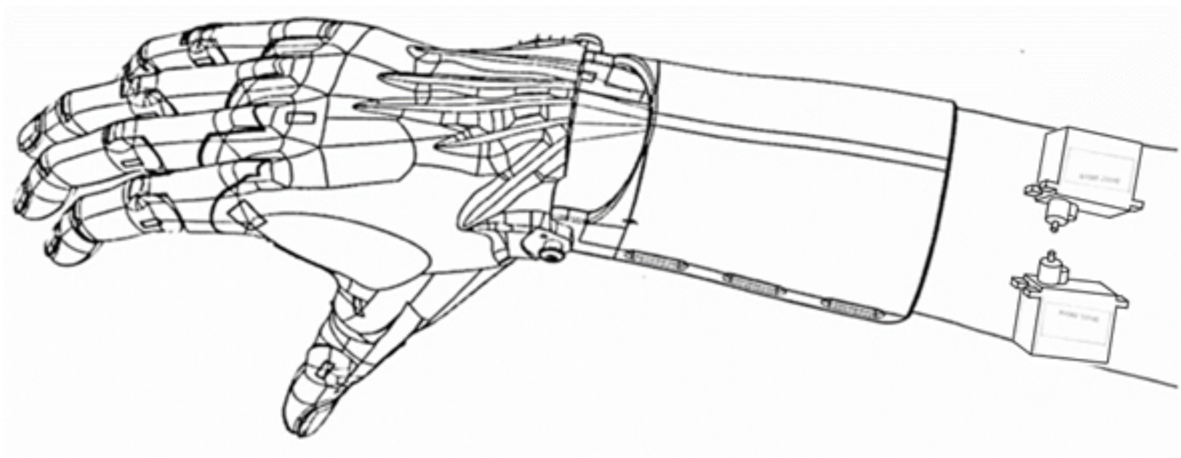


Figure 8 - Actuation Concept 2: Micro Servo-motors

The second option was to have two small servo-motors incorporated into the gauntlet that pull on two separate finger groups as shown in *Figure 8*. The finger groups would either be the index on one motor and the three remaining fingers on another or the index and middle finger on one and the ring and pinky finger on the other. The thumb would be mechanically put into position. Multiple fingers will be connected using a whippletree.

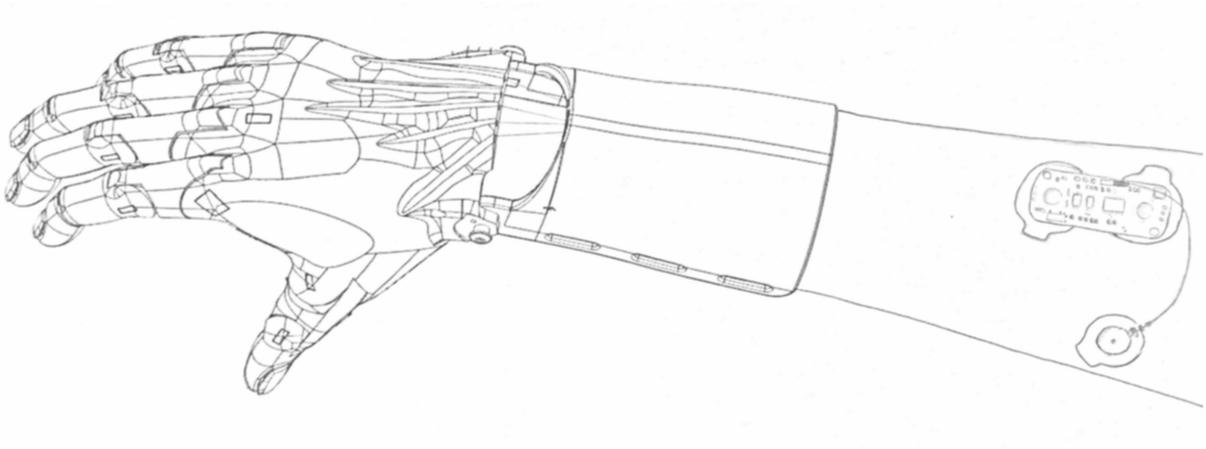


Figure 9 - Sensor Concept 1: EMG sensor

The first option considered for the sensing was a myoelectric sensor that uses a number of electrodes positioned on the surface of the skin (*Figure 9*) to detect the electromagnetic signal emitted by a nerve during a muscle contraction. The sensor picks up this signal and transmits it to a microprocessor. This is then converted into a signal that initiates the movement of the actuator which closes the fingers of the device.

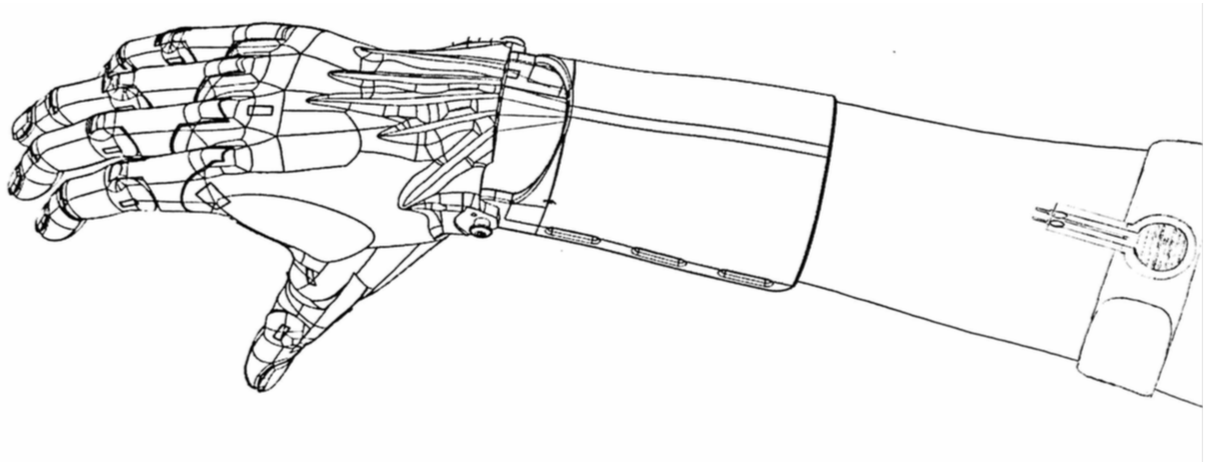


Figure 10 - Sensor Concept 2: Force Sensor

The second option was force-sensing resistor that uses its position on the skin to detect the muscle contraction (*Figure 10*). It is made of a conductive polymer which changes its resistance as a force is applied on its surface. In the circuit, this changes the signal received by the processing board. A signal proportional to the force of contraction is then emitted by the board to the actuator, which is then activated.

B. Concept Evaluation and Selection

A thermoformed gauntlet was considered although the need for accurate dimensioning of the electronic component casing made this choice imprudent.

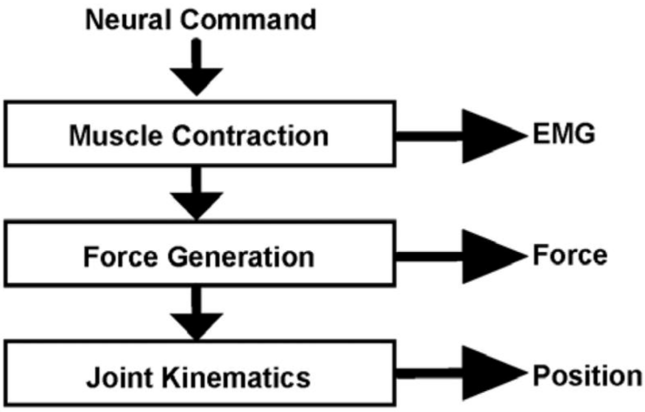


Figure 11 - Decomposition of neural command signal processed by human operator [a]

Each element of the solution including actuation, sensing, feedback and wrist isolation are conceptualised and combined to create the design. This will allow analysis of the elements that are independent of one another. Through the *Table 3*, different aspects are weighed and scored in order to reach a decision regarding the elements to be used in the final design.

Table 3 – Concept Evaluation Table

Name	Final Score	Complexity of Design (Weight 5)	Score	Weighted Score	Cost (Weight 3.5)	Score	Weighted Score	Weight (Weight 2.5)	Score	Weighted Score	Ease of use (Weight 5)	Score	Weighted Score	Functions (Weight 4)	Score	Weighted Score
Single Linear/Servo	**42**	Moderate More easily adapted Simpler circuitry/coding	2	**10**	≈ €10 - 80	2	**7**	10 - 40g	2	**5**	Easy to use Easier to assemble Longer battery life	3	**15**	Basic functions Single grip pattern Lower grip strength	1	**5**
Double Linear/Servo	**29**	Complex More design rework More complex circuitry More variables (coding)	1	**5**	≈ €20 - 160	1	**3.5**	20 - 80g	1	**2.5**	More complex Shorter battery life More difficult to assemble Less intuitive More bulky	2	**10**	More grip patterns Better grip strength	2	**8**
Force Sensor	**56**	Simple Ease to determine sensing range for code	3	**15**	≈ €5 (Not including band)	3	**10.5**	5g	3	**7.5**	Easy to put on/calibrate Longer product life	3	**15**	Easier to maintain	2	**8**
Myoelectric Sensor	**33**	Moderate Difficulty to determine sensing range	2	**10**	≈ €35 (+ electrodes ≈ 5€ for a pack of	1	**3.5**	30g	1	**2.5**	Harder to place/calibrate Electrodes need replacing frequently	1	**5**	Sensitive to	3	**12**
Finger Force Sensor	**30**	Complex Coding/circuitry Placing - design would have to be rethought	1	**5**	≈ €5	2	**7**	5g + circuit	2	**5**	Difficult to assemble More easily damaged Could require anti-slip sensor	1	**5**	Limits Offers feedback	2	**8**
No Feedback Sensor	**52**	Simple Uses existing hand	3	**15**	€ -	3	**10.5**	0g	3	**7.5**	Easy to use	3	**15**	Could difficult to grip fragile objects Will be difficult to regulate grip	1	**4**
Wrist Flex Sensor	**35**	Complex Several modifications in existing hand More complex circuitry/coding	1	**5**	≈ €5 - 10	2	**7**	5g	2	**5**	Intuitive Complex calibration	2	**10**	More movement Limits waterproofing	2	**8**
No Wrist Sensor	**52**	Simple Uses existing hand	3	**15**	€ -	3	**10.5**	0g	3	**7.5**	Easy to use	3	**15**	Wrist movement may inadvertently make hand open/close	1	**4**

C. Other Design Considerations

1) Index Releasing Mechanism

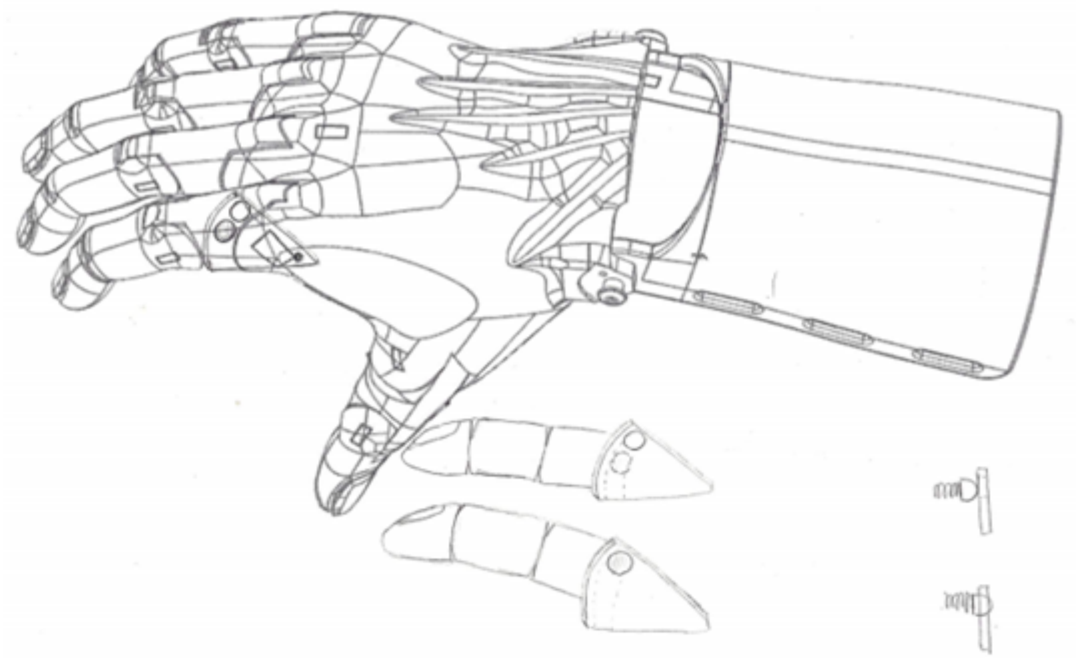


Figure 12 - Index Releasing Concept 1: Locking button

A Releasing Mechanism for the index finger was envisioned to allow for the user to type, primarily. This aspect was reinforced as an important addition to the design by the Founder of e-Nable France, as it is a demand from users. For that matter, two main ideas were conceptualized. The first one being a mechanism with a button and a spring that would lock the finger in an erected position by pulling it back, which would keep it from moving forwards when the actuator pulled on the gripper box (*Figure 12*).

