Affordable Universal Controller for Upper Limb Prosthetics

By

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February 2023

Contents

1 Introduction

1.1 Problem

2 million people in the United States have lost a limb [3], a number that is expected to double by 2050 [1]. Despite the growing population of prosthetic-users, inexpensive prosthetic alternatives are largely unavailable in the market. In fact, as of 2009 the medical costs of US amputation totaled over $8.3 billion [3]. Furthermore, the average cost associated with a myoelectric prosthetic costs about $18,703 for a partial hand and up to $61,655 for a loss at the shoulder [7]. Such grand costs especially accumulate over a lifetime as prosthetists recommend replacing prosthetics when changes in activity, structural integrity, and compatibility of parts occur [9]. The exorbitant cost is so burdensome that it has prevented 9 out of 10 people worldwide from accessing the prosthetics they need [10].

1.2 Solution

Our project will focus on building an EMI-shielded, standalone sEMG device capable of being removed and used with various designs of transradial prosthetic devices. We plan on designing an electrode armband that measures a number of EMG signals related to wrist and hand movement. The EMG signals will then undergo amplification, filtration, and processing via a PCB. Next, the processed EMG signal will be inputted into a MATLAB program that relates EMG signal measurements to a set of movements. Finally, a set of 3 motors will receive an appropriate signal from the MATLAB program and move a wooden, prosthetic hand to demonstrate the desired movement.

The key advantages of our modular design is universal compatibility and minimal costs. Creating a sEMG device that can be used across different prosthetics allows patients to select new prosthetics and prosthetic parts for replacement and repair without compromising functionality. Especially favorable for prosthetic-users who change their prosthetics over the course of their lifetime, buying an entirely new prosthetic would no longer be necessary with our design. Rather, a prosthetic-user only needs to buy and replace the mechanical component of a prosthetic, saving them thousands of dollars in the long-run.

1.3 Visual Aid

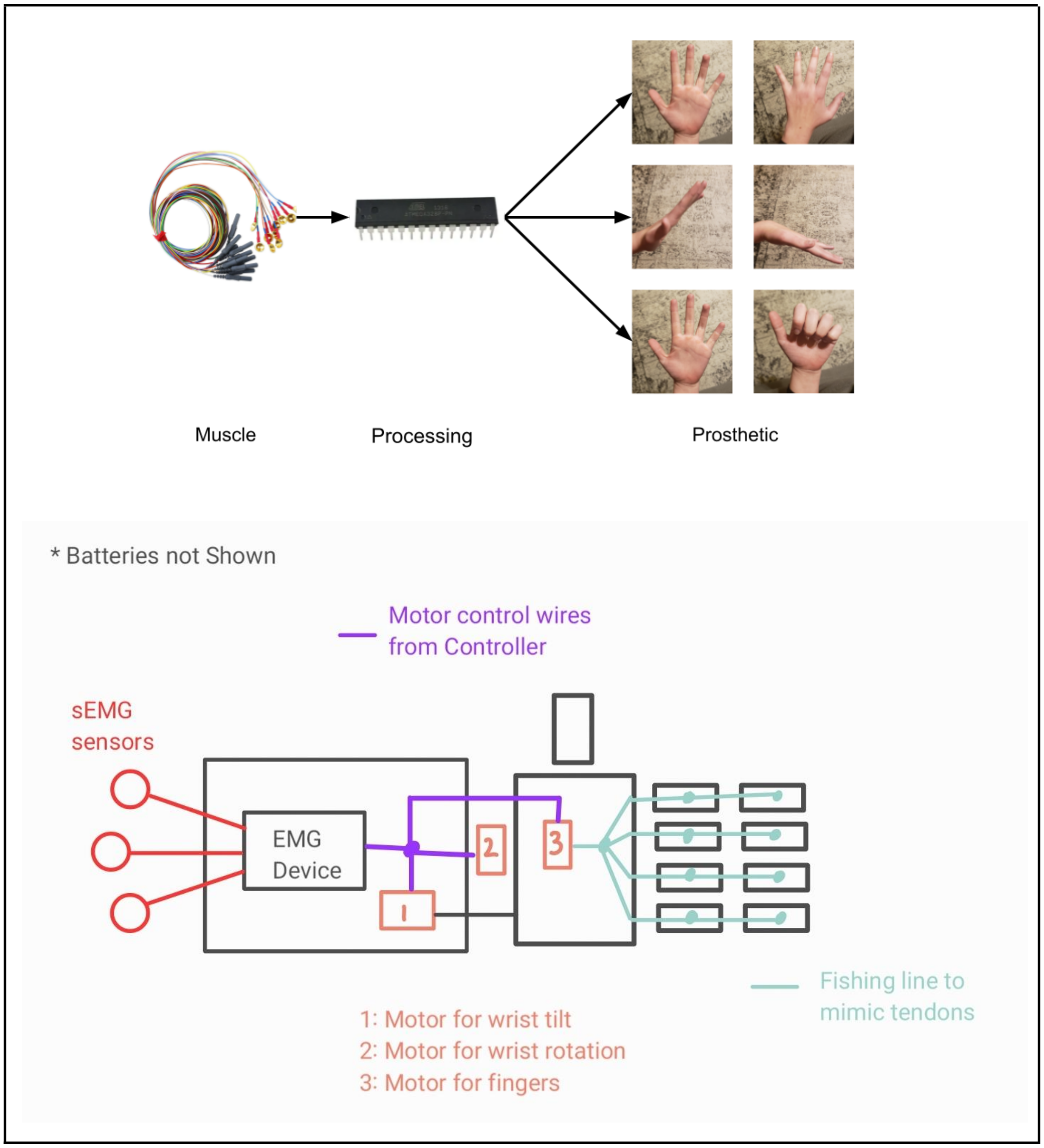

Figure 1.1 High level visual aid

1.4 High-Level Requirements List

- EMG device must be able to resist at least 70 dB of electromagnetic interference in the 10kHz-30kHz range [5].
- EMG device must be able to return to neutral orientation within 15 degrees of initialized position after at least 50 prosthetic movements.
- Prosthetic arm should mimic 6 distinct hand movements with at least 70% accuracy.

