THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

SCHOOL OF SCIENCE, ENGINEERING, AND TECHNOLOGY

ELECTROMYOGRAPHY-CONTROLLED ROBOTIC ARM

NICOLE HILL
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Reviewed and approved* by the following:

Seth Wolpert
Associate Professor in Electrical Engineering
Thesis Supervisor

Xinwei Niu
Assistant Professor in Electrical Engineering
Faculty Reader

David Witwer
Director of Capital College Honors
Honors Adviser
* Electronic approvals are on file.

ABSTRACT

This document presents an array of background information on the topic of using electromyography (EMG) signals in conjunction with a robotic arm as a means of control. A brief introduction of this topic is given, followed by the technical literature which gives insight on the designs of prosthetics and exoskeletons, and how these devices have been modernized in various ways. Then, the different components of an EMG circuit are analyzed in detail to understand how this circuit will control a robotic arm. This is followed by the creation of a motor circuit that connects to a robotic arm. These two subsystems are combined to control the X-R3 Robotic Arm. In the final section of this paper, the effectiveness of the complete system is discussed as well as improvements for the future.

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ACKNOWLEDGEMENTS

First, I would like to thank God for his continuous blessings. I would also like to thank the School of Science, Engineering, and Technology at Penn State Harrisburg for exposing me to a resourceful atmosphere with many dedicated and experienced engineering faculty. I believe the work we do as engineering students at Penn State Harrisburg is rigorous and this has set me apart from other students at other universities.

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Chapter 1: Literature Review

Introduction

Strokes have been ranked as the number two cause of death, globally accounting for nearly nine percent of the annual death toll [8]. One of the greatest side effects of a stroke is muscle weakness [9]. Other causes of limb defects can be attributed to sports injuries, spinal cord injuries, and trauma. Standard rehabilitation processes have been adopted to help patients gain strength in their disabled limbs; however, this is time-consuming, requires a trained and skilled professional, and takes a lot of patience [14]. New technology, such as the exoskeleton, has shown promising results in helping physically disabled patients increase their mobility. The exoskeleton is an electromechanical structure placed on the outside of the human body that aids in limb movement [8].

The exoskeleton device is relatively new and current research lacks a detailed investigation into the EMG circuit design of the robot. The goal of this research is to explore the electromyographic signals that controls the exoskeleton and design a complete circuit that will capture the most significant regions of the frequency spectrum of the EMG signal in order to improve efficiency and maintain human-like motion. The literature review will summarize research on exoskeletons, including electromyography signals, physical and mechanical design structures, and control systems. Current research of the exoskeleton focuses on eliminating the bulky mechanical structure with lightweight material such as plastic or thin cables [22]. Other studies have focused on different control systems that improved the devices' overall efficiency [23], or various mechanical components that improved joint mobility [14].

Exoskeletons

Exoskeletons are robotic devices that aid in limb mobility, contributes to improving handicapped functions, and helps physical therapists in their work. Its structure resembles human body parts which further enhances support and stability. This differs from orthosis which are mechanical devices that attach to the anatomy of the body and help to restore and correct the movements of limbs through the use of braces. Figure 1 is the schematic view of the exoskeleton robot; it shows the general structure of the robotic complement of orthosis [17].

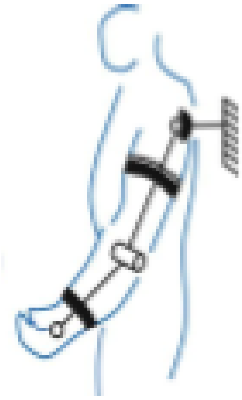


Figure 1: Schematic view of the exoskeleton robot [17]

Research was conducted that classified the exoskeleton into four categories. The first, shown in figure 2, is the parallel-limb exoskeleton which works in parallel with the lower limbs of the human body. The purpose of this exoskeleton is to allow for load transfer to the ground. The second, shown in figure 3, is the parallel-limb exoskeleton which works with the joints to allow torque and work enhancement. The third is a parallel-limb exoskeleton that develops human endurance. Lastly, the series-limb exoskeleton, shown in figure 4, includes various elastic shoes and exoskeletons that act in series with the lower body limbs [9].

Figure 2: Parallel-limb exoskeleton [9]

Figure 3: Parallel-limb exoskeleton for torque [9]

Figure 4: Series-limb exoskeleton. [9]

For each of these categories, the researcher highlights the design of hardware, control systems, and actuation and draws conclusions on the design flaws and the future of exoskeletons. The most important conclusion was that the future of technology that enhances human mobility is becoming highly more innovative compared to the 20th century where wheeled devices were used to improve physical disabilities. Now, exoskeletons allow humans to make movement in a human-like manner [9].

Several different control factors are used to operate the exoskeleton and they include electromyographic signals, biomechanical signals, peripheral nervous system signals, and the central nervous system signals. The most efficient and widely used process is the electromyographic signals [17].

Electromyographic Signals (EMG)

Electromyography signals are electrical signals sent from an individual's muscles that tell the body what movements to make. These signals provide robust motor control data, which is used to determine a user's desired motion. The research focused on surface EMG signals showed its efficiency in fluent control of the robot, its motor movements, and the production of more human-like motion. However, the researchers discovered that the major challenges with EMG signals include determining the proper placement of electrodes to read signals, and how to read signals in environments that may distort the signal readings [17].

Another study complementing the previous research implemented the use of EMG signals on an exoskeleton with five degrees-of-freedom; this includes the shoulder (3-degrees-of-freedom) and the elbow (2-degrees-of-freedom). An electromyography amplifier was used to increase the signal given from the muscles because it is a relatively small signal. The study included the use of an analog to digital converter, a computer interface and the motor control and motor driver for joint movement in the arm. Researchers found that the use of electromyography signals as inputs, in combination with a motor controller and pulley system, allowed efficient control of the direction and movement of the exoskeleton

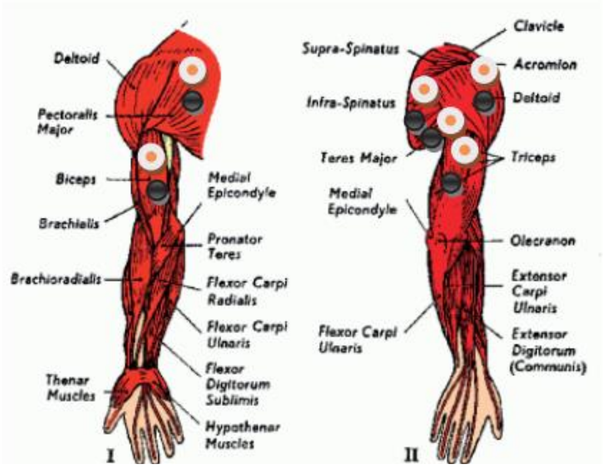


Figure 5: Placement of electrodes (black and white circles) [18]

arm. They also noted that more degrees-of-freedom allows an exoskeleton to move more human-like [18]. Figure 5 shows the different placements of the electrodes.

Physical/Mechanical Design Structure

The design structure of the exoskeleton can be divided into two parts; the design of the control system, and the physical and mechanical design of the exoskeleton. Starting with the physical and mechanical design of the robot, researchers used the kinematics and dynamics of the upper body limbs to create an exoskeleton with seven degrees-of-freedom. This was named the cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN)-7. They studied where to place the motors and the pulley system to create the most efficient design. This design had low inertia, high-stiffness links, zero-backlash within the back drivable transmissions, and smooth movements in the elbow and wrist joints. Mechanical human machine interfaces (mHMIs) were used to connect the mechanics of the exoskeleton to the human arm. This design developed a robotic arm that was efficient and lightweight [13].

In a similar study, researchers proposed using plastic cables which reduced the size and weight of the system. The exoskeleton was built with plastic adjustable cables having five degrees-of-freedom which focused on force control. By studying an optimal cable tension planner, they found that in-line load cells helped control the cable tensions. The force control was successful in aiding various hand motions. It was tested on several healthy human subjects and the results showed an increase in motion performance.

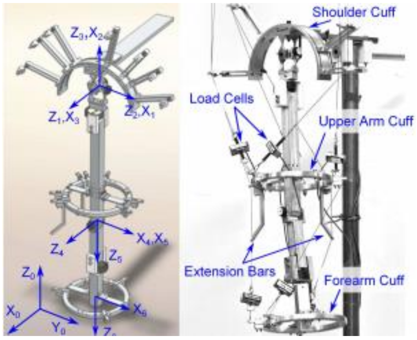


Figure 6: Left: CAD model. Right: Prototype [22]

Figure 6 shows the CAD model and prototype for this system. The team planned to take this research further by studying the effects of a tangential and damping force [22].

Contrary to the previous studies, another project researched the use of a specific joint for robotic movements. It focused on a modular joint design that included a motor, harmonic encoder drive, brake, cross roller bearing, and joint torque sensor. The modular joint was used for neurorehabilitation in medical devices. The researchers pointed out two methods that are typically used to discover external forces. The first is to detect force through current sensors in motor circuits. This was difficult to get an accurate reading because of the noise that was generated. The second method was to use a torque sensor which can either use a 6-axis force-torque sensor (expensive), or a joint torque sensor.