The second one was to have slider mechanism to which the end of the cable on the index finger would be tied to. By sliding the slider back, the user would be able to release tension from the artificial tendon, which would allow for it to not be actuated by pulling the gripper box (*Figure 7*).

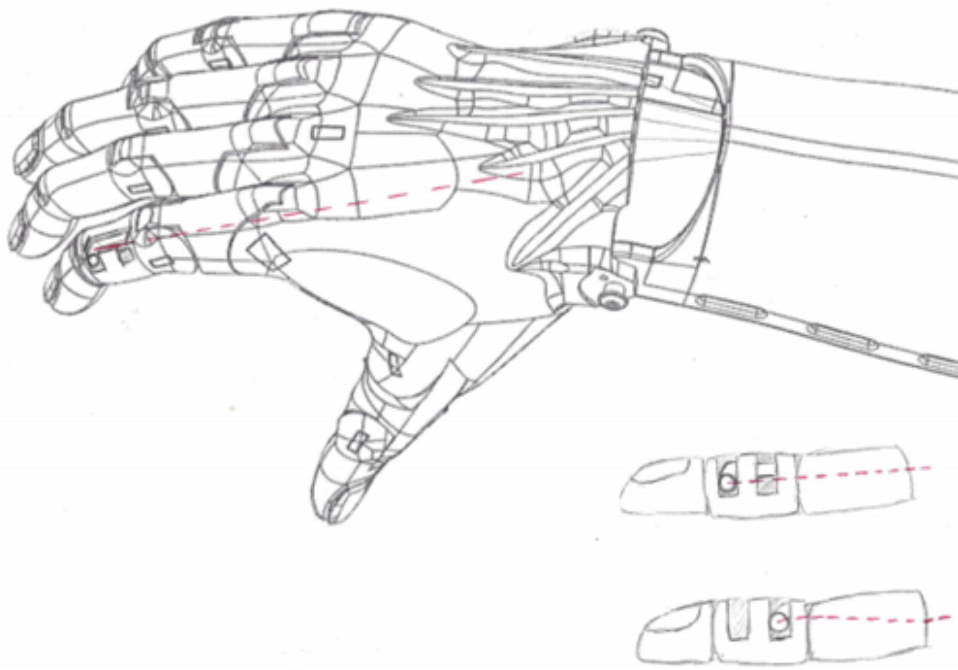


Figure 13 - Index Releasing Concept 2: Tension Adjustment

Due to its reduced complexity both in the development and in the assembly of the model, the slider mechanism was chosen for implementation.

2) Free Wrist Movement

Another concern was to allow for the movement of the user's wrist while using the hand, but without actuating the fingers or tightening the grip. Three main concepts were considered for solving that problem.

The first option was to integrate a flex sensor on the wrist, which would sense the flexion made and send a signal to the ARDUINO, which, in turn, would adjust the extension of the actuator arm to maintain the tension on the wires without impairing the grip. This is shown in *Figure 14.*

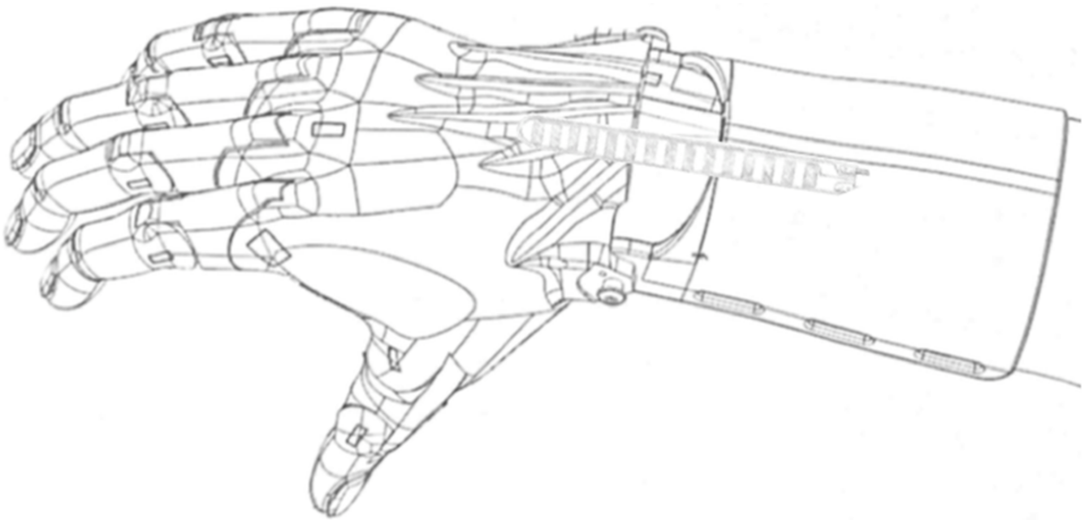


Figure 14 - Wrist Movement Concept 1: Flex Sensor Feedback

The second option was to divert the cables into pivot points in each side of the wrist joints, which would demand a rework on the internal design of the wire path inside the palm portion of the model (*Figure 15* below).

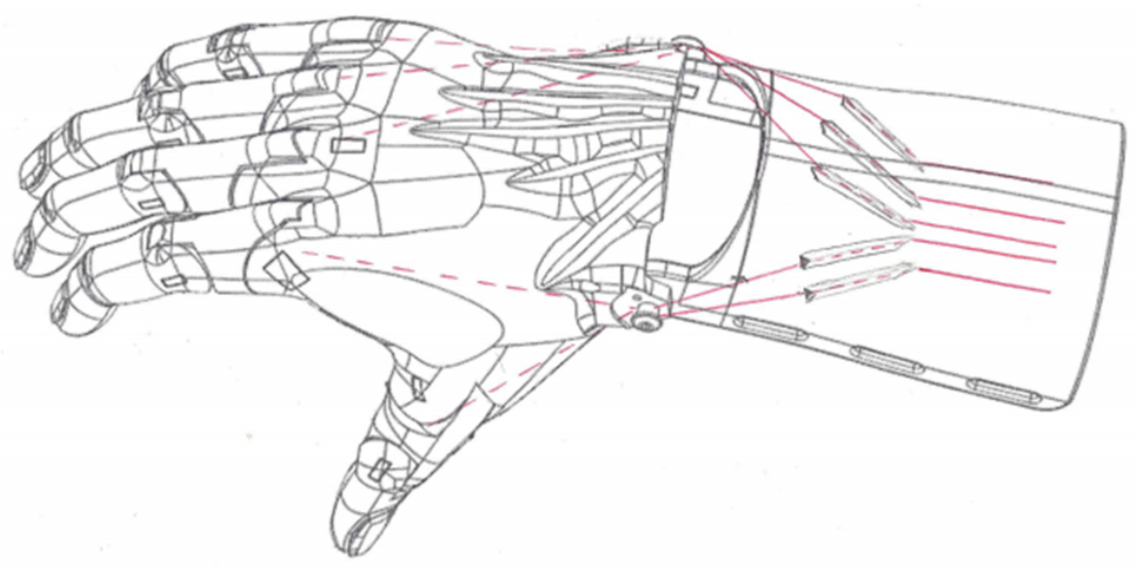


Figure 15 - Wrist Movement Concept 2: Cables Bypass Wrist

Finally, the third option was to make use of Bowden Cable which is an inner wire encased in a concentric hollow tube that is tensioned and fixed at either end. The outer tube has slack that allows it to bend without impinging upon the inner cable. This would allow the actuation of fingers by pulling on the inner cable and wrist freedom by bypassing the wrist. This concept is shown in *Figure 16* below.

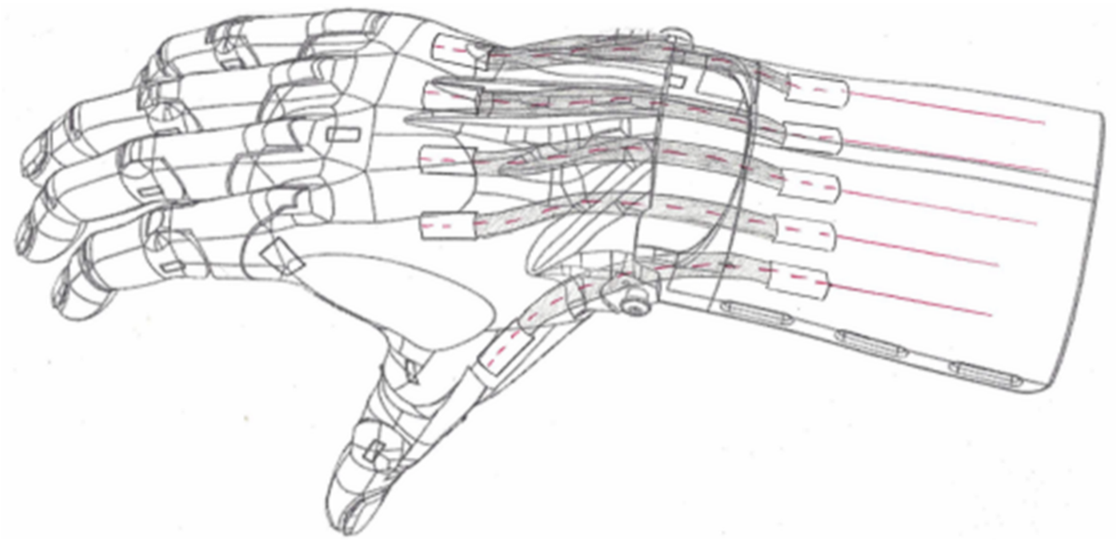


Figure 16 - Wrist Movement Concept 3: Bowden Cables

3) Grip Friction

Figure 17 - Grip Friction Concepts: Filaflex (left), Silicone Tips (right)

Two different options for the fingertips were considered to increase the friction of the grip. The first option was to use Flexible Filament to 3D print the ends and inner parts of the fingers. The second option was to buy in off the shelf fingertip grips made from gel, silicon or rubber from companies like Open Bionics and fixing these onto the fingers post assembly for added grip. Both options are pictured in *Figure 17* above.

4) Independence from Battery

To allow for a more dynamic usage of the prosthesis, it was considered as an important feature for the user to be able to use the hand even when the electronics are disabled, for a lack of battery for example. It was noted that the design still had all of its mechanical properties that allowed for it to actuate the fingers by flexing the wrist. However, once the cable was attached, connecting the gripper box to the actuator, there was a concern regarding damaging the electronic by excessive effort to maintain a position

A way of avoiding this would be to have a cable that can be detached from the actuator arm for the mechanical actuation.

VII. Embodiment Design

Due to the open source aspect of the project, it is known that the proposed model will be printed using various printers, material and precision. However, this section aims to give the specifics of the prototyping made during the project.

A. Material

The thermoplastic of choice can vary, and some of the most popular options available are the ABS (acrylonitrile-butadiene-styrene copolymer) and the PLA (Polylactic Acid). As the model proposed by this project is to be reproduced by different people with various printers, those materials are both considered as options for the printing of the present prosthesis.

The ABS is known for being broadly used in the plastic injection industry, and the PLA is a bio plastic (derived from renewable sources) used in medical implants and in daily life objects, such as disposables. Due to its lower Glass Transition Temperature, as can be seen in Table X, the PLA can provide sharper corners and features, when compared to the ABS. More details and comparisons between both materials are presented below in Table X.

Table 4 - Comparison of ABS and PLA Properties [b]

Properties	ABS	PLA
Tensile Strength	27 MPa	37 MPa
Elongation	3.5 - 50%	6%
Flexural Modulus	2.1 - 7.6 GPa	4 GPa
Density	1.0 - 1.4 g/cm3	1.3 g/cm3
Melting Point	N/A (amorphous)	173 ℃
Biodegradable	No	Yes (under the correct conditions)
Glass Transition Temperature	105 ℃	60 ℃
Spool Price (1kg, 1.75mm, black)	$USD 21.99	$USD 22.99
Common Products	LEGO, electronic housings	Cups, plastic bags, cutlery

During the printing of the final prototype, ABS was the available material and therefore used in this specific project. Nonetheless, the choice of filament to print with is down to the maker, and one is not globally superior to the other. The PLA has higher resistance to tension and is more environmentally friendly, but the ABS can produce lighter parts and is cheaper. It depends on the creator's priorities.