2. Design

2.1 Block Diagram

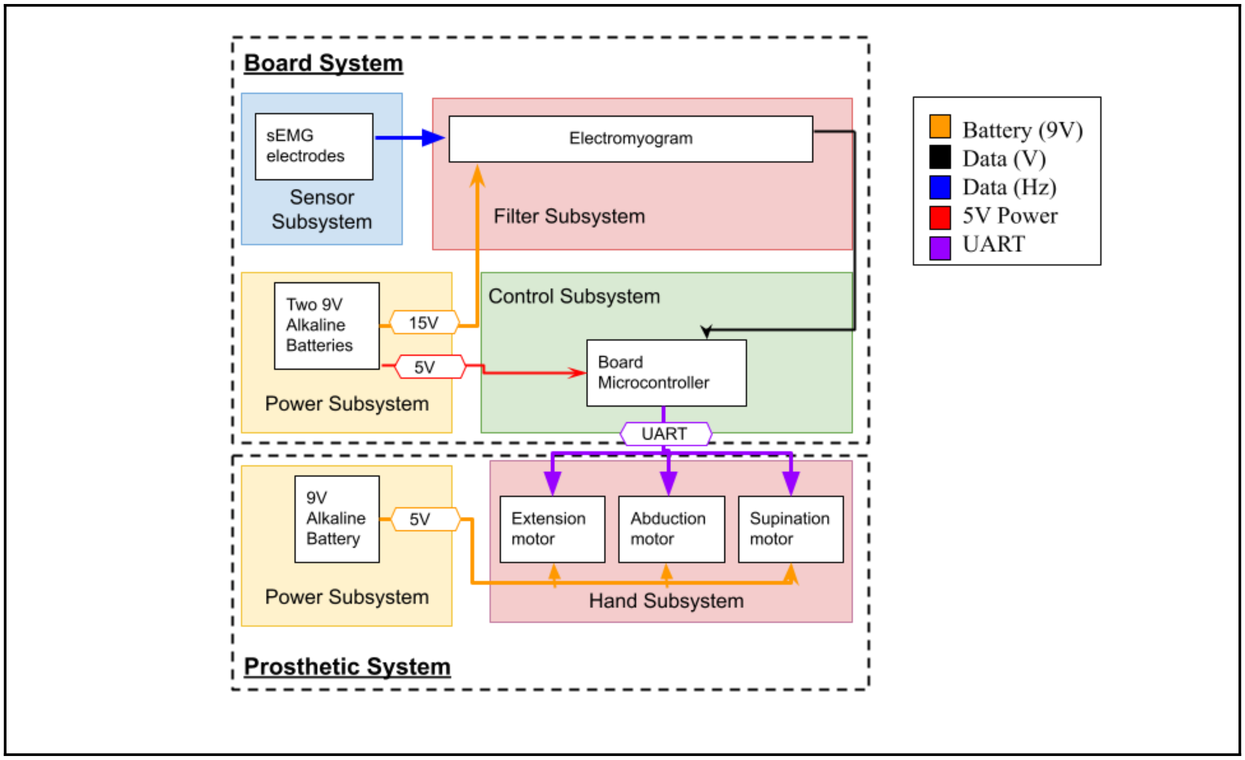

Fig 2.1 Block diagram for EMG device and prosthetic hand

2.2 Physical Design

Movement	Key
Digit Flexion	
Digit Extension	
Palmar Supination	
Palmar Pronation	
Palmar Flexion	
Palmar Extension	

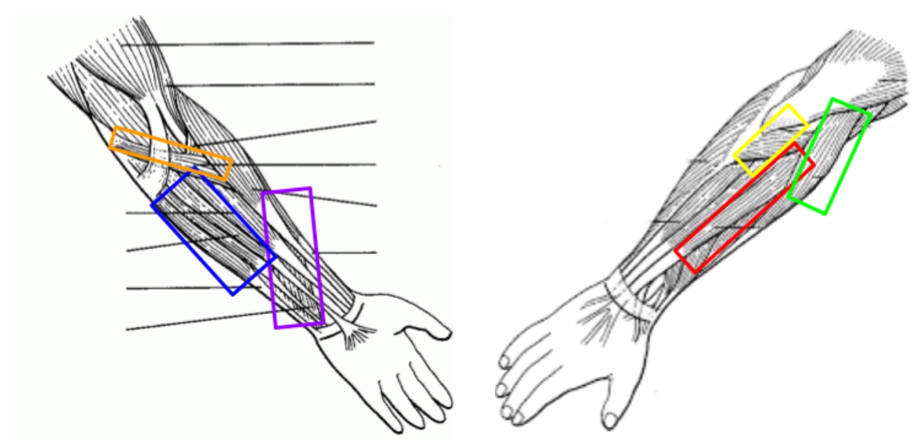

Figure 2.2 Sensor Placement Regions Diagram

We will place 6 sensors on the arm to evaluate the EMG signal of hand and wrist movements. The 6 sensor placements are shown in Fig 2.2 and each one corresponds to a muscle in the arm. The combinations of these muscles control the fingers, hands, and wrist.

The 6 sensors will be part of a sleeve put over the arm. This will simplify the process of placing all sensors in the correct positions every time. The sensors are wired to a 3D printed enclosure that will contain the amplifier, filter, rectifier combo circuit as well as the microcontroller. The prosthetic arm will be a separate build that is not attached to the user and it contains three motors that require control signals that come from the microcontroller.