The team used the joint torque sensor within their modular joint design. In their methods, they created a structure for the modular joint, designed the joint torque sensor, ran a FEM (finite element method) analysis on the joint torque sensor, then calibrated the sensor. At the conclusion of the project, they created a modular joint unit. In future work, the team made plans to implement safety algorithms for controlling the joint and remove unwanted movements [3].

Another study focused on the design of a three degrees-of-freedom exoskeleton that uses electromyography (EMG) signals to facilitate movement. It is the electromyography signals from muscles that determine the type of movement the body wants to make. The team uses a force vector to allow for a smooth, human-like movement. They also integrated an algorithm that helps to prevent any impact between a user's limb and the machine itself. The methods include the creation of the robotic frame for the exoskeleton. This included research on weight reduction, safety operation, comfort, and maintenance [14].

Next, the team considered the control system, EMG signal processing, and a muscle model. It is the EMG signal that determines the movement of the exoskeleton arm. Lastly, the exoskeleton robot controller was created. This includes a force sensor-based controller (FBC), and the EMG-based controller (EBC). They used two healthy human males to test the effectiveness of the exoskeleton. The results from the experiment shows smooth movements with the robot [14].

Control System

In addition to the physical structure of the exoskeleton, the control system plays a pivotal role, serving as the brain of the system and some researchers preferred to focus more on this. A hybrid FES-exoskeleton (functional electrical stimulation) mathematical method was designed which emphasized shoulder movements (flexion, extension, abduction, adduction, and medial and lateral rotations). They studied the biomechanics of the upper limb, created a dynamic model, and studied the muscle's drive under varied FES actions. In conclusion, a math model of this exoskeleton was designed to help improve range of motion, increase reaction time and limit disordered movements. The researchers were able to model the muscle-tendon, create a length-tension curve of the entire muscle, determine electrical stimulus parameters, view the muscle response to different impulses, and determine where to place electrodes for stimulation. The researchers' next steps in the future will be to consider actuation and sensorial system models [8].

Another study took a different approach with the control system. The control system's task was to create movements that were accurate and suitable to the desired motions of the patient. Specifically, the research team wanted to control the exoskeleton by using information from force feedback and the limb's positioning. They used Kinect and Haptic sensors. The Kinect sensor gathered the angles of rotation and translation for the limb while the Haptic sensor recorded the mechanical force. The architecture of their system included two parts; the Kinetic-Haptic Control System (KHCS) and the Exoskeleton Control System (ECS). The two systems communicated together in real-time. After the construction of the arm, the team built a prototype to test the control system. In their conclusions, the KHCS gave information on motion control and it received accurate force feedback. They also noted that more safety precautions needed to be implemented and further studied. They noticed that to have higher quality results, force values should be debugged [4]. Figure 7 a functional decomposition of the Kinect-Haptic and exoskeleton control system.

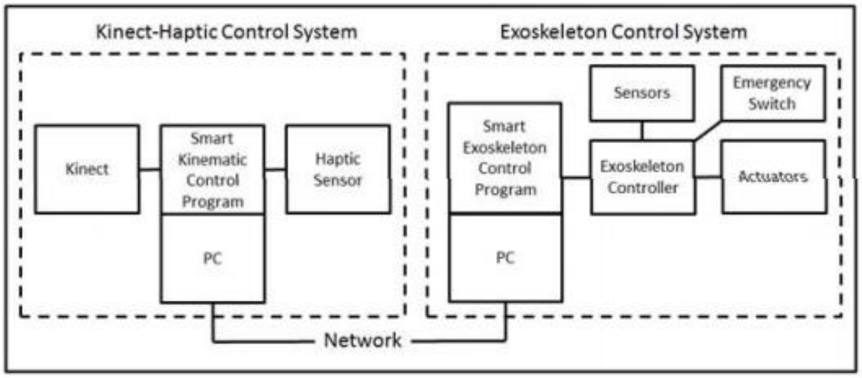


Figure 7: Control system [4]

Electromyography signals play an important role in the efficiency of the robotic arm allowing for more human-like motion. In order to have a robot that can accurately mimic human motion, it needs information directly from the limbs. EMG signals gather information on muscle activities such as contractions. Information from muscle contractions also gives data on force exertion and motion. To capture EMG signals, we only need electrodes. This replaces the need for other bulky mechanisms that can add to the overall weight of the system, thus contributing to a more beneficial design structure [16].

Another common theme in the studies is the need to make the system operation more human-like. Whether the topic of the research was EMG signals, the control system, or the physical and mechanical design structure, the end goal was fluent motion. On the contrary, what most of the articles failed to research was the circuitry that reads EMG signals from the muscles. EMG signals are very sensitive and in order to get the most accurate readings and accurate robotic response in any environment, under any circumstance, special attention should be made with the EMG circuit design. Due to the lack of research in EMG circuitry, I propose the question, can an EMG circuit be designed that has a critically detailed design which will capture the strongest spectrum of an EMG signal?

Chapter 2: Research Methodology

EMG Signal and Circuit

When a muscle undergoes flexion or extension, it produces motor unit action potential (MUAP) which is electrical activity on the skin's surface. This information is gathered through electromyography signals to interpret the electrical activity. The electromyography (EMG) circuit is designed to take the voltages produced in a muscle, and convert it into information that can be read by a microcontroller or computer. The voltages in the muscle are very small (0-10 millivolts) [15]. The EMG circuit takes this small, AC signal, amplifies it, filters it to eliminate noise, and rectifies the signal to convert it into a positive DC voltage that a computer can understand. This research project works specifically on the bicep muscle. The following section will discuss in detail the different components of the EMG circuit.

Instrumentation Amplifier

The EMG circuit starts with an instrumentation amplifier which is a differential amplifier that allows for high input impedance and the gain that can easily be modified by changing the gain resistor. The instrumentation amplifier takes two inputs (positive and negative) and amplifies the difference between the two while eliminating the extra noise. In this case, the two input signals come from the middle and end of the bicep muscle. The common-mode rejection ratio (CMMR) rejects common-mode signals. This can be signals that emerge simultaneously or are in phase. The instrumentation amplifier used in this research will be the INA106 by Texas Instruments [2]. It has a monolithic gain of 10. Equation (1) is used to determine the gain (A_V) which will be -110. The sum of the internal resistance and external resistance ($R_{internal}$ and $R_{external}$ respectively) of the chip was divided by the internal resistance to get the gain. Figure 8 shows a schematic of the instrumentation amplifier and figure 9 shows the INA106 pinout.

$$A_v = \frac{R_{internal}+R_{external}}{R_{internal}} \tag{1}$$

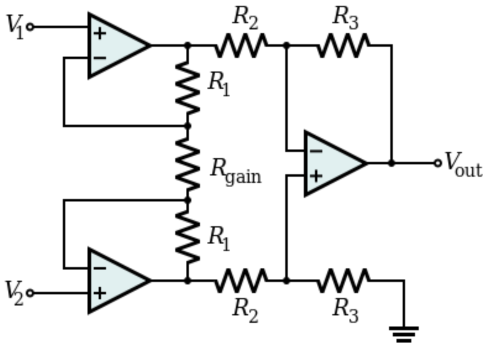


Figure 8: Instrumentation amplifier [5]

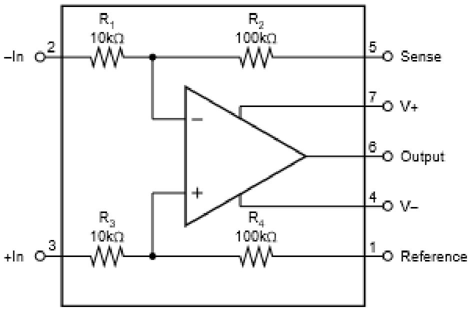


Figure 9: INA106 pinout [2]

Bandpass Filter

EMG signals come with a lot of noise that is inescapable and in order to eliminate unwanted noise, filters are used to obtain the raw EMG signal. An EMG signal has a frequency range of 0 to 500 Hz; however, the dominant frequency is produced between 10 Hz – 200 Hz [13]. Figure 10 shows the frequency spectrum of the EMG signal.