Another type of filament that can be used with FDM printers is the Flexible Filament (Filaflex). This material is a TPE (thermoplastic elastomer) based in polyurethane filament and certain additives, which make it malleable and allows for more adherent surfaces. Because of its properties, it becomes harder to achieve a high level of precision, and some printers can often have problems when extruding the material through the nozzle, so there is a need for adaptation in such cases. For this material, the percentage of infill affects directly on the tensile force. Its elongation can be up to 700% in the breaking point. Its printing temperature is around 220°C on a cold bed and it is not biodegradable. The spool price (1kg, 1.75 mm, black) is found at US$ 26.99 [f].

In this project, the use of Filaflex is advised for printing the parts specified in the Manufacturing Instructions. That use of a different material is due to the necessity of a certain amount of friction between the prosthetic hand and the held objects, for a better grip.

Printing the hand completely in flexible material could offer higher friction throughout the full surface of the hand, which could provide a better grip of held objects. However, the same elevated friction could also cause problems with the tensioning cables that pass through the fingers and the palm portion of the hand. Other factors that argues against such use of the Filaflex are the level of precision of certain parts, such as holes for joints and for the wires, and the higher cost of the filament.

B. Equipment Used

The vast majority of the parts were printed using Zortrax M200 machines out of ABS. These machines are able to print parts with dimensions up to 200x200x200mm, which was more than enough for all of the parts in the design. These printers come with their own software which slices parts according to the input parameters and automatically generates adequate supports. This printer uses a standard Cartesian coordinates system.

Other FDM printers were tested such as a standard RepRap printer and a Delta coordinates printer configured for PLA. However, it was found that the Zortrax printers offered superior quality in the printed parts and the supports being generated automatically was a very useful feature.

VIII. Final Design Description

A. Printing

As stated previously, the majority of the parts were printed out of ABS filament with software generated supports using the following printing parameters on the Zortrax machine:

- Layer thickness: 0.19mm
- Infill: Medium
- Supports: 20°
- Quality: High

The parts where the software generated supports were switched off and custom supports had to be generated were the thumb proximal phalanx and the palm.

Some parts were printed on a separate machine using Filaflex, a flexible filament. These parts included the finger tips and lower parts intermediate phalange of the middle, ring and little fingers as well as the lower part of the thumb tip. The parameters used for printing these parts on a Prusa-like "LOGresse" printer were:

- Layer thickness: 0.1mm
- Support: None
- Cooling: Off
- Extruder temperature: 235°C
- Platform temperature: 65°C

B. Assembly

The first thing that can be assembled once all of the parts have been printed is the gauntlet with all of the housings for the different electrical components such as the actuator, battery pack and ARDUINO board. The diagram in *Figure 18* details these steps. Once this is assembled, the covers for the actuator and electronics housings can be secured in place with M2.2 x 4mm screws in each corner.

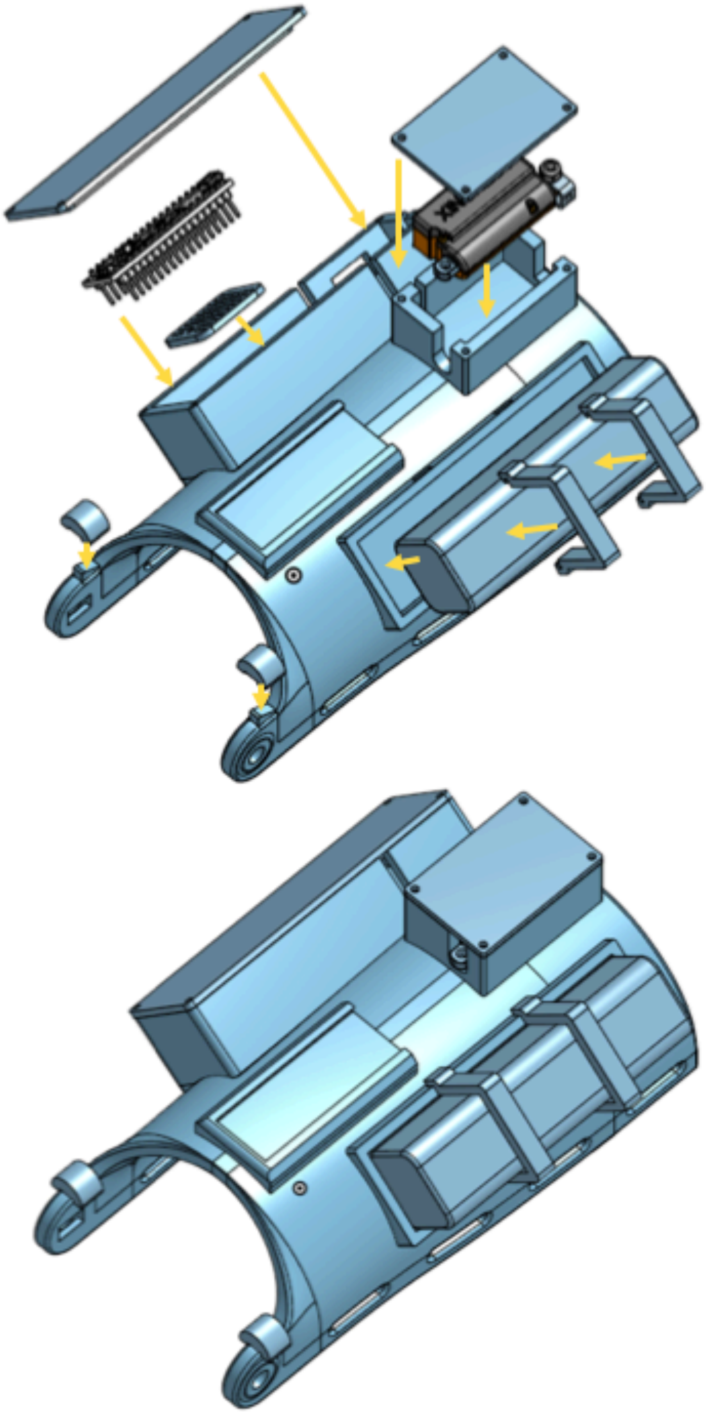


Figure 18 - Assembly Electrical Components in Gauntlet

Next, the gripper box with the whippletree mechanism can be assembled as shown in *Figure 19.*

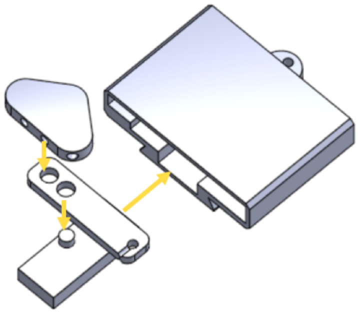


Figure 19 - Assembly of Whippletree in Gripperbox

Once this is done the gripper box can be inserted into the slider on the gauntlet and the palm and gauntlet fastened together (*Figure 20*).

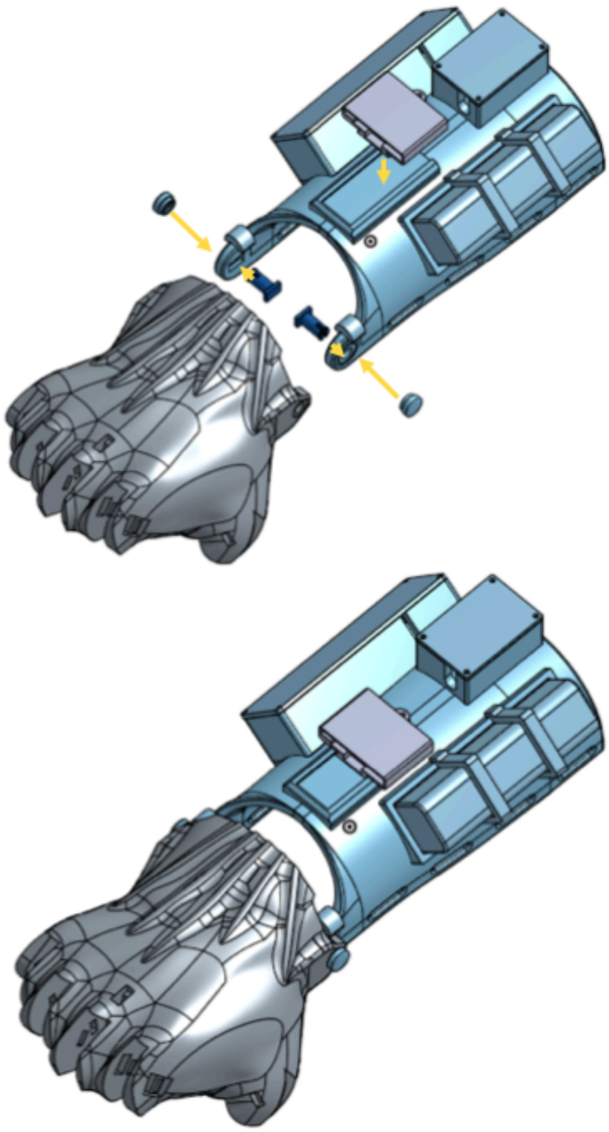


Figure 20 - Assembly of Palm and Gauntlet

Next, the fingers can be assembled and attached to the palm. The middle, ring and little finger are all assembled according to the diagram in *Figure 21* below. In the first step detailed in the diagram, the two parts of the proximal and intermediate phalanges are glued together using acetone. The second step is to insert the flexible tip of the finger onto the intermediate phalange and the latter into the proximal phalange. Once this is done, the third and final step is to insert the hinge for the corresponding finger into the joint. The process is similar for the thumb, however there is no intermediate phalange. In this case, the tip is split into two parts which are assembled in the same way.

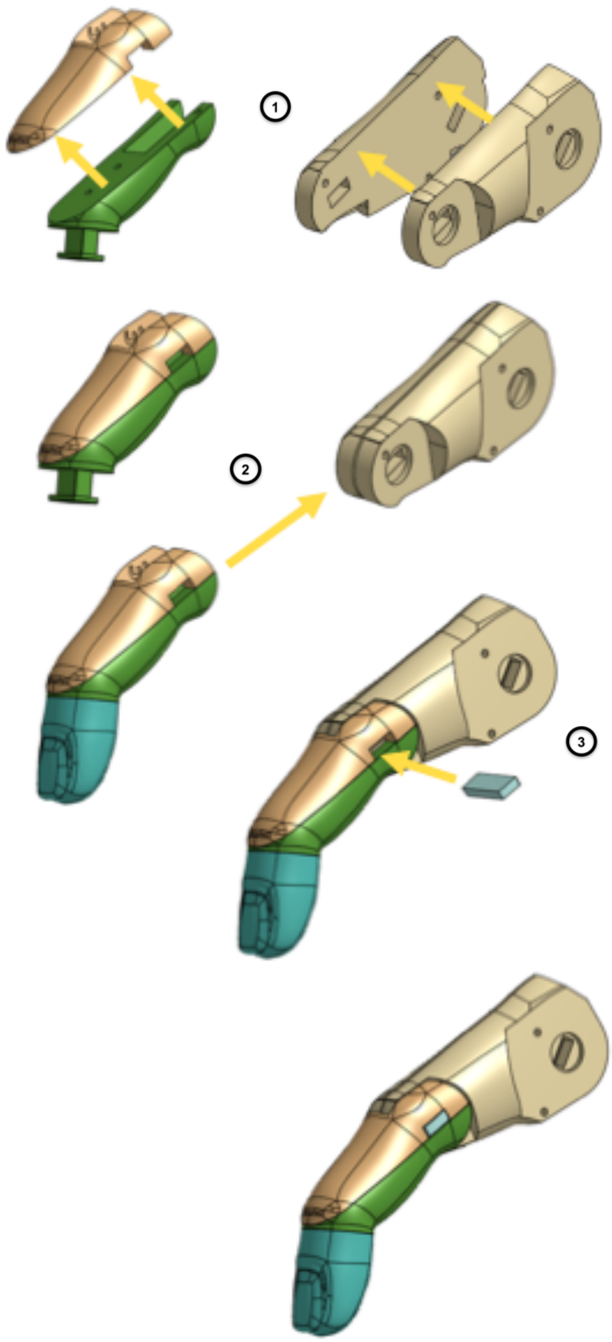


Figure 21 - Assembly Process for Middle, Ring and Pinky Fingers

The assembly process is slightly different for the index finger due to the inclusion of the releasing mechanism. The proximal phalanx is identical to the other fingers, however the finger tip and lower part of the intermediate phalanx are one piece. This must be glued to the upper part with the locking slider in between the two, being careful not to impede the sliding mechanism with the glue. Pay attention to glue AFTER putting the tendon line (see next page). This assembly is shown in *Figure 22*. The distal hinge can then be inserted to join the finger.