2.3 Subsystems

2.3.1 Board Subsystem

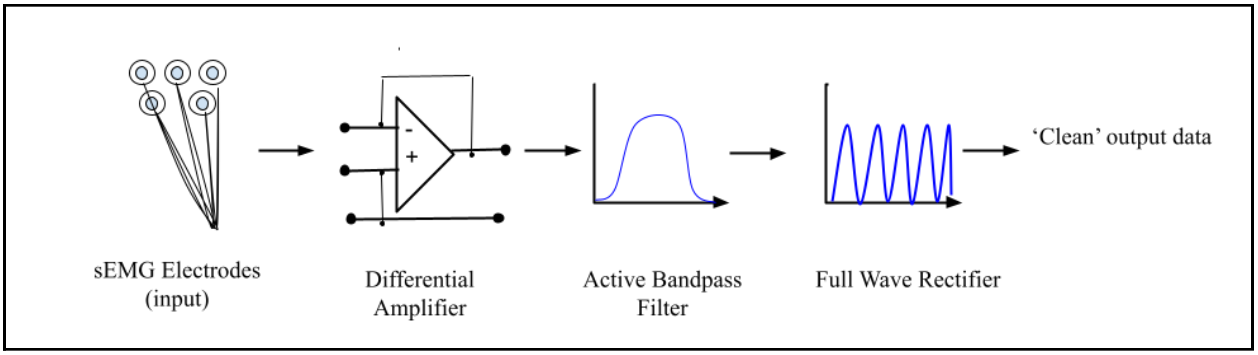

Fig 2.2 Data pipeline for the EMG device

Sensor

The sensor system serves to acquire the sEMG signals of the muscles used for digit flexion, digit extension, supination, pronation, wrist extension, and wrist flexion. This system will be implemented as a wearable sleeve consisting of six panels of copper sheet metal ¾ inches in diameter. The 6 copper panels will be at fixed positions along the longitudinal midline of the muscles and will measure the raw EMG signal. The raw EMG signal will then be sent to the EMG PCB via a soldered wire for signal processing.

Table 1: Sensor Requirements and Verifications

Requirements	Verifications
Requirement 1: Copper panels should be able to measure EMG signals with amplitudes ranging from 0.1 mV to 2.5 mV.	Using the function generator, input a sinusoidal signal wave with an amplitude of 0.01mV to the copper panel. Connect the copper panel to the oscilloscope and note the amplitude of the wave. Repeat

	this procedure but change the amplitude of the function generator to 2.5 mV. Verify the wave has an amplitude of 0.1 mV ± 0.1 mV and 2.5 mV ± 0.1 respectively.

Filter

The filter system will receive the raw EMG signal from the sensor armband for signal processing which consists of amplification, filtration, and rectification. A differential amplifier will be used to suppress the common baseline noise due to inherent noise of the electrode, movement artifacts, electromagnetic noise from the environment, and internal noise from physiological factors like body fat [8]. Since the EMG signal is very weak with amplitudes ranging from 50 uV - 2,000 uV, the differential amplifier will also accomplish an ideal gain between 100 V/V - 10,000 V/V [12]. Upon amplification, the EMG signal will pass through a bandpass filter constructed from capacitors and resistors. Filtering the measurements that are outside the frequency range of the EMG signal, the bandpass filter will specifically have a low cutoff frequency of about 5 Hz and a high cutoff frequency of about 500 Hz [11]. The amplified and filtered EMG signal will then undergo a full wave rectifier to ensure the average of the AC EMG signal is not zero and finally be input to the board microcontroller for interpretation to prosthetic movement.

Table 2: Filter Requirements and Verifications

Requirements	Verifications
Requirement 1: The gain of the differential amplifier should be 5,000 V/V ± 1,000 V/V.	Using a function generator, prepare a sinusoidal signal with a frequency of 250 Hz, an amplitude of .1 mV, an offset of 0V, and phase of 0°. Using an oscilloscope, connect the sinusoidal signal from the function generator into channel 1 and connect the output of the amplifier circuit to channel 2. Input the sinusoidal signal into the amplifier circuit. Observe and obtain the amplitude of the outputted sinusoidal wave from the oscilloscope. Verify the outputted sinusoidal signal is 5 V ± 1 V..
Requirement 2: The bandpass filter must have a low cutoff frequency of 5 Hz ± 5	Using a function generator, prepare a sinusoidal signal with an amplitude of .1 mV, an offset of 0V, and phase of 0°.

Hz and a high cutoff frequency of 500 Hz ± 5 Hz.	Using an oscilloscope, connect the sinusoidal signal from the function generator into channel 1 and connect the output of the amplifier circuit to channel 2. Input the sinusoidal signal into the bandpass filter circuit. To determine the low cutoff frequency, set the frequency of the sinusoidal input signal to 15 Hz. Decrease the frequency of the sinusoidal input wave until $\frac{amplitude\ of\ output\ (mV)}{amplitude\ of\ input\ (mV)}$ has a magnitude of 0.707. Verify the low cutoff frequency is 5 Hz ± 5 Hz. To determine the high cutoff frequency, set the frequency of the sinusoidal input signal to 490 Hz. Increase the frequency of the sinusoidal input wave until $\frac{amplitude\ of\ output\ (mV)}{amplitude\ of\ input\ (mV)}$ has a magnitude of 0.707. Verify the low cutoff frequency is 500 Hz ± 5 Hz.
Requirement 3: The circuit should supply at least 500mA continuously at 5V +/- 0.1V to the microcontroller.	Using a multimeter, measure the output voltage. Verify the step-down output voltage is at least 5V +/- 0.1

Calculations for Determining the Gain of the Differential Amplifier

Based on the Figure 2.4, KCL, and KVL, we know:

$$I_1 = \frac{V_1 - V_-}{R_1} \quad \text{Eq 1.}$$

$$I_2 = \frac{V_2 - V_+}{R_2} \quad \text{Eq 2.}$$

$$I_{out} = \frac{V_- - V_{out}}{R_3} \quad \text{Eq 3.}$$

Understanding the output voltage is the difference between the voltage in the non-inverting input and the voltage in the inverting amplifier for differential amplifiers, we come to the following equation:

$$V_{out} = -V_1 \frac{R_3}{R_1} + V_2 \frac{R_4}{R_2+R_4}\left(\frac{R_1+R_3}{R_1}\right) \qquad \text{Eq 4.}$$