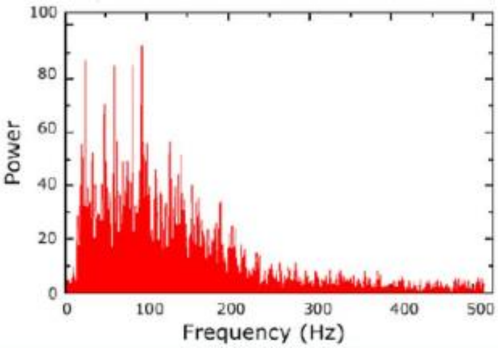


Figure 10: Frequency spectrum of EMG signal [15]

The bandpass filter rejects high and low frequencies that do not fit in the range determined by the designer of the filter. This range is commonly referred to as the passband and is designed to be (50 Hz-170 Hz). The bandpass filter shown in figure 11 consists of a low pass filter, a high pass filter, and an operational amplifier to increase the signal by a gain of -15. The low pass filter allows frequency below (170 Hz) to pass while the high pass frequency allows frequency above (50 Hz) to pass. The low and high-frequency cutoffs (ω_{CL} and ω_{CH} respectively), in radians, are determined by using different capacitor (C) and resistor (R) values. Equations (2), (3), and (4) were used to design the bandpass filter. The subscripts in the following equations correspond to figure 11.

$$\omega_{CL} = \frac{1}{R_2 * C_1} = f_{CL} * 2\pi \text{ (low pass)} \tag{2}$$

$$\omega_{CH} = \frac{1}{R_3 * C_2} = f_{CH} * 2\pi \text{ (high pass)} \tag{3}$$

$$A_v = \frac{R_6}{R_5} \text{ (gain)} \tag{4}$$

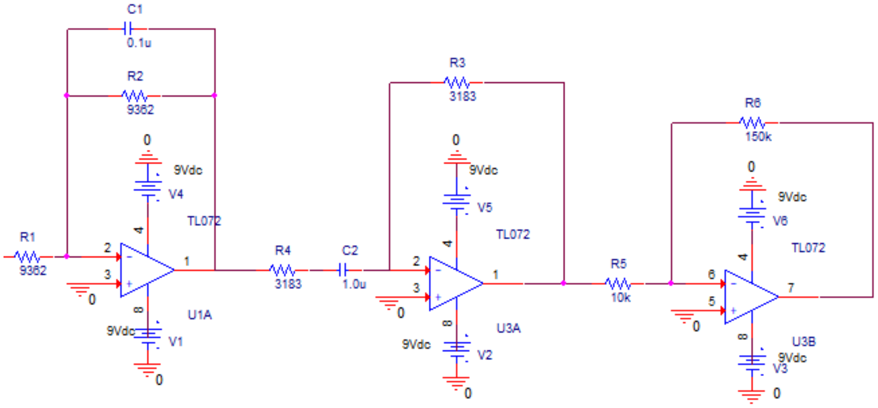


Figure 11: PSpice designed bandpass filter

Full Wave Rectifier

The full wave rectifier is the next stage of the EMG circuit. The signal coming from the bicep is an analog AC (alternating current) signal. In order for the signal to be read by a microcontroller or a computer, it must be a DC (direct current) signal. AC signals change directions and have voltages that constantly switch between positive and negative voltages as shown in figure 12, whereas DC signals travel in one direction and always remain positive, as shown in figure 13.

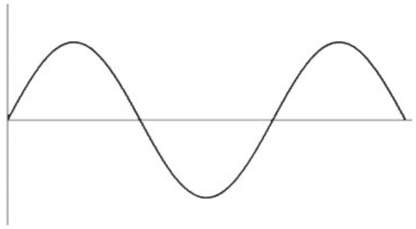


Figure 12: AC Signal

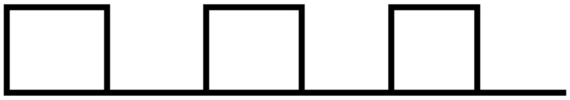


Figure 13: DC Signal

The full wave rectifier converts the AC signal into a smooth DC signal and eliminates negative voltage so that a computer can interpret the information. This is illustrated in figure 14. At the input of the full wave rectifier, the EMG AC single has two half cycles, one positive and the other negative. As the signal travels through the rectifier, it is converted into a pulsating DC signal.

Figure 14: AC to DC conversion through full wave rectifier [7]

The full wave rectifier has two 1N4148 diodes. The diodes are used to ensure that current travels in one direction. As mentioned before, an AC signal has a positive half cycle and a negative half cycle, both of which travel in different directions. The diode will only allow the positive half cycle through and the output signal is seen as purely positive pulses. The full wave rectifier is then coupled to an envelope detector which is a low pass filter that serves to eliminate the high frequency and give an envelope of the entire signal. The high frequency, also known as the carrier frequency, serves to transport (carry) the important information of the signal. The envelope signal is a smooth outline of the amplitudes from the high frequency. This can be illustrated in figure 15. The final full wave rectifier circuit is shown in figure 16.

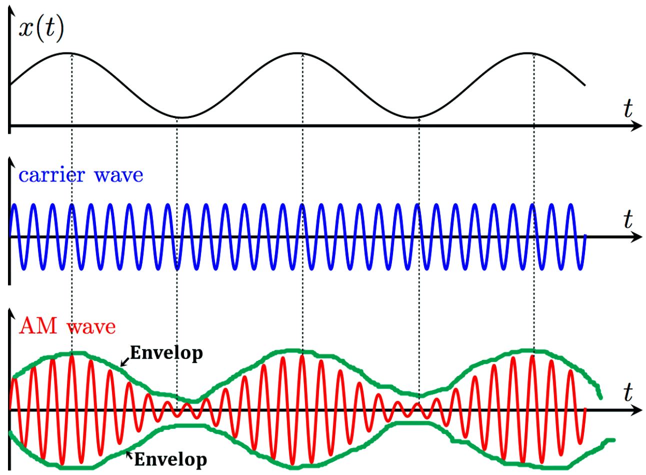


Figure 15: Amplitude modulation

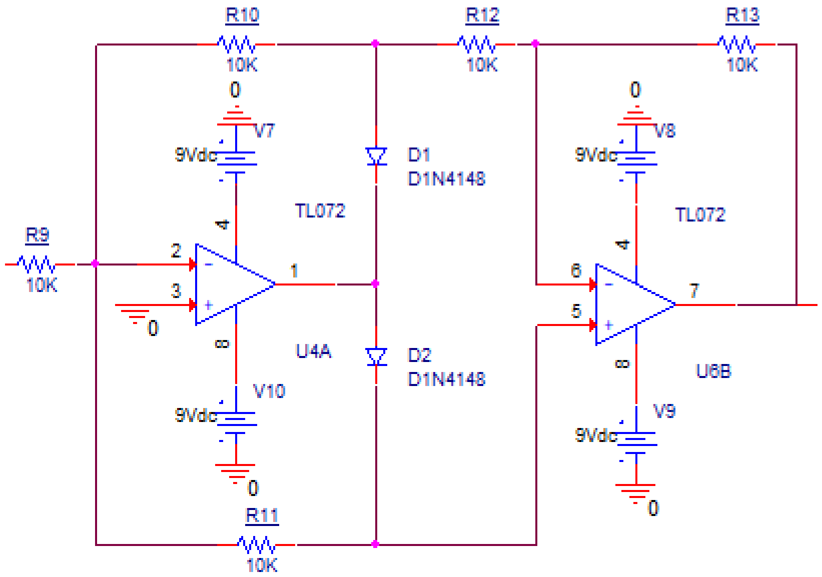


Figure 16: PSpice designed full wave rectifier

Final Amplification and Smoothing

In the final stage of the EMG circuit, the new DC signal is passed through a low pass filter with a gain of 1 which further smooths the signal. Then, it is passed through another operational amplifier where the gain, which controls amplification, is controlled by a 10kΩ potentiometer so the user can continue to adjust the signal as needed. This can be viewed in figure 17. Equations (2) and (4) are used to design this segment of the circuit.

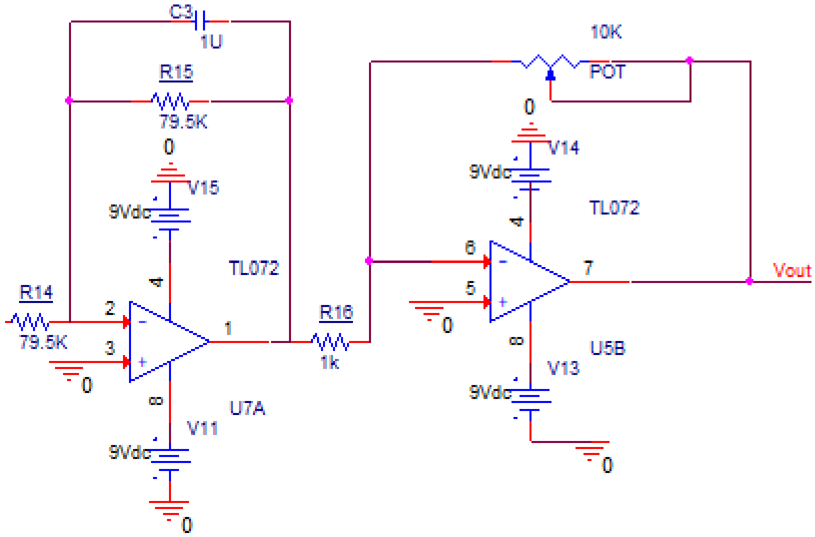


Figure 17: PSpice designed amplification stage

All of the operational amplifiers used in the EMG circuit are TL072 by Texas Instruments [17]. A pinout of this amplifier is shown in figure 18.