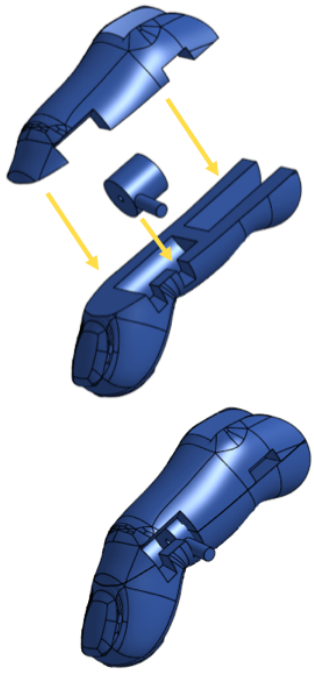


Figure 22 - Assembly of Index with Tension Release

Once all of the fingers are assembled in the manner detailed above, they can be mounted to the palm. In order to do this, they should be inserted into the correct slot and fastened in place using the flexible proximal joints as shown in the diagram below.

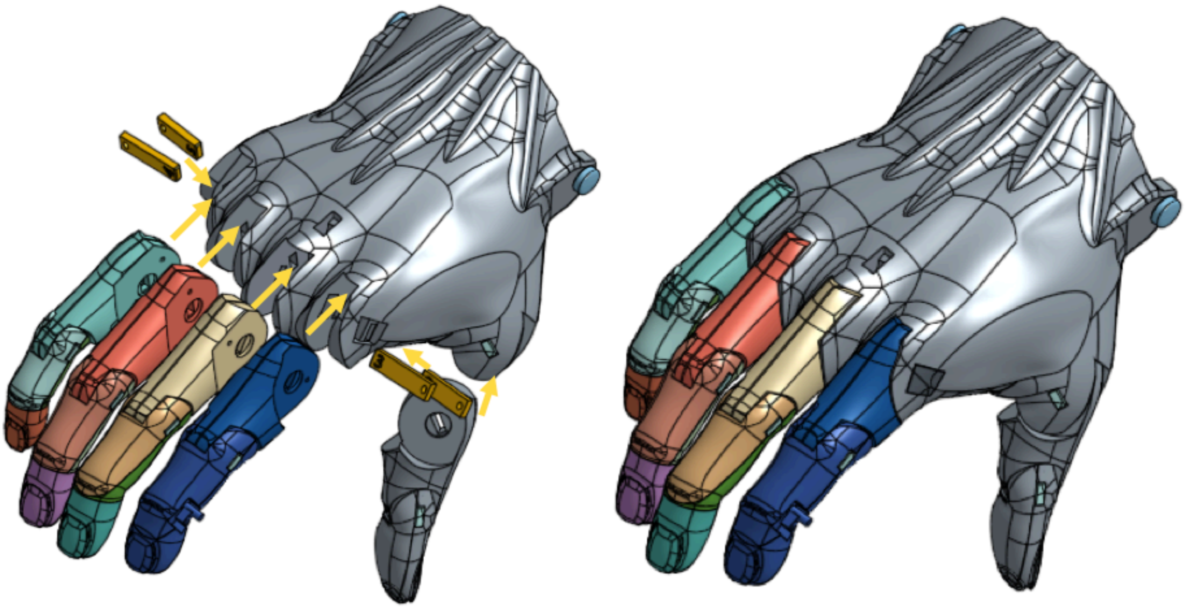


Figure 23 - Assembly of Fingers and Palm

A very important aspect of the assembly process is the correct wiring on the tensioning lines from the gauntlet, through the palm and into the fingers.

N.B.: All knots are tied with a Hangman's knot as shown in *Figure 24.*

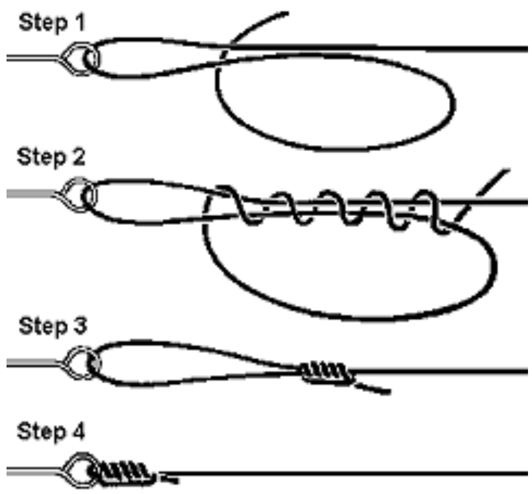


Figure 24 - Hangman's Knot Instructions [r]

The first digit to be wired tensioned with fishing line is the thumb. Start by tying the thumb to the balancer in the whippletree with the desired tension. The cable is tied at one end on the balancer runs through the main tube in the palm, through the thumb and back, and tied at the other end of the secondary tube.

Next, cut two strings about double the full length of the hand and gauntlet and tie them to the tubing keys that slot into the back of the middle finger and front of the ring finger. Thread them through the middle and ring fingers, the hand and around the two 'pulleys' on the whippletree pivot. Thread them back through the hand to the index and pinky fingers, respectively, and tie a single knot on each that can still be adjusted. This can be done once the middle, ring and pinky fingers are glued together, however the threading must be carried out before gluing the index due to the presence of the internal releasing mechanism.

Adjust the tensions on those two strings until the whippletree sits straight and holds the balancer straight when the mechanism is assembled. Once everything is balanced, tighten the knots on both the index and pinky fingers to make them secure.

C. Electrical components

1) Actuation

A number of different options of actuation were considered for use in this project. From the research that was carried out, a range of sizes, types and quantity of actuators can be found in electronically assisted prostheses already on the market. Prosthetic limbs can be found utilising linear actuators, servo-motors and other types of motors as the means of actuation. The majority of prostheses of this type are for above the wrist amputees, therefore there is less of a space constraint and the actuators can be housed within the palm of the device. For this project, the space constraints were the main determining factor in the selection of actuators.

Tests were run with the Phoenix Hand that was produced by Philippe, in order to determine the rough magnitude of the stroke length and the force required to contract the palm. A Vernier calliper and a force meter were used for these tests. It was found that the cable pull required to completely close the hand into a fist was 14mm. The different loads measured for closing the fingers of the Phoenix and Raptor hands as well as a number of other activities are in the *Table 5* below.

Table 5 - Forces Required for Different Actions

Item	Weight	Force
Closing fingers (Raptor)	2200g	21.5N
Closing fingers (Phoenix)	1600g	15.7N
Water Bottle	550g	5.4N
Smart Phone	200g	1.9N
Move a chair	900g	8.8N

This data then allowed for the requirements of the actuation system of the device to be determined. This then left for the type of actuator to be selected. A list of options that fit the criteria determined by the testing was collated in order for a comparison to be made, and the most viable solution to be selected. For the linear actuators, it was determined from the cable pull required that a stroke length of around 15mm would be required to control the hand.

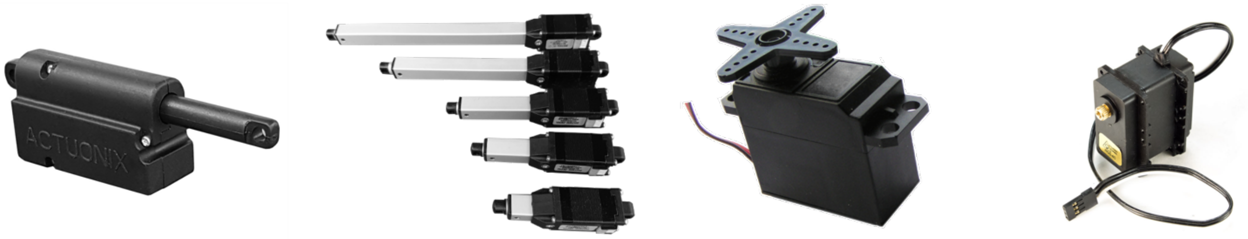


Figure 25 - Actuators Considered: PQ12, L12, FS90MG and Robotgeek Servo (from left)

Table 6 - Actuator Comparison Table

	Type	**Max Load**	**Weight**	**Dimensions**
Actuonix PQ12 20mm	Linear	40N	15g	64x22x15mm
Actuonix L12 30mm	Linear	80N	34g	90x18x15mm
SG90/FS90R/FS90MG	Servo-motor	18N With 10mm radius spool	10g	32x12x31mm
Robotgeek CR Servo	Servo-motor	45N With 10mm radius spool	60g	51x45x30mm

Due to the low strength provided by individual small servos like the SG90, FS90R or FS90MG, multiple of those would be required to achieve the necessary power for working the prosthesis. The added complexity and space that came along with having multiple motors and a spool mechanism for winding the fishing line were the main factors in dismissing such servo-motors as an option.

Although offering higher strength, the Robotgeek servo-motor is significantly heavier than the other options and so was discounted on that basis.

The two linear actuators, the PQ12 and the L12 linear actuators from Actuonix were considered to be the most favourable options due to their compactness, high strength and the simplicity of design that could be achieved with them. These actuators were available in a number of different ranges that catered for different needs. The different models available are:

- The R series, which enables RC linear servo control, these are compatible with ARDUINO and the limit switches can be adjusted by this means.
- The S series offers the additional functionality of limit switches that stop the

actuator just before the end positions, however the stroke length can't be altered any further. Therefore, this option was discounted as for the hand being designed, a custom stroke length was required.
- The P series can be used as a linear servo but requires an external controller specific to the model. This option was disregarded due to the fact that an ARDUINO board is being used for the project.
- The I series combines all of the functionality of the R, S and P series and is therefore the most expensive option of the four.

Due to space being the main constraint of the design, the actuator with the best strength to size ratio was selected, the PQ12 model. It was also found that using the L12 model would result in the gauntlet being too long and it interfering with the mobility of the user. From *Table 6*, from the theoretical calculations, the PQ12 model also provides more than enough force to actuate the hand and lift a range of day to day objects.

2) Sensing

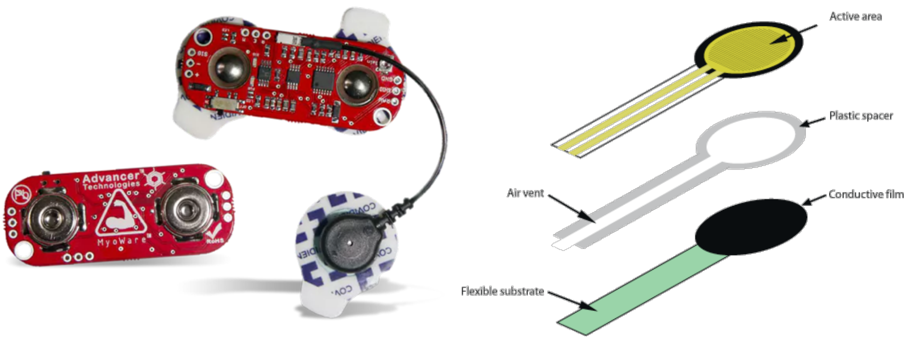


Figure 26 - Sensors Considered: EMG and Force

Sensors are a crucial part of any electronically powered prosthesis, because they are the medium that transforms a signal from the user into a signal to be read by the controller. In the known usages of sensors, some serve the purpose of controlling the prosthetic itself and others provide feedback on different parameters of the surrounding environment.

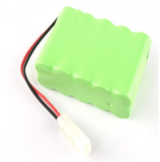
Of the two solutions considered for the sensing system of the prosthetic hand (i.e. myoelectric sensor and force resisting sensor), the force sensor was selected as the preferred option.

Although the use of a myoelectric sensor does not require much physical effort as the entire muscle contraction does not need to occur to initiate movement, the sensor is highly sensitive to unwanted noise and vibrations. Additionally, this sensing method requires accurate positioning of the electrodes and precise calibration of the system. The electrodes that are adhered to the skin must be replaced with every use incurring additional expense and inconvenience.

On the other hand, the force sensor has a relatively simple interface and does not require accurate placement, it can be easily calibrated by the user. Additionally, it is relatively insensitive to noise and vibration and can be used many times without replacement. Its thinness and low cost make it very suitable for an affordable and light prosthetic device. However, it does not offer as precise of a measurement and does not adhere to the skin so a strap and placement pad were designed to locate the sensor accurately. The force sensor was deemed simplest and cheapest option available that could accomplish the required functions.

