BIONIC EVO: Prosthetic Arm Design Document

Peterson Guo, Jun Kim

Contents: 2

I. Needs Assessment

A. Client/Customer Definition

Amputees struggle with independence, work, and hobbies. They often feel dependent on family members and friends, relying on them to take care of them. In addition, they may be forced to retire from work or switch careers entirely due to their amputation. It makes it harder for them to make a living, oftentimes relying on government aid for survival [1]. With this prosthetic arm, we aim to recreate a normal human arm, allowing amputees to regain independence, and begin to perform daily tasks such as grooming, dressing, eating, etc. without assistance [3]. They will also be able to work, and continue any hobbies they may have had to quit due to their medical circumstance, digging them out of the hole of their financial situation that the amputated arm may have put them in. Overall, the project aims to improve the overall quality of life of adult amputees living in urban areas from the lower to the middle class who have access to healthcare/hospitals, empowering them to pursue new hobbies and projects and leading them to live more fulfilling and active lives [2].

B. Competitive Landscape

1) Traditional Prosthesis

Traditional prostheses give users a sense of independence and an increase in mobility by acting as an artificial limb. It allows users to maintain balance and offers a practical solution to improve the quality of life of an individual with limb loss. They are a cost-effective way for users to regain lost motor functions and they are reputable for their durability and accessibility. On the other hand, they lack basic functionalities such as rotation. They also have a huge learning curve as users must learn to adjust to the weight of the new object, and they are not adaptive or energy efficient. Prostheses are also uncomfortable and can cause blisters, cysts, and dermatitis, and alter the center of mass on the residual limb. To compensate for the new device, amputees adjust their movements in abnormal ways leading to degenerative arthritis, joint pain, and back pain with 51% of people with a traditional prosthetic complaining about pain in some area [1]. To counter these problems, amputees must meet with prosthetists who make technological alterations and they must meet with professionals such as prosthetists, physiatrists, and physiotherapists [2].

2) Myoelectric Prosthesis

A myoelectric prosthesis is a more advanced type of prosthesis which help users regain advanced motor controls such as individual limb control and limb rotation. They function by reading electrical signals from EMG sensors which are attached to the amputee's body. The signals are processed by the computer on the prosthesis and then they are converted to an output which moves the arm.

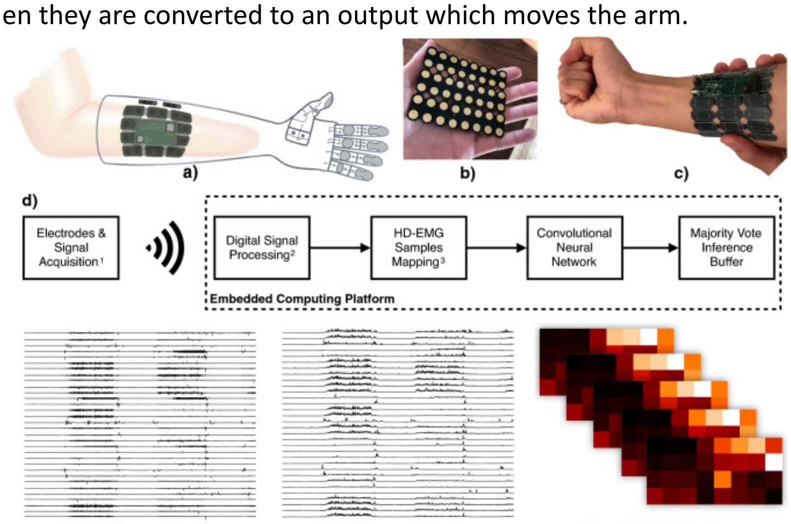


Fig. y demonstrates how sensors are attached to the user's body and how they are processed such that they can be used as outputs [1, Fig. 1]

These prostheses will often store energy and use feedback loops to improve usability. Using the technologies in Fig. y, prostheses will also have more features than a traditional prosthesis such as shock absorption and real-time adjustments. These features are processed with the onboard computer, doing small things such as adjusting the shock absorption when a step is taken to reduce the stiffness of a prosthetic leg [2].

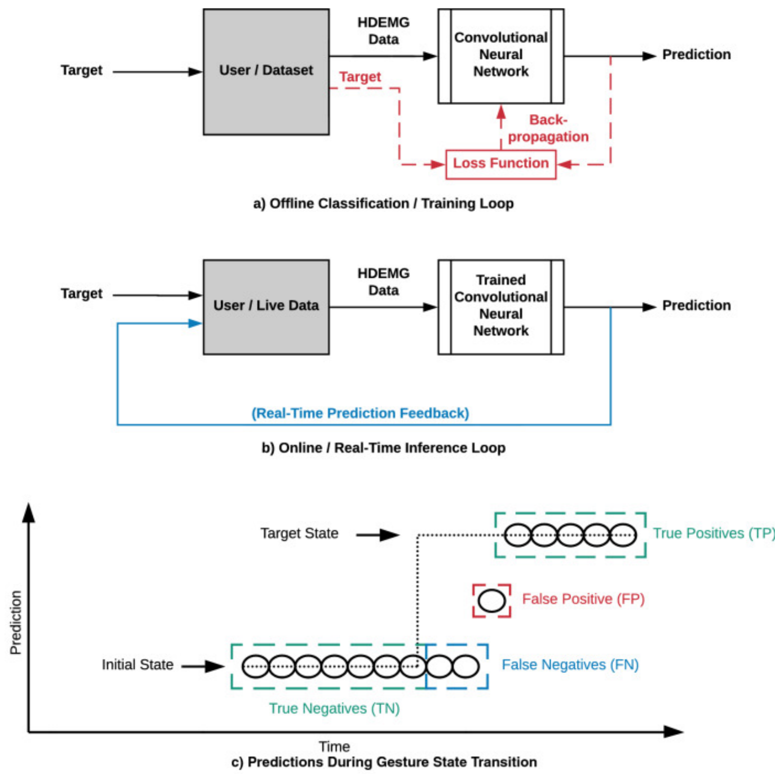


Fig. x depicts the algorithm used by myoelectric prosthetics [1, Fig. 2]

Despite all the features of myoelectric prostheses, they are often used less than traditional prostheses because of their non-intuitive user interface. In addition, they are extremely expensive compared to a traditional prosthetic, being $15,000 to $50,000 on the market, forcing users to rely on insurance and government coverage to remain affordable [3]. With all these downsides considered, a myoelectric prosthetic arm may not be practical for the price at which it is offered.

3) Cosmetic Prosthesis

A cosmetic prosthesis has no functional component. It is a silicon limb that is attached to the missing limb which is coloured the same as the user's skin tone [1]. The main purpose is often just to appear as though the limb is still attached [2]. Although it is extremely cheap, users do not regain any missing functionality from their lost limb.

C. Requirement Specification

Functional Requirements:

- The entire prosthetic arm weight must not exceed 5 pounds.
- Minimum 100 degrees of flexion and extension for each finger, minimum 180 degrees of wrist rotation.
- Must exert a minimum grip strength of 20 Newtons (N).

Technical Requirements:

- Arm components must withstand 100 cycles of movement without failure.

- The arm must withstand at least 450N of compressive force and 600N of tensile force.
- Fingers must withstand at least 350N of tensile force and 200N of compressive force.
- Must withstand 5V of shock from the outer shell.
- Must be IP64 (sweat & dust) resistant.

Safety Requirements:

- The prosthetic arm should comply with electromagnetic compatibility (EMC) standards to prevent interference with other electronic devices and ensure user safety.
- 5 cm total shock absorption throughout the arm

II. BIONIC EVO: Prosthetic Arm Design Document Analysis

A. Design

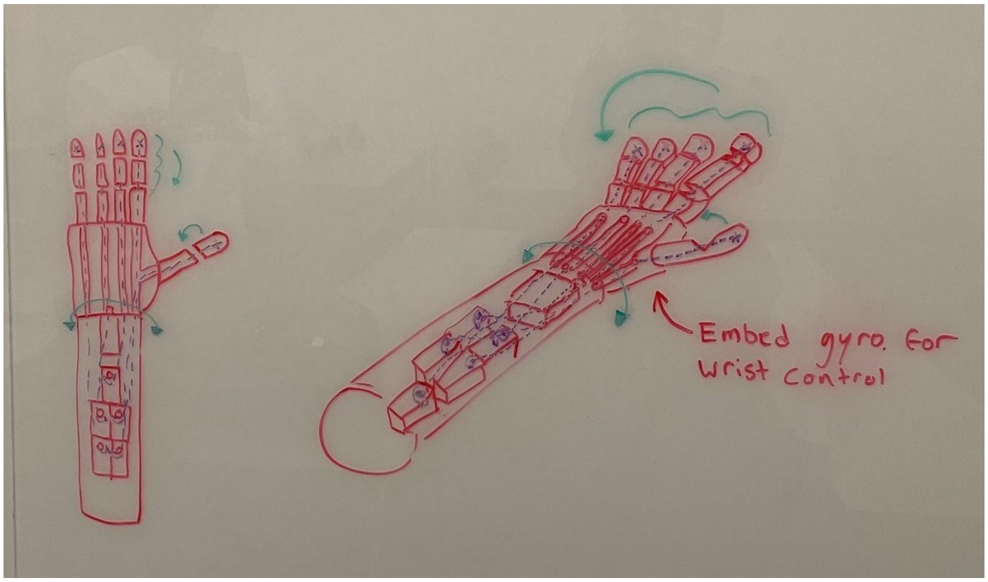


Fig 1: Rough Diagram of Final Prosthetic Arm Design

Presented in Fig 1 is the Bionic EVO's rough diagram, which describes the general functionality of the prosthetic, along with an X-ray view of what components would be used, where each component would be stored, and the general channels directed to each finger. Overall, the rough diagram of the final prosthetic arm entails utilizing 3D printed PLA for the body of the prosthetic system, 5 SG90 servo motors to operate each finger, and a potentiometer to control the fingers, in which the potentiometer will be used as an alternative motive of control opposed to EMG muscle controlled sensors.