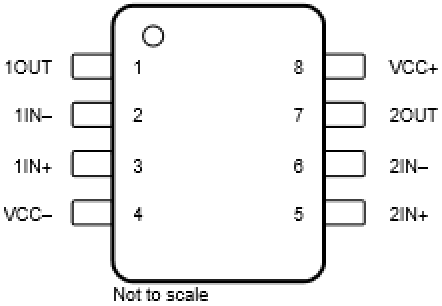


Figure 18: TL072 pinout [19]

Electrode Placement

The EMG circuit is designed so that the user's biceps brachii, more commonly known as the biceps, will control the motion of the robotic arm. The bicep is a skeletal muscle located on the front side of the upper arm, lying between the shoulder and the elbow. This is shown in figure 19. It can be referred to as a bi-articular muscle, meaning it is in charge of controlling two joints. In the case of this research, the only joint that will be studied is the elbow. The bicep is the muscle that allows an individual to flex and rotate the forearm.

Figure 19: Bicep brachii location [1]

EMG electrodes are used to gather electrical activity inside a muscle. This research uses surface electrodes which can be placed on the skin without being invasive like needles. The surface EMG is easy to use, whereas a needle EMG requires a medical professional. The disadvantage to the surface EMG is that because the electrode is not in direct contact with the muscle at use, there will be more noise or crosstalk as the electrical signal travels through the skin before reaching the electrode. This is important considering that electrical signals from the signals are very small and sensitive. Also, the condition of an individual's skin can change hour to hour. It can change from being moist, soft, dry, hard, the pores can be open or close and this can alter the electrical signal being picked up by the surface EMG. These factors must be taken into consideration when designing the circuit and the code.

The placement of the surface electrode is also important in picking up a strong, clean electrical signal. Three electrodes are in use for the EMG circuit. One electrode is placed at the center of the bicep (mid-muscle electrode). The second electrode is centered at the end of the bicep (end-muscle electrode). The final electrode is placed on the back of the forearm in the bony area surrounded by the elbow. This electrode is known as the reference electrode which will serve as the ground for the signal. Before placing any of the electrodes, it is important to properly clean the area of the skin where the electrodes will make contact. This prevents dirt, oil, or dead skin from interfering with the electrical signal as it passes through the surface electrode.

Another key factor that affects the EMG signal is the noise, which has many origins. Some of these sources include light and radio signals which typically have a frequency between 50-60 Hz. Noise also comes from crosstalk. Crosstalk occurs when the three wires that connect to the electrodes pass signals that interfere with one another. In order to eliminate it, the electrode wires should be braided together. This technique ensures signal integrity.

X-R3 Robotic Arm Integration

The X-R3 Robotic Arm was purchased by the electrical engineering department at Penn State Harrisburg in 1992. It has five degrees of freedom which includes the wrist rotation, wrist flex, shoulder, elbow, and waist. This research focuses only on the elbow’s ability to flex and extend the arm. The user’s bicep will control these actions. Figure 20 shows a scheatic of the robotic arm while figure 21 is the actual robotic arm.

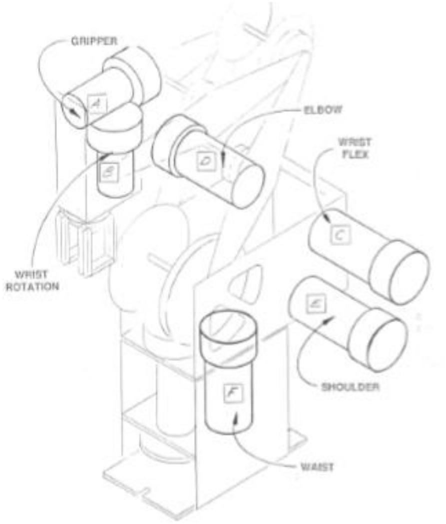


Figure 20: X-R3 Robotic arm schematic [6]

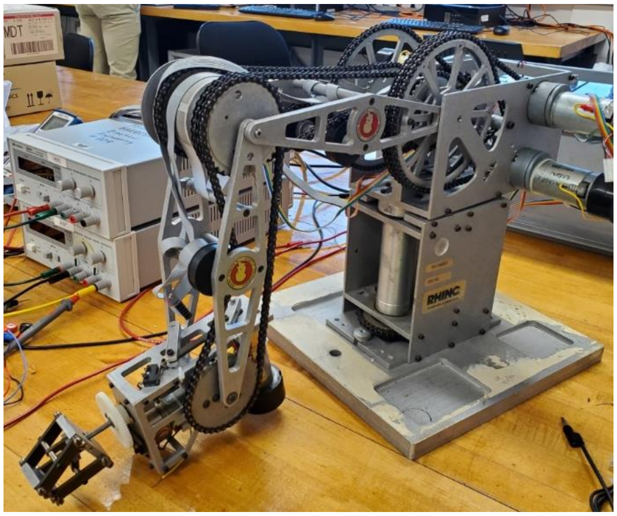


Figure 21: Actual X-R3 robotic arm

Motor Circuit

Now that the EMG circuit is complete, it is time to build the motor circuit in order to integrate the robotic arm into the system. The robotic arm will be controlled using the H-bridge circuit. The H-bridge circuit allows for bidirectional control of the motor. In this case, the motor should rotate forward to represent the flexion of the arm, and backward to represent the extension of the arm. The direction of the motor is determined by how the positive and negative wires of the motor is connected in the H-bridge circuit. This circuit makes it easy to control the direction, otherwise the user would have to manually change the leads each time the direction needs to be changed.

The H-bridge circuit is constructed using power MOSFETS (metal-oxide semiconductor field-effect transistor); two p-channel (IRF4905) and two n-channel (IRFZ44N). MOSFETS are the most common transistors and are used to control the switching of signals. It is made up of three terminals; source, drain, and gate. The MOSFET has a very high input impedance and is controlled by the gate-source voltage. This differs from the BJT which is a current controlled device. The MOSFET is a voltage-controlled device.

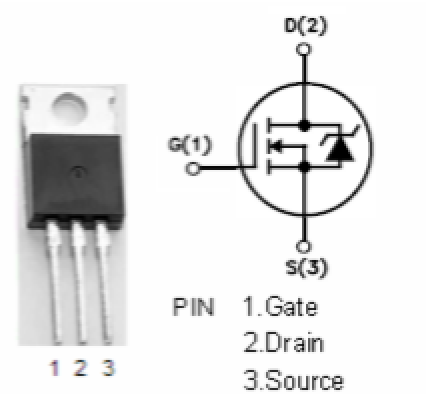


Figure 22: IRFZ44N pinout [10]

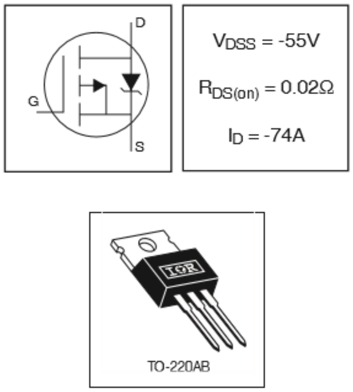


Figure 23: IRF4905 pinout [11]

The motor that accompanies the X-R3 Robotic Arm needs 12 volts to operate. The four MOSFETS mentioned previously have an operating voltage of 5V-20V and this works perfectly for the overall system. When the voltage is applied to the gate on the MOSFET, the space charge region between the source and drain is widened. The wider the space charge region, the more effective the MOSFET works. Specifically, for an n-channel MOSFET, the source terminal connects to ground and when the voltage is applied to the gate, the MOSFET turns on. To turn the MOSFET off, the gate must be connected to ground. For the p-channel MOSFET, the source is connected to the power which is 12 volts. To turn the motor on, the gate is connected to the ground. To turn the p-channel MOSFET off, it is pulled back to the power rail. The voltages applied to the MOSFET will be determined by the signal given from the EMG circuit.

Forward and Reverse Motion

As discussed before, the bicep is only in charge of the flexion motion. It is not involved with extension. The triceps brachii, commonly known as the triceps, controls the extension movement and it is located at the back of the upper arm. This is shown in figure 24. Because this research only focuses on the biceps, a push button will be implemented into the circuit to produce the extension motion of the arm.

Figure 24: Triceps brachii location [20]

The H-bridge circuit gets it names because of its H-like configuration in the circuit. There are two diagonal pairs of MOSFETS. Only one pair is activated at the same time. When Q1 and Q3 are activated, the motor moves in the forward motion. When Q2 and Q4 are activated, the motor moves in the reverse direction. The motor is in the braking motion when either both of the p-channel MOSFETS are activated or both of the n-channel MOSFETS are activated. The complete motor circuit is shown in figure 25, and the H-bridge configuration for direction in shown in figure 26.