3) Power source

Table 7 - Battery Comparison Table

Duracell HR 9V	12V Rechargeable Battery Pack	3.7V 18650 Rechargeable Battery
		
Type: NiMH **Capacity:** 170mAh **Weight:** 56g **Estimated Life:** 15min - 400 cycles	**Type:** NiMH **Capacity:** 1600mAh **Weight:** 251g **Estimated Life:** 2.4h - 3700 cycles	**Type:** Lithium Ion **Capacity:** 9800mAh **Weight:** 24g **Estimated Life:** 14.3h - 22,000 cycles

A number of options were considered for powering the circuit that controlled the prosthetic device. Once again the size and weight of this power supply were the primary considerations in the selection process as the device was to be kept as compact as possible. The three main options that were considered, shown in *Table 7* were the following:

- A Duracell HR9V rechargeable battery. This option provided a high enough voltage to power both the actuator and the ARDUINO board and was very light and compact but its capacity and estimated battery life were much lower than the other options.
- A 12V Rechargeable Battery Pack. Although this option provides a higher voltage and capacity, it is significantly bulkier than the other options.
- A 18650 3.7V rechargeable lithium ion battery. This option combines the positive aspects of the previous options. It has a very good battery life and is very compact.

Figure 27 - Power Bank Used [s]

The lithium ion battery was the preferred option of the three due to its low weight and high capacity. However, due the safety risk of using an exposed lithium ion battery, an alternative to use this type of battery integrated into a power bank (*Figure 27*) was decided upon. This ensures that the battery was housed and isolated adequately and does not come into contact with the user.

As sold, the power bank comes with a USB to micro-USB cable, which differs from standard USB cables, which have the D+ and the D- wires for sending and receiving data between the devices. The USB cable provided can only be used for powering devices, therefore this should be replaced by a USB cable that can transfer data to the ARDUINO. The comparison between the cables can be seen below:

Figure 28 - Difference between Data and Power USB cables

a. Boost Converter

It has been presented that the power bank provides 5V of electric tension. This amount of voltage is precisely the required from the ARDUINO Micro USB port and from the force sensor, but it is below of the voltage demanded by the linear actuator PQ12 R, which is 6V. To allow for the actuator to be powered by this same source, it was necessary to increase that voltage. A few electrical components were considered for that matter, such as operational amplifiers (op amp), MOSFETs, but it was decided that a boost converter would be the component of choice.

The MOSFET would require designing a circuit to integrate it, and the op amp demanded symmetrical sources of tension (-5V and +5V), which would not be possible with the availability of space, while the boost (also known as step-up) converter demanded only one source of voltage and the circuit was all integrated into a small printed circuit board (PCB).

When ordering the components from the supplier, it was still uncertain which type of battery would be used. Because of that, the input voltage was still undecided, once the power sources considered had voltages of 5V, 9V or 12V. The ordered components had to be comprehensive of all possibilities, and so a voltage converter that could be both a step-up and a step-down would be ideal for the situation.

The Pololu Step-Up / Step-Down Voltage Regulator S7V8A was the converter used in this project. It can take input voltages from 2.7V to 11.8V, generating an output between 2.5V and 8V that is adjustable through an integrated potentiometer. The range of voltages, combined with its simple interface and reduced size made it ideal for applying to the project. The component is illustrated below.

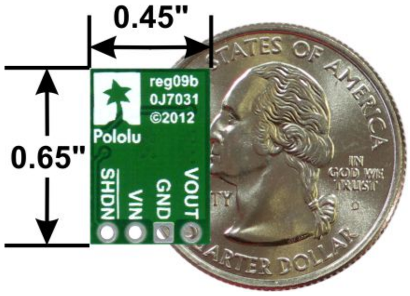


Figure 29 - Pololu Step-Up / Step-Down Voltage Regulator S7V8A [o]

4) ARDUINO Micro

Analysing the ARDUINO small sized boards, the list was narrowed down to the Nano and the Micro. Considering that the developed circuit and code only use four pins of the board and do not demand the use of a large amount of memory, both options had the capabilities needed to execute the desired commands for the robotic aspect of the prosthesis. Below, a comparison table for both the boards considered can be seen.

Table 8 - Comparison table for ARDUINO Boards Nano and Micro

Board	Processor	Analog In	Digital IO/PWM	SRAM (kB)	USB	Dimensions (mm)	Price	Headers
Nano	ATmega328P	8	14/6	2	Mini	43.18 x 18.54	€ 20,00	with
Micro	ATmega32U4	12	20/7	2.5	Micro	48.00x 18.00	€ 18,00	with or without

The most important characteristics were then the cost of the board and the dimensions, as the usage of physical space is very relevant for the project. It is perceptible that the dimensions of the Nano are smaller than that of the Micro, but the fact that it could not be ordered without headers (the pins compatible with a breadboard) made it an unfavourable solution. The added height of the headers would result in the gauntlet being too bulky, and they could become a difficulty for soldering. Given this and the lower price, the chosen board was the ARDUINO Micro.

The ARDUINO Micro is a reduced in size version of the retired ARDUINO Leonardo. The schematic for the board can be seen in Figure Ç. It comes with 20 pins for digital input/output, out of which 7 can be used as PWM outputs and 12 as analogue inputs. The connection to a computer for uploading the code can be made through a micro USB port. The board can be powered through that same micro USB connector (demanding an input voltage of 5V) or through the V_{in} power pin (demanding an input voltage from 7V to 12V).

In the ARDUINO Micro there is also a component that can be found on almost all ARDUINO boards, which is the reset button. It restarts the microcontroller and makes the code run from the Setup() function again. When pressing the reset button, a LED attached to the board should flash, signalling that it was effective.

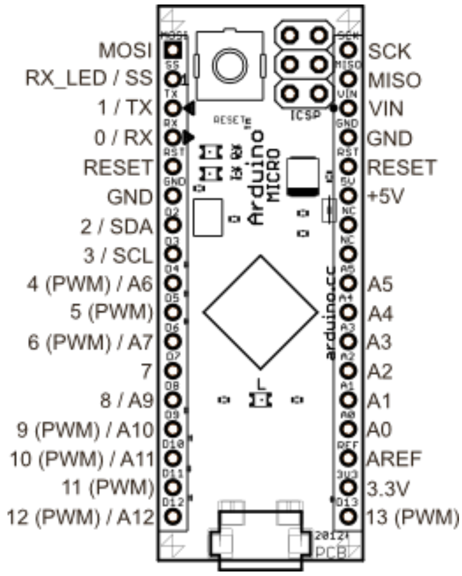


Figure 30 - ARDUINO Micro Schematic

In general, the programming and use of the Micro is similar to other ARDUINO boards. An important difference that must be pointed out is that this board uses the ATmega32U4 [h] as a microprocessor, which is a single microcontroller to both run sketches and communicate through USB with the computer. This feature permits more flexibility in its communication with the computer.

5) Circuit

The assembly of the circuit is what assures the connection between all the electronic components for the correct transmission of current and signals for the functioning of the hand. In this section, the considerations for the design of the circuit will be explained.

To provide the power for the circuit as a whole, the battery has to be connected through a USB cable. If a standard USB cable is used for powering the system, it can also be used for uploading the ARDUINO code into the board through the computer. The wiring of the circuit to be respected is as follows:

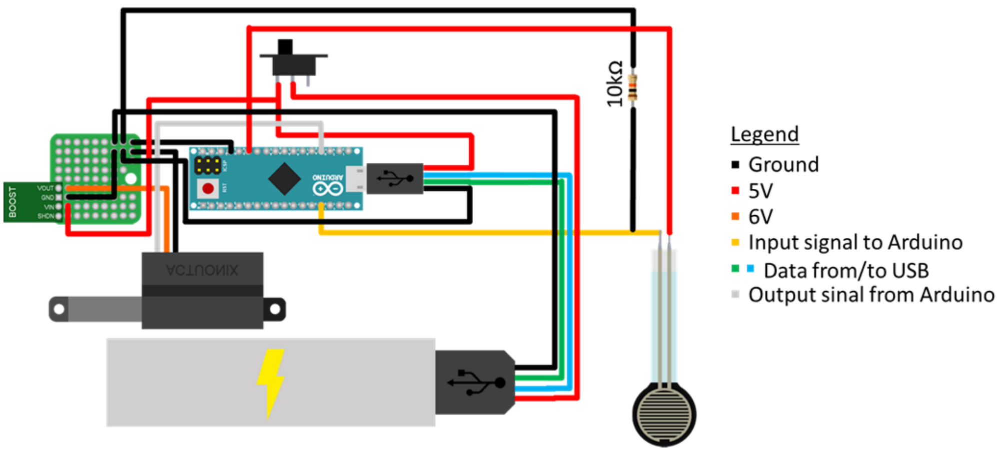


Figure 31 - Circuit Used in Prototype

If a power USB cable is used, the circuit follows the same logic, but ignoring the presence of the data wires.

To avoid having to split the cable too many times, it was decided that the force sensor would be powered directly through the 5V output pin of the ARDUINO Micro, which provides the sensor with the voltage that it needs. The second pin for the force sensor is the same for ground and for signal. That wire must be split, and the use of a 10kΩ resistor was necessary as a pull-down to ground in order to not overload the signal pin A0 of the ARDUINO.

Because the power supply does not have a on/off button, the integration of a switch to the circuit was found to be necessary. This would allow for the user to continuously leave the USB cable connected, turning the prosthesis on and off as desired. For this purpose, a simple SPST switch would serve. However, due to the availability of parts in the laboratory inventory, a SPDT was used, because, when only one throw is wired, it functions exactly like a SPST. For the prototype, an APEM G series slide switch was used. It is illustrated below.

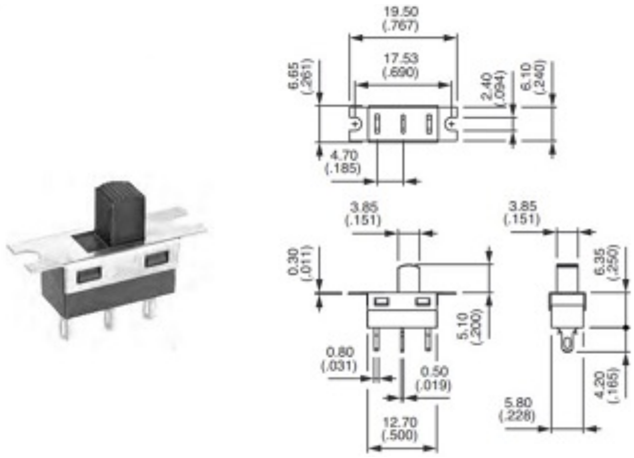


Figure 32 - G Series Switch Used in Prototype[n]

A small protoboard was used for a better organisation of the wires. It was used as a hub for grounding all of the components in one single place, making it simpler for understanding and organisation. It was also used for connecting the Boost Converter to its needed wires.

In the circuit diagram, it is noticeable that the boost converter has one pin which is left disconnected. The SHDN (Shutdown) pin of the step up converter is used for turning it on and off by sending it different voltages. In the model, the regulator is meant to be continuously enabled as long as the circuit is on, which is done by not connecting the pin.

The linear actuator PQ12 R is a model compatible with ARDUINO boards and, therefore, only has three wires, as would a normal servo motor. The signal wire is connected to the ARDUINO digital pin 9, because it is one of the pins that work with the Servo library (to be explained in the next section) for its PWM properties.

6) Code

The code written for controlling this prosthesis uses only two pins from the ARDUINO Micro: the analogue port A0 and the PWM port 9. These ports are respectively used for input from the force sensor and for output to the linear actuator.

The ARDUINO programming language has a specific library to control servo motors, called <Servo.h>. The servo library transforms values from 0 to 180 into angles of movement in the same scale to the servo motor through the function *write*. Another way of controlling the servo through the library is with the function *writeMicroseconds*, which relates the movement to read values. In most servos, a value of 1000 is a fully counter-clockwise turn, 2000 is a fully clockwise turn, and 1500 is the middle position. For continuous movement servos, both functions work analogously.

The R version of the Actuonix PQ12 has the advantage of working with an ARDUINO board as a servo motor, having the maximum extended arm position at the value 0 and the maximum retraction at the value of 180. For that reason, the <Servo.h> library could be used for controlling it. Other linear actuators could require a different type of control by not being compatible with the library used.

A new void function named “*move*” was created on the code for writing the new values to the actuator when required. This function also prints the sensor input values and the actuator position on a serial monitor when the ARDUINO board is plugged to a computer. This allows for the programmer to monitor the signals for configuring the sensor threshold, and also to observe the behaviour of the hand and how it relates to the values provided.