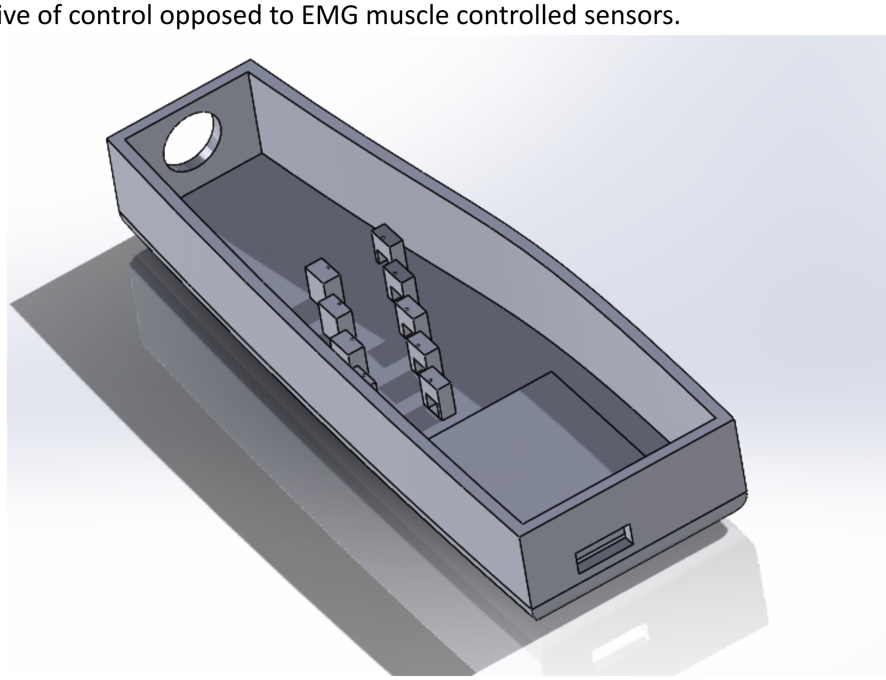


Fig 2: Forearm 3D Model

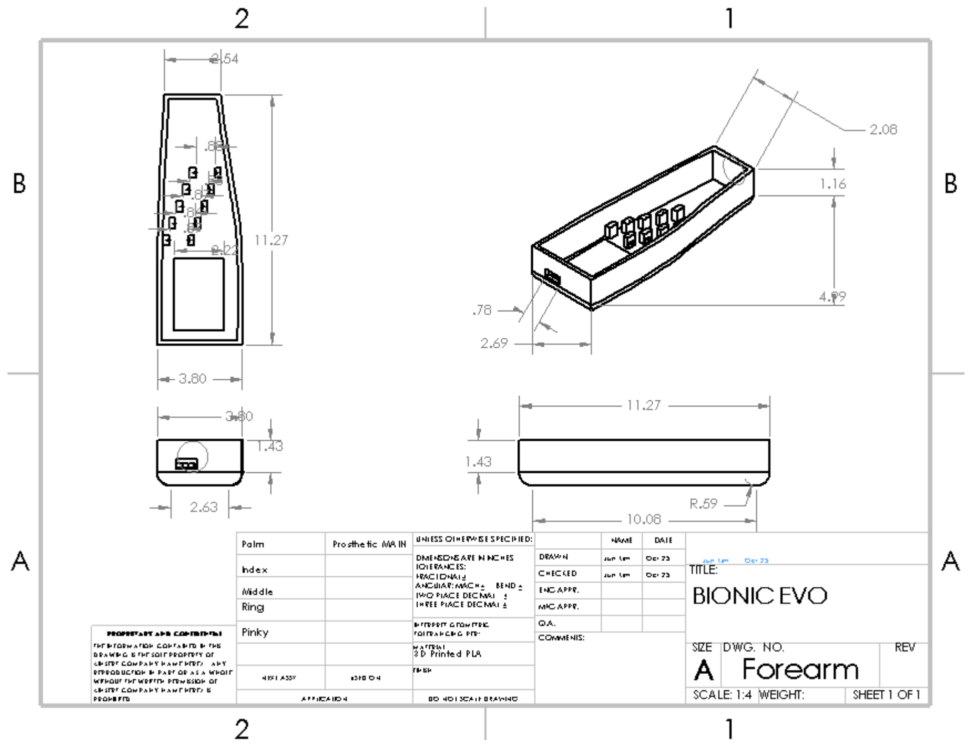


Fig 2: Forearm Technical Preview

Initially designing the Prosthetic Forearm 3D model (Fig 1) within SOLIDWORKS as seen in Fig 2, this specific part was designed to house the primary electrical framework of the entire prosthetic. With a length of 11.27” and 3.8” wide from the bottom and 2.54” wide from the top, the forearm was modeled intuitively to accurately resemble a humanoid forearm. Integrating five SG90 servo motors mounted inside, each servo is spaced evenly between each other to enable a wire to be connected to its corresponding finger for control, easily pulling the wire for contractions. Furthermore, it includes a dedicated slot for the STM32 Microcontroller board, enabling simple access to connectivity from all electronic components to the main processor. Furthermore, a strategically placed side hole enables external access to the STM32 Microcontroller’s USB slot, which allows external charging capabilities and connection to a computer for program updates and more. In addition to this, the potentiometer will be externally connected to the STM32 Microcontroller by accessing it from this side hole. In terms of installation, each dedicated slot for each servo has perforated to easily screw and fasten each servo to their mount, this also goes for the STM32 Microcontroller mount, with dedicated perforated slots to screw and fasten the component. Furthermore, a perforated section in the front of the forearm allows the wires to access the palm and fingers and allows the palm to slot into the forearm as intended. In terms of the construction of this part, it would entail 3D printing this model, which would mean exporting the design as an STL model, exporting it to a 3D printer, and using PLA filament to print the structure of the part.