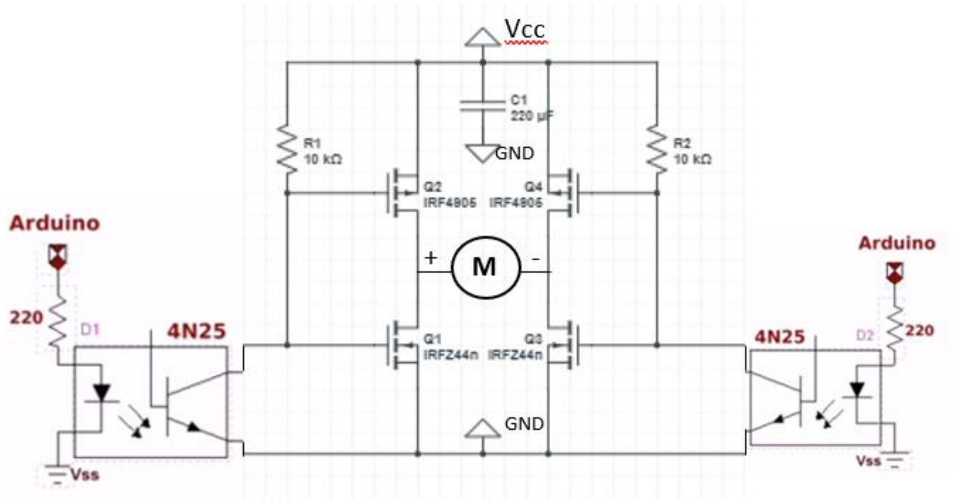


Figure 25: Motor circuit

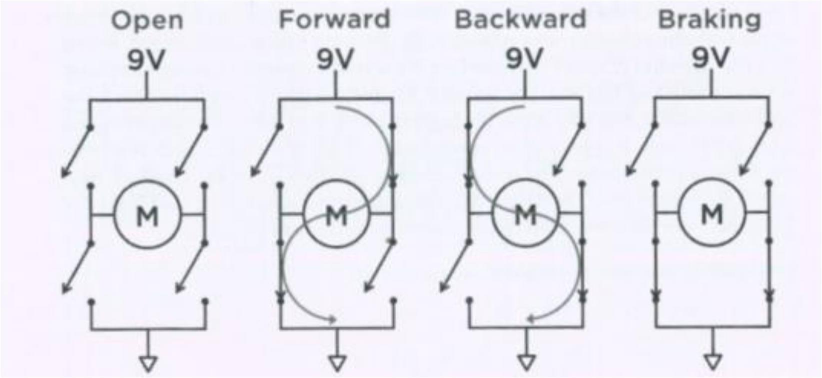


Figure 26: H-bridge configuration [12]

The H-bridge circuit also comes as an integrated circuit which is compatible with many microcontrollers. Because the finished system includes the use of voltages coming from the bicep, it is important to isolate the motor circuit from the EMG circuit to prevent electrical shock or damage to the muscle. For this reason, the H-bridge integrated circuit is not used because in its internal circuitry, it shares the ground of the microcontroller and the motor. By building the H-bridge, this eliminates the shared grounds.

Optocoupler

The optocoupler, also known as an opto-isolator, is an electronic circuit that allows a signal to pass through two different circuits through the use of an IR LED (infrared light-emitting diode) and a phototransistor. The 4N25 phototransistor optocoupler eliminates the need for the EMG circuit to electrically connect to the motor circuit; the circuits remain isolated. This is important when dealing with medical devices. The optocoupler protects high voltages from the robotic arm motor from interfering with the EMG signal. The EMG signal passes through the left side of the optocoupler in figure 27, which turns on the IR LED. The range in voltage of the EMG signal will control the intensity of the IR LED. The photoresistor on the right side of the optocoupler controls the motor circuit by reading the intensity of the LED. The optocoupler keeps the EMG circuit and the motor circuit isolated but also allows the two circuit to communicate with each other. This is an important step in the subsystem integration phase.

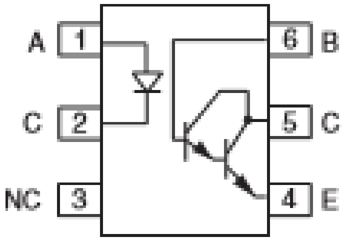


Figure 27: 4N25 pinout [21]

Subsystem Integration

The two subsystems are the EMG circuit and the X-R3 motor circuit. The EMG circuit communicates with the motor circuit to determine the robotic arm movement. As discussed previously, the optocoupler is used to ensure the two subsystems are not connected electrically but are still able to communicate. The final stage is to implement a microprocessor which is an integrated circuit that has many of the same features of a computer processing unit (CPU). The microprocessor serves as the brain of the entire system.

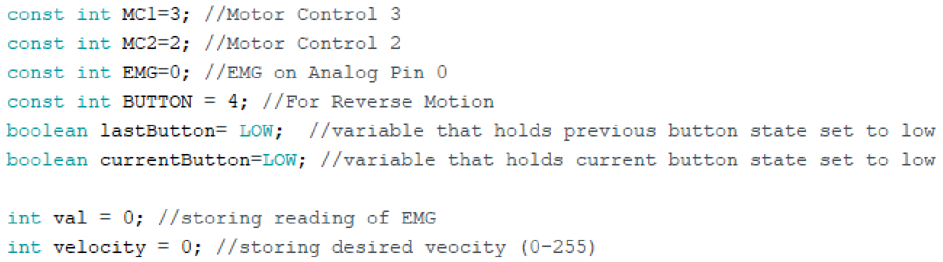
Arduino Integration

The Arduino Uno is the microcontroller that will command the project. This specific microcontroller is chosen because it is well equipped with features such as operating at 5 volts for digital pins and capable of reading between 0 to 5 volts for analog inputs. This will serve good for reading the output signal produced by the EMG circuit which converts 0 to 10 millivolts to a range between 0 and 5 volts. There are also 14 digital input and output (I/O) pins and six analog input and output pins. This is more than enough space because the EMG controlled robotic arm will only utilize three digital pins and one analog pin.

A USB cable can be connected between the Arduino UNO and a computer and this will provide 5 volts while also creating a serial port between the two devices. This device is inexpensive, and can run across different platforms. Arduino also comes with an integrated development environment (IDE) that has sample plenty of sample codes. One of the example codes known as ‘AnalogReadSerial’ is an important function in verifying and providing a visual of the EMG signal as it exits the EMG circuit. Lastly, the electrical engineering program at Penn State Harrisburg has a microprocessors class that is built around the Arduino Uno. Given that I am most skilled with the Arduino Uno compared to other microcontrollers, it is more appropriate and pragmatic to work with.

Code

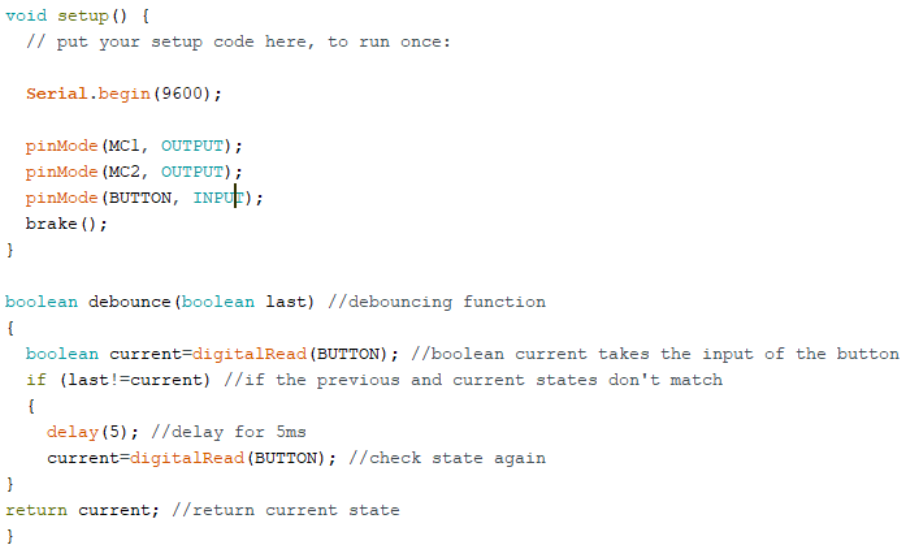
The code serves as a set of procedures for the Arduino Uno to follow in order to operate the entire system. All the data taken from the EMG circuit will be combined with the information from the motor circuit to establish the movement in the robotic arm. The beginning of the code is shown in figure 28.



```
const int MC1=3; //Motor Control 3
const int MC2=2; //Motor Control 2
const int EMG=0; //EMG on Analog Pin 0
const int BUTTON = 4; //For Reverse Motion
boolean lastButton= LOW;  //variable that holds previous button state set to low
boolean currentButton=LOW; //variable that holds current button state set to low

int val = 0; //storing reading of EMG
int velocity = 0; //storing desired veocity (0-255)
```