The ARDUINO board processing capacity is higher than the actuator speed of movement. In an effort to avoid the accumulation of too much information in the actuator buffer, a short delay (*ActDelay)* of 0.1s was added between each increment to the actuator auxiliary variable. Another delay added to the code was the *DelayMax* of 1 second, which happens when the arm of the actuator is in its extreme positions, it being fully retracted or fully extended. This delay was placed in order to give the user time to stop applying pressure on the force sensor before the actuator changes it direction of movement.

The complete code can be found in the Appendix 1, with explanatory comments throughout for better understanding. The code is to be used and improved upon for better results in the future, or for incorporating new functionalities.

The current program uses 5980 bytes (20%) of the ARDUINO Micro program storage space, that has a maximum of 28672 bytes. The global variables use 220 bytes (8%) of the dynamic memory, leaving 2340 bytes for local variables. The maximum is 2560 bytes. The code was left simple and short, which gives it a higher upload speed:

- Writing flash (5980 bytes): 0.45s
- Reading on-chip flash data: 0.05s

D. Method of Operation

1) Mechanisms

a. Adaptive grip

A whippletree mechanism was integrated into the gripperbox of the device to evenly distribute the load across all of the fingers. This allowed the other fingers to continue closing if one was obstructed and to provide a grip that could better adapt to different shaped objects.

The whippletree mechanism that was originally used in the e-Nable Phoenix hand shown in *Figure 33 (Left)* included the four fingers but not the thumb. The thumb was separately attached to a tensioning pin. This meant that when the thumb was stopped, the rest of the fingers would not be able to be pulled by the actuator any further.

The thumb on Nathalie's hand had very limited movement, which meant that this whippletree was not a viable solution. Therefore, a whippletree which integrated the thumb was implemented so that the gripper box could be pulled by the actuator even with the limited range of motion of the thumb. This mechanism is shown in *Figure 33 (Right)*

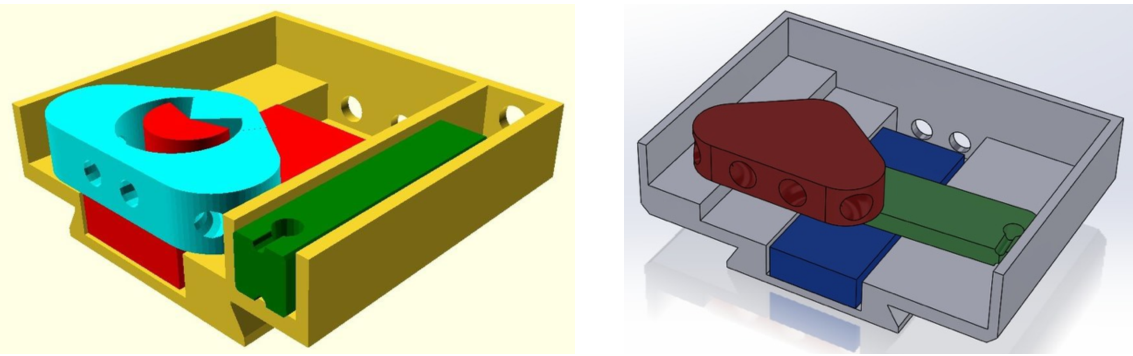


Figure 33 - Initial and Final Whippletree Considerations [q]

b. Index Releasing Mechanism

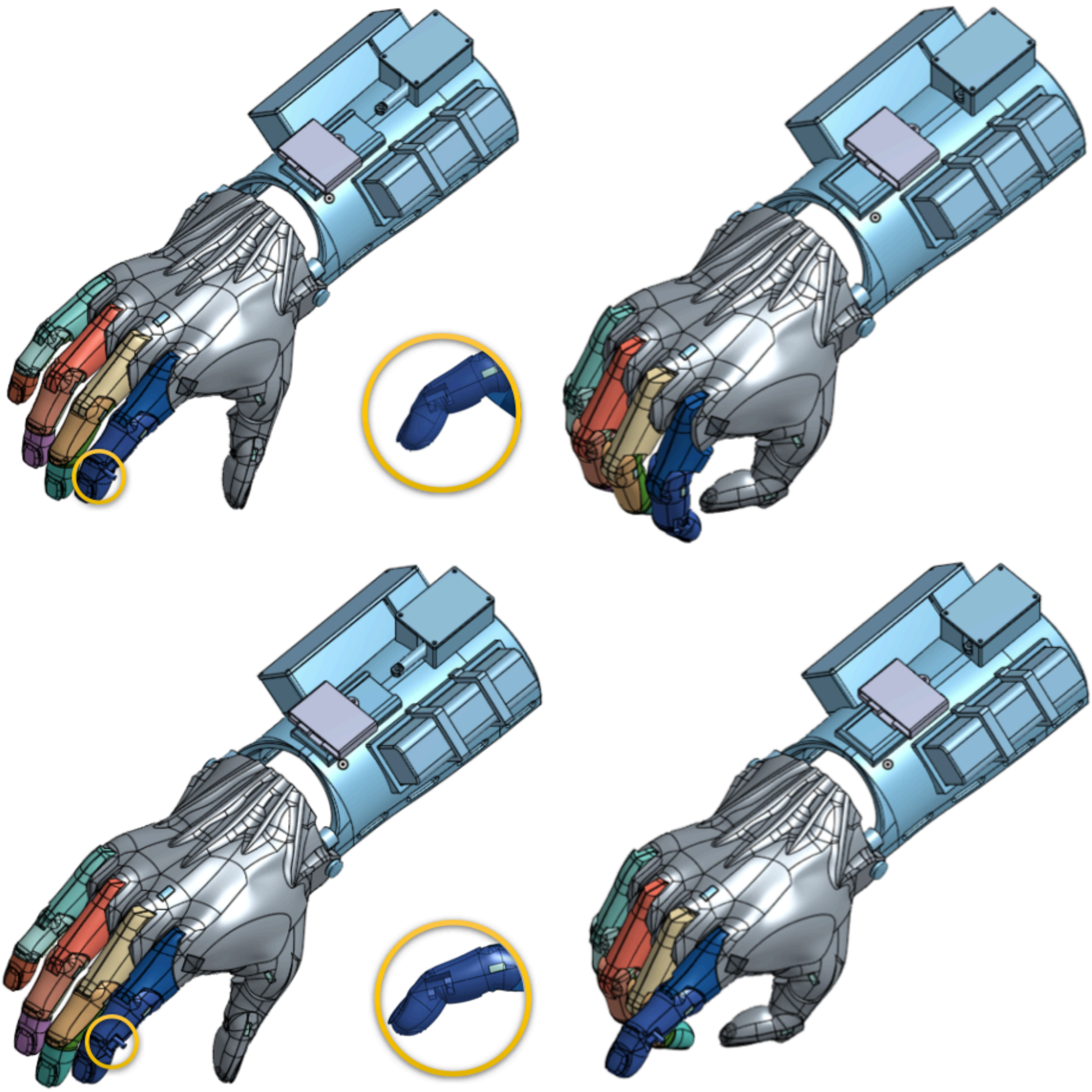


Figure 34 - Diagram Showing the Index Releasing Mechanism in the Final Design

2) Electronics

For an optimal use of the prosthetic hand, a small calibration should be made before the first use. The values used in the code have been chosen through testing on the developing team and must therefore be re-calibrated right before connecting the battery to the circuit, following the steps:

1. Open the code in the ARDUINO IDE;

2. Use the USB port to connect the ARDUINO Micro to the computer that has the code and make the upload;
3. Open the serial monitor on the ARDUINO IDE while the board is still connected;
4. Contract the arm and detect the point of most flexion on the muscle;
5. Relax the arm and close a Velcro strap around the FSR making sure that it touches the skin surface on the point chosen;
6. Avoid pulling the straps too tight around the arm, in order to allow for normal blood flow and comfort;
7. Contract the arm and observe the *Sensor* values changing on the monitor;
8. Choose a value that corresponds to a normal level of contraction;
9. Enter chosen value into the 'int SensorThresh' (currently at the value of 500 in line 9 of the code);
10. Re-upload the code to the ARDUINO after changes have been made;
11. Safely disconnect the ARDUINO Micro from the computer;
12. Finalise circuit and model assembly;
13. Turn on the prosthesis and test the device;
14. Readapt the threshold if necessary.

Once the code is uploaded with the proper adjustments and charging of the battery, combined with the full assembly of the printed parts, the prosthesis is ready to operate. The following section describes how the user and the prosthesis will interact during use.

The signal to open and close the fingers will be sent through a force sensor attached to a Velcro band around the arm. The user must flex the muscle in the part of the arm to which the band is attached, thus provoking a change in the arm's diameter, which presses against the band and activates the force sensor. The actuation of the force sensor will only be read by the processor if it is above a certain value (that can be calibrated by modifying the *SensorThresh* value in the ARDUINO code, as specified above). The choice of said value aims to avoid an accidental activation, which could be caused by involuntary flexion.

Once the ARDUINO board reads that the value provided by the sensor is above the specified threshold, it activates the linear actuator. The linear actuator continues in motion for as long as the sensor value is above the threshold, alternating between movements of opening and closing the fingers with each activation. If the user continually sends a signal through the application of force, even after the fingers are fully opened (or fully closed), the processor will give it the interval of one second between initiating the movement in the direction of closing (or opening).

There is no user feedback related to applied grip force or slipperiness of held objects. In this case, it remains a responsibility of the user to visually check if the held object is secured in the grip and then apply new force to achieve the estimated position needed for the ideal grip. Otherwise, the user can also flex their wrist, provoking the mechanical tightening of the fingers, as done in a standard e-Nable hand. It is important to note that the mechanical actuation of the fingers when the cable is still attached to the linear actuator should only be done in very small scales. The actuator is not able to withstand a great amount of force, so if the user flexes their wrist too much, pulling on the cable which pulls on the actuator arm, it could provoke irreparable damage to the component.

An option for the mechanical operation of the hand is still available by detaching the cable from the actuator and placing it on the auxiliary place of attachment indicated on the diagram (appendix S).

E. Prototype

During the week after the arrival of the hardware that was ordered in for the project, a prototype was built. Due to the limited time available to assemble the device, this prototype was more of a proof of concept, rather than a final working solution. However, it is hoped that with more time and some rework, the device could be turned into a working solution with all of the features and functionalities it was designed to have.

The following *Figure 35* demonstrates the prototype in some of its possible positions.

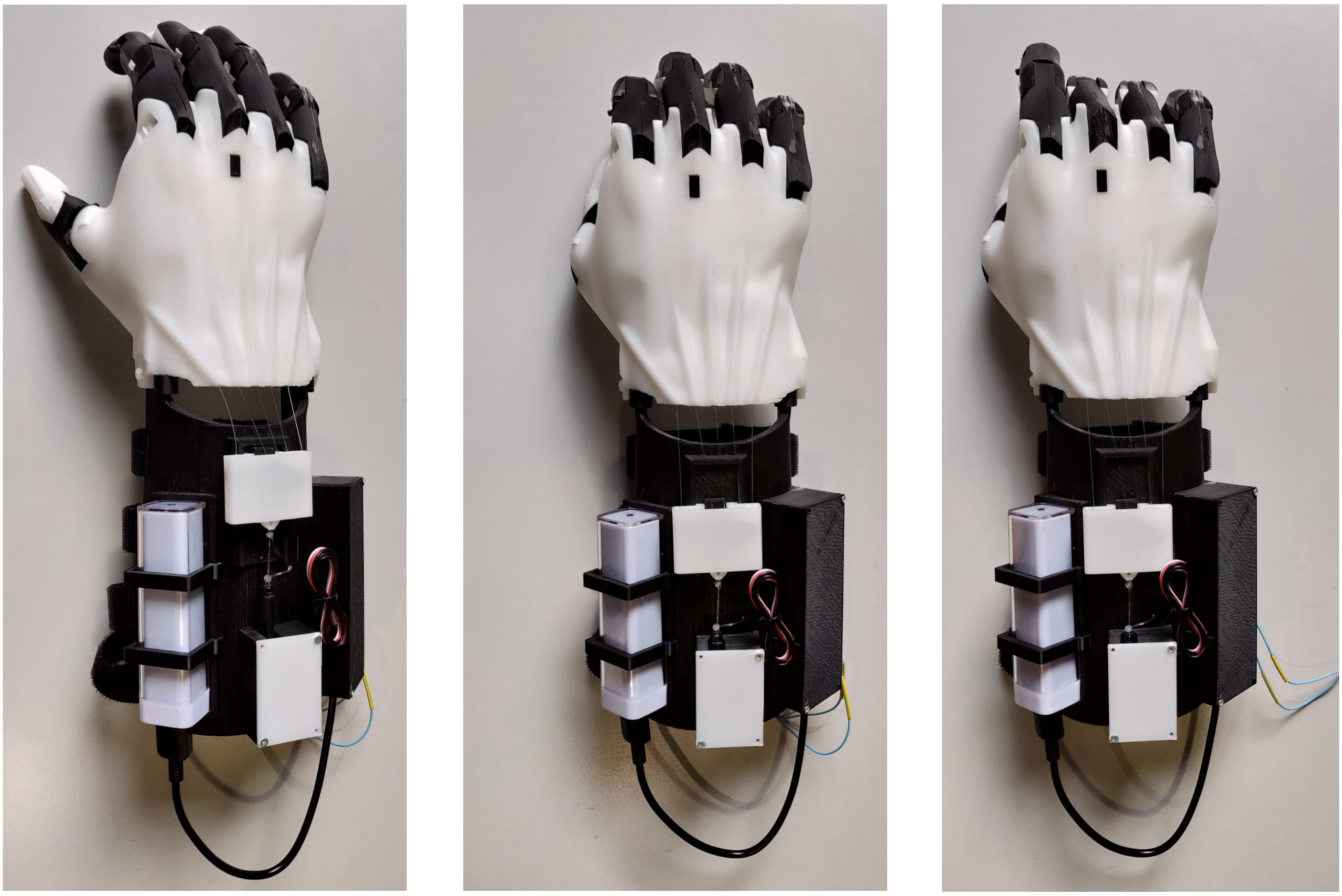


Figure 35 - Positions of the Prototype: Open, Closed and with Index Released

In the limited time available for testing, a few tests were run with the prototype to quantify its grip strength. The device was not able to lift a full 500 mL bottle of water as was hoped, only managing a half full bottle. Although the prosthesis did not meet this objective, it is believed that with some small modifications to decrease the friction in the fingers, the grip strength could be improved significantly.