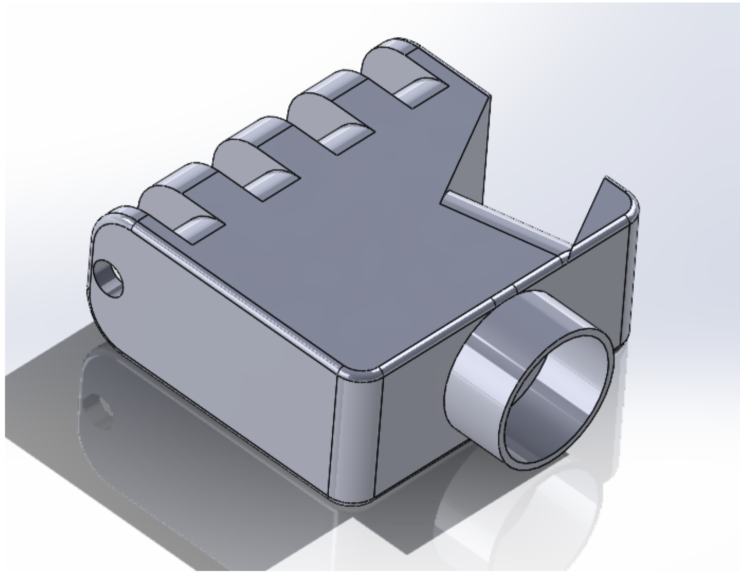


Fig 3: Palm 3D model

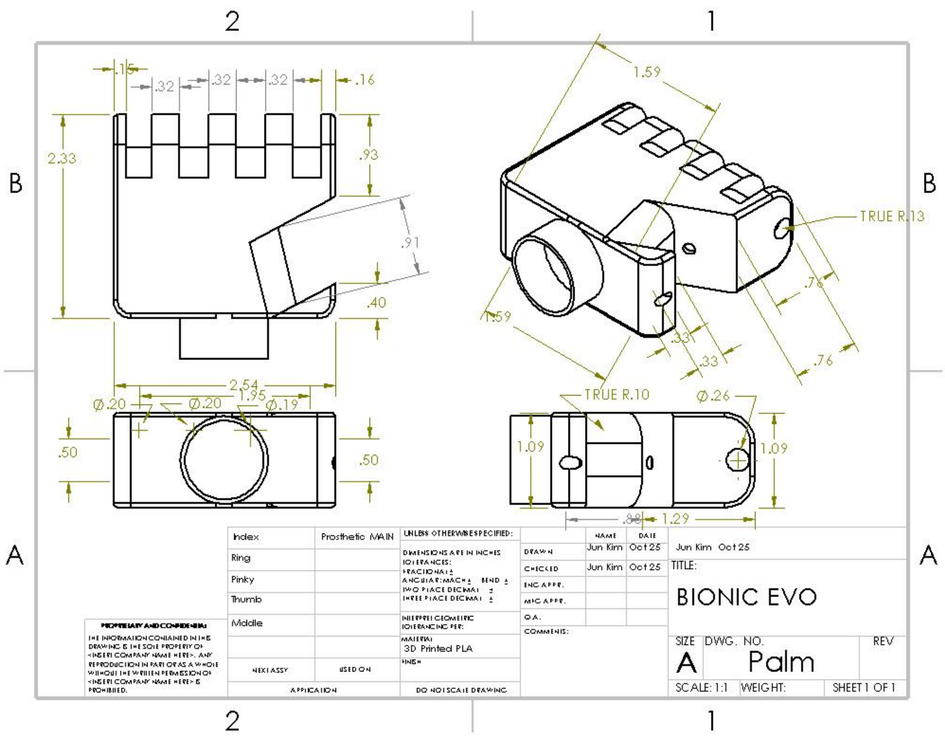


Fig 4: Palm Technical Preview

With a length of 2.33" and width of 2.54", the palm part of the prosthetic, as seen in Fig 3 and Fig 4, has been fitted to the other extending parts of the design such as the forearm and the fingers. Furthermore, these measurements have been. The palm features a framework of 5 distinct channels to allow wires to be accessed both by the extending fingers attached to the palm and the servos within the forearm. The palm features slots for the thumb, and four finger parts respectively. Furthermore, the integration of the holes between each finger joint allows for a rod to be placed in between to act as a hinge mechanism for the fingers to have a rotational degree of motion from the palm. For installation of the fingers, simply channeling wires for each hole, attaching each finger to its respective slot, and inserting the joint rods will suffice. For installation of the palm to the forearm, simply attaching the palm to the forearm will install it to the system. The installation of the connecting wire would be required, which simply instructs threading a wire through the perforated channels within the finger assembly. Regarding this part's production, it would also entail 3D printing, which would mean exporting the design as an STL model, exporting it to a 3D printer, and using PLA filament to print the structure of the part.

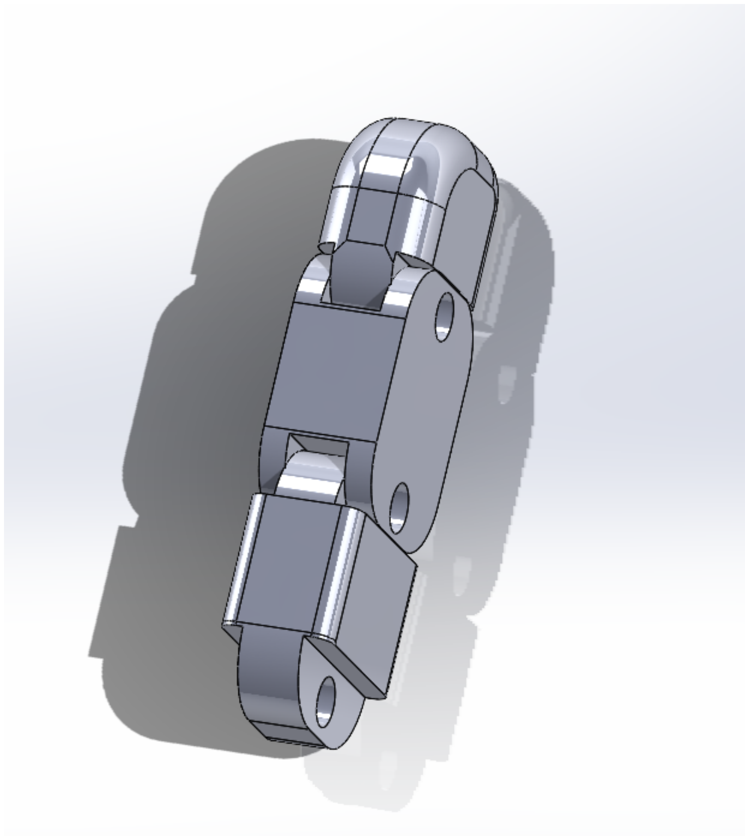


Fig 4: Finger Assembly *3D Model*

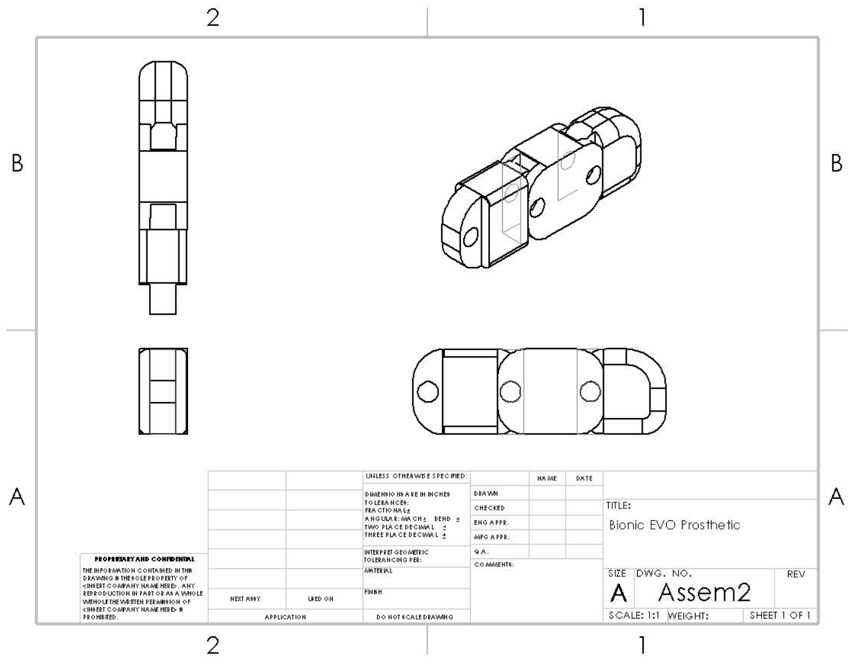


Fig 4: Finger Assembly Technical Preview

Fig 3 and Fig 3 represent the fully attached assembly of one of the 5 prosthetic fingers, which when combined, have a length of 3.23”, 0.6” in width, and 1.09” in height. Similar to a real humanoid finger, the Bionic EVO’s fingers have two joints in between the three parts of a finger; two joints in between the distal phalanx, the middle phalanx, and the proximal phalanx. Each of these described parts is its own modelled parts which come together in one assembly as shown in Fig 3. Similar to how the fingers are attached to the palm, the joints between each part of the finger assembly are connected by the integration of the holes between each joint, allowing for a rod to be placed in between to act as a hinge mechanism for each part of the finger to have a rotational degree of motion from the palm. In terms of its operation and movement, it is controlled by a channelled wire through the finger assembly, which is connected to the palm and to the forearm where the SG90 servo motors are stored and operate the finger’s movement by pulling the string for a contraction. For the installation of the complete finger assembly, with the following installation instructions applied to attaching the finger to the palm, simply inserting a rod into each joint where each part connects will suffice. Additionally, further installation of the connecting wire would be required, which simply instructs threading a wire through the perforated channel within the finger assembly. Reiterating from prior parts, as the complete body would require 3D printing, which would mean exporting the design as an STL model, exporting it to a 3D printer, and using PLA filament to print the structure of the part.