For simplification, if we set $R_1 = R_2$ and $R_3 = R_4$, we can simplify the derived equation above:

$$Gain = \frac{V_{out}}{V_{in}} = \frac{R_3}{R_1} \text{ in V/V} \qquad \text{Eq 5.}$$

To obtain our desired gain of 5000 V/V, we set $R_1 = R_2 = 4\Omega$ and $R_3 = R_4 = 20k\Omega$.

$$Gain = \frac{20{,}000}{4} = 5{,}000 \text{ V/V}$$

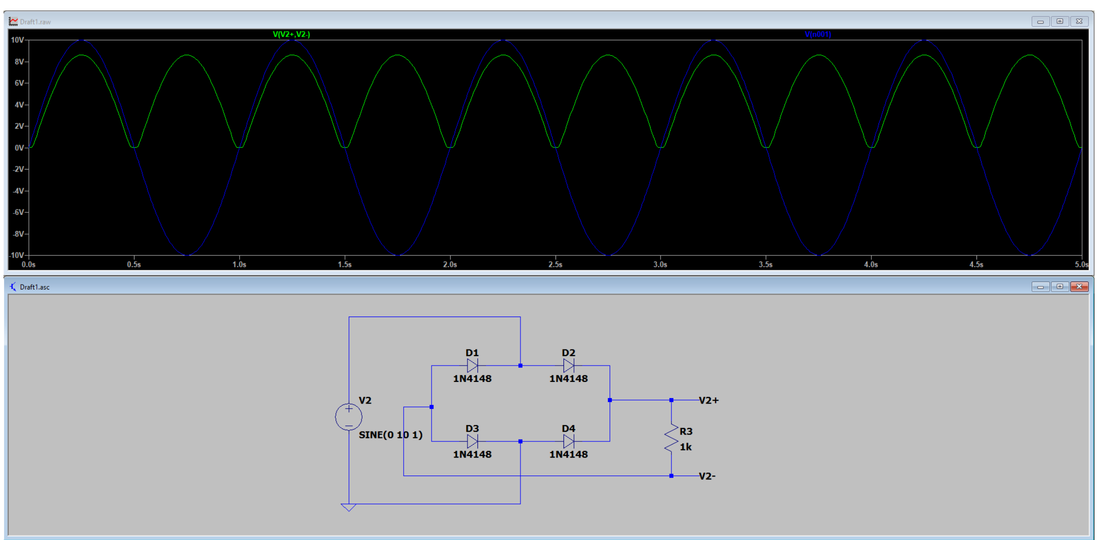

Figure 2.3: Circuit schematic and simulation of rectifier circuit in LTspice. Note the input sinusoidal wave is depicted in blue and the output sinusoidal wave is depicted in green.

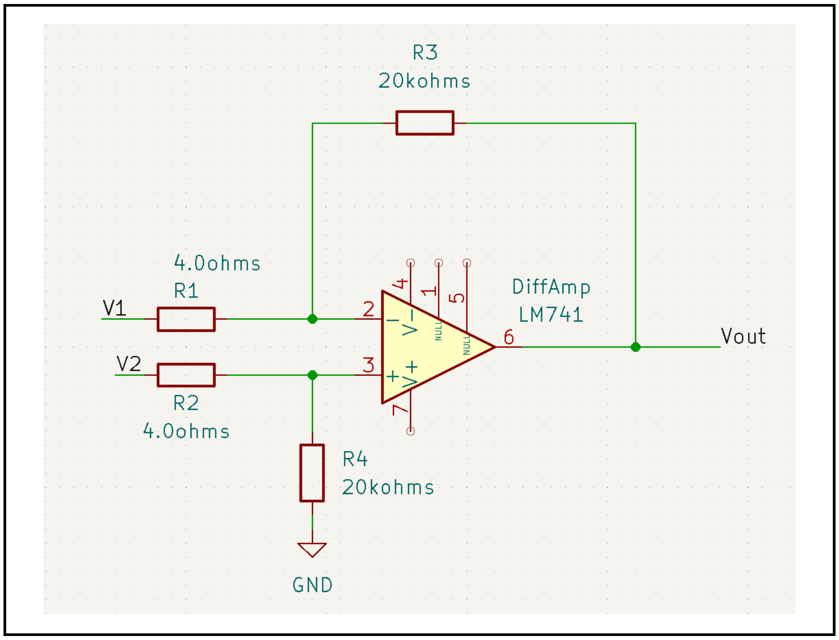

Figure 2.4: Circuit schematic of the differential amplifier circuit with a gain of 5000 V/V.