The device was also weighed at 447.5g, well below the requirement of the device weighing less than 500g. This is considered a big success of the project, as although a large amount of hardware was integrated to provide the electronic assistance to the device, it still weighs less than the average human hand.

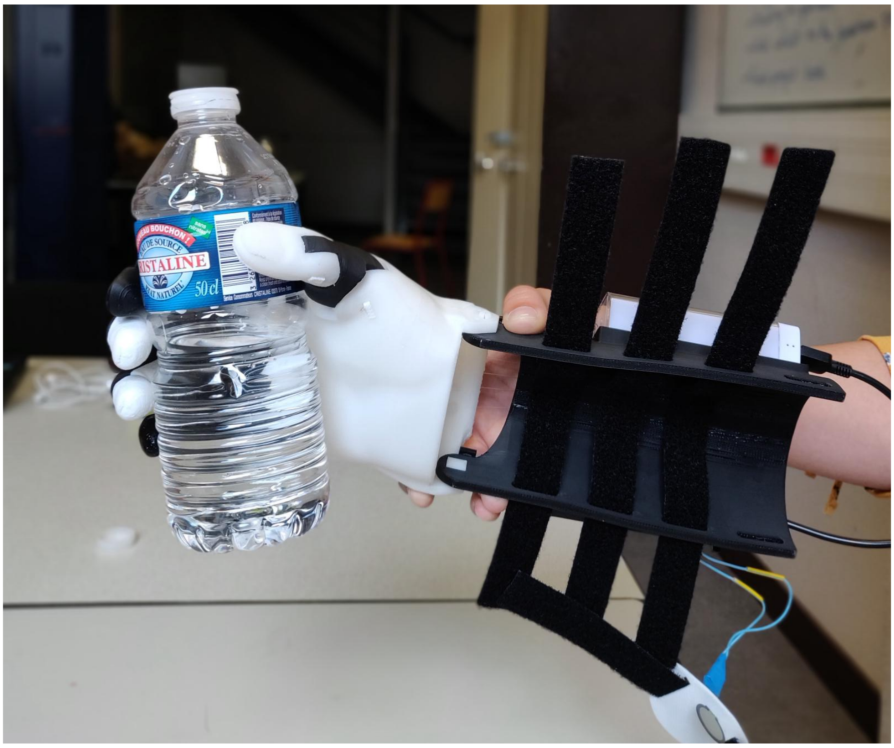


Figure 36 - Prototype Lifting a Half Full 500 mL Bottle

F. Costs

As one of the principle requirements of the project was to design an affordable solution (circa €500), a number of cost estimates were generated throughout the project to ensure that this was met. The aim of the device is fill the gap in the market for a low cost electronic prosthetic device for below the wrist amputees.

An analogical cost estimating model was drawn up during the state of the arts phase of the design, using the costs of other similar projects. The cost of a standard mechanical e-Nable hand comes to around $50 in materials. This does not include any overheads or fixed costs such as the labour required to produce the device or the 3D printer running costs. Other 3D printed electronic devices that have been produced by other projects generally cost between $100-$200, therefore it was hoped that the project would be able to achieve a figure similar to this for the device.

An expert judgement estimate was based on the instruction of the project supervisor that the project cost should be within the order of magnitude of €500. This indicated that this would be a good high level estimate for the total cost of the project in question.

A parametric cost estimate based on the forecast costs of individual components and materials to be used was created ahead the Intermediate Defence Presentation for the project. The following *Table 9* summarises this estimate and the total that was came from this analysis was between €117 - 152. This estimate was well within the budget set at the start of the project and hence the project supervision gave the team the green light to proceed with this design.

Table 9 - Initial Parametric Cost Estimate for Project

Component	Cost
Materials for printed hand	$20-50
Additional material for extended gauntlet and housing	$10-20
Cost of additional fishing line (negligible)	$0
Force sensor	$7
Single linear actuator	$70
9V battery	$4
ARDUINO Nano Board	$22
Solder board	$3
Switch	$2
Electric wires (1-2m) - $3/m	$3-6
Resistors x2 (negligible)	$0
Battery adaptor	$1
Total	**$142 - 185 (€117 - 152)**

Once the prototype was completed a detailed breakdown of the costs was produced to verify that the estimates drawn up earlier on in the project were accurate. This cost breakdown is detailed in *Table 10* below.

Table 10 - Final Costs of the Prototype Parts and Hardware

Component	Cost
ABS printed parts	€7.15
Filaflex printed parts	€3.87
PQ12 Linear actuator	€68.29
ARDUINO Micro	€19.85
Force sensor	€6.44
ProtoBoard	€1.47
Battery pack	€16.90
USB cable	€2.98
Step up converter	€5.81
Electric wires (1m)	€3-6
Screws	Negligible
Fishing line	Negligible
TOTAL	**€135.76**

The cost of the hardware was based on the invoice from the RobotShop online order and the material costs for the printed parts were based on the weights of the parts and their supports. This information was generated by the Z-suite software used for slicing the parts before being printed. This cost does not take into account the fact that the supports were recycled once removed which would save some costs.

G. Safety

The developed prosthetic hand is robotic and, consequently, it has electrical components that demand care during operation, in order to avoid the risk of burns and electric shocks. Most of the attention must be paid during the assembly of the model.

The failure mode and effects analysis below identifies all the possible ways components in the final design can fail. The cause describes the events that can lead to a failure, the modes describe the way it can fail and the effects describe the consequences of such a failure. Methods for prevention and detection by the user or builder have been identified to limit failure occurrence.

Each components potential failure has been rated in terms of likelihood of failure (the probability of failure during the components lifetime), severity of failure (the effect on the original purpose of the hand) and potential to overlook a failure (the probability that a problem will be detected and acted upon before failure) to determine the risk priority [p]. Components with a higher risk priority must be monitored closely. It is shown below that electrical components tend to have a higher risk priority as they are hidden within a case and cannot be easily overlooked and have a great potential for causing catastrophic failure of the prosthetic hand as a whole.

Table 11 - Failure Modes, Effects and Criticality Analysis

Component and Use	Potential Causes of Failure	Failure Mode	Likelihood {1 - 10}	Potential Effects of Failure	Severity {1 - 10}	Prevention	Detection	Potential for Overlook {1 - 5}	Risk Priority (L x S x PO)
Force Sensing Resistor. Uses pressure on its surface to send signal to Arduino that controls the actuator.	Liquid comes into contact with sensor wires.	Contamination	4	Changes in electrical characteristics, cumulatively changing calibration.	7	Do not expose sensor to water.	No signal received from force sensor when connected to Arduino IDE.	3	84
Electric Cables. Used to connect the circuit.	Twisting or bending of cables causing damage to copper wires.	Loss of continuity	5	Loss of conductivity within circuit	3	Carefully fixing cables to prevent any twists or bends.	Non-functional circuit.	5	75
Soldered Electrical Contacts. Connects circuit to protoboard.	Excessive movement of electrical components and shifting of joint. Excessive thermal cycling.	Mechanical Stress Thermal Fatigue Mechanical vibration fatigue	4	Loss of conductivity within circuit	3	Handle electrical components carefully.	Non-functional circuit.	4	48
Switch. Used to turn on/off power supply.	Wear. Excessive force.	Mechanical	5	Need for manual connection and disconnection of power supply.	3	Use switch carefully.	Visual inspection of switch locking.	3	45
Boost Converters (Voltage Regulator). Steps up voltage while stepping down current to translate power to the Arduino and actuator from power supply.	Overheating control integrated circuit. Initial rush of current when connecting to electronics.	Voltage Overshoot LC (inductance and capacitance) Voltage Spikes	2	Excessive voltage to the actuator and Arduino causing failure (short circuit). Destruction of voltage regulator.	8	Switch to disconnect power source and boost converter when there is a short circuit load condition. Power supply with high inductance.	Non-functional circuit.	2	32
Gauntlet Power Bank Casing. Encloses the power bank with openings for charge input and output.	Rough handling. External impact.	Shear	4	Loss of power supply.	7	Avoid external impact to gauntlet.	Manual visual inspection.	1	28
Resistor. Pull down resistor. Ensures sensor input signal received by Arduino remains at zero volts when there is force input.	Rough handling. Overheating causing overload or oxidisation from contact with water.	External stress Open (going to infinite resistance), fail short (going to close to zero resistance)	2	Connection between sensor and ground breaks. Signal will not be received from force sensor.	4	Handle resistor carefully. Seal electrical components in protective casing.	No signal from force sensor.	3	24
Arduino board. Microprocessor used processes inputted sensor signal and output signal to instruct actuator.	Board may crack under mechanical load.	Stress	2	Unreliable circuit that can not read sensor signal nor drive actuator.	4	Handle Arduino board carefully.	Manual visual inspection.	3	24

Component and Use	Potential Causes of Failure	Failure Mode	Likelihood {1 - 10}	Potential Effects of Failure	Severity {1 - 10}	Prevention	Detection	Potential for Overlook {1 - 5}	Risk Priority (L x S x PO)
Protoboard. A matrix of small holes used to connect electronic components.	Board may crack under mechanical load.	Stress	2	Unreliable circuit that can not read sensor signal nor drive actuator.	3	Handle Arduino board carefully.	Manual visual inspection.	4	24
Gauntlet Arduino and Protoboard Casing. Encloses the electronics with holes for wiring.	Rough handling. External impact.	Shear	3	Loss of circuitry.	7	Avoid external impact to gauntlet.	Manual visual inspection.	1	21
Gripper Box and Slider. Connects the finger and thumb lines to the gauntlet and actuator.	Excessive pulling, when the actuator is retracted, by bending of the wrist. Rough handling. External impact.	Shear	3	Actuator cannot pull fingers. No finger movement allowed.	7	Do not bend wrist when hand is closed.	Manual visual inspection.	1	21
Electric Linear Actuator. Makes use of control signal to tensions and release fishing line to drive finger movement mechanism.	Loss of power Incorrect wiring of the circuit. Excessive pulling on the actuator.	Locking in place (fail-as-is) Excessive voltage breakdown - stalling.	3	System becomes rigid. Short circuit. Overheating. Destroyed actuator.	7	Maintain a charged power bank. Do not bend wrist when hand is closed.	Visual inspection of locked actuator stroke position.	1	21
Power Bank. Powers Arduino and Linear Actuator.	Defective connections. Overcharging. High ambient/storage temperature. Physical impact. External short circuit	Overcharging Overheating Mechanical Stress	3	Overheating Decrease in power storage abilities	3	Cell level safety devices. Maintain in cool (approx 25°C), dry environments. Dissipate heat. Battery housing is built tolerant to abuse. Cell level safety devices and fuses.	Inspect USB cables. Battery giving off heat. Inspect battery power bank housing.	2	18
Gauntlet Actuator Casing. Encloses linear actuator.	Excessive pulling, when the actuator is retracted, by bending of the wrist. Rough handling. External impact.	Shear	2	Loss of actuator function.	7	Do not bend wrist when hand is closed.	Manual visual inspection.	1	14
Dovetail Retention Clip	Rough handling.	Shear	1	Unable to retain gripper box. Actuator cannot pull fingers. No finger movement allowed.	5	Do not remove retention clip.	Manual visual inspection.	2	10
Gauntlet. Houses all hardware. Allows relative movement between forearm and hand.	External impact.	Stress	1	No finger movement allowed.	8	Do not load gauntlet excessively.	Manual visual inspection.	1	8