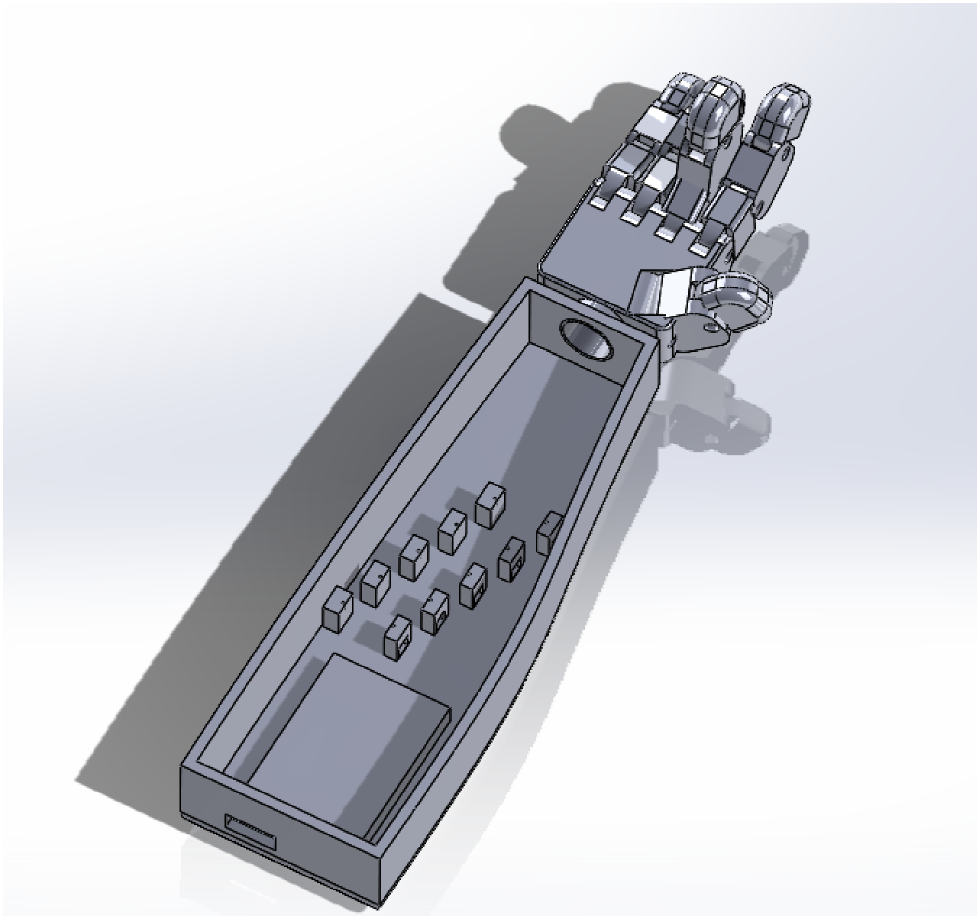


Fig 4: Full Assembly 3D model

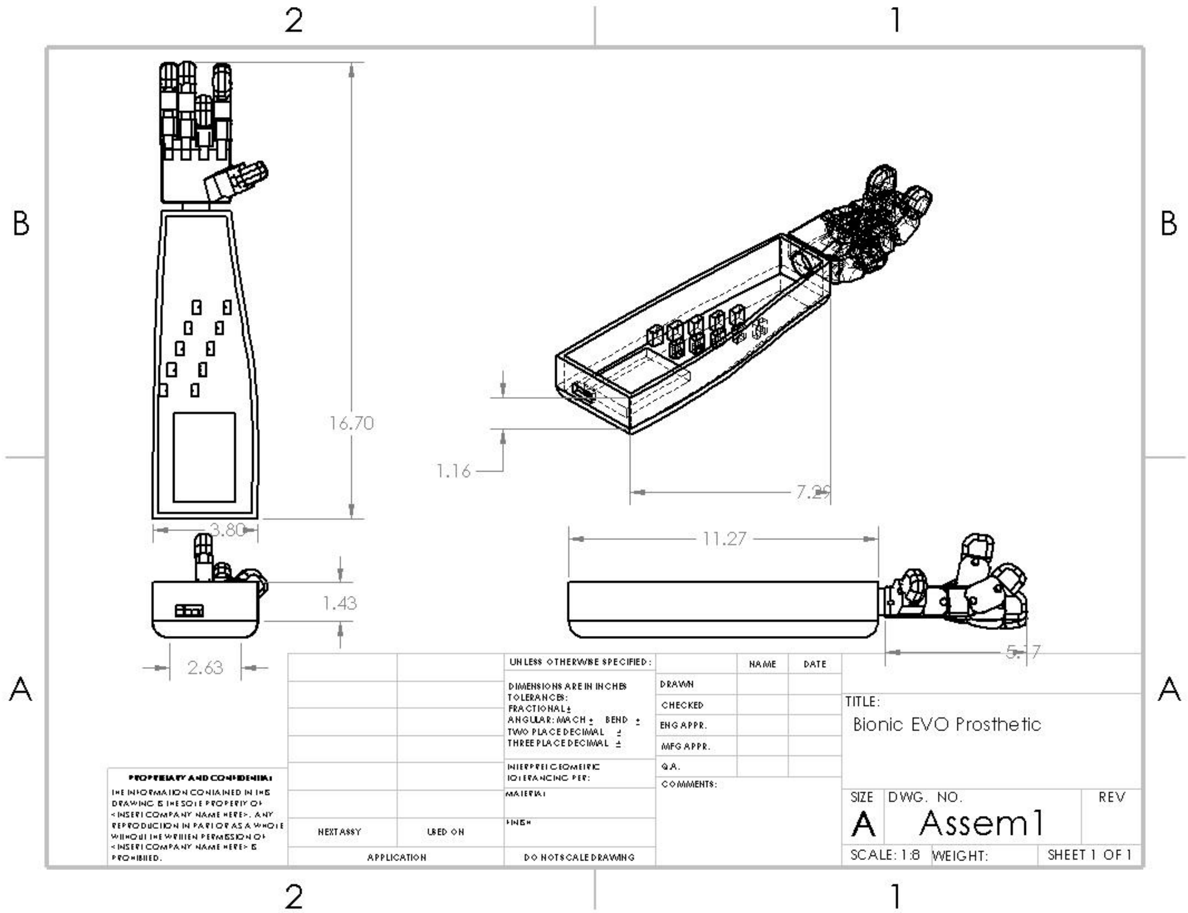


Fig 4: Full assembly Technical Preview

The ultimate, final, 3D design as depicted in Fig 4 showcases the complete prosthetic system with dimensions measuring 16.70” in length, 3.80” in width, and approximately 1.60” in height, these measurements being completely derived from the measurements of a real-life arm and hand. This final assembly represents the final culmination of the design with each part such as the palm, forearm, and finger assembly assuming their intended place to create the full system. As illustrated in Fig 4, the forearm is connected to the palm, which then extends to the connecting 5 fingers as per a typical humanoid hand. Each finger is connected to the palm by the insertion of a rod at its rotational point to create a hinge-like mechanism, and the palm itself is simply inserted into the wrist. Overall, the Bionic EVO design embodies a functional prosthetic system that is worthy of practical use, which has been meticulously crafted to resemble a real humanoid arm and hand. In terms of the overall installation of the prosthetic, if all other components and parts have been installed as described with each installation instruction stated prior, meaning all electrical components such as the STM32 microcontroller and servos have been mounted and all wires have been wired through their respective finger channel, simply attaching each finger by a rod at each end joint to the palm, and inserting the palm to the forearm will complete the installation of the system. Finally, as a complete system, the body will be 3D printed, which would mean exporting each part as STL models, exporting them to a 3D printer, and using PLA filament to print the structure of each part.

B. Scientific/Mathematical Principles

1. Supervised Machine Learning and Statistical Modelling

a. Regression

$$Y_i = f(X_i, \beta) + e_i$$

Eq. (1) Approximation for the equation of best fit (Regression Analysis)

$$TSS = \sum_{i=1}^{n} (y_i - \overline{y})^2$$

Eq. (2) Sum of Squares Formula (Logistic Regression)

Regression relates an independent variable to a dependent variable. It can be done by pre-training an equation of best fit as seen in eq. (1) using data given independent and dependent variables [3]. The sum of squares formula seen in eq. (2) allows the model to be trained by calculating the deviation of data from an equation of best fit. Calculating the variance of the data set from its mean gives a value that determines how well a modelled equation fits the given dataset thus, allowing the equation to be changed to improve the accuracy of the predicted data. Reducing the sum of squares means the model is more accurate than a model with a higher sum of squares. It is useful in determining whether a line of best fit is more accurate than a polynomial or exponential equation of best fit. Using eq. (1, 2) will allow the program to determine potential outliers in the EMG readings. It can be used to smooth out any arm movements and interpret any readings. Using muscle activity reading from the EMG sensors and modelling it to an equation where the position is the dependent variable and the readings are the independent variable, allows the position vector to be mapped such that the intended position can be determined.

2. Classification

Classification is a supervised machine learning model that is pre-trained with training data and can predict and label a set of data [4]. Classification can be used to determine actions and gestures that the robotic arm should make. Given the EMG readings, the arm may decide to grasp an object or it may decide to wave, which can be determined using the classification machine learning model.

a. Random Forests and Decision Trees

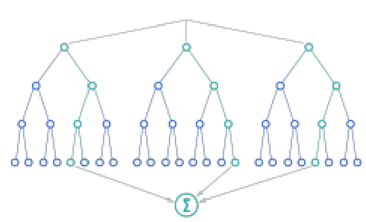


Fig. 4. A visual representation of random forests in [5, Fig. 3].