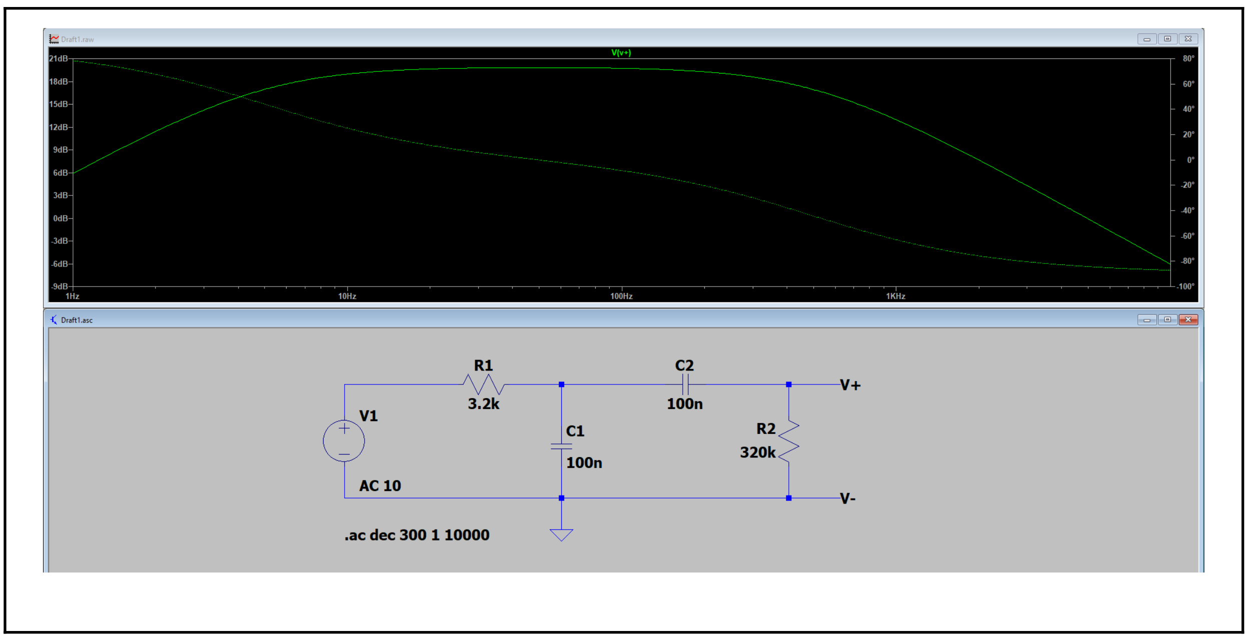

Figure 2.5: Circuit schematic and simulation of the bandpass filter in LTspice.

Power(s)

Two 9V batteries will be used to power the EMG device. This will ensure that the filtering components as well as the microcontroller gets enough power. The batteries will need to be adjusted before being fed to the various components. The microcontroller needs 5V while the operational amplifiers require 15V. The battery on their own may overload the components so a voltage regulator circuit will be built to step down the voltages appropriately.

Another 9V battery will be connected to the prosthetic device to ensure continuous motor power. Only one motor will be activated at a time to minimize the load on the battery. The voltage will also need to be stepped down to meet the specification of the motors (5V). While the power comes from the battery, the signal to turn the motor will come from the control subsystem.

Table 3: Power Requirements and Verifications

Requirements	Verifications
Requirement 1: The board power system must be able to provide 5.0 V ± 1.0 V at 250 mA to the microcontroller.	Measure the voltage from the output of the PCB using a multimeter. Verify the voltage is 5.0 V ± 1.0V
Requirement 2: The board power system must be able to provide the operational amplifiers at least 15V ± 3V with current at 1.7 - 2.8 mA.	Using a multimeter, measure the voltage across the 9 V battery Verify battery is at least 15V ± 3V.
Requirement 3: The prosthetic power system must be able to provide the motors at least 5V ± 0.5V and 200mA to each motor when needed.	Using a multimeter, measure the step down output voltage feeding into the motors. Verify the step-down output voltage is at least 5V +/- 0.5V .

<u>Control</u>

The control unit will consist of the ATmega328P that receives the processed EMG signal from the EMG PCB. Defined voltage thresholds of an EMG signal from a particular copper panel of the armband correspond to certain hand and wrist movements. The ATmega328P will be programmed such that when voltage measurements of the EMG signals exceed these defined voltage thresholds, corresponding to certain hand and wrist movements. Then the microcontroller will send the appropriate signals to the motors to move the prosthetic to the correct orientation.

Table 4: Sensor Requirements and Verifications

Requirements	Verifications
Requirement 1: Program should output the hand/wrist movements within 2 seconds.	Use the clock of the ATmega328P to measure how long it takes to classify the input signal to hand/wrist movement in software.

Requirement 2: Program should correctly interpret hand/wrist movements with at least 85% accuracy.	Use the clock of the ATmega328P to measure the how long it takes to classify the input signal to hand/wrist movement in software.

2.3.2 Prosthetic System

Hand

The prosthetic hand system consists of 3 independent stepper motors to perform movements with 3 degrees of freedom. Specifically, the motors receive a signal from the microcontroller and the motor will move the prosthetic accordingly. After each movement, the motors return the hand to the neutral position as depicted in Table 6. The motor system will be mounted onto the prosthetic and will be physically separate from the board system, which remains attached to the controlling muscle.

Table 5: Sensor Requirements and Verifications

Requirements	Verification
Requirement 1: The hand must be able to move from the neutral position to the desired position in under 2 seconds and within 15° of desired position.	Turn on the motors. Set a camera in a fixed position facing the range of motion. Record the wooden hand moving from neutral position to desired position. Based on the video, determine the time the wooden hand takes to move from neutral to desired position, and using the app Angulus measure the angle of the desired position with respect to the neutral position. Reset wooden arm to neutral position and repeat time and angle measurement for each following position. Note the camera should not move during recording but can be adjusted between positions to record the correlating range of motion.Verify the time and angle between neutral and desired position is under 2 seconds and within 15 degrees of the angle outlined in Figure 6 respectively.
Requirement 2: The motors must return the prosthetic hand within 15° of the	Turn on the motors. Set a camera in a fixed position facing the range of motion. Record the wooden hand moving from neutral position to 30 different positions.

	After 30 consecutively completed movements, use the app Angulus to measure the angle of the final neutral position. Verify the angle of the final neutral position is within 15° of the neutral position defined in Figure 6.