Component and Use	Potential Causes of Failure	Failure Mode	Likelihood {1 - 10}	Potential Effects of Failure	Severity {1 - 10}	Prevention	Detection	Potential for Overlook {1 - 5}	Risk Priority (L x S x PO)
Finger and Thumb Filaflex Tips. Primary contact point for gripping objects.	Contact with hot object.	Thermal transition - melting	2	Reduction in grip efficiency.	1	Do not handle hot object above approx. 200°C.	Manual visual inspection.	3	6
Fishing Line. Tensions to allow finger movement.	Excessive pulling, when the actuator is retracted, by bending of the wrist.	Tension stress - snapping	2	Cannot transfer motion from actuator to fingers.	2	Do not bend wrist when hand is closed.	Inability to move finger/fingers	1	4
Joint Pins. Connects finger sections while allowing relative movement.	Excessive load on fingers.	Shear	1	Individual fingers may not be able to function.	2	Do not handle more than specified load limit. Distribute load across fingers where possible.	Visual inspection of finger joint movement.	1	2
Palm. Connection point for finger and thumb bases and gauntlet. Fishing lines pass through from fingers to gauntlet.	Contact with hot object.	Thermal transition - melting	1	Non significant.	1	Do not handle hot object above approx. 200°C.	Manual visual inspection.	2	2

Table 12 – ABS Material Safety Information

Description of First Aid Measures	
Ingestion	Remove material residues from mouth and rinse mouth with water
	Drink plenty of water
	Do NOT induce vomiting
	In case of discomfort, contact a physician
Indication of any immediate medical attention	
Notes to physician	Treat symptomatically
Safety Data Sheet	
Exposure limits	The product does not contain any hazardous substances with occupational exposure limits
Individual protection measures, such as personal protective equipment	Store at temperatures between 20 and 30˚C
	Ensure proper ventilation, especially in confined spaces
Engineering Controls	
Thermal hazards	No fire hazard under normal use conditions
Environmental exposure controls	Do not allow to enter into drains, ground and surface water
Physical and chemical properties	Melting point/freezing point - 104˚C
	Flammable in constant flame

H. Maintenance

When replacing parts, make sure to have the same dimension for printing as the other parts of the hand, to be able to fit properly. Be careful when disassembling the hand to avoid unnecessary damage

To clean the prosthesis, the use of a humid cloth is advised. The model was not designed to be waterproof. Any contact with water or liquids in general should therefore be avoided out of risk of damaging the electronic components, making the hand robotically inoperable.

IX. Future Developments

A. Sensor Sensitivity

In the current model, for the builder to adjust the threshold for each user, it is necessary for them to make modifications on the code. Considering that not all builders have experience with programming and might make mistakes that would keep the code from working properly, a good addition to the model would be to have a physical potentiometer. The potentiometer has an analogue adjustment according to position and it could communicate with the ARDUINO through one of the analogue ports, providing it with the threshold value.

Since the potentiometer has the same range of values as the force sensor (from 0 to 1023), because they are both variable resistors, it would not demand mapping of the read values. This factor would make for an easy integration, demanding only an adjustment of the circuit for that matter.

B. Electronic to Mechanical Device

The team began developing a way of detaching the gripper box from the actuator so that the hand can be used as a mechanical solution without damaging the actuator. This would require the cable to be fully tensioned when attached to the actuator in its extended position. As such tools, like a hook, that would require some slack to attach to the actuator head have been dismissed.

The idea of attaching the gripper box cable to a bolt that would fix into the hole at the head of the linear actuator was promising. This would maintain the tension of the cable while still allowing straightforward. Including a nut to secure the bolt in place was not possible due to the limited space available below the actuator head. Therefore an actuator-head-cap was designed with a hole that would be small enough to secure the bolt in place. In case of battery failure, the bolt would be detached from the actuator creating a mechanical solution and reattached using the secure actuator cap.

C. Increased Force Output from Actuator

The choice of actuator was based on estimates from a smaller e-Nable hand with a different design. As such the force required to close the hand and the effect of friction between the cables and the Filaflex fingertips was underestimated. The PQ12 Linear Actuator used had limited actuation of the hand and stalled at its most retracted position, where there was the greatest tension in the cables.

Another option for linear actuator was the L12 which had twice the force output this would likely provide the required force. However, this actuator has a much larger body and stroke length and will require the gauntlet to be extended considerably. The actuator and gauntlet will add weight to the design. Alternatively, multiple actuators can be integrated into the design.

D. Index Finger Release Mechanism

The index releasing mechanism didn’t function as well as was hoped so further work on this is needed to yield a working solution. It is believed that the solution implemented could function well if the length of the tube in the index in which the locking slider sits was longer. This would enable more slack to be given to the cable and the index to stay in a more open position upon contraction.

I'm not convinced, as a modification of the whippletree would be needed also to make index and middle finder independant... (?) Further analysis and development seems to be required.

X. Conclusions

In conclusion, the project was a global success with the majority of the requirements set out at the start being met. A functioning prototype was produced which was used as proof of concept of the final design. However, a number of adjustments and some design rework is required in the future to develop the device further and create a fully functional prosthesis that can be used by people with below the wrist amputations.

It is hoped that the design produced by the project is a very positive step in the direction of making low cost electronically assisted prostheses accessible to those in need, and ultimately improving their quality of life.

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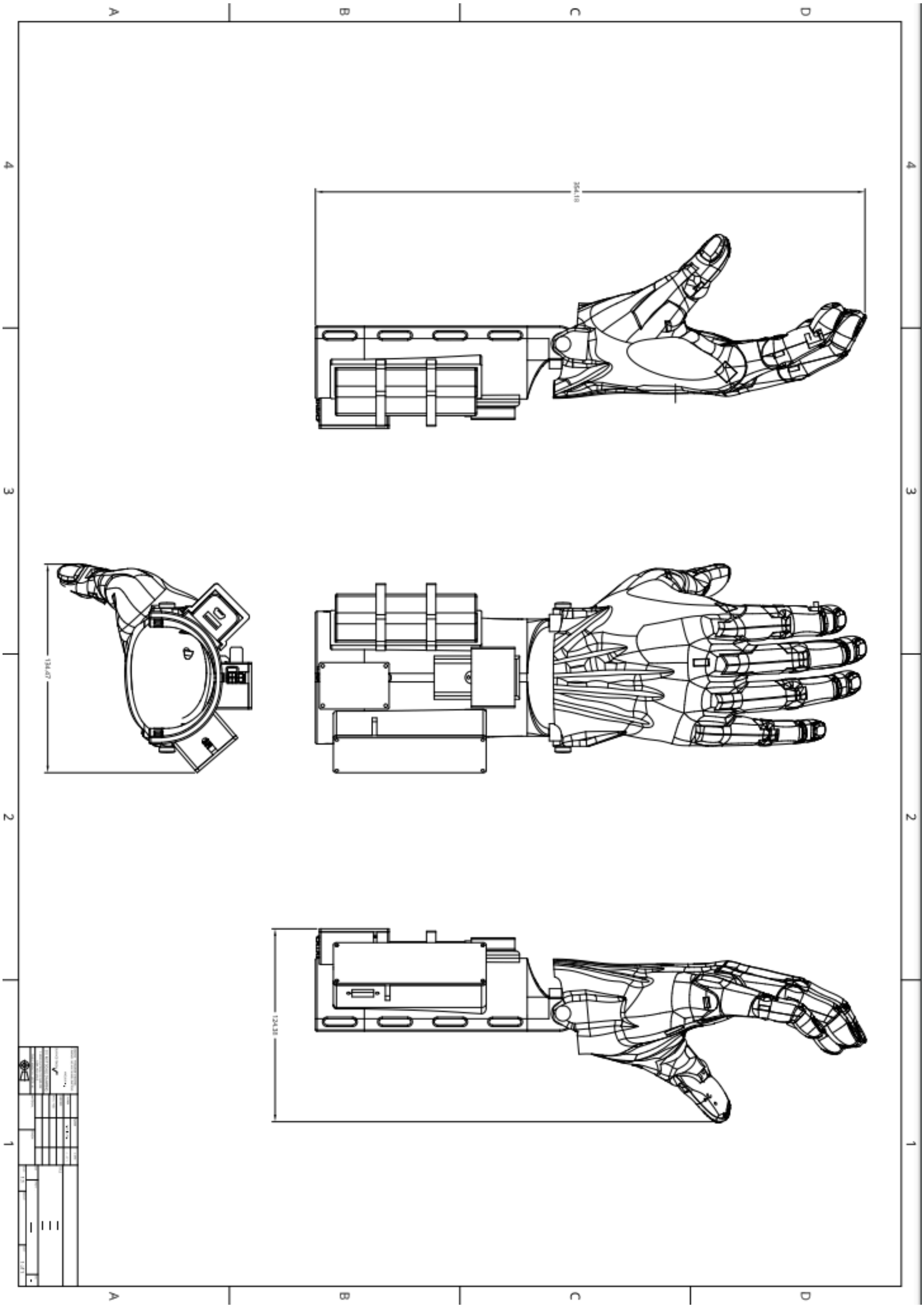
XII. Appendices

Appendix 1 - Code

```
/*
This project is associated with the development of an assistive upper
limb 3D printable design

The prosthetic hand includes a sensor to capture signals from the user
and a linear actuator to pull on the prosthetic fingers once the signal
is perceived
*/
#include <Servo.h>

//CHANGE SENSOR THRESHOLD HERE
int SensorThresh = 500; //threshold for the sensor

int ActuatorPin = 9; //connects actuator to pin 9
int SensorPin = A0; //connects sensor to pin A0
int MaxOpen = 0; //the hand will be fully opened when actuator is fully
extended
int MaxClose = 180; //the hand hand will be fully closed when actuator
is fully retracted
int ActuatorValue; //to be sent to the Actuator
int SensorValue; //will store the value from SensorPin
int aux = 0; //to be used in 'for' loop
int ActDelay = 100; //time (in ms) before new position is sent to
actuator
int DelayMax = 2000; //time (in ms) before the hand starts contrary
movement
Servo Actuator; //create servo to control the linear actuator
bool lastMove = LOW; //identifies if the last move was opening (LOW) or
closing(HIGH) the fingers
bool press = false; //to identify if sensor is being pressed

void move (int act,int sens)
{
  //Sets the servo to its new position
  Actuator.write(act);
  //sends information to serial monitor
  Serial.print("Sensor: ");
  Serial.println(sens);
  Serial.print("Position: ");
  Serial.println(act);
}
```

```
void setup() {
  Serial.begin(9600); //starts serial monitor
  //declare servo as output and sensor as input
  pinMode (ActuatorPin,OUTPUT);
  pinMode (SensorPin,INPUT);
  Actuator.attach(ActuatorPin, MaxOpen, MaxClose); //attaches the linear
actuator as a servo
  press = false; //sensor is not being pressed
}

void loop() {
  SensorValue = analogRead(SensorPin); //reads the value from the sensor

  if (SensorValue >= SensorThresh) //if the sensor signal is above the
chosen threshold
  {
    press = true; //the sensor is being pressed
    ActuatorValue = aux;
    //adjusts the opening/closing movement at the extreme positions
    if (aux >= 180) lastMove = HIGH;
    else if (aux <= 0) lastMove = LOW;
    if (lastMove == LOW) //if the last movement was opening the fingers
      {
        move(ActuatorValue, SensorValue); //moves the actuator
        aux = aux + 10; //increases the position
      } else {
        move(ActuatorValue, SensorValue); //moves the actuator
        aux = aux - 10; //decreases the position
      }
    //if actuator is at one of the extreme positions, it will wait for 1
second before it starts moving
    if (ActuatorValue >= MaxClose) delay(DelayMax);
    if (ActuatorValue <= MaxOpen) delay(DelayMax);
    delay(ActDelay); //to avoid sending information to the servo faster
than it can process
  } else if (press == true){
    press = false; //the sensor is not being pressed
    //adjusts the opening/closing to alternate between actuations
    if(lastMove == HIGH) lastMove = LOW;
    else if (lastMove == LOW) lastMove = HIGH;
  }
}
```

Appendix 2 – Assembly Draft



Appendix 3 – Assembly Draft