Fig. 4. is a visual representation of a decision tree used in random forests and decision trees. Initially, the random forests are divided into three subcategories which are manually defined. Decision trees are then split based on simple questions, leading to two branches: a ”Yes” branch and anOther” branch. This process is repeated recursively, creating subsets of data that lead to more accurate results. Fig. 4. also highlights that random forests use feature bagging and relevant questions to prevent overfitting and produce more realistic predictions. Algorithms such as the Gini impurity, information gain, and mean

squared error can be used to evaluate the quality of the trees, and trees are typically trained using the CART algorithm as described in [5]. Random forests use decision trees and feature bagging which are used to create a forest of uncorrelated decision trees. The major difference between decision trees and random forests is that random forests use all possible feature splits to determine an answer while random forests only use relevant questions [5]. This prevents the model from being overfitted with data that only produces a correct answer while training but cannot produce answers correlated to real-world data. In this case, random forests can be used to determine what gestures the arm should make. It may determine readings from the EMG sensors and shake its hand or it may decide to make a fist.

b. Support Vector Machines / Multiclass Classification

$$z = w_0 + \sum_{i=1}^{\infty} w_i \vec{x}_i$$

Eq. (3) A hyperplane equation where w represents scalar multiples of vector x.

$$maximize_{\alpha} \sum_{i=1}^{n} \alpha_i - \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_i \alpha_j y_i y_j K(X_i^T \cdot X_j)$$

Eq. (4) An equation representing the kernel trick to get the dot product of two vectors, [6, eq. (15)].

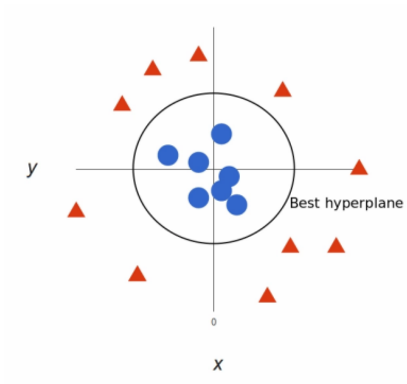


Fig. 5. A visual representation of how a hyperplane is used to divide points to classify data, [7, Fig. 4].

Support vector machines use vectors to split up datasets to classify them. As shown in Fig. 5. A hyperplane is used to divide clusters of data. The hyperplane is optimal when it maximizes the distance between any point stated by [8]. As described in [7], training data is given to the machine in vectors and fed to the algorithm to train the model. Any new data can also be fed to the model which will output a classification of the data. Robotic arms can incorporate SVMs and eq. (3, 4) with regression analysis to find a vector equation to classify the data. This will help it determine gestures, and classify the EMG signals. It will also help with anomaly detection, user intent prediction, and adaptive control. The EMG signals can be input into the machine as vector equations and the algorithm can output different classifications such as anomalies and classified gestures.

3. Mathematical Modelling

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

Eq. (5) PID Control equation where Kp, Ki, Kd are PID constants, respectively [9, eq. (1)].

Proportional control is used to adjust to motor error measured. A higher Kp will help the variable reach the set point faster as described in [9]. Too high of a value will result in oscillations and the variable will always have static error. Integral control is used to address the static error in proportional control. An adequately set P and I value will allow the motor control to converge with the set point [10]. The derivative tune is used as a multiplier based on the ROC of the change of error. It dampens the effect of the error, making the motor less “jittery” by minimizing the over-adjustment of the correction factor. In this project, PID control can be used on numerous motors to smooth out motor control and reduce ”jittering” when the motor is in motion. With a typical arm, the arm must be able to move smoothly and stay in one place. PID control can be used to artificially replicate this function. Electromyography (EMG) sensors will be used in this project to measure the muscle activity of an area. When detecting the activity, a lot of variance is introduced which influences the fidelity of the signal. Signal distortion and the signal-to-noise ratio contribute to the readings thus EMG signal processing is needed to reduce the signal error. Raw EMG data provides valuable information in a useless form. Different algorithms such as wavelet analysis, and auto-regressive

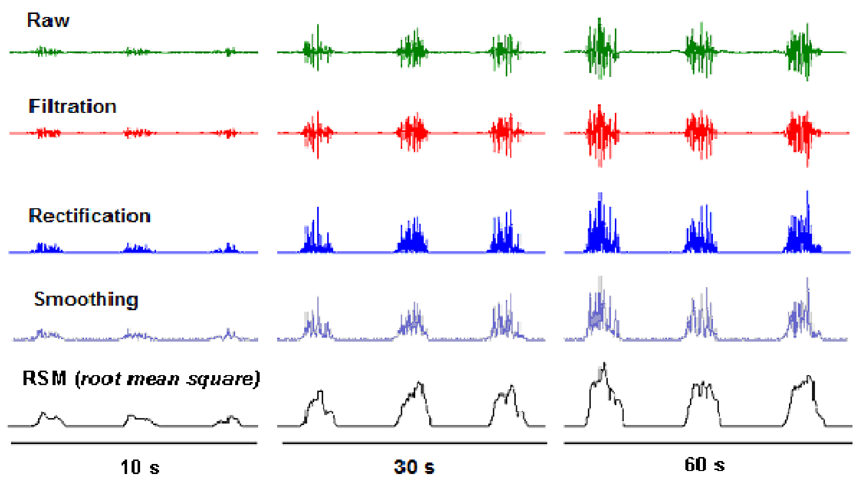


Fig. 3. depicts the recommended method for EMG signal processing, in [11, Fig. 2].

models, artificial intelligence, and higher order statistics must be used to parse this data [2, 11]. This project will use neural networks, artificial intelligence, auto-regressive models, and statistics to process the raw EMG data. It will allow the arm to replicate the intended movement of the user acting as a method of input to the program where the motors will be the output.

4. Physics

$$P = IV$$

Eq. (6) Wattage (P) formula

Eq. (6) is often used for electrical circuits and power. The formula computes the wattage(P) in watts(W) of a given circuit using the voltage(V) of the circuit and the current in amperes(A) [cite]. We will use the formula in our project to approximate the power draw of our circuit and ensure that our device remains under our requirements.

$$E = Pt$$

Eq. (7) An equation involving wattage (P) and time (t) to solve for electrical energy (J)

Eq. (7) is a formula for electrical energy given by the product of power(from eq. (6)) and time. It is used to calculate the energy used by a device stating that the longer a device is on or the more wattage is used, the higher the consumption of energy. The equation is commonly used to calculate the cost of operating a circuit. We will use the eq. (7) to compute the energy our device uses which can help compute operating costs, the anticipated usage duration, and the expected lifetime of our device.

$$E = F\Delta d$$

Eq. (8) An equation involving some force (F) and displacement (d) to solve for mechanical energy (J)

Eq. (8) is an alternate equation used to find the work done by an object by relating it to the integral of the vector of the force applied with respect to its position vector. We will use the equation in our analysis of our prosthetic to determine the amount of work done by our arm when it moves.

III. Costs

A. Manufacturing Costs

Technologies Required
3D Printer
CNC Machine
Bending Machine

Material/Component Name	**Manufacturer**	**Vendor(s)/Distributor(s)**	**Cost**	**Req. Amount**
SERVOMOTOR RC 4.8V	DFRobot (Shanghai, China)	Digikey (Canada)	$5.30	5 Servos
NUCLEO-F401RE	STMicroelectronics (Grenoble, France)	Digikey (Canada)	$19.87	1
3D printing filament	3D Printing Canada (Hamilton, Ontario)	3D Printing Canada (Canada)	$22.95/kg	~2.3kg
Wires	Elegoo (Shenzhen, China)	Amazon (Canada)	$12.99	~30
Potentiometer	Amphenol Piher Sensing Systems (Tudela,	Digikey (Canada)	$1.03	5

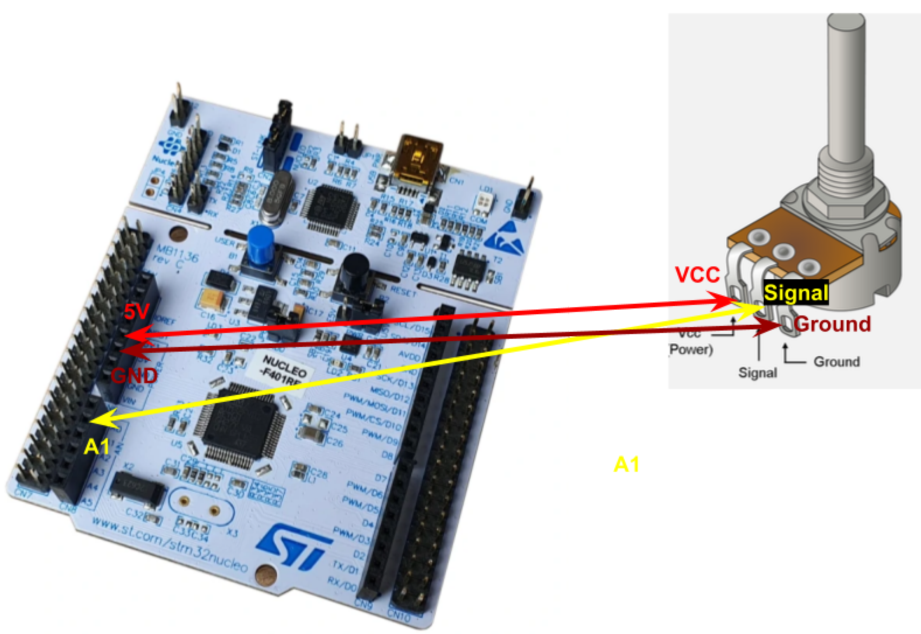
	Spain)			
220Ω Resistors	Visaton GmbH & Co. KG (Haan, Germany)	Digikey (Canada)	$1.29	~5
Aluminium 24 x 48 x 0.025-inch	Paulin (Ontario)	Home Depot (Canada)	$49.85	1