Figure 28: Initializing variable

The code begins by initializing the input and output pins of the Arduino Uno that will be in use. The motor for the elbow joint in the robotic arm has a positive and a negative wire which in the code is referenced as MC1 and MC2. The two wires are connected to digital pins 3 and 2 respectively. The output EMG signal from the EMG circuit connects to analog pin 0. The output of the push button is connected to digital pin 4. A boolean variable has two outputs; true and false. This feature is used for the push button and will be discussed in greater detail later on. The final two variables that are initialized in the first section of the code are “val” which will store different numerical values given by the EMG signal, and “velocity” which holds pulse width modulation (PWM) values. PWM is a method used to represent analog signals in digital form. The next section of the code is shown in figure 29.



```
void setup() {
  // put your setup code here, to run once:

  Serial.begin(9600);

  pinMode(MC1, OUTPUT);
  pinMode(MC2, OUTPUT);
  pinMode(BUTTON, INPUT);
  brake();
}

boolean debounce(boolean last) //debouncing function
{
  boolean current=digitalRead(BUTTON); //boolean current takes the input of the button
  if (last!=current) //if the previous and current states don't match
  {
    delay(5); //delay for 5ms
    current=digitalRead(BUTTON); //check state again
}
return current; //return current state
}
```

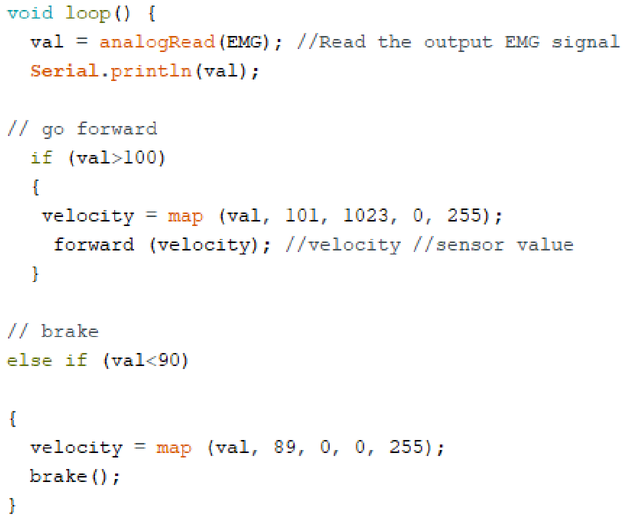
Figure 29: Void setup

The void setup section of the code is the list of instructions for the Arduino Uno to should run once. 'Serial.begin(9600)' activates the serial monitor in the Arduino IDE. The serial monitor allows the user to view results in real time and moves at a data rate of 9600 bits per second. Next, the 'pinMode()' function sets each pin as either an input or an output. The two motor pins, MC1 and MC2, will serve as output pins while the push button is an input pin.

The boolean debounce function is used for the push button. When the button is pressed, the output state does not change immediately. The signal bounces from low to high several times before it settles on one state. The bouncing occurs for a few milliseconds and is illustrated in figure 30.

Figure 30: Switch debouncing [12]

Through software, it is possible to write code that waits for the bouncing to stop before assigning the state. A debounce function can be created which will compare the current and previous states (which were initialized to low) to see if they differ. When the current and previous states differ (!=), this suggests that bouncing will occur. The delay of five milliseconds waits for the bouncing to conclude and then reads the state of the output. If the current and previous state differ in value, then the reverse motion is activated. Next, the ‘void loop ()’ function shown in figure 31 is described.

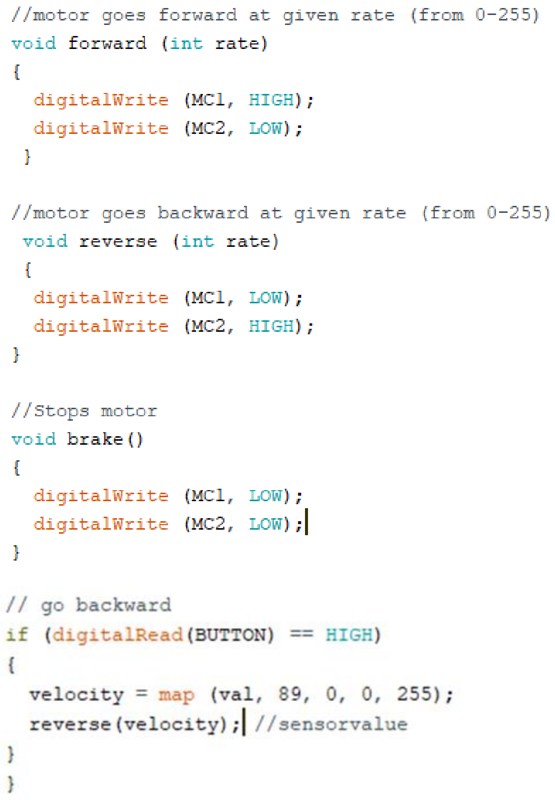


```
void loop() {
  val = analogRead(EMG); //Read the output EMG signal
  Serial.println(val);

// go forward
  if (val>100)
  {
   velocity = map (val, 101, 1023, 0, 255);
    forward (velocity); //velocity //sensor value
  }

// brake
else if (val<90)

{
  velocity = map (val, 89, 0, 0, 255);
  brake();
}
```

Figure 31: Void loop

All the information in the ‘void loop()’ are repeated. First, the variable ‘val’, which was initialized earlier, is set to hold the numerical output value given by the EMG signal. This value will be printed in the serial monitor. Then the threshold for forward motion of the robotic arm is established. Whenever the EMG sensor value in the serial monitor is above 100, the robotic arm will move in the upward motion. 100 is reached when the user flexes their arm. If the sensor value is below 100, the arm is no longer flexing and the robotic arm should stop. This is the braking motion.

The backward motion is controlled by the push button. Whenever the state of the button is high, the robotic arm will move backward. The final section of the code is shown in figure 32.



```
//motor goes forward at given rate (from 0-255)
void forward (int rate)
{
  digitalWrite (MC1, HIGH);
  digitalWrite (MC2, LOW);
 }

//motor goes backward at given rate (from 0-255)
 void reverse (int rate)
 {
  digitalWrite (MC1, LOW);
  digitalWrite (MC2, HIGH);
}

//Stops motor
void brake()
{
  digitalWrite (MC1, LOW);
  digitalWrite (MC2, LOW);
}

// go backward
if (digitalRead(BUTTON) == HIGH)
{
  velocity = map (val, 89, 0, 0, 255);
  reverse(velocity); //sensorvalue
}
}
```

Figure 32: Forward, reverse, and brake functions

In the last stage, the creation of the forward, reverse, and brake functions that actually control the state of the two motor pins. In the forward motion, MC1 is high while MC2 is low creating a clockwise motion. In the reverse motion, MC1 is low while MC2 is high creating the counterclockwise motion. To stop all movement, both MC1 and MC2 must be low.

Chapter 3: Experimental Results

Completed EMG Circuit

Figure 33 shows the completed EMG circuit schematic. The electrodes pick up the signal and feed it into the INA106, an instrumentation amplifier by Texas Instruments. The difference between the mid muscle and the end muscle inputs was increased by a gain of -110 while extra noise was eliminated. The signal then passed through a high pass filter, low pass filter, and an amplifier with a gain -15 which created the bandpass filter. This filter allows frequencies between 50 Hz and 170 Hz to pass through. This range in frequency is where the signal is the strongest. The next two amplifiers created the full wave rectifier which converted the signal from AC to DC. The final two amplifiers were used as a low pass filter to get rid of any remaining noise, and to invert the signal one last time with a gain that can be controlled by the user.