Position/Movement	Angle Relevant to Neutral Position
Digit Flexion	>45° θ_p
Digit Extension	0° θ_p
Wrist Flexion	>90° θ
Wrist Extension	<60° θ
Supination	0° θ_x
Pronation	>|150°| θ_x

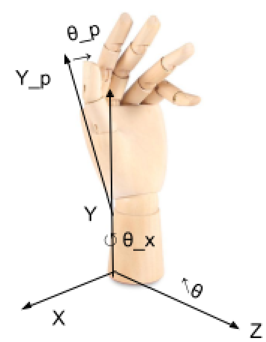

Figure 2.6: Positions and Angles of Hand Movement

2.3.3 Software Design

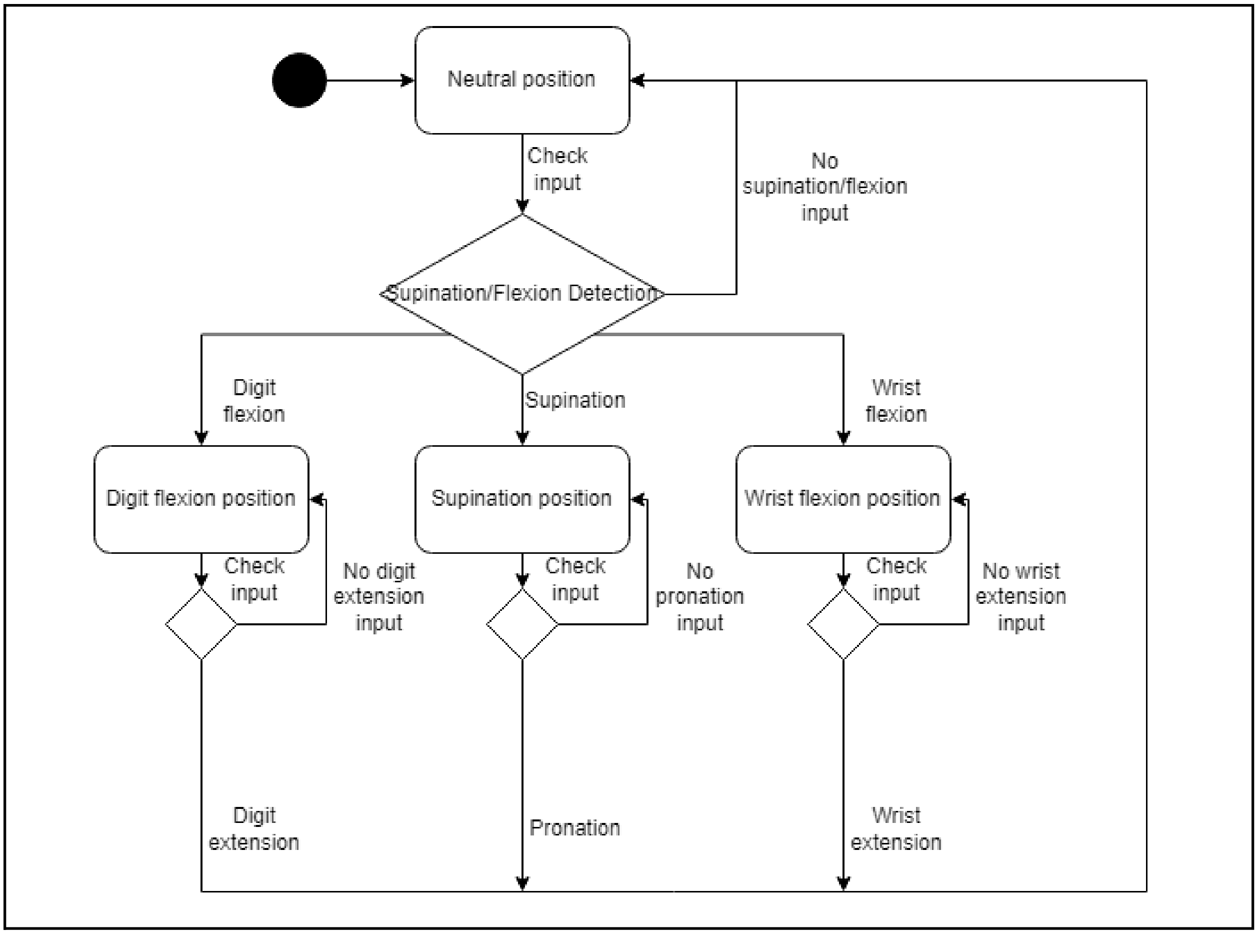

Figure 2.7: EMG Movement Detection State Diagram

The ATmega328P will be uploaded with a program that can input the filtered sensor readings and make a classification on which hand movement is correlated with the signals. This will be done by implementing a machine learning algorithm to classify the signals. Machine learning is ideal for this task because we do not know in detail how different combinations of muscle activities result in different motions. The algorithm will determine the pattern on its own with some labeled data we will provide for it to train with. 10% of the labeled data will be kept on the side (not part of the training date) to verify the algorithm at each iteration.

Movement	Primary Muscles	Key
Digit Flexion	Flexor Digitorum Profundus Flexor Digitorum Superficialis	
Digit Extension	Extensor Digitorum	
Palmar Supination	Supinator	
Palmar Pronation	Pronator Teres Pronator Quadratus	
Palmar Flexion	Flexor Carpi Ulnaris Flexor Carpi Radialis	
Palmar Extension	Extensor Carpi Radialis Longus Extensor Carpi Radialis Brevis	

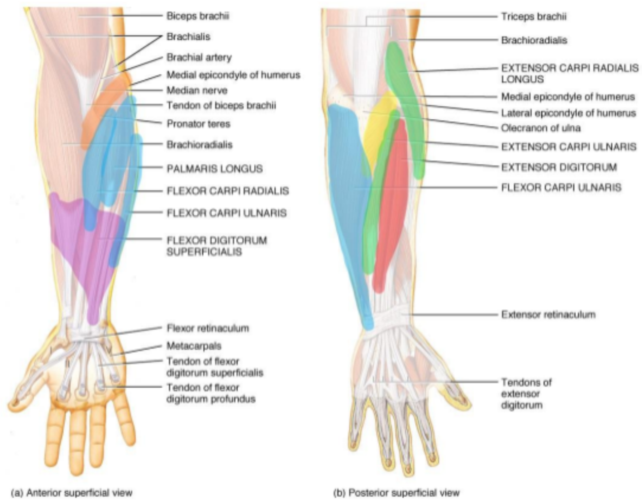

Figure 2.8: Physiology of Targeted Upper Limb Movements

2.4 Tolerance Analysis

The filter subsystem of our design poses a risk to successful completion of the project. Proper filtering of the EMG signal by the bandpass filter is critical to suppress noise, prevent artifact contamination, and ultimately preserve the EMG signal of interest. Loss of information about the EMG signal due to improper filtering will result in not only inconsistency in EMG signal readings but also improper movement of the prosthetic. To ensure our project is still feasible with this risk, we will calculate the resistor and capacitor values of the bandpass filter to ensure the cutoff frequencies of the bandpass filter is appropriate for our EMG signal. The expected range of data from the sEMG sensor is between 5 and 500 Hz. Using equation 1, we can determine the necessary resistor and capacitor values for the high and low pass filter. With a lower cutoff frequency of 5Hz and upper cutoff frequency of 500Hz, the following resistor and capacitor values have been calculated (note this is one of infinitely many possible values):

Given the high-pass filter circuit schematic in figure 2.3.1 and a desired high-pass filter cutoff frequency of 5 Hz, we can determine the resistor and capacitor values using the following equation 6.

$$2 * \pi * F = \frac{1}{R*C} \qquad \text{Eq 6.}$$

Where F is the desired cutoff frequency

$$2 * \pi * 5Hz = \frac{1}{R*C}$$

$$31.42 = \frac{1}{R*C}$$

If

Resistor = 320,000 Ω
Capacitor = 100 nF

Then

High-pass filter cutoff frequency = 31.25 / 2π = 4.97 Hz

Percent Error = $\left|\frac{4.97 - 5}{5}\right|$ = 0.53%

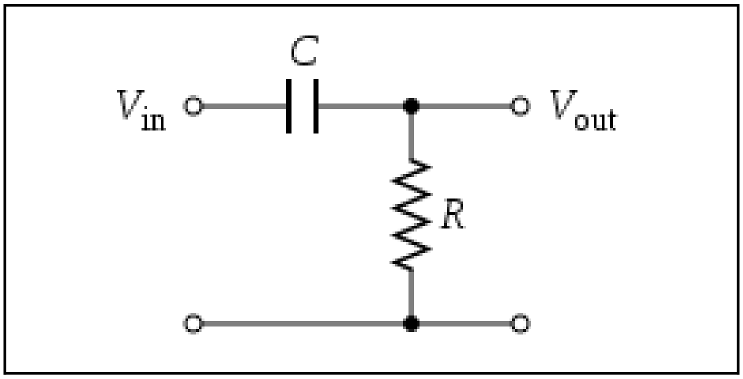

Fig 2.9: High-pass filter circuit schematic

Given the low-pass filter circuit schematic in figure 2.3.2 and a desired low-pass filter cutoff frequency of 500 Hz, we can determine the resistor and capacitor values using the same equation.

$$2 * \pi * 500Hz = \frac{1}{R*C}$$

$$3142 = \frac{1}{R*C}$$

If

Resistor = 3,200 Ω
Capacitor = 100 nF

Then

Low-pass filter cutoff frequency = 3125 / 2π = 497 Hz

Percent Error = $\left|\frac{497 - 500}{500}\right|$ = 0.52%

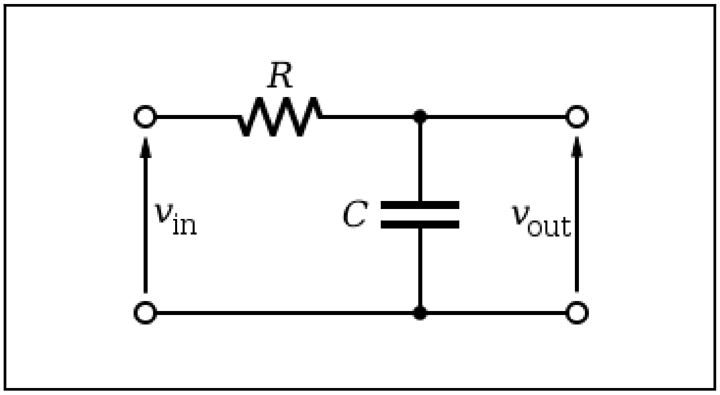

Fig 2.10: Low-pass filter circuit schematic

Granted the low percent errors of our low-pass filter and high-pass filter are both 0.51%, we can ensure the bandpass filter is precise enough to only allow the EMG signal from the desired range of 5 Hz - 500 Hz to pass.

3. Cost and Schedule

Parts List

Description	**Manufacturer**	**Part Number**	**Quantity**	**Extended Price**	**Link**
Wooden hand model	Blick	21650-1004	1	*$9.80*	Link
100nF Capacitors	Kyocera AVX	04023C104KAT2A-62	2	*$0.74*	Link
3.2k Ω Resistor	Vishay	TNPW08053K20BEEA	1	*$0.78*	Link
320k Ω Resistor	KOA Speer Electronics	RN73H2ATTD3203F100	1	*$0.07*	Link
3.9 Ω Resistor	Stackpole Electronics	RMCF2512JT3R90	12	*$0.56*	Link
20k Ω Resistor	ROHM Semiconductor	SFR18EZPJ203	6	*$0.96*	Link
Operational Amplifier	Texas Instruments	LM741CN/NOPB	6	*$5.40*	Link
5V Stepper Motor	Seeed Technology	1597-1203-ND	6	*$27.00*	Link
EMF Shield Tape	Parker Chomerics	1944-05-0720-0272-0	1	*$3.05*	Link