B. Implementation Costs

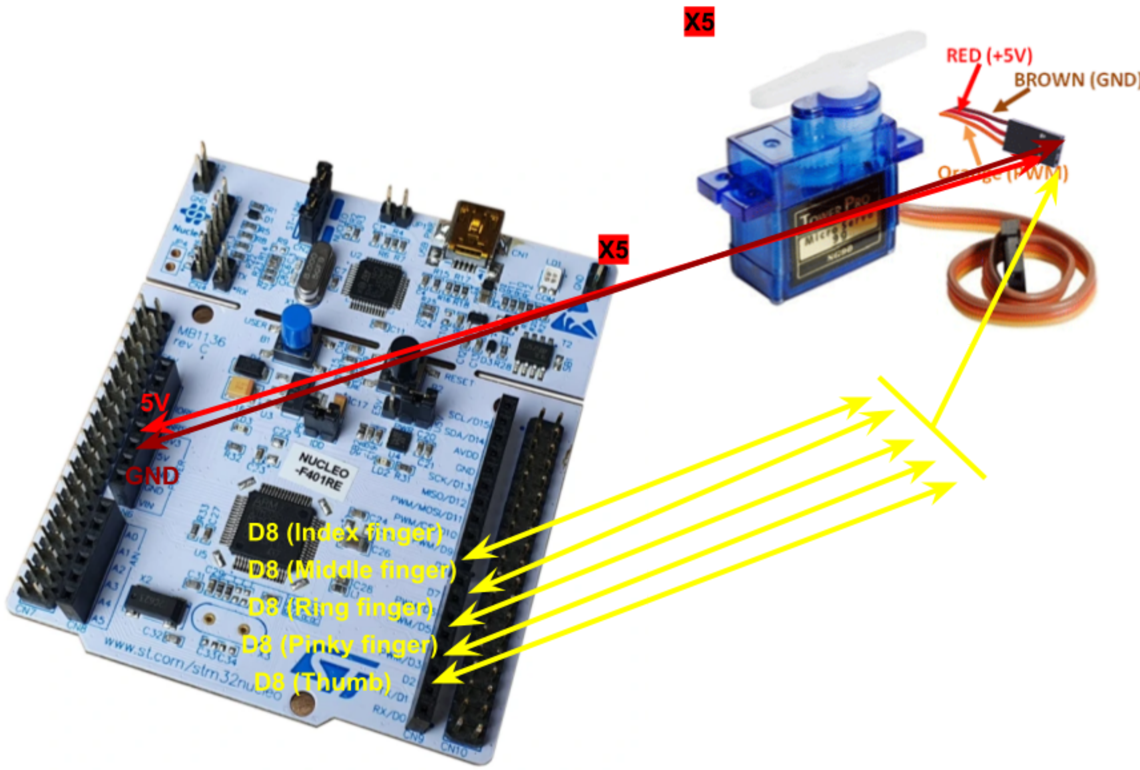
Include a brief Installation Manual and User Guide within the Design Document. Ensure the instructions are comprehensive and user-friendly.

Installation Manual for Electrical components:

1. Connect the potentiometer and its VCC (power), signal, and ground pins to the 5V, A1, and GND pins respectively as shown:

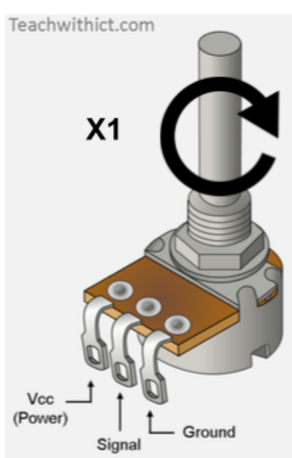


2. Connect 5 servo motors and their respective 5V (red), GND (brown) and PWM (orange) wires to the respective 5V and GND pins on the STM32 Microcontroller, while for the PWM (orange) follow which servo to connect for each individual signal pin:

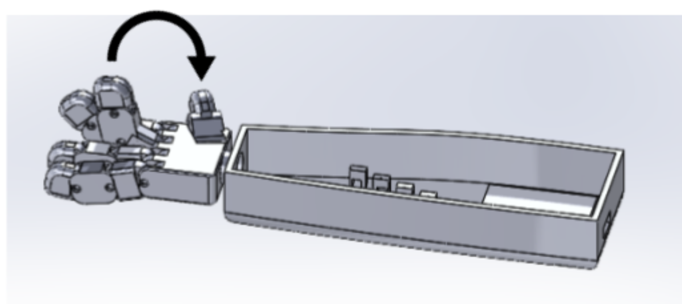


User Guide

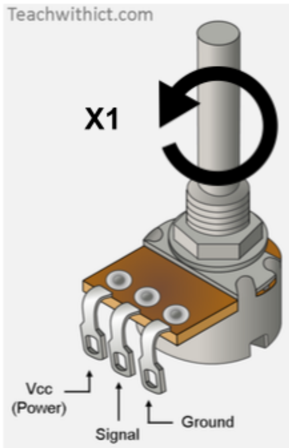
1. Rotate the potentiometer once clockwise to contract all five fingers at once



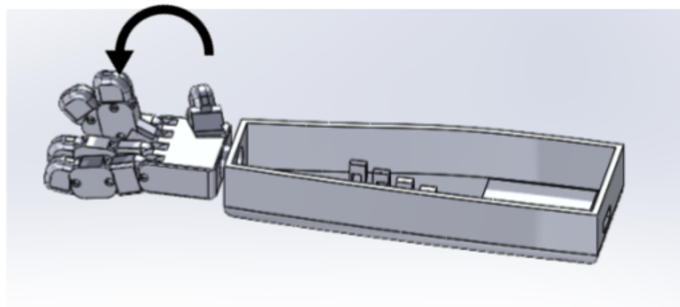
5 Fingers Contract



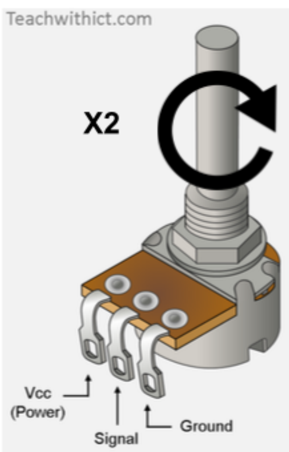
2. Rotate the potentiometer once counter-clockwise to release all five fingers at once