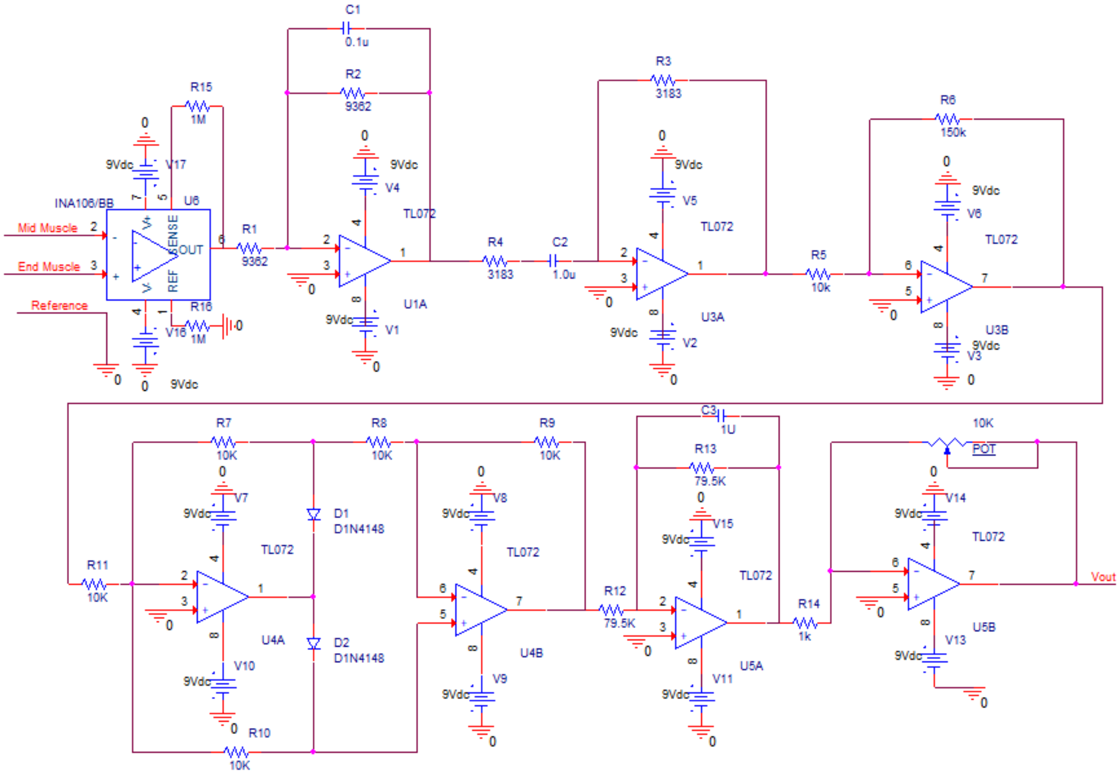


Figure 33: Complete EMG circuit

Figure 34 is an oscilloscope screenshot of the signal as it exits the EMG circuit. The voltage value highlighted in the red circle shows a voltage of 1.52V. This low voltage value is given when the user inputs a very low resistance from the potentiometer. Figure 35 shows another oscilloscope screenshot with the output signal being 4.02V when the potentiometer value was increased. The EMG signals were successfully amplified and smoothed into a signal that can be read by the Arduino Uno. This signal, with a value of 4.02V was inputted into the Arduino Uno. The circuit has achieved its primary goal.

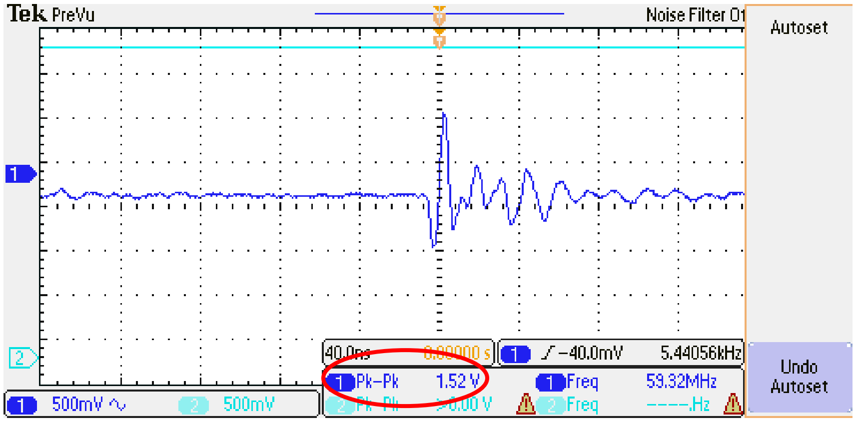


Figure 34: EMG circuit output 1

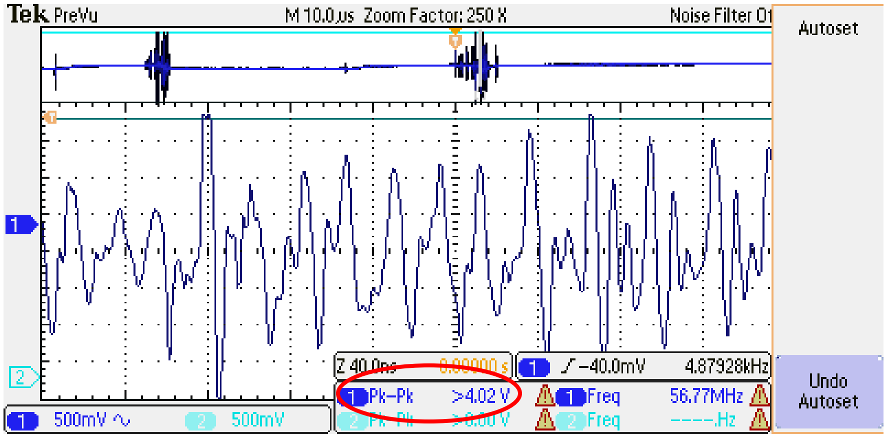
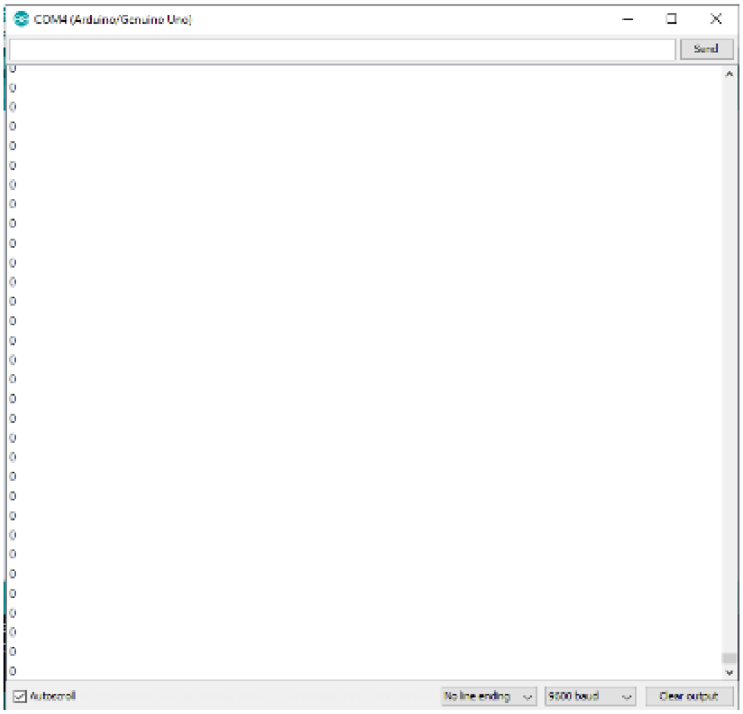


Figure 35: EMG circuit output 2

Completed Motor Circuit

As stated before, the motor circuit controls the movement of the X-R3 Robotic Arm and it is made up by an H-bridge. Figure 25 shows the motor circuit's connection. This circuit includes two p-channel MOSFETs, two n-channel MOSFETS, and two 4N25 optocouplers. The center of the circuit is the H-bridge which controls the robotic arm. The two optocouplers on the left and right of the circuit allows the H-bridge to communicate with the Arduino Uno. Three movements were activated by the circuit, forward (flex), reverse (extension), and braking.

When the arm was at rest, the output in the serial monitor was 0 and there was a steady signal as shown in figure 36 and figure 37 respectively. The robot did not move with these conditions.



```
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
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0
0
0
0
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0
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0
0
0
0
0
0
```

Figure 36: Serial monitor during braking

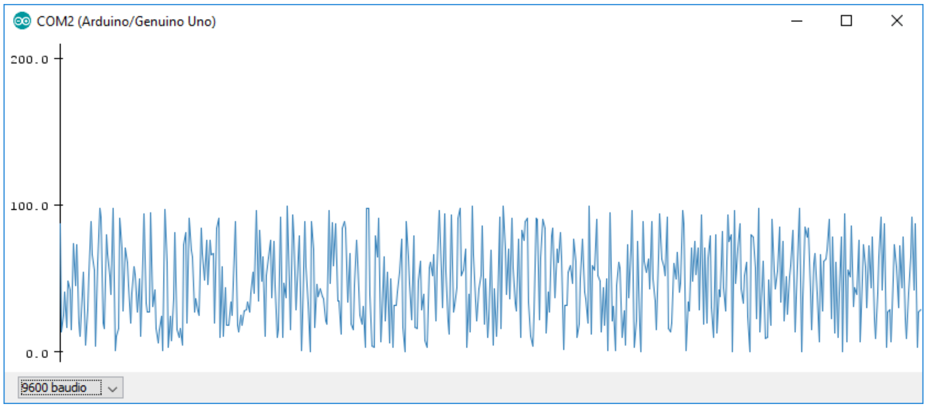
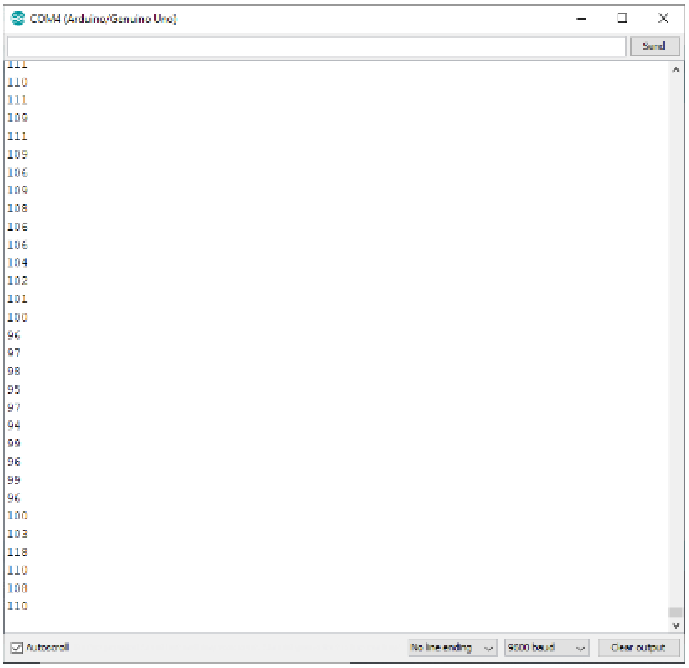


Figure 37: Serial plotter during braking

Forward motion was activated once the threshold, 100, established in the code, was reached. This is shown in Figure 39. At this point, the serial plot shows voltage spikes in the EMG signal as the muscle is being flexed. The robotic arm moved in the formation of a flex under these conditions. Figure 39 shows the response of the serial plotter when the bicep was being flexed once while the figure 40 shows the bicep being flexed multiple times.



```
111
110
111
109
111
109
106
109
108
106
106
104
102
101
100
96
97
98
95
97
94
99
96
99
96
100
103
118
110
108
110
```

Figure 38: Serial monitor when flexing

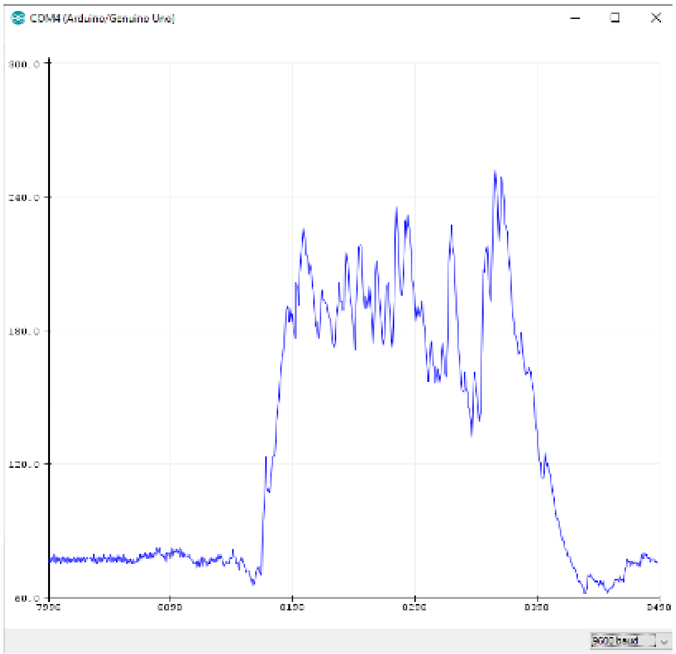


Figure 39: Serial plot during single flexing

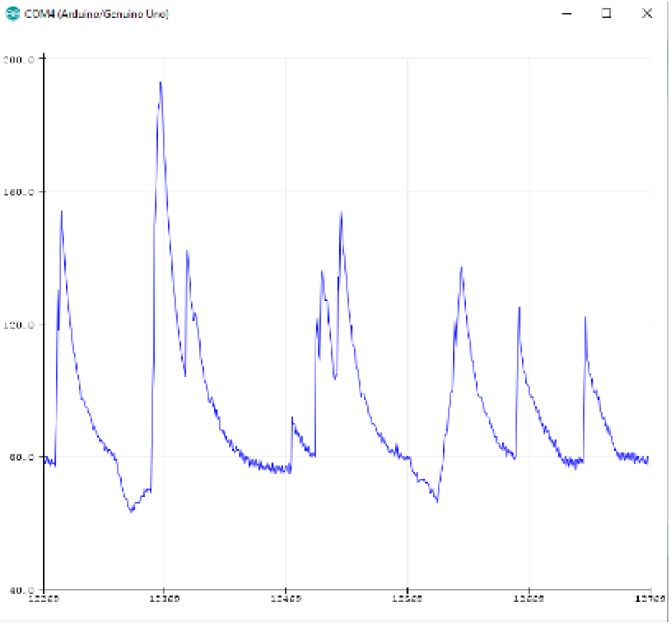


Figure 40: Serial plot of multiple flex

The reverse motion is activated by a push button. As long as the push button is pressed, the robotic arm moved in the reverse movement. The bicep muscle does not associate with the reverse motion of the arm. In order to eliminate the push button, another EMG circuit must be connected to the triceps brachii. The integration of the EMG circuit, the motor circuit and the Arduino Uno worked effectively and efficiently and achieved the overall goal.

Chapter 4: Conclusion

There were three subsystems that needed to be combined to create one system, the EMG controlled robotic arm. The first was the EMG circuit which took the EMG signal from the biceps, amplified, filtered, and smoothed the signal. The second was the motor circuit, which controlled the motion of the robotic arm. The final system was the X-R3 Robotic Arm. When all three systems were integrated together using the Arduino Uno, the EMG signal effectively moved the robotic arm. This eliminated the need to use a separate controller to operate the robotic arm.

At the beginning of this research, the question proposed was, can an EMG circuit be devised that has a critically detailed design which will capture the strongest spectrum of an EMG signal? After designing the EMG circuit and motor circuit and connecting it to the robotic arm and using a human arm to control the robot's movement, the answer is yes. The EMG circuit took the frequency range of 50 Hz – 170 Hz and used this information to dictate the movement of the robotic arm based on the user's bicep muscle. This is very important in medical devices such as the exoskeleton. For stroke patients or those who have been in a serious accident or have limbs that are no longer functional, this circuit design can help give patients movement in a disabled limb. Although the circuit used in this research was connected to a robotic arm, it can be implemented and integrated into an exoskeleton design. This circuit design has the potential to contribute to further improvements in existing prosthetics and exoskeletons. Because the strength of an EMG signal can differ from person to person, the potentiometer incorporated into the circuit design allows the user to control the gain in the final amplification stage. This versatility in this EMG circuit is another reason it can be beneficial to the medical industry.

Future Work

More design features can be added to this design that can make it more effective for a patient. Allowing for variable speed within the motor will produce a system that moves more human like. Currently, as the user flexes the bicep, the robotic arm moves in one speed. The addition of variable speed creates a more realistic product. In addition, to further enhance this project, instead of using the robotic arm, a lightweight frame, with a motor attached, can be designed to be placed around the human arm to form an exoskeleton. With this approach, one can study the effectiveness of the EMG circuit attached to an exoskeleton. From here, the possibilities are limitless.

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ACADEMIC VITA OF NICOLE HILL

EDUCATION

Bachelor of Science in Electrical Engineering
The Pennsylvania State University, Harrisburg, PA
Schreyers Honors College
Graduation: May 2020

SKILLS

Tools: TDR, VNA, Oscilloscope, Function Generator, Board Assembly/Testing, ARM Cortex, ATMega
Software and Programming: HFSS, Altera's MaxPlus II, Altera's Quartus, MATLAB, Qt, PSpice, Arduino, Confluence, Git, Bitbucket, Agile

WORK EXPERIENCE

Lockheed Martin Rotary and Mission Systems (Orlando, FL) **May 2019 – August 2019**

Systems Engineer Intern

- Developed flight application and graphical user interface in C++ and Qt software which aided in reducing the time a customer spent on troubleshooting with the software
- Created/executed test plans for software application ensuring every functionality of the application worked properly
- Established/updated design documentation of software application
- Implemented Agile software development method and contributed to Sprint planning

Penn State Applied Research Laboratory (State College, PA) **June 2018 – August 2018**

Embedded Systems Engineer Intern

- Established software/hardware foundation for development of a CAN BUS based embedded application in C++ which helped the hardware team determine the best microprocessor to invest
- Debugged and tested software/firmware, documented algorithms
- Practiced software safety, implemented configuration management tools

Department of Defense (Fort Meade, MD) **September 2015 - August 2016**

High School Work Study computer aid for the National Security Agency

- Familiarized with many coding languages (Python, Java, JavaScript)
- Aided in the programming of various apps
- Provided ideas and collaborated with teams of individuals working on various computer and system related projects

ENGINEERING EXPERIENCE

Security Alert System (Penn State) **October 2018**

- Designed and created a small-scale security alert system for a drawer using an Arduino Uno
- Coded an algorithm to create a push button password required for entry
- Generated an alert message that was sent wirelessly between two Arduino Unos through the NRF24L01 Transceiver Module when an incorrect password was entered

LEADERSHIP

President, National Society of Black Engineers

-Lead the chapter to awards which included *Event of the Year*, *Most Improved Chapter of the Year*, *Comeback Chapter of the Year*, and *Penn State Harrisburg Club of the Year*

Volunteer, So Others Might Eat (SOME)

Member, Diversity and Educational and Equity Committee (DEEC)