		2-DS-ND			
PLA filament	UIUC Fab Lab	(Not provided)	200g	*$15.00*	Link
9V Battery	Energizer	A1604 BK210J	2	*$4.32*	Link
Micro controller	Microchip Technology	ATMEGA328P-PU DIP28	1	*$7.70*	Link
16MHz crystal	Interquip Electronics	7C16000183AKAF40 Q5	1	*$0.75*	Link
20 pF Capacitor	Vishay	561R10TCCQ20QA	2	*$2.28*	Link
10k Ω Resistor	Vishay	MBA02040C1002FC1 00	1	*$0.44*	Link
10uF Capacitor	Vishay	MAL203878109E3	1	*$0.43*	Link
USB to UART adapter	SiLabs	CP2012	1	*$9.95*	Link
Total				*$268.05*	

Figure 3.1: Itemized List of Components and Costs

Additional Costs

The ECE Machine Shop will be helping us build the prosthetic hand for our project. This may include a number of screws, cables, pieces of fabricated metal. Additionally, they will cut out 12 pieces of circular copper that will be our sensors in our EMG device. The estimated time for the Machine Shop is 3 hours.

We will use solder and soldering iron to build the PCB as well as the oscilloscope provided by the ECE Department for debugging and verifying systems.

Labor Cost

UIUC Grainger College of Engineering reported that the average starting salary for ECE graduates was around $80k - $105k [14]. This comes out to about $43 per hour wage. We expect to put in roughly 12 hours per week working on this project for 9 weeks. With 3 people working on this project, the total labor cost will be $13,932.

$$\$43/hour \ * \ 12\ hours/week \ * \ 9\ weeks * 3\text{ members} = \$13{,}932$$

The total cost for the project will then be $13,932 for labor added with $268.05 for materials, which is $14,200.05.

3.2 Schedule

Week	Task	Team
February 20 - February 26	Order parts for prosthetic	Minwoo, Kathleen
	Begin PCB design	Leanne, Minwoo, Kathleen
	Outline comprehensive requirements	Leanne, Minwoo
February 27- March 5	Manufacture dry electrodes	Minwoo, Leanne, Kathleen
	Create CAD model for armband	Kathleen
	Begin printing armband	Leanne, Kathleen
	Evaluate subcircuits in LTSpice	Minwoo
March 6 - March 12	Assemble arm band with electrodes	Kathleen
	Finalize PCB design	Leanne
	Assemble breadboard subcircuit	Minwoo
	Finish prosthetic assembly	Kathleen, Minwoo
March 13 - March 19	Pass audit	Leanne, Kathleen, Minwoo
	Send PCB to first round printing	Leanne, Kathleen, Minwoo
	Structure program ML backbone	Kathleen

March 20 - March 26	Revisions to PCB design	Leanne
	Begin initial testing	Kathleen, Minwoo
	Finalize arm band design	Kathleen, Leanne, Minwoo
March 27 - April 2	Revisions to PCB design	Leanne
	Continue testing	Kathleen
	Begin accuracy evaluation	Minwoo
April 3 - April 9	Revisions to PCB design	Leanne
	Finalize armband assembly	Kathleen
April 10 - April 16	Finalize testing model	Kathleen, Minwoo
April 17 - April 23	Demonstration	Leanne, Kathleen, Minwoo

Figure 3.2: Schedule for Project Progression

4. Discussion of Ethics and Safety

We recognize the importance of technologies and their capability to affect lives throughout the world. Thus, we agree to commit ourselves to follow the Code of Ethics adopted by the IEEE and uphold the highest standards of integrity, responsible behavior, and ethical conduct with making the Affordable Universal Controller for Upper Limb Prosthetics.

I. **We will not store nor share any patient data as to protect the privacy of others and to prevent any conflicts of interest [13].**

   With online privacy becoming a bigger concern in recent history, we will ensure that no personal information is saved. This is not only ethical but also aligns with the strict Illinois privacy laws. By not storing information, we will also not be able to sell any data as a way to fund the project.

II. **We will accept criticism of our work, and be honest in stating claims or estimates regarding our device [13].**

   The design and building process will reveal flaws in our system and talking to more experienced people, they will provide feedback and offer suggestions. We will accept all criticism and tweak our design to mitigate any weaknesses or oversights on our part. When testing and verifying our system, we will be truthful with the data and include all relevant results, even one time outliers as a part of the analysis in the capability of our design.

III. **We will treat all persons fairly and strive to ensure the code of ethics is upheld by colleagues [13].**

   We acknowledge that we all come to this group with different skills and it will take our combined efforts to create a successful project. We will divide workloads fairly to each member, taking into consideration what they specifically excel at. We will be kind to each other and all persons that we may interact with. We will also be each other witnesses to make sure that the code of ethics is followed and respected.

IV. **We hold paramount the health and welfare of the public [13]**

   The prosthetic controller will be made affordable with the idea that all people who can benefit from a prosthetic will be able to receive them without the burden of heavy costs.

Safety

One of the most dangerous parts to our design is the battery. They are dense in energy and if used improperly, they could lead to explosions or severe burns. We will minimize the chance of injuring others by using dry cell batteries instead of a lithium ion battery as the device will be attached to the user. Lithium batteries may overheat and burn the user or even catch fire and cause even more severe injuries. Dry cell batteries are not immune to these issues but greatly decrease the risk of such accidents. To further increase the safety of our design, we will also ensure the batteries cannot be short circuited in any case which prevent excessive wear on the battery.

We will also avoid using motors that are more powerful than necessary. The prosthetic hand will be close to the user and powerful motors could tear the build apart in the event of malfunction and injure people around it. As our project will only be for demonstration purposes, we will use weaker motors that can move the necessary components but are not powerful enough to break any other components or cause harm to any body parts.

Our design utilizes low voltages and although the sensors are located on the person's arm, there is no other interaction that may cause serious dangers. The sensors are made of copper which is harmless and overall, our design includes minimal safety concerns. Every member of the group has completed the safety training and therefore is knowledgeable in appropriate behaviors in the lab and interacting with equipment, electronic components, and colleagues. Every member is also trained in how to act in the case of possible emergencies.

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