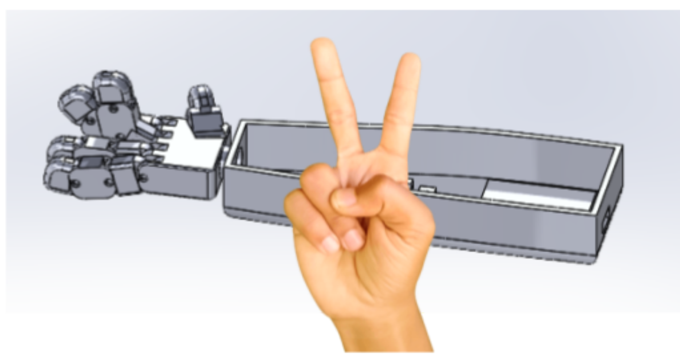
5 Fingers Release



3. Rotate the potentiometer twice clockwise quickie use a peace sign gesture



Peace Sign



IV. Risks

A. Energy Analysis

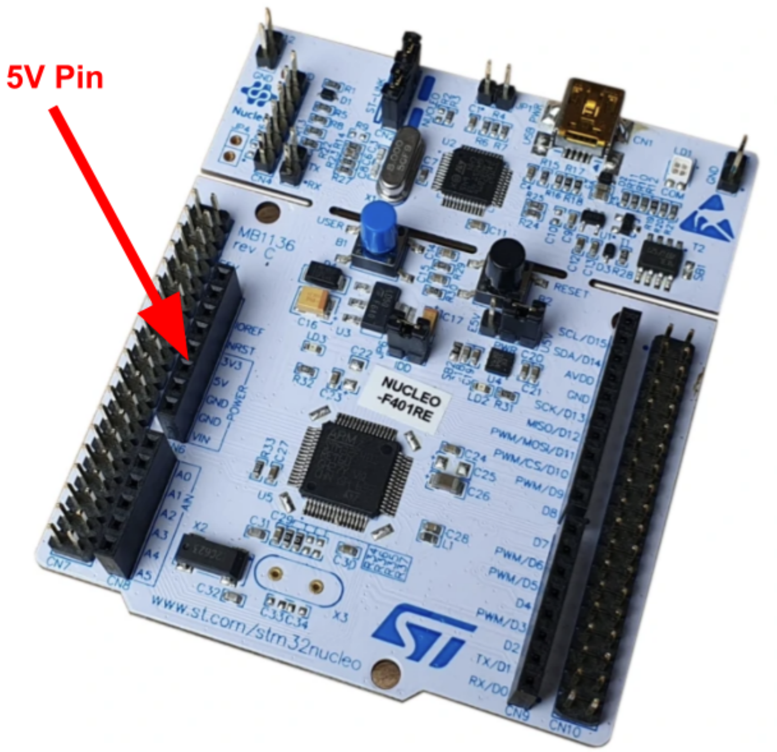


Fig. 6 Image of STM32 with 5V pin labelled

In a practical application, according to the International Electrotechnical Commission (IEC), specifically within their international standards for medical electrical equipment (IEC 60601), handheld medical equipment (ME) should not surpass 250 V [14]. Hence, for our prosthetic as an ME, This standard shall be used as our baseline power level in terms of voltage, ensuring that all equipment does not utilize more than 250 V. Applying this standard to the primary components of the BIONIC EVO prosthetic, one individual SG90 servo motor utilizes operates at a voltage range of 4.8 ~ 6 DC volts [13], with this operating voltage range being applied to all 5 SG90 servo motors utilized for each respective finger of the prosthetic. However, though the operating range is 4.8 ~ 6 DC volts, our device will utilize the same 5V connection through the STM32 microcontroller for each servo motor. In terms of the potentiometer used, as a variable resistor, the potentiometer will output a range of 0V to the amount of voltage connected to it. Provided this, connected to the same 5V channel through the STM32 microcontroller, the potentiometer will utilize 0V to 5V of power, decreasing and increasing value based on the position of the potentiometer. Finally, considering the microcontroller itself, the STM32 can utilize 3.3 to 12V of power from an external source, however, due to all components using only the 5V pin of the microcontroller (Fig 5), it is assumed that the microcontroller itself uses only 5V of the voltage supplied by the external source.

Fig. 7 Photo of travel charger

Regarding this external source, assuming that the microcontroller draws power directly from an adapter connected directly to an outlet, the adapter itself must be CSA approved as it passes as a device connected to a building electrical supply outlet (110V AC outlet). The adapter shown in Fig. 7, referring to the recognized approval marks by the electrical safety authority (ESA) [12], has the recognized CSA label by Intertek Testing Services, hence the device is CSA-approved. More importantly, it inputs 100V to 240V, but steps this voltage down to 5V, 9V and 12V based on its usage; in this case, 5V. Overall, the maximum usage of each component, with the five SG90 servo motors utilizing 5V, the potentiometer using a maximum of 5V, the STM32 board utilizing only 5V based on the maximum usage of 5V from each component, and the power adapter stepping the voltage down to 5V, we can confidently say that the full device only utilizes a maximum of 5V considering each component, which is well below the handled ME electrical standard of 250V; therefore the design is appropriate for this standard, and in turn, the standard is appropriate for the design.

Based on our provided components including but not limited to the STM32 microcontroller, SG90 servo motors, and potentiometers, there are no electrical energy-storing components such as a battery, capacitor, or any sort of conductor. Nor are there any electrical energy-storing materials contained within each device, for example, SG90 servos are primarily made of plastic and some metal, while metal may store some electrical energy, the electrical energy supplied to the servo is directly and completely converted into mechanical energy, and the energy stored by the metal would be an extremely insignificant amount of electrical energy is stored by the servo [13]. This concept applies to both the STM32 microcontroller and potentiometer, where though containing metal, a conducting material, the electrical energy stored would be extremely insignificant.

Referring to eq. (7), to determine the electrical energy produced by the prosthetic's components, we are required to find the wattage (P) produced by the design, which requires a known value of voltage, and current (I) which is unknown. Concerning the technical specification of each component, one SG90 servo motor utilizes 100 mA to 250 mA of current during movement, taking the average of these two current values, 175 mA, we get that one servo motor uses 0.175 A. Now, as we are using 5 servo motors, the total amperage of the servo motors alone is 0.875 A. Insignificantly, as a potentiometer is simply a resistor, the amperage of this component can be ignored. Using eq. (6) to solve for wattage, we can use 0.875 A as our current value (I) and 5V for our voltage value (V), which gives us a total operational wattage of 4.375 W. Referring back to eq. (7), our final electrical energy value would be our wattage value of 4.375 W multiplied by an arbitrary value of time.

Using eq. (8) to solve mechanical energy, with the fingers of the prosthetic being the only objects in motion in the device, we can analyze mechanical energy using the displacement one finger travels, which can be within the range of around 7.5 cm (0.075 m), and the force, which in this case is the gravitational force applied to the finger during motion, with a mass around 150 g (0.001 kg) and a gravitational value of 9.81. Given these values and multiplying accordingly, we can get a mechanical energy of about 0.0007 J per finger. However, please note due to the lack of required measurements due to the device still being in production, these values may have been estimated inaccurately, though it demonstrates the clear distinction between the energy produced by our device compared to the energy standard requirements provided.

Finally, supplementary to this primary standard, additional standards through the power and energy requirements described within the project requirements state that the design shall not consume, transfer, discharge or otherwise expend more than 30 W including electric energy, electric potential energy, mechanical kinetic energy, or mechanical potential energy as forms of energy. The wattage/power produced from our device was already found to be 4.375 W, which is lower than 30 W, fitting our device within the requirements provided.

B. Risk Analysis

Though using Bionic EVO's design as intended generally aims to improve the quality of life for amputees, there may be potential negative consequences on safety or the environment that may be considered even through its intended use. Some of the negative consequences on safety to consider that may occur after its intended use may include issues such as:

- injury or discomfort from the prosthetic; which can occur if not fitted correctly,
- allergic reactions; where some users may develop or already have allergic reactions to such adhesives or PLA plastics used in the design,
- or infections; where a poorly maintained prosthetics can create an environment where infections may develop.

Each of these safety issues primarily relies on how the end user maintains or utilizes the prosthetic, rather than any technical or design flaw. Considering the potential negative consequences on the environment after Bionic EVO's intended use, mainly relate to the production and disposal of the prosthetic, where the manufacturing process, though 3D printed, may utilize the power that contributes to pollution or waste generation of plastics, or the end-of-life disposal of the device may be difficult provided electronic components and non-biodegradable plastics used in the design may be challenging to dispose of responsibly. Primarily, through its intended manufacturing, there are flaws with the sustainability of the device and poses a negative consequence to the environment, and through its intended end-of-life disposal, the device proves difficult to dispose of, proving a negative consequence at this point of the product's lifetime.

Considering the negative consequences of simply using the device incorrectly such as not following installation steps or proper alignment of the prosthetic to the arm, regarding safety, there is a potential risk of injury; incorrect usage such as failing to secure the prosthetic correctly may lead to:

- damage to the prosthetic; where improper use may place excessive stress on the prosthetic components leading to impacting the longevity of the prosthetic due to structural or internal damage,
- decreased mobility; where incorrect usage can limit the prosthetic's functionality,
- and long term health issues; where consistent use of the prosthetic incorrectly can have long term effects on the user's health such as chronic pain or joint damage.

In terms of the potential negative consequences on the environment after its unintended use, primarily regarding the improper disposal of the product including

- waste generation; where improper use of prosthetics can cause frequent repairs or replacements which can cause increased waste generation,
- and resource consumption; where improper use can cause more repairs or replacements that consume various resources for its components.

In consideration of the negative consequences to the safety and the environment, if misusing the prosthetic design, significant issues arise. Regarding safety, there is a potential:

- Risk of causing injury; where misuse of the prosthetic for other purposes may harm individuals based on its use,
- Damage to the prosthetic; where improper use of the prosthetic can cause structural or internal damage,
- And chemical exposure; where when placed in the wrong conditions due to misuse the prosthetic may be harmful to the user or others.

In terms of the potential negative consequences on the environment after its misuse, this relates directly to incorrect usage, which again primarily regards the unintended, improper, disposal of the product including:

- waste generation; where improper use of prosthetics can cause frequent repairs or replacements which can cause increased waste generation,
- chemical exposure; which additionally to being a potential safety risk may be harmful to the environment if damaged components leach into soil or water if disposed of incorrectly,
- and resource consumption; where improper use can cause more repairs or replacements that consume various resources for its components.

However, please note these are probable negative consequences from proper and improper use if the prosthetic was used in commercial use. To reiterate, our current design for this project avoids human testing, choosing to use potentiometers to mimic muscle-controlling sensors, therefore the specified negative consequences that include human use such as discomfort and infection only entail if the prosthetic is used on the body with skin to skin contact.

Some possible ways our design could malfunction include:

- user error; which can occur if the prosthetic is improperly maintained the prosthetic with proper care leading to loose joints or incorrect finger alignment,
- electronic or control system malfunction; where external EMF waves may affect the operation of electronics or control system of the device,
- Material degradation; which may occur due to exposure to environmental factors such as moisture or radiation,
- And simple mechanical failure; which can occur after due to fatigue after long mechanical stress

and strains during use.

Some safety consequences associated with each specified malfunction may include:

- a reduction of safety over time due to a gradual degradation or misalignment due to user error,
- a loss of balance and coordination due to an inability to control the prosthetic from electronic or control system malfunction,
- a potential failure of the device while the user is engaged in physical activity due to material degradation,
- and a safety risk for the user if engaged in activity during use from loss of support due to mechanical failure.

Some environmental consequences associated with each specified malfunction may include:

- increased resource consumption due to a need for additional maintenance and repair from user error and improper care of the prosthetic,
- the increased disposal of e-waste due to a need for additional electronic maintenance and replacement from electronic or control system malfunction,
- increased resource consumption due to a need for additional maintenance and repair from material degradation,
- and increased resource consumption due to a need for additional maintenance and repair from mechanical failure.

V. Testing and Validation

A. Arm components must withstand 100 cycles of continuous movement without failure.
   a. Under standard testing conditions [2], all components of the arm must pass all the below test cases before continuing to this test case. The arm will then perform all functions such as wrist rotation, and finger flexion simultaneously 100 times, with inputs provided by a computer. The components must not fail during the cycles and all functions will be validated after the cycles are run to ensure that they are working, done by redoing the following test cases. The arm must pass all test cases to pass the durability test. The consecutive movements are performed to ensure that the arm does not overheat or fail under intense conditions such as exercise, extreme weather, etc.

B. The entire prosthetic arm weight must not exceed 5 pounds.
   a. Prosthetic arm is weighed on a spring scale and weighs less than 5 lbs +-10% under standard testing conditions

C. Minimum 100 degrees of flexion and extension for each finger, minimum 180 degrees of wrist rotation.
   a. Fingers start in 100% flexion and an input is sent to extend the fingers as far as possible. Using a protractor to measure the angle travelled, all limbs on the finger are measured and must travel strictly greater than 100 degrees. Similarly, wrist rotation will be measured by using a protractor with the hand in a closed fist, as far as possible in one direction. The wrist will be given a signal to rotate 100% in the opposite direction and the test is passed if the measured degree of rotation is greater than 180 degrees. The test will be run in standard testing conditions

D. Must exert a minimum grip strength of 20 Newtons (N).
   a. A digital hand grip scale is used on the arm. The hand will clench all its fingers and curl its hand on the scale. The highest reading will be used and must be greater than 20N of force. Since the reading is in lbs, the reading given will be divided by the accepted gravitational constant on Earth. The test will be run under standard testing conditions.

E. The arm must withstand at least 450N of compressive force and 600N of tensile force.
   a. While the arm is laid horizontally, 45.6 kg of weight will be put onto the arm while lying on

the ground. The arm must be able to hold the weight up without crippling the arm. The next test will proceed by attaching the two sides of the arm to the strings. While hanging, the arm must be able to statically hold 60 kg of weight without dislocating any parts. The tests will be performed without the electronics attached and will be under standard testing conditions.

F. Fingers must withstand at least 350N of tensile force and 200N of compressive force.
    a. While the arm is laid horizontally, 20 kg of weight will be put onto each finger while lying on the ground. The fingers must be able to hold the weight up without crippling. The next test will proceed by attaching a string to the forearm and another to each of the fingers. While hanging, the fingers must be able to statically hold 36 kg of weight without dislocating any parts. The tests will be performed without the electronics attached and will be under standard testing conditions.

G. Must withstand 5V of shock from the outer shell.
    a. Under standard testing conditions, 5V of shock is delivered to the outer shell of the arm by using an electrical circuit. This test is run twice in a non-conductive environment, once while the arm is off and again when the arm is on. The arm must retain all circuitry functions such as servo rotation to pass this test.

H. Must be IP64 (sweat & dust) resistant.
    a. The standard IP64 tests are run particularly at the seams of the device. Dust, sand, and dirt will be introduced to the arm under standard testing conditions. The arm must not have any particles inside the arm by the end of testing. Water will then be splashed on the device. The interior of the arm must remain completely dry and have no harmful effect on the arm.

I. 5 cm total shock absorption throughout the arm
    a. The shock absorption will be tested linearly on the arm from the forearm to the tip of the middle finger. While laying the arm flat, and shock absorption uncompressed, the arm's length is measured. While compressing the arm, the arm is measured again and must be at least 5 cm shorter. The arm must uncompress automatically and should remain uncompressed while lying horizontally. The test will be run under standard testing conditions.

References:

[1] amputation. section: conditions. [online]. available: https://www.nhs.uk/conditions/amputation/

[2] “osseointegrated prosthetic implants for people with lower-limb amputation: a health technology assessment,” vol. 19, no. 7, pp. 1–126. [online]. available: https://www.ncbi.nlm.nih.gov/pmc/articles/pmc6939984/

[3] a. asghar, s. jawaid khan, f. azim, c. s. shakeel, a. hussain, and I. k. niazi, “review on electromyography based intention for upper limb control using pattern recognition for human-machine interaction,” vol. 236, no. 5, pp. 628–645.

[4] l. j. marks and j. w. michael, “artificial limbs,” vol. 323, no. 7315, pp. 732–735. [online]. available: https://www.ncbi.nlm.nih.gov/pmc/articles/pmc1121287/

[5] s. tam, m. boukadoum, a. campeau-lecours, and b. gosselin, “Intuitive real-time control strategy for highdensity myoelectric hand prosthesis using deep and transfer learning,” vol. 11, p. 11275. [online]. available: https://www.ncbi.nlm.nih.gov/pmc/articles/pmc8163779/

[6] j. a. maun, s. a. gard, m. j. major, and k. z. takahashi, “reducing stiffness of shock-absorbing pylon amplifies prosthesis energy loss and redistributes joint mechanical work during walking,” vol. 18, no. 1, p. 143. [online]. available: https://doi.org/10.1186/s12984-021-00939-8

[7] t. Inglis, “myoelectric hand.”

[8] an evaluation of the use made of cosmetic and functional prostheses by unilateral upper limb amputees - pubmed. [online]. available: https://pubmed.ncbi.nlm.nih.gov/9881609/

[9] an evaluation of the use made of cosmetic and functional prostheses by unilateral upper limb amputees - pubmed. [online]. available: https://www.aopa.org.au/documents/item/724

[10] what is regression? definition, calculation, and example. [online]. available: https://www.investopedia.com/terms/r/regression.asp

[11] what is supervised learning? | Ibm. [online]. available: https://www.ibm.com/topics/supervised-learning 22

[12] what is random forest? | Ibm. [online]. available: https://www.ibm.com/topics/random-forest

[13] support vector machInes(svm). introduction: all you need to know… | by ajay yadav | towards data science. [online]. available: https://towardsdatascience.com/supportvector-machines-svm-c9ef22815589

[14] support vector machines (svm) algorithm explained. [online]. available: https://monkeylearn.com/blog/introduction-tosupport-vector-machines-svm/

[15] t. evgeniou and m. pontil, “support vector machines: theory and applications,” in machine learning and Its applications: advanced lectures, g. paliouras, v. karkaletsis, and c. d. spyropoulos, eds. springer berlin heidelberg, pp. 249–257. [online]. available: https://doi.org/10.1007/3-540-44673-712

[16] pId “proportional, integral, and derivative” control theory. [online]. available: https://www.crystalinstruments.com/blog/2020/8/23/pidcontrol-theory

[17] how do pId controllers work | pId working principle | omega. [online]. available: https://www.omega.co.uk/prodinfo/how-does-a-pidcontroller-work.html

[18] l. altimari, j. l. dantas, m. bigliassi, t. kanthack, a. moraes, and t. abrao, Influence of different strategies of treatment muscle contraction and relaxation phases on emg signal processing and analysis during cyclic exercise, 10 2012.

[19] d. c. p. department and openstax, “4.4 electric power and energy – includes heat energy,” book title: douglas college physics 1207. [online]. available: https://pressbooks.bccampus.ca/introductorygeneralphysics2phys1207/chapter/24-electric-power-and-energy/

[20] 7.2: work. [online]